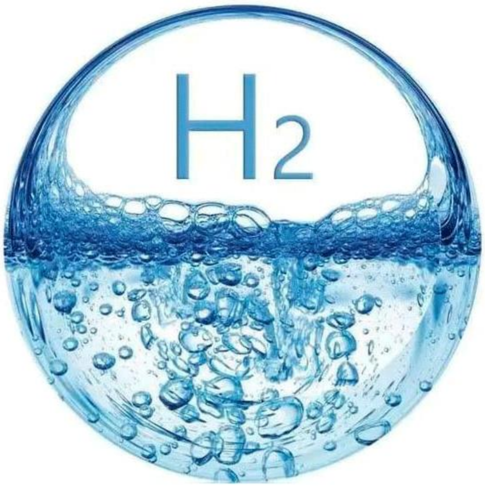
Utrecht University

An exploratory study on the integration of a renewable-powered electrolyser in a local energy system



Master's Thesis - Energy Science

GEO4- 2510

Faculty of Geosciences

Author

Thijs van der Woude (5549310)

m.r.vanderwoude@students.uu.nl

Supervisor Utrecht University

Prof. Dr. Madeleine Gibescu

Second reader

Dr. Sanne Akerboom

Supervisor Coinversable

Erwin Bisschop

Date: 11th of June 2021

Abstract

The current energy transition towards a more sustainable future opens opportunities for new types of energy systems in the Netherlands. A newly proposed system utilises electrolysers to convert locally generated renewable electricity into hydrogen for local industries. This multi-energy carrier (MEC) system serves as a cross-sectional solution to increase the amount of renewable electricity sources and reduce the fossil fuel use of local industries.

An explorative study is conducted to determine how a MEC system could be incorporated in the regulatory framework of the Netherlands and what would be the best design options. A literature review and interviews are conducted to determine how this system can exist within the regulatory framework of the electricity system in the Netherlands. With the results of these in consideration, the design options for both the electricity as the hydrogen part of the MEC system are evaluated.

Furthermore, a case study with a techno-economic analysis is conducted upon the first pilot project, which consists of an MEC system with a microgrid. The inputs and specifications of the local renewable electricity sources (RES), the electrolysers and the hydrogen consumers are used to build three models. These give the opportunity to determine the effect of the addition of hydrogen storage and the addition of dynamic electricity prices on the self-consumption rate and the fuel costs in a MEC system.

The literature review resulted in recommendations on how to incorporate the pre-determined requirements in the MEC system. The resulting recommendations are used to evaluate the proposed design options for both the structure and the market layer of the system. The advantages and disadvantages of each option are qualitatively assessed.

The results of the techno-economic analysis showed that hydrogen storage capacity is maximized to fulfil all the hydrogen demand. The size of the storage capacity is dependent on the flow rate of the electrolyser and the consumption pattern of the hydrogen consumers. The addition of hydrogen storage capacity and dynamic electricity prices to the system lower the fuel cost for hydrogen consumers. Dynamic electricity prices do have a negative effect on the self-consumption rate of the system. This is caused by the low price of a European Guarantee of Origin (GoO) relative to the fluctuations of the electricity price.

Preface

This document contains my master's Thesis. It is written as the requirement to graduate for the Master program Energy Science at the University of Utrecht. My goal was to work on a topic that was part of the integration of hydrogen into the energy systems of the Netherlands. I believe that the integration of hydrogen is an important development in the energy transition and therefore I wanted to contribute to it. I found this topic in the GROHW project, in which Coinversable takes part.

As the Thesis was written during the middle of the Covid-19 lockdowns of 2021, I learned a lot about working independently and with relatively limited input due to the lack of direct social communication. I am proud to have finished it under the difficult circumstances during the time of writing.

Acronyms and abbreviations

aFFR = automatic Frequency Restoration Reserve

AIB = Association of Issuing Bodies

BRP = Balance responsible party

BSP = Balancing service provider

EECS = European Energy Certificate System

FCR = Frequency containment reserve

GoO = Guarantee of Origin

GROHW = GReen Oxygen, Hydrogen and Waste heat (name of the pilot project in Deventer)

LHV = Lower Heating Value

MEC = Multi-energy carrier system

PEM = Polymer electrolyte membrane

PV = Photovoltaics

RES = Renewable Electricity Sources

TSO = Transmission system operator

Contents

1. Introduction

1.1 Societal background or problem

In 2019 the Netherlands presented their Climate Agreement in which their targets were set for the energy transition to combat climate change. Their main target for 2030 is to reduce the greenhouse gas production to 49% of the levels of 1990. This reduction will have to be achieved over five sectors: Built environment, mobility, industry, agriculture and electricity. The Climate Agreement stresses the importance of a cross-sectoral approach for reaching the target (Rijksoverheid, 2019).

One of the initiatives from the Climate Agreement is the ‘Regional Energy Strategies’ (RES). The RES identifies 30 important local energy systems the Netherlands, which each have to develop strategies to reduce their greenhouse gas emissions (Rijksoverheid, 2019). This initiative builds on earlier efforts that energy needs to be more locally generated and consumed. Local energy systems are stimulated to introduce more renewable energy sources (RES) while reducing their greenhouse gas emissions by both European and national directives (Netherlands Ministry of Economic Affairs, 2016)(European Parliament, 2018).

A possible cross-sectoral configuration for a local energy system is that excess of locally generated renewable energy is used for generating green hydrogen with electrolysers. Renewable electricity is increasingly generated from energy sources like photovoltaics (PV) and wind. This trend is present in the Netherlands where the PV and wind energy generation grew respectively 40% and 7% in 2019 (CBS, 2020). These energy sources are intermittent and therefore present challenges for the local electricity grid. The high variability of PV for example, can cause large fluctuations which must be balanced by the grid. The grid has to employ a lot of reserve power to balance these fluctuations in the energy production (Fares, 2015). Electrolysers can be used to balance the variability of the RES by adjusting the power consumption rate. This can reduce the magnitude of the grid problems and transform electricity into hydrogen.

The produced hydrogen by the electrolyser can be used by local consumers. The government in the Netherlands stimulates hydrogen projects as they its potential as a clean fuel for the industries. It can be used in the chemical and steel industry, heavy transport or district heating (Rijksoverheid, n.d.). Overall, this configuration can reduce the grid problems of intermittent electricity, while it also reduces the amount of greenhouse gas emissions by industries in local energy systems.

1.1.1 Project GROHW

Project GROHW (GReen Oxygen, Hydrogen and Waste heat) is a pilot project which is under development in Deventer by a coalition of local companies. The aim of the project is to explore the concept of creating a multi-energy carrier system where locally generated electricity is used to create green hydrogen with an electrolyser. This green hydrogen would then be used by local industries. Several local companies are interested in acquiring green hydrogen to improve their sustainability and are signed on to the project. Oxygen and waste heat from the electrolyser are also included in the energy system to improve the business case (E. Bisschop, personal communication, November 2020).

The overall goal is to test the feasibility of a creating a multi-carrier energy system, consisting of a local electricity system with an integrated green hydrogen system. The managing partner Witteveen + Bos is developing a method for integrating green hydrogen in local electricity systems with GROHW as its first test case. If GROHW is proven feasible, this method can also be used in a series of further projects in the province Overijssel (E. Bisschop, personal communication, November 2020).

A core element of this project is a trading platform that is being developed by Coinversable. The trading platform will be the market layer between the electrolysers, the RES and the hydrogen consumers. It is developed to communicate between participants and to ensure fair prices for the produced electricity and hydrogen. The idea of having the participants of the system use the platform to trade their energy production or consumption peer-to-peer (P2P) is also explored, if they can be flexible in demand. (E. Bisschop, personal communication, November 2020).

In the first phase of the project, several companies are contracted to buy the hydrogen from the electrolyser. The electricity will be generated from local wind turbines and solar parks. In a later phase, excess solar energy from households could also be included as input for the electrolyser. However, this is still dependent on how the government of the Netherlands implements the EU directives concerning aggregations of households (E. Bisschop, personal communication, November 2020).

1.2 Scientific background

Several topics which are relevant for project GROHW have been explored in scientific literature.

Intermittency problems of PV and wind energy

PV and wind energy are intermittent RES which means that their energy generation is not constant but dependent on factors like weather, season and the time of the day. The generation of wind turbines is dependent on the wind speed and the generation of PV is dependent on the amount of solar irradiance that the panels receive.

The variability of these sources can cause several problems for the grid and the electricity markets. In the past, PV and wind energy were not considered reliable enough to provide a significant contribution to the grid’s baseload in the past. The high fluctuations would cause balancing problems in the electricity grid (Sovacool, 2009). More recent studies indicate that solar and wind energy can complement each other’s production to some degree and thereby reducing this problem. However, even combined it still is not seen as a stable source (Prasad et al., 2017).

Another problem occurs when the renewable energy production is very high. This can cause a supply-demand mismatch, which can drop the market price of electricity to sometimes even below zero. The Netherlands witnessed its first day with an average negative energy price on the 13th of April 2020, due to a combination of reduced economic activity by the Corona virus outbreak and a high amount of renewable electricity production. Although the circumstances were not normal, the increasing amount of wind and PV energy sources in Central Western Europe will likely increase events like this (Laurent, 2020).

To counter these problems RES will have to be combined with storage systems or large-scale power to gas installations like electrolysers. This can help to reduce the supply-demand mismatch (Mesfun et al., 2017).

Hydrogen in industries

The use of hydrogen in large industries has been investigated. The qualities of hydrogen for different commercial purposes are described by Jain (2009), in which several use cases for decarbonization through hydrogen are highlighted. Ostadi et al. (2020) investigated how the process of creating hydrogen through electrolysis could be integrated within the chemical industry. The addition of hydrogen in different industrial processes is examined and compared with other methods. Sadeghi et al. (2020) evaluated the production cost and life cycle assessment of a solar powered electrolyser for the petroleum and gas industries. The main purpose of the research was to compare the cost of this method of producing hydrogen with methods that use fossil fuels.

Electrolysers in local energy systems

There have already been some case-studies on the use of electrolysers in local energy systems. Parra et al. (2016) evaluated the efficiency of hydrogen community energy storage in a low carbon energy system. Nojavan et al. (2017) present a model for determining the selling price of hydrogen in when utilising an electrolyser system in a smart grid. However, the hydrogen in both studies was used to generate electricity in fuel cell for the grid instead of industrial purposes.

A research from Estermann et al. (2016) investigates the feasibility of using excess solar power from low-voltage and mid-voltage grids to produce hydrogen. Together with carbon dioxide from biomass this would be used to produce synthetic methane. Although this results in a different end-product, it showcases the potential of using excess solar power from local energy grids.

1.3 Literature gap

The proposed utilisation of local renewable energy to generate green hydrogen for local industries is not featured in scientific literature. The GROHW concept explores a new type of hydrogen system where electrolysers supply many different hydrogen consumers. When coupled with local RES this will create a new multi-energy carrier system that could increase the cross-sectoral sustainability of the region.

This research will explore the regulatory and technical requirements that are encountered when implementing such a system in the Netherlands. As this system is the first of its type, many options must be explored on what would be the most optimal design.

1.4 Research question

The aim of this research is to propose a design for a multi-energy carrier system in the Netherlands which combines local electricity generation with hydrogen consumption and assess to what extent the design can improve the sustainability of local energy communities. The main research question is therefore:

How to integrate a renewable-powered electrolyser in a local energy system consisting of large energy producers and consumers and how could the sustainability of the system and economic welfare of the participants be improved?

To help answer the main research question the following sub-questions are formulated:

- *What are the requirements and designs for a local electricity system for large producers and consumers in the Netherlands?*
- *What would be the best designs for the electricity and the hydrogen system with a shared electrolyser?*
- *To what extent can storage capacity and dynamic electricity prices help the proposed system to maximize the consumption of local renewable energy?*
- *To what extent does the integration of storage capacity and dynamic electricity prices affect the economic welfare of participants in the new energy system?*

Other energy carriers which are created in the electrolysis process like oxygen and waste heat are not included in the scope of this research. Furthermore, local aggregations of households are also not included as potential energy prosumers.

1.5 Scientific relevance

The research provides an explorative study on the challenges and opportunities for a new type of energy system in the Netherlands. The national energy transition will put pressure on the local electricity systems. By exploring new system configurations, more knowledge and data is gathered about the challenges that need to be solved for a local system properly function within the larger energy system of the Netherlands.

Furthermore, this research can assess the feasibility and economic viability for local industries to participate in a local system with electrolysers that are contracted to supply multiple parties. As the system is a pilot project, a lot of interesting data can be gathered from the initial participants. Local industries that want to become more sustainable can then more easily determine if a system with a shared electrolyser is the best suited for them. If the GROHW concept proves to be economically viable, it can serve as a blueprint for future projects in the Netherlands.

1.6 System components

In order to better understand this new multi-energy carrier (MEC) system with electricity and hydrogen, some components are elaborated. These components are used for creating new energy systems with an electrolyser. For clarification purposes, the proposed energy system is referred to as the MEC system in the research.

1.6.1 Multi-energy carrier system (MEC)

The proposed MEC system's main goal is to implement an electrolyser and the attached hydrogen system into the local electricity system. The electrolyser has a central role in the system as the link between the electricity system and hydrogen system. Coinversable is responsible for the trading platform which facilitates the supply-demand matching and communication between the participants. Figure 1**Error! Reference source not found.** gives a visual overview of the system.

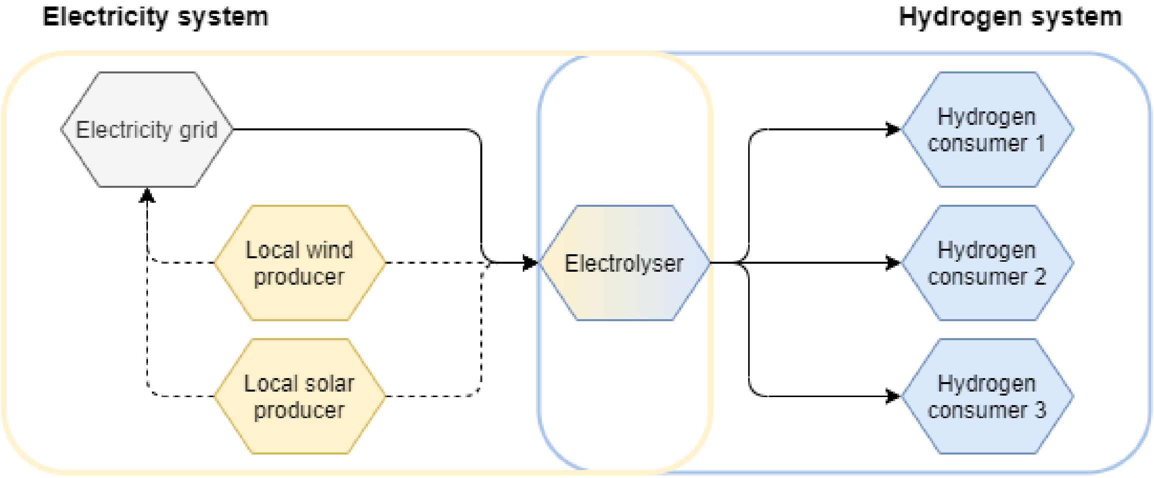


Figure 1: schematic overview electricity and hydrogen systems of the MEC system

The MEC system has several requirements that are pre-determined in consultation with Coinversable and other stakeholders in GROHW and listed below:

- Regulatory: the MEC system must function within the regulatory framework of the Netherlands.
- Green: the MEC system must only use green electricity for the creation of hydrogen.
- Technical: the technical constraints of the MEC system must be determined.
- Flexibility: the MEC system must be able to profit from fluctuations in electricity prices and hydrogen demand.

The requirements are used as base for the design of the MEC system.

1.6.2 Electrolyser

An electrolyser is a key technology in the proposed energy system. It uses electricity to split water into hydrogen, oxygen and waste heat. There are three types of electrolysers: Alkaline, Polymer electrolyte membrane (PEM) and Solid oxide (SOEC). SOEC electrolysers are not commercially available yet and therefore are not considered in this research (Gallandat et al., 2017).

The type of electrolyser used in the GROHW project was determined in December 2020. PEM-electrolysers with a stackable output were chosen. PEM-electrolysers are considered more suitable for working with variable loads from intermittent electricity sources than alkaline electrolysers (Barbir, 2005).

1.6.3 Trading platform

The trading platform is another key component of the proposed MEC system. It is currently under development by Coinversable. The trading platform serves as the market layer of the MEC system. It will facilitate the communication and trading between four types of participants: electrolysers, renewable energy sources (RES), hydrogen consumers and the local electricity grid.

The trading platform will be built on blockchain technology. The use of blockchain technology is motivated by three important factors:

- Blockchain is a very reliable and robust technology. This is important as energy systems are important for the safety and welfare of the participants within.
- Blockchain technology enables the platform to label energy sources. This is important as consumers are willing to pay a premium for green energy. With labelling they have certainty about the origin of the energy.
- Blockchain provides the option of trading energy P2P. Although no decision has been made on whether to implement this, the option can be explored at a later phase.

This research serves an explorative effort to find the requirements and design of the platform.

1.7 Outline

This thesis has the following structure: in Chapter 2 the methodology is explained on how the requirements and design of the MEC system are identified. Furthermore, the construction of the models for a case study on the GROHW system is elaborated. In Chapter 3, the results of the research on the requirements and design options of the MEC system are presented. Chapter 4 presents the data collection and processing for the inputs and parameters. Furthermore, the results of the optimization of the GROHW system are presented. In Chapter 5, the results are analysed and discussed. Chapter 6 gives a conclusion to the research.

2. Methodologies

This chapter describes the methodology used to answer the sub-questions. First, the requirements and challenges of the MEC system are presented, and their importance for the system is defined. Secondly, the design options on how electrolysers could interact with the local RES and grid in the electricity part of the MEC system are proposed. Thirdly, the options for designing the hydrogen part of the MEC system, consisting of electrolysers and hydrogen consumers, are proposed.

To answer the third and fourth sub-question, a techno-economic analysis on the current set-up of GROHW is conducted. The methodology behind the construction of the models to perform the analysis is explained. Lastly, it is explained how the models can be used to simulate the sustainability and economic performance of the MEC system.

2.1 Requirements energy system

The requirements for the proposed MEC system in the Dutch electricity system from Section 1.6.1 are listed in Table 1 below. The challenges of each requirement are presented and their importance for the system is explained. The challenges are answered by a literature review and interviews with stakeholders. Recommendations are given on how to build the MEC system with them in consideration.

Regulatory requirements		
Requirements	**Challenges**	**Importance**
Regulatory framework	- How and on what markets can electrolysers enter the electricity market? - How are direct connections with renewable energy sources legally possible? - Can electrolysers help with grid balancing? - What are the laws and standards on hydrogen trading?	The system must be able to function in the electricity markets of the Netherlands. The laws and standards for trading electricity are already well established. For project GROHW and successive projects it is important that the electricity trading system is operating according to the legal rules from European and national government. Adapting the rules of the MEC system to the directives and regulations is the first step in the design process. Also, the laws and standards of trading hydrogen must be determined if there are any. One of the key differences with electricity is that hydrogen does not already have a whole market system with platforms and standards in place.
Green energy	- How are green energy certificates traded now? - Are there hydrogen certificates? - What are the future developments for certificates trading?	Hydrogen consumers have required that all the energy that is used to create hydrogen is green. The regulations and standards on green certificates for electricity and hydrogen must therefore be explored.
System requirements		
Technical constraints	- What are technical specifications that can affect the energy system?	The technical constraints of the energy system must be identified for the market layer of the MEC system.
Flexibility	- Determine how the electrolysers can use dynamic prices	Electrolysers can reduce the price of creating hydrogen by taking advantage of dynamic

	when buying green electricity? - Determine to what extent hydrogen consumers can be flexible in their demand?	electricity prices. The system requirements to facilitate this must be identified. At the hydrogen demand side, there could also be opportunities to be flexible in demand, thereby buying hydrogen at a cheaper price. The requirements for these options must be identified.

Table 1: Requirements and challenges MEC system

2.2 Design electricity system

In this section, the possible configurations for the MEC system with the electricity grid are evaluated. The electricity part of the MEC system consists of local renewable electricity producers, one or multiple electrolysers and the local distribution grid as actors. All the actors must be able to trade with each other.

2.2.1 Design

In consideration of the regulatory and system requirements for MEC systems, the following configurations are evaluated to find the most suitable option for MEC systems to connect with RES:

- Administrative connection: the electrolysers are only connected to the local electricity grid. The connection to local renewable electricity producers is made administratively by buying their green certificates for the electrolysers.
- Microgrid: a microgrid with local renewable electricity producers connected with the electrolysers behind a shared connection point to the electricity grid. The RES are owned by another party than the electrolysers.

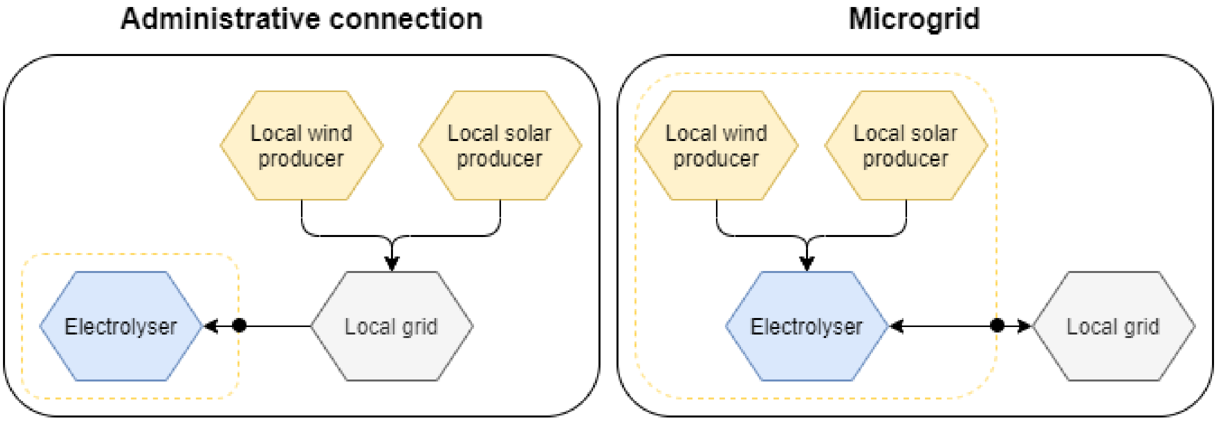


Figure 2: Configuration options for the electricity system

Figure 2**Error! Reference source not found.** gives a visual representation of the two options, where the dot represents the grid connection point. The option of buying or building a wind turbine or solar farm and connecting it to the electrolyser under the same owner is not considered in this research.

2.2.2 Trading platform for electricity

The requirements of the trading platform need to be determined. This depends on the choice of configuration and other recommendations from the regulatory and system requirements. In all cases, it needs to ensure that the prices of electricity are fair for the RES and the electrolyser.

2.3 Design hydrogen system

In this section, the possible configurations for the hydrogen part of the MEC system are explored. Figure 3 gives an overview of the actors in the hydrogen system. Based on the project plans of GROHW, the electrolysers have plans to install hydrogen storage capacity to temporarily store the produced hydrogen.

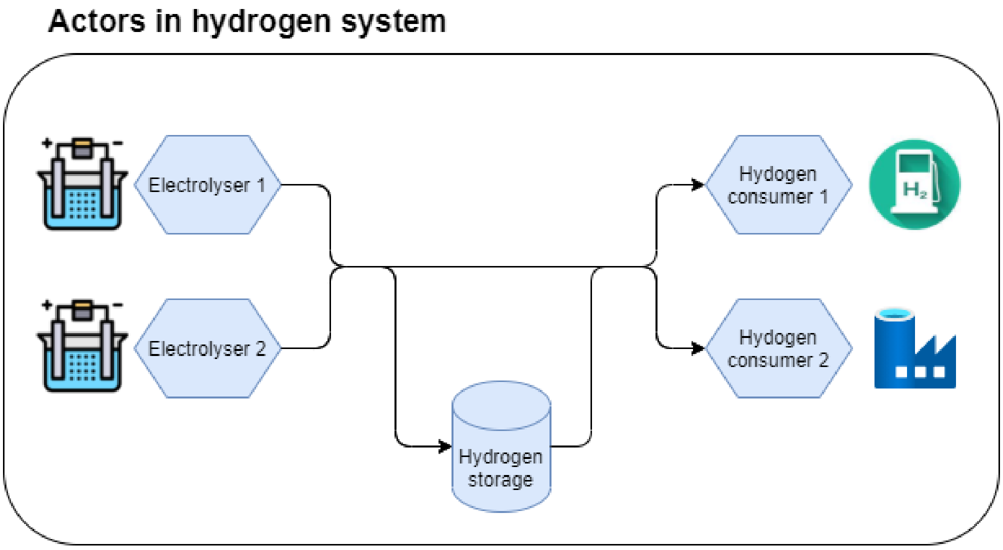


Figure 3: Overview structure and actors in the hydrogen part of the MEC system

2.3.1 Design

Two design options for the hydrogen part of the MEC system are considered being considered, where the main difference is the ownership of the electrolyser:

Option A: Electrolysers act as independent agents. Another market between the electrolysers and the hydrogen consumers is created. In this market the electrolysers are the sole sellers and hydrogen consumers are the only buyers. A market layer must be created to find the optimal solution for the participants.

Option B: Electrolysers act as agents of the hydrogen consumers. Electrolysers trade directly for hydrogen consumers on the electricity market. Hydrogen consumers can influence the bid prices of an electrolyser in the electricity market. This option could be more suitable when electrolysers are partly or fully owned by the hydrogen consumers.

Both options are qualitatively assessed and discussed with stakeholders. If possible, a decision is made on which is the most suitable for each situation.

2.3.2 Trading platform for hydrogen

In case of option A, there are two options considered for the market layer of the hydrogen system:

Fixed bilateral contracts: The hydrogen consumers agree on fixed contracts with the electrolysers. An example of this could be a contract between the electrolyser and the hydrogen consumer for a fixed premium per kilogram hydrogen.

Free marketplace: A marketplace will be established between the electrolysers and the hydrogen consumers on the trading platform. This gives hydrogen consumers the option to trade with the rights on batches of hydrogen.

Again, both options are qualitatively assessed and discussed with stakeholders. If option B is preferred by stakeholders, this section is not used.

2.4 Case study model construction

The second part of the research is focussed on the sustainability and economic performance of the MEC system. A techno-economic analysis is conducted in Python based on the initial set-up of the GROHW system in Deventer.

In order to build the models for the analysis, the set-up and the specifications of the participants of the GROHW energy system in the current development phase need to be determined. Figure 4 gives an overview of the energy and information flow on which the model is based.

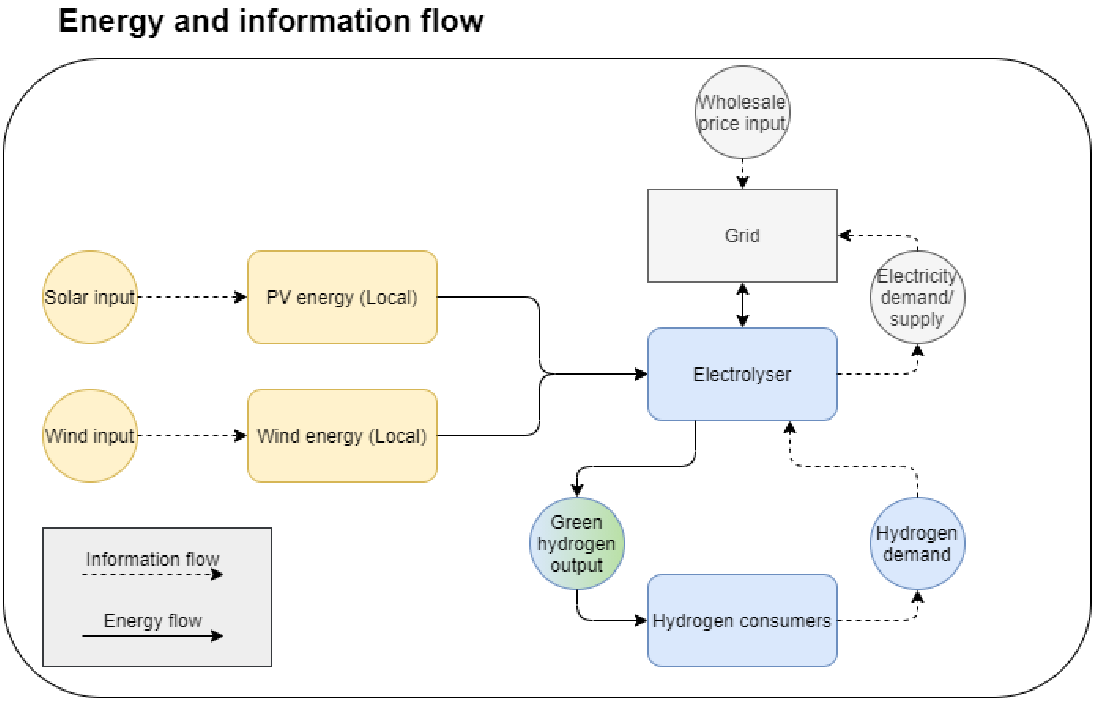


Figure 4: overview of energy and information flow in the model

2.4.1 Model type and set-up

The models for the simulation and optimization are built in Python 3.7.3. The tool used for the optimization model is Gurobi 9.1.1.

System set-up

The system uses a ‘brown field’ approach where the electrolyser, wind turbines and solar farms are already built. The components are based on the participants in the early development phase, found in Section 2.4. The set-up assumes that a microgrid is created between these components and that the electrolysers are owned by third parties.

Both electricity and hydrogen are converted to kWh to indicate the energy content. This is a suitable unit for the models as hourly timesteps are used.

Timesteps

The models are used to run a simulation and optimization of the hourly performance of the system in different periods. A typical three-week period of each season in 2020 is chosen to reduce the computing time. An hourly timeframe gives each three-week period 504 timesteps. The following periods are chosen from 2020:

- Winter: 01-01-2020 01:00 to 22-01-2020 00:00
- Spring: 01-04-2020 01:00 to 22-04-2020 00:00
- Summer: 01-07-2020 01:00 to 22-07-2020 00:00

- Fall: 01-10-2020 01:00 to 22-10-2020 00:00

2.4.2 Technical specifications electrolyser

The following technical specifications of the electrolysers are determined:

- Electrolyser: The amount, size and efficiency of the electrolysers need to be determined. Also, other specifications that can affect the hydrogen output need to be determined.
- Additional systems at the electrolyser: Storage tanks, pressurizers and other treatments that can influence the efficiency or output of the electrolyser need to be determined.
- Infrastructure: The transportation methods of hydrogen and the expected efficiency losses need to be determined.

2.4.3 Participants of the electricity system

The following aspects of local RES in the electricity system are determined:

- Type of renewable energy (PV, wind, biomass)
- Size (MW)
- Output (kWh)

If the output data of the RES in the four time periods cannot be obtained, the data is simulated with weather data in Python. Weather data from the closest KNMI weather station near Deventer is used as input to determine the electricity generation of the local solar farms and wind turbines in these periods. The KNMI provides the wind speed data in metres per second at 10 meters and the irradiance data in joule per square centimetre (KNMI, n.d.).

Wind

The Hellman exponential law to is used to calculate the wind speed at the hub height of the wind turbines (Bauelos-Ruedas et al., 2011). Equation 1 presents the used equation, where α is Hellman's exponent and h_0 is the height at 10 metres. The value of α is determined from Table 20 in Appendix A.

Equation 1

$$v_{hub} = v_{ground} * \left(\frac{h_{hub}}{h_0}\right)^{\alpha}$$

The wind electricity generation is calculated by using the corresponding power in the power curve of the wind turbine. The brand and model of the local wind turbines need to be determined to find the corresponding power curve.

PV

Equation 2 is used to convert the irradiance from joule per square centimetre per hour (I_{old}) to Watts per square metre (I_{new}).

Equation 2

$$I_{new} = I_{old} * \frac{10000}{3600}$$

The irradiance data is then used to calculate the AC power output of a solar panel at a static orientation by using the pvlib library in Python. If the static orientation and type of solar panels cannot be obtained from the solar farms, a typical tilt, orientation and efficiency is chosen.

Grid

The grid in this model is assumed to be an always available source of electricity. There is no maximum grid connection capacity used in this model.

Dynamic electricity prices

The price data from EPEX day-ahead market of 2020 is gathered from the ENTSO-E transparency platform (ENTSO-E Transparency Platform, n.d.).

2.4.4 Hydrogen consumers

The following demand characteristics of hydrogen consumers in the GROHW system are determined:

- Demand profile (energy consumption per timestep)
- Required condition hydrogen (pressure, temperature)
- Type of hydrogen transportation

As there are no chemical industries present in this project, the assumption is made that hydrogen is only used for heating processes. If the hydrogen consumers are unable to provide their future energy demand in kg hydrogen, their natural gas demand is used to calculate their energy demand.

To compare hydrogen with electricity in the model, the hydrogen is conversed to kWh, with $H_{customer,n,t}$ is the hydrogen demand of a customer in kWh. If the energy demand is expressed in volume of natural gas, Equation 3 is used to converse it to hydrogen in kWh. $H_{n.gas}$ is the energy demand in m^3 natural gas and the lower heating value (LHV) of natural gas is 31.65 MJ/ Nm^3.

Equation 3

$$H_{customer,n,t}(kWh) = H_{n.\ gas} * LHV_{n.\ gas}$$

If the energy demand is expressed in kg hydrogen, Equation 4 is used to converse it to hydrogen in kWh. The LHV of hydrogen is 120.0 MJ/kg.

Equation 4

$$H_{customer,n,t}(kWh) = \frac{H_{demand,t}\ (kg) * \ LHV_{H2}}{3.6}$$

The hydrogen demand of the customers in the GROHW system is combined into a single hydrogen demand profile. This is done with Equation 5.

Equation 5

$$H_{demand,t} = \ H_{customer\ 1,t} + H_{customer\ 2,t} + .. + H_{customer\ n,t}$$

2.5 Case study analysis

In this section, the research goals and the mathematic rules of the models based on the MEC system of GROHW are described.

2.5.1 Questions

The models of the MEC system of GROHW are used to answer the following two sub-questions:

- *To what extent can storage capacity and dynamic electricity prices help the proposed system to maximize the consumption of local renewable energy?*
- *To what extent does the integration of storage capacity and dynamic electricity prices affect the economic welfare of participants in the new energy system?*

The use of local RES is measured by the self-consumption rate. In case of GROWH, the local RES are assumed to be in a microgrid with the electrolysers. The economic welfare for participants is measured by the 'fuel cost'. Fuel costs are the base prices that the electrolysers pay for electricity and the hydrogen consumers for hydrogen, without any profit margins or operational costs added.

In order to answer the sub-questions, they are broken down into four questions that can each be answered by an optimization or simulation.

- *Q1: To what extent can the initial proposed system of GROHW run on self-consumption?*
- *Q2: What is the most optimal size of hydrogen storage for the initial proposed system and to what extent can it increase the self-consumption?*
- *Q3: What effect do dynamic prices have on the most optimal size of hydrogen storage and the self-consumption?*
- *Q4: To what extent does the integration of a hydrogen storage and dynamic prices affect the costs of electricity green hydrogen in the MEC system of GROHW?*

The system's current set-up is one without any hydrogen storage capacity. The self-consumption rate of the MEC system can be determined. This is important to determine to what extent the local RES can supply the projected hydrogen demand. The Q1 simulation model is used to determine this.

Energy storage is an important component for the GROHW system. There are no plans for an electricity storage system in the MEC system of GROHW. There is a plan for a hydrogen storage system near the electrolysers. However, the capacity of the hydrogen storage system is still undetermined. With an optimization, an attempt is made to find an optimal size for the storage capacity while trying to increase the self-consumption and decrease the unfulfilled hydrogen demand. The Q2 optimization model is used to determine this.

The effect of dynamic electricity prices on the system is determined. The use of dynamic electricity prices can lower the average buying price of electricity, but it could also affect the hydrogen storage capacity and the self-consumption rate of the system. The Q3 optimization model is used to determine these effects.

Lastly, the fuel costs of the systems are determined for all the three systems in Q4. This is important as the price of hydrogen for the hydrogen consumers is very dependent on the fuel costs. By comparing the fuel costs of the system without hydrogen storage with the system with hydrogen storage, one can determine how much it will cost to increase self-consumption. Q4 does not require a simulation or optimization model.

The performance of the system is simulated for a period in each season. This presents an opportunity to compare the results for different seasons and to identify bottlenecks.

2.5.2 Description of the models

This section describes the models that are used to answer the questions presented in Section 2.5.1. A different model is built to answer each of the first three questions (Q1, Q2 & Q3). Q4 is answered by using the results of the first three.

Indices and inputs

In order to explain the models and equations, the indices, variables and parameters are first introduced. Table 2 presents the indices that are used.

Index	Definition
$t \in T$	Timestep

Table 2: Indices

The models use four datasets as input. These are presented and defined in Table 3 below.

Dataset	Definition
PV generation	The PV generation of the solar farms
Wind generation	The wind generation of the wind turbines
Hydrogen demand	The combined hydrogen demand of the local industries
EPEX day-ahead prices	The EPEX day-ahead prices

Table 3: Data sets

Variables

The following variables are used in the equations and constraints of the models. These are presented and defined in Table 4.

Variable	Unit	Definition	Type of variable
E_H	kWh	Electricity demand by the electrolyser at a timestep	Dependent
E_{PV}	kWh	Electricity generated by PV units and used by the electrolyser at a timestep	Input (pre-determined)
E_{Wind}	kWh	Electricity generated by wind turbines and used by the electrolyser at a timestep	Input (pre-determined)
$E_{Grid,in}$	kWh	Electricity bought from the local grid and used by the electrolyser at a timestep	Decision
$E_{Grid,out}$	kWh	Electricity sold to the local grid at a timestep	Decision
$H_{PEM,out}$	kWh	The flow of hydrogen produced by the electrolyser at a timestep	Dependent
H_S	kWh	The amount of hydrogen stored in the hydrogen storage at a timestep	Decision
$H_{S\text{->}Demand}$	kWh	The flow of hydrogen moved from the hydrogen storage to the hydrogen customers at a timestep	Dependent
H_{Demand}	kWh	The total hydrogen demand at a timestep	Input (pre-determined)
p_E	€/kWh	EPEX day-ahead price at a timestep	Input (pre-determined)

Table 4: Variables used in the model.

Parameters

The parameters presented in Table 5 need to be determined to run the models. The use and methodology on how their value is determined, is explained below.

Parameter	Unit	Definition
$E_{H,\ max}$	kWh	The maximum input of the electrolyser in MW per hour
$E_{H,\ min}$	kWh	The minimum input of the electrolyser in MW per hour
η_{PEM}	%	The efficiency of the PEM electrolyser
η_{Other}	%	The combined efficiency of the after treatments of the hydrogen
p_{GC}	€/kWh	Price of a green certificate per unit of electricity bought at the grid
$p_{Penalty}$	€/kWh	Penalty of having to buy green hydrogen from outside of the GROHW system.

Table 5: Parameters used in the models.

$E_{H,\ max}$ and $E_{H,\ min}$ are the maximum and minimum electricity inputs of the electrolyser. These are dependent on the size and specifications of the electrolyser. The electrolyser efficiency parameter η_{PEM} is needed to converse the electricity to hydrogen. η_{Other} represents the efficiency of after treatments for hydrogen like pressurization and purification.

Lastly, the price of a green energy certificate (p_{GC}) and the penalty for buying green hydrogen outside of the system ($p_{Penalty}$) must be determined. The price of a green certificate is added to every kWh that is imported from the grid. This will cause the model to favour the RES in the microgrid over the grid. The penalty for buying green hydrogen is represents the price that hydrogen consumers would have to pay if they had to rely on an external supplier for the hydrogen.

Optimization parameters

The optimization models used for Q2 and Q3 have some extra variables and parameters for the storage capacity which are presented in Table 6 and explained below.

Name	Type	Definition
S_{tank}	Variable	Total storage capacity
p_{tank}	Parameter	Price of a kWh of storage capacity, ‘annualized’ for the chosen time-period.
$H_{s,\ t=1}$	kWh	Amount of hydrogen in the storage tank at the electrolyser at the start of the cycle

Table 6: Extra parameters for optimization

The price of a kWh of storage capacity (p_{tank}) needs to be calculated. First, the cost of a storage tank unit (C_{tank}) is determined by using the Equivalent Annual Costs (EAC) Equation 6. The EAC can be determined by dividing the investment cost by the annuity factor ($A_{t,r}$) with addition of the operating costs.

Because the optimization runs for three weeks instead of one year, the EAC also need to be converted for three weeks. Equation 8 is used to achieve this. In these Equations, r is the cost of capital and t is the number of years.

Equation 6

$$EAC = \frac{C_{Investment}}{A_{t,r}} + C_{Operating}$$

Equation 7

$$A_{t,r} = \frac{1 - \frac{1}{(1+r)^t}}{r}$$

Equation 8

$$C_{tank} = EAC * \frac{3}{52}$$

Finally, the cost of a storage tank unit is divided by the capacity of a storage tank unit ($H_{s,tank}$) with Equation 9.

Equation 9

$$p_{tank} = \frac{C_{tank}}{H_{s,tank}}$$

Lastly, a starting value for the amount hydrogen in the storage tank must be chosen.

Q1: GROHW without storage

Question to answer	*To what extent can the initial proposed system of GROHW run on self-consumption?*
Perspective	System
Components	- PV - Wind - Grid - Electrolyser - Hydrogen demand
Method	Simulation in Python
Outcome	Dataframe with resulting values of the variables of the energy balance for every timestep.

Renewable energy sources to electrolyser

$$E_{H,t} = E_{Wind,t} + E_{PV,t} + E_{grid,t}$$

Electrolyser to customer

$$H_{demand,t} = H_{PEM\ out,t} + H_{unfulfilled,t}$$

Electricity to hydrogen

$$H_{PEM\ out,t} = E_{H,t} * \eta_{PEM} * \eta_{other}$$

Combined energy balance equation

$$\frac{(H_{demand,t} - H_{unfulfilled,t})}{(\eta_{PEM} * \eta_{other})} = E_{Wind,t} + E_{PV,t} + E_{grid,t}$$

Constraints

$$H_{PEM\ out,t} \leq H_{demand,t}$$

$$E_{H,t} \leq E_{H,max}$$

$$E_{H,t} \geq E_{H,min}$$

$$E_{grid,t}, E_{H,t}, H_{unfulfilled,t}, H_{PEM\ out,t} \geq 0$$

Post processing

$$Selfconsumption = \frac{\sum_{t=1}^{T}(E_{Wind,t} + E_{PV,t} - E_{grid\ out,t})}{\sum_{t=1}^{T}(E_{Wind,t} + E_{PV,t} + E_{grid\ in,t} - E_{grid\ out,t} + \frac{H_{unfulfilled,t}}{(\eta_{PEM} * \eta_{other})})}$$

Q2: GROHW with storage

Question to answer	*What is the most optimal size of hydrogen storage for the initial proposed system and to what extent can it increase the self-consumption?*
Perspective	System
Components	- PV - Wind - Grid - Electrolyser - Hydrogen storage - Hydrogen demand
Method	Optimization with Gurobi in Python
Decision variables	- S_{tank} - $H_{unfulfilled,t}$ - $E_{grid\ in,t}$
Outcome	Storage size of a hydrogen tank. Dataframe with resulting values of the variables for every timestep.

$$MIN: \sum_{t=1}^{T} C$$

Objective function

$$C = S_{tank} * p_{tank} + \sum_{t=1}^{T} E_{grid\ in,t} * p_{GC} + H_{unfulfilled,t} * p_{Penalty}$$

In this objective function it is important to take a realistic value for p_{GC}, $p_{Penalty}$ and p_{tank} as the ratio between these parameters determines the outcome. The variable C is only used to let the optimization model perform. It gives no usable data about the cost of the system.

Energy balances

$$E_{H,t} = E_{Wind,t} + E_{PV,t} + E_{grid\ in,t} - E_{grid\ out,t}$$

$$H_{PEM\ out,t} = E_{H,t} * \eta_{PEM} * \eta_{other}$$

$$H_{s,t} = H_{s,t-1} + H_{PEM\ out,t} - H_{s\rightarrow demand,t}$$

$$H_{demand,t} = H_{s\rightarrow demand,t} + H_{unfulfilled,t}$$

System rules & constraints

$$H_{s,max} = S_{tank}$$

$$H_{s\rightarrow demand,t} \leq H_{demand,t}$$

$$E_{H,t} \leq E_{H,max}$$

$$E_{H,t} \geq E_{H,min}$$

$$H_{s,t} \leq H_{s,max}$$

$$H_{s,t} \geq H_{s,min}$$

$$E_{grid\ in,t}, E_{grid\ out,t}, E_{H,t}, H_{unfulfilled,t}, H_{PEM\ out,t}, H_{s\rightarrow demand,t}\ \geq 0$$

$$H_{s,1} = H_{s,504}$$

The last constraint is added to ensure that the optimization is not solved by emptying the storage tank in the last time steps.

Post processing

$$Selfconsumption = \frac{\sum_{t=1}^{T}(E_{Wind,t} + E_{PV,t} - E_{grid\ out,t})}{\sum_{t=1}^{T}(E_{Wind,t} + E_{PV,t} + E_{grid\ in,t} - E_{grid\ out,t} + \frac{H_{unfulfilled,t}}{(\eta_{PEM}\ *\ \eta_{other})})}$$

Q3: GROHW with storage and dynamic prices

Question to answer	*What effect do dynamic prices have on the most optimal size of hydrogen storage and the self-consumption?*
Perspective	System
Components	- PV - Wind - Grid - Electrolyser - Hydrogen storage - Hydrogen demand - Dynamic electricity prices
Method	Optimization with Gurobi in Python
Decision variables	- S_{tank} - $H_{unfulfilled,t}$ - $E_{grid\ in,t}$
Outcome	Storage size of a hydrogen tank. Dataframe with resulting values of the variables for every timestep.

$$MIN: \sum_{t=1}^{T} C$$

Objective function

$$C = S_{tank} * p_{tank} + \sum_{t=1}^{T} (E_{grid\ in,t} * p_{GC} + H_{unfulfilled,t} * p_{Penalty} + E_{H,t} * \ p_{E,t})$$

This model is almost identical to the model used in Q2. The same energy balances and constraints are used. The only difference is the inclusion of dynamic electricity prices ($p_{E,t}$) in the objective function of the model. This causes the model to search for the most optimal timesteps to buy electricity for the electrolyser.

Energy balances

The same as Q2.

System rules & constraints

The same as Q2.

Post processing

The same as Q2.

Q4: Prices of electricity and hydrogen

Question to answer: *To what extent does the integration of a hydrogen storage and dynamic prices affect the costs of electricity green hydrogen in the MEC system of GROHW?*

The following equations are used to find the 'fuel cost' of electricity and hydrogen for the systems without storage (Q1), with storage (Q2) and with storage and dynamic electricity prices (Q3).

System without storage (Q1)

$$C_{electricity1} = \sum_{t=1}^{T} (E_{Wind,t} * \ p_{e,t} + E_{PV,t} * \ p_{e,t} + E_{grid\ in,t} * \left(p_{e,t} + p_{GC}\right) - E_{grid\ out,t} * \ p_{e,t})$$

$$E_{supplied} = \sum_{t=1}^{T} E_{h,t}$$

$$p_{electricity1} = \frac{C_{electricity1}}{E_{supplied}}$$

$$C_{hydrogen1} = C_{electricity1} + \sum_{t=1}^{T} (H_{unfulfilled,t}) * \ p_{Penalty}$$

$$H_{supplied} = \sum_{t=1}^{T} H_{demand,t}$$

$$p_{hydrogen1} = \frac{C_{hydrogen1}}{H_{supplied}}$$

Systems with storage (Q2 & Q3)

$$C_{electricity23} = \sum_{t=1}^{T} (E_{Wind,t} * \ p_{e,t} + E_{PV,t} * \ p_{e,t} + E_{grid\ in,t} * \left(p_{e,t} + p_{GC}\right) - E_{grid\ out,t} * \ p_{e,t})$$

$$E_{supplied} = \sum_{t=1}^{T} E_{h,t}$$

$$p_{electricity23} = \frac{C_{electricity23}}{E_{supplied}}$$

$$C_{hydrogen23} = C_{electricity23} + S_{tank} * p_{tank} + \sum_{t=1}^{T} (H_{unfulfilled,t}) * \ p_{Penalty}$$

$$H_{supplied} = \sum_{t=1}^{T} (H_{demand,t})$$

$$p_{hydrogen23} = \frac{C_{hydrogen23}}{H_{supplied}}$$

The results will not provide the final price that electrolysers and hydrogen consumers will have to pay. However, it does give an indication of the differences between fuel costs of green electricity and green hydrogen in the different systems. To compare the differences between the systems, Equation 10 is used.

Equation 10

$$Difference = \frac{(p_{new} - p_{old})}{p_{old}} * 100\%$$

2.6 Data collection

The data and information for the requirements of both electricity and hydrogen systems are obtained from interviews with experts and desk research. Interviews with experts are aimed to be the primary source of information and desk research serves as a validation and additional source of data collection. If data cannot be acquired or is not known, assumptions are made. These are carefully substantiated.

Data for the simulation of the effectiveness and welfare is acquired from stakeholders in the project. Witteveen + Bos and other technical partners can provide all the technical data of the system and consumption data from potential hydrogen consumers. Together with data from available literature, this is used to build a model.

Candidates for interviews are the following:

- Experts/consultants from Witteveen + Bos: Witteveen + Bos is a large engineering consultancy which has a lot of expertise on technical, economical and regulatory areas. As they are the managing partner in project GROHW, they have a lot of useful data.
- Tennet: the Dutch TSO can provide valuable insight in the workings of the EPEX markets and the different options for integrating a hydrogen system in the electricity grid.
- Local hydrogen consumers: local hydrogen consumers are interviewed to assess the options and willingness for flexibility on the hydrogen demand side.
- Experts from universities: The Copernicus institute of Sustainable Development from Utrecht University can be a valuable source of information. Also, there are contacts with university of Twente at HanzeNet/Coinversable which can also be used.

3. Design requirements

In the first section, the results of a literature review and interviews on the challenges of the pre-determined requirements are presented. In the second and third section, the results are used to give advice on how to design and implement MEC systems with electrolysers in the Netherlands.

3.1 Regulatory requirements

This section evaluates the requirements and challenges of the MEC system with specific focus on the integration in the Dutch regulatory frameworks for energy. Advice is given on how the requirements and challenges can be met by the MEC system.

3.1.1 Access to dynamic electricity prices

Direct or indirect access to the electricity market is important to profit from dynamic electricity prices. The legal requirements and boundaries of the electricity market are well established in the Electricity Act 1998 of the Netherlands and the EU Directives 2019/943 and 2019/944. Electricity trading in the Netherlands is facilitated on the EPEX SPOT platform. The EPEX SPOT platform facilitates day-ahead and intraday trading between countries in Central Western Europe and the United Kingdom (EEX Group, n.d.). On this platform buyers and sellers can place bids with a minimum size of 0.1 MW for their electricity production and consumption (EEX Group, 2019).

To be allowed to trade on the European electricity markets, one must become a registered balance responsible party (BRP) or delegate the responsibility to an existing BRP. This requirement is stated in Article 5 of EU Directive 2017/943 on the regulations of internal trading markets. BRP’s are financially responsible for imbalances in the energy production and consumption of their assets. They must be registered to the national transmission system operator (TSO) to settle the financial responsibility according to Article 17 of EU Directive 2017/2195 (European Commision, 2017). TenneT is the national TSO in the Netherlands. A BRP communicates the planned energy use of its assets for the day-ahead to TenneT on daily basis with a 15-minute resolution. In case of imbalances in its actual production or consumption, a Dutch BRP has to settle this with TenneT (TenneT, n.d.).

For a company or holding representing a local energy system, which in its current plans only has two electrolysers with a maximum total output of 8 MW, it is not economically viable enough to become a BRP. The possible costs of the imbalance payments to TenneT would carry too much financial risk for a small company. A more suitable option would be to join an existing BRP and authorize them to buy electricity according to a buying scheme (A. Tijdink, personal communication, 2021).

The buying scheme can be constructed and send by the electrolysers based on the forecasted demand of the MEC system. The buying scheme must be sent more than one day-ahead of the time of use as the BRP will need time to combine all their customer’s buying schemes. Through this method, the electrolyser can have indirect access to the EPEX SPOT platform.

3.1.2 Balancing markets

Participation in the ancillary service markets for grid balancing could provide extra income for the owners of electrolysers. A PEM electrolyser can adjust its consumption of electricity within a time range of a few seconds. Therefore, it could be used as a demand-response unit.

To provide balancing services to the grid, a party with balancing units must be registered by the TSO as a balancing service provider (BSP) according to Article 16 of EU Directive 2017/2195 (European Commision, 2017). In the Netherlands, a BSP must send its bids to TenneT. A BSP must also be assigned to a BRP to settle imbalance payments (van der Veen & Hakvoort, 2016).

There are two types of balancing services that could be of interest for electrolysers: Frequency containment reserve (FCR) and automatic Frequency Restoration Reserve (aFRR).

FCR is the first reserve that is deployed after a frequency disruption. TenneT requires that the contracted bids automatically activate within 2 seconds and can be fully deployed in 30 seconds. Another requirement is that the reserves can be deployed for a maximum of 15 minutes. The minimal size of an induvial unit or group of units to be qualified for FCR is 1 MW (TenneT, 2021a).

aFFR is the second reserve that is deployed to restore a frequency disruption. The bids are contracted by TenneT for either upward regulation or downward regulation. TenneT requires minimum bids of 1 MW of electricity with a maximum start-up time of 30 seconds for the aFFR services market. The contracted bids has to be fully deployed within 15 minutes with a minimal ramp rate of 7% (or 10% if the bid is smaller than 4 MW) (TenneT, 2021b).

PEM electrolysers can be used in the balancing markets for FCR as the response time and size are within the requirements (Schmidt et al., 2017). An electrolyser can also be used for the aFFR if it is large enough to change the electricity input with at least 1 MW. A possible technical bottleneck for balancing services is the destination of the produced hydrogen. The hydrogen will have to be stored or directly sold. The availability of storage capacity at the electrolysers will therefore play an important role in the viability of using electrolysers in the balancing markets.

3.1.3 Connection to renewable energy sources (RES)

The MEC system aims to be connected to local RES either administratively or physically (or both). There are two realistic options to achieve this. The administrative option is acquiring green energy certificates for electricity imported from the grid. This option is further discussed in Section 3.1.4.

The option to be physically connected to local RES installations, is to create a microgrid with a shared grid connection to the public grid. In the microgrid configuration, a grid connection point with a single smart meter and assigned identification number (EAN) is shared between electrolysers, solar farms and wind turbines. In the Netherlands, this configuration is possible because of the existence of the MLOEA-arrangement (multiple suppliers at one connection point) (Juffermans, 2018). Under current regulations, solar farms and wind turbines can even legally share a grid connection point while not being located on the same property. This has been made possible due to an amendment in the Dutch Electricity Act of 1998 on 9 July 2020 (Ministerie van Economische Zaken en Klimaat, 2020).

The microgrid configuration has two advantages. First, the cost of having a grid connection point is shared between multiple parties. Even without an electrolyser, the combination of solar farms and wind turbines on one grid connection can reduce the size of the peak grid connection capacity because of the synergy between these RES (Kole, 2020) (Prasad et al., 2017). With an electrolyser, the produced electricity can be consumed within the microgrid. This could further reduce the size of the peak grid connection capacity, which especially for large grid connections can significantly reduce the fixed costs. As the exact size and number of the electricity participants in a MEC system can differ in each case, the reduced costs are difficult to quantify.

Secondly, the number of solar farms or wind turbines that can be implemented into the local grid is limited at several places in the Netherlands because of grid congestion. The DSO's are reinforcing the grid but in some places it could take 5 to 10 years for a large renewable installation to be connected (DNV GL, 2020). Reducing the grid connection size by creating a microgrid with an electrolyser could help to gain permits for connecting renewables more easily (A. Tijdink, personal communication, 2021).

To conclude, the microgrid configuration can be considered for the MEC system. However, the availability of the configuration is dependent on the existence of interested solar farms and wind turbines in the region. This could make it more challenging to construct.

3.1.4 Green certificates

Electricity from the grid is a homogenous good. This makes it impossible to determine the exact origin of the electricity that is consumed. In Article 15 of EU Directive 2009/28/EC, Guarantees of Origin's (GoO's) were commissioned to solve this problem (European Parliament, 2009). GoO's are certificates which are issued for a renewable energy producer to sell their greenness of their RES to other parties in the market (Wimmers & Madlener, 2020). By acquiring GoO's, the electrolysers of the MEC system can be administratively connected to (local) RES.

Within the EU, the Association of Issuing Bodies (AIB) created the European Energy Certificate System (EECS) to set up standards and regulations for the issuance and trading of GoO's for green electricity and gas. Each country in the EU has their own certifier institution that is responsible for controlling this process (Hulshof et al., 2019). The responsibility of applying green certificates for electricity produced in the Netherlands lies with the Ministry of Economic Affairs and Climate according to Article 73-77 of the Electricity Law 1998. They have mandated this task to CertiQ. CertiQ is an independent institution attached to the transmission system operator TenneT. They provide the EU-standardized GoO certificates to electricity producers for every renewable MWh of produced electricity in the Netherlands (Ministerie van Economische Zaken, 2014).

The GoO's can be traded on the EECS platform by traders recognized by CertiQ. Most BRP's are also registered as GoO traders (CertiQ, n.d.). This could provide options to acquire GoO's for electricity through the BRP contracted by the MEC system.

As of June 2021, there are no government mandated GoO's for hydrogen in the Netherlands. Some propositions have already been made on how a hydrogen GoO should work (Natuur & Milieu, 2019). On European level, the necessity for a clear and transparent regulation is also evident in advice reports from the European Committee of the Regions (Hone, 2020). This could indicate that regulation for hydrogen GoO's can be expected in the next few years.

An important advantage of using a trading platform that runs on blockchain technology, is the option to label energy from RES. The blockchain technology can create a tamper-proof label which can state the precise energy source and the type of energy. For the MEC system, it would be valuable to explore whether GoO's can officially be put on the blockchain technology that runs the trading platform. The electricity traded within the system would then have an official, tamper-proof GoO, which is valuable for all the participants in the system. The GoO's for hydrogen could still be transferred from electricity to hydrogen unofficially. If hydrogen gets official GoO's in the future, this step will already be in place in the system.

To conclude, to acquire official GoO's for electricity, a GoO trader recognized by CertiQ will have to be contacted. This does not have to be the same party as the BRP, but it would be convenient. Also, it is interesting to explore the possibilities of putting GoO's on a blockchain behind the trading platform and transfer it from electricity to hydrogen.

3.1.5 Aggregators

A market party which can offer a combination of electricity market access, balancing services and certificate trading is an aggregator. An aggregator is a relatively new concept in the European and Dutch electricity markets. As of this moment there is no general agreement on the precise description and function. The Dutch Ministry of Economic Affairs and Climate describes an aggregator as follows: a market party that couples of the production, consumption and flexibility of electricity producers and consumers into a legal entity and cleverly trades within its pool to reduce imbalances (Dutch Ministry of Economic Affairs and Climate Policy, 2016). The EU has set regulations in EU Directive 2019/944 on how market participants engaged in aggregation can operate within the European electricity markets (European Parliament, 2019).

The consumers and producers within the portfolio of an aggregator can range from small to industrial scale, depending on the type and scope of the aggregator. The aggregator can offer the combined flexibility of its portfolio to the electricity and imbalance markets. In the Netherlands, the role of aggregator can be combined with official roles in the electricity market. Aggregators are often registered as a BRP with direct access to the EPEX SPOT markets (Juffermans, 2018).

An aggregator-BRP can offer the electrolysers access to dynamic electricity prices. It can also serve as the BRP that is required for providing balancing services. Lastly, it can provide electrolysers the option to buy GoO's from RES within its portfolio (A. Tijdink, personal communication, 2021).

Joining an aggregator-BRP could be considered as an all-in-one solution for access to dynamic prices, balancing market services and certificate trading. It is difficult to determine which aggregator is best suited as a partner. Each aggregator has its own business model and portfolio. Advice for MEC systems would be to talk to aggregators who are active in their region and explore their options. An example of an aggregator-BRP that offers a combination of the by GROHW required services in the Netherlands is Next Kraftwerke.

3.1.6 Hydrogen framework

The legal requirements and framework of trading hydrogen are less developed in the EU and the Netherlands compared with electricity. As of June 2021, there are no hydrogen exchange platforms like the EPEX SPOT active in the Netherlands. However, this is expected to change soon.

The Dutch Ministry of Economic Affairs and Climate Policy has released an explorative report on the potential of a national hydrogen exchange backed by nationwide infrastructure of pipelines. In this report, the challenges and opportunities of creating such a system are explored (Ouden, 2020). A national hydrogen exchange with physical infrastructure, also called the hydrogen backbone in this report, could lower the costs of hydrogen by better matching the demand and supply. This can accelerate the energy transition for industries in the Netherlands and neighbouring countries. The hydrogen backbone will connect all the hydrogen hubs in the Netherlands, which will increase the diversity of supply and demand.

The report expects it will take at least 6 years before the hydrogen backbone is built. Until this time, they want to stimulate local initiatives to start exploring the potential of such a system. The following suggestions are made in the report:

- Create a local hydrogen hub with an exchange if there is enough market diversity to allow it.
- Start the trading of green certificates for hydrogen.
- Create a hydrogen price index to compare hydrogen prices between different local systems. This can help to determine a fair market price for green hydrogen.

The creation of a national hydrogen system is a very interesting development for the multi-carrier energy systems like GROHW. In a few years there could be an opportunity to attach the MEC system to the proposed national system.

3.2 System requirements

This section evaluates the system requirements and challenges of the MEC system that were determined by the stakeholders. Advice is given on how the requirements and challenges can be met in the MEC system.

3.2.1 Technical constraints

The technical constraints of the multi-energy system are centred around the electrolyser. This component is the link between the electricity system and the hydrogen system. Three constraints are identified by consultation with stakeholders and the literature review.

A first important constraint is that the electrolyser should always be operating except for maintenance. This is due to the 24-hour demand for hydrogen and avoiding the decrease in performance by reducing the number of cold-starts of the PEM electrolyser. The operating range is 10% to 100%, so the power input must always range between these limits (MTSA data). As a result, the electrolyser is required to buy at least 10% of the maximum electricity input at any given time, regardless of the price.

Secondly, the electrolyser owner must process the energy losses of the conversion and pressurization of hydrogen. PEM electrolysers have an conversion efficiency between 67 and 82% (Schmidt et al., 2017). Hydrogen has a very low density at room temperature (293 K) and normal atmospheric pressure (1 bar) as 1 kg of hydrogen has a volume of 11 m^2. For storage and transportation, it needs to be pressurized to at least 200 bar (Andersson & Grönkvist, 2019). The output pressure of hydrogen at the PEM electrolyser in GROHW is 34 bar, so a pressurizer is needed on site (MTSA data).

The electricity input must be converted to determine the available amount of hydrogen for consumers. There are two options:

- Determine the available hydrogen output directly from the electricity input by using the efficiency calculations.
- Measure the outputs of the electrolyser. The energy losses can be calculated administratively.

The first option could be more difficult to accurately determine because of the changes in efficiency under variable loads. However, the available hydrogen and its price can be calculated in advance if the electricity buying scheme of the electrolyser is known. This could expand the options for a local hydrogen marketplace. The second option is easier to execute, but this reduces the possibility for hydrogen consumers to buy hydrogen in advance.

The last important constraint is the maximum input and output of the electrolyser. The electrolysers in the MEC system have a maximum input and output depending on the chosen size. This could be a constraint for the participants as their hourly hydrogen consumption cannot be higher than the output of the electrolyser. Installing hydrogen storage capacity at the electrolyser is an option to solve this problem. This is further evaluated in Chapter 4.

3.2.2 Demand-side flexibility

The cost of the production of hydrogen is dependent on the price that is paid for the electricity inputs. To take full advantage of dynamic electricity prices, the MEC system needs to have demand-side flexibility. Demand-side flexibility is defined as ‘the ability of a customer to deviate from its normal electricity consumption (production) profile, in response to price signals or market incentives’ (European Smart Grids Task Force EG3, 2019). In the MEC system, demand-side flexibility could lower the overall cost of the production of hydrogen.

The amount of demand-side flexibility in buying electricity is dependent on the availability of the following factors:

- Accurate forecasts of supply and demand.
- Energy storage capacity in the energy system.
- Demand-response capacity from hydrogen consumers.

Firstly, demand-side flexibility is dependent on the time interval in which the supply and demand are known. Most hydrogen consumers estimate that they have a good forecast of their hydrogen demand one week before use (Hydrogen consumers, personal communication, 2021). Weather prediction models for forecasting renewable energy generation are also accurate for 15 days (IRENA, 2020). EPEX SPOT prices are not known a week before, but they are correlated with the renewable energy generation (Saraber, 2016). The use of forecasts can give the electrolysers the opportunity to develop the most optimal trading plan on when to buy electricity within the time interval of a week.

Demand side flexibility does require an energy storage system to either store electricity or hydrogen. Such a system would allow the electrolyser or the hydrogen consumers to buy energy at low demand and prices and store it for times when the demand and prices are higher. This would reduce the average buying price of electricity and therefore the cost of the hydrogen production. The effect of adding storage capacity is explored in the case study in Chapter 4.

Demand response is defined as ‘a set of demand-side activities to reduce or shift electricity use’ (Cui et al., 2014). This research explored if this concept could also be extended to reducing or shifting the hydrogen use of hydrogen consumers. The potential of demand-response capacity of hydrogen consumers was discussed with them. In general, hydrogen consumers are open for being more flexible in their hydrogen demand if it does not affect the business of their customers. However, they found it difficult to determine to what extent they can be flexible at this early phase of the project. None of the hydrogen consumers has any short-term plans for installing a hydrogen storage tank at their own location. On the long term, they envision having a small storage buffer in case of scarcity (Hydrogen consumers, personal communication, 2021). The uncertainty of the hydrogen consumers and the lack of consumer storage capacity limits the options for using demand-response activities.

To conclude, the amount of flexibility in the MEC system is dependent on the extent to which the factors are met. Accurate supply and demand forecasts and energy storage capacity are crucial if one wants to profit from dynamic electricity prices. Demand-response capacity from hydrogen consumers is not crucial, but it would increase the demand-side flexibility.

3.3 Design electricity system

This section aims to give advice on the design options for the MEC systems, given the requirements considered in Section 3.1 and 3.2.

3.3.1 Design

In Section 2.2, two design options are presented: administrative connection and creating a microgrid.

For the MEC systems, an administrative connection to renewables is a necessity. The electrolysers always need to be connected to the grid in case of low renewable electricity generation in a microgrid. As the electricity is required to be green, GoO’s must be bought to ensure this. This can be achieved by certificate trading as described in Section 3.1.4.

A microgrid could be created as an addition to the administrative connection. This could provide the electrolysers with potentially renewable electricity (depending on the power purchase agreements), which is generated by visible local RES. For a project that emphasizes local production and consumption, this can be very valuable in terms of visibility and social impact.

3.3.2 Trading platform for electricity

In case of an administrative connection, the electrolysers need to sign a contract with the BRP or aggregator for the electricity and GoO’s that are bought. They also need to provide the BRP or aggregator with a buying scheme for the electricity that they require and the possible deviations. The specifications of this buying scheme are dependent on the requirements of the BRP or aggregator.

In case of a microgrid, another power purchase agreement must be made between the electrolysers and the RES. The owners of the solar farms and wind turbines are third parties, so they will have their own interests. The assumption is made that the electricity price is approximately equal to the EPEX day-ahead price. Otherwise, solar farms and wind turbines have little economic incentive to sell their electricity to the electrolyser. Furthermore, the price of the missed green electricity certificates must be compensated by the local buyer. The electrolysers must be able to trade with the solar farms and wind turbines their own microgrid as well as the electricity wholesale market.

Another option for MEC systems would be to give the control of the electricity trading to the aggregator. An aggregators business model is to profit from arbitrage (Juffermans, 2018). They could have more advanced trading strategies to reduce the average electricity price for the electrolyser. In case of a microgrid, the RES could also join the portfolio of the aggregator.

3.4 Design hydrogen system

This section aims to give advice on the integration of the hydrogen system, given the requirements considered in Section 3.1.

3.4.1 Design

The decision between electrolysers being owned by independent agents (option A) and the electrolyser being directly owned by the hydrogen consumers (option B) is made in consultation with stakeholders.

Option A is chosen as the most ideal design for the MEC system of GROHW. This decision is made because shared ownership is not deemed very realistic at this phase of the project. The hydrogen consumers see project GROHW as an exploratory effort, they do not want to fully commit to hydrogen yet. Therefore, acquiring an electrolyser is not considered. Furthermore, option A reduces the chance of conflicts of interest between the hydrogen consumers. Hydrogen consumers have different demand profiles and reliance on hydrogen. This makes it difficult to determine a fair structure to share the ownership.

A possible disadvantage is the market power of the owner of the electrolyser. With no alternative to get hydrogen elsewhere, this could result in higher prices for the hydrogen consumers or a switch back to conventional fuels. Agreements will have to be made to prevent such a scenario.

3.4.2 Trading platform for hydrogen

In this section, the two options for the market layer between the electrolysers and the hydrogen consumers are explored.

Bilateral contracts between electrolyser and hydrogen consumers.

The use of bilateral contracts between the electrolyser party and the hydrogen consumers has several advantages and disadvantages.

An advantage of a bilateral contract is that the prices or price margin are fixed for both parties for the duration of the contract. This reduces uncertainty, which is useful with the assumed high investment cost of the hydrogen consumers as they have to switch from conventional fuels. Also, it takes less effort to participate as no frequent trade-related communication is involved.

A disadvantage is that a system with bilateral contracts is less scalable than an open marketplace. New participants will have to negotiate a new contract with the electrolyser agent that is already obliged to uphold their current contracts. The capacity to add new participants to the hydrogen system is therefore already reduced.

Requirements for an open marketplace.

The other option is to create an open marketplace between the electrolysers and the hydrogen consumers. The exploratory report for the Ministry of Economic Affairs and Climate Policy on the potential of a national hydrogen exchange is one of the few scientific data sources for this topic. This report determines that a functioning exchange for hydrogen should have the following requirements (Ouden, 2020):

- A standard location for a hub with open access for participants: Participants need to be able to join the hydrogen system or hub on both IT level as physical access. The transportation network capacity will play an important role for this.
- Diversified participants in the marketplace: To have a marketplace or exchange deliver the most optimal results for its participants, there must be enough diversity in the buyers and sellers. A high number of participants in the system with different demand and supply patterns improves the competition and reduces the market power of a single participant.
- A standardized product: Hydrogen can be produced in different specifications of pressure, temperature, purity and form. Uniform standards will have to be made to improve the tradability of hydrogen. Furthermore, the origin and production process of each unit of hydrogen needs to be clear. Guarantees of Origin can play an important role for this aspect. Lastly, standards and rules will have to be determined for mixing hydrogen with natural gas or other substances like ammonia.

For the GROHW system, the option of creating a marketplace between its participants in the hydrogen system does yield some advantages. An open market ensures that every consumer pays the same price for hydrogen. Furthermore, a system with a marketplace is more scalable for new participants.

However, there are some disadvantages for a marketplace. Firstly, the preference of the initial participants in the system must be taken into account. The hydrogen consumers see the first phase of GROHW as an opportunity to experiment with hydrogen. They do not want to commit to a full transition yet. Therefore, they might prefer bilateral contracts which make the costs more predictable. Secondly, the number of initial participants in the GROHW system is relatively low on the buyer side and limited to one or two parties on the seller side. This can lead to a monopoly or duopoly in the market.

To conclude, both options have their advantages and disadvantages. The choice for the GROHW system will have to be made when the plans are finalised, and the participants fully committed.

3.5 Overview

Table 7 presents an overview of the recommendations for MEC systems based on the results of the interviews and literature review of Section 3.1 to 3.4.

Regulatory requirements	
Requirements	**Recommendations**
Access to dynamic electricity prices	- Join a BRP. A BRP can give the electrolysers access to dynamic electricity prices.
Balancing markets	- Explore the options of providing FCR and aFFR services to generate extra revenue for the electrolysers
Connection to renewable energy sources	- Explore the option to create a micro-grid if there are interested parties in the region
Green certificates	- Contract a certificate trader to acquire GoO’s for the electricity that is imported from the grid. - Explore the option to officially put GoO’s on the blockchain of the trading platform.
Aggregators	- Explore the option of contracting an aggregator who can provide BRP, balancing market and certificate trading services. This all-in-on solution removes the necessity of contracting multiple companies.
Hydrogen framework	- Hydrogen trading is done bilateral. There is no hydrogen trading platform active in the Netherlands yet.

	- Explore the requirements made in the report from the Ministry of Economic Affairs and Climate to be included into the national hydrogen infrastructure.
System requirements	
Technical constraints	- Constraint 1: 24-hour operational requirement of the electrolyser. - Constraint 2: determine the most suitable method for processing the conversion losses of the electrolyser in the MEC system. - Constraint 3: the size of the electrolyser can be a limiting factor if no storage capacity is added to the system.
Demand-side flexibility	- Energy storage capacity and good forecast for supply and demand are essential to profit from dynamic electricity prices. - Demand response activities from hydrogen consumers are not crucial but would provide extra demand-side flexibility
Design electricity system	
Design	- An administrative connection is always necessary for MEC systems for times of low renewable generation. - A micro-grid would be a valuable addition, but it is dependent on the presence of interested RES.
Trading platform electricity	- In case of an administrative connection, only a power purchase agreement between the electrolysers and the BRP or aggregator needs to be made. - In case of a microgrid, a power purchase agreement must be made between the electrolysers and the RES. - Explore if it is desirable that an aggregator takes over the electricity trading activities.
Design hydrogen system	
Design	- Option A: an electrolyser owned by a third party, is a better configuration for the hydrogen system. This has less chance of conflict than option B, where an electrolyser is in shared ownership of the hydrogen consumers.
Trading platform hydrogen	- Bilateral contracts are an easy and reliable solution for the hydrogen system. However, the system is less scalable than a marketplace. This reduces the expansion possibilities of the system in the future. - An open marketplace can be an option. This option is more scalable. However, there are some bottlenecks in terms uncertainty among hydrogen consumers and market power of the electrolyser owners that need to be

Table 7: Overview of recommendations MEC systems

4. Techno-economic analysis

In Section 4.1, the results of the data collection for the variables and parameters of the model based on the GROHW system are presented. Section 4.2 presents the results of a techno-economic analysis made by the model.

4.1 Model construction

The case study of GROHW is based on the initial set-up in the first phase of the project. The electrolysers are assumed to be already built. This is motivated by the fact that the project is largely subsidized, cost distribution is undetermined and the lack of available price data. Local green electricity is bought from two wind turbines and two solar farms which are located near Deventer. These RES are assumed to be connected to the electrolysers within a microgrid, so they are able to directly deliver their electricity to the electrolysers. If the RES sources cannot provide enough electricity to satisfy the demand, electricity will be bought from the local grid. The hydrogen demand is derived from five local hydrogen consumers, based upon the participants in the first phase of the GROHW project.

4.1.1 Technical specifications electrolyser

The technical specifications of the electrolyser are derived from data of MTSA. This company develops and builds electrolysers ranging between 1 and 10 MW. The electrolysers are scalable with units of 1 MW. The specifications for a 1 MW unit are presented in Table 8.

Specification	**Value**
Efficiency (LHV)	74%
Nominal output	1.0 MW
Max input	1.35 MW
Min input	0,135 MW
Response time	Within seconds
Start-up time	Within minutes
Temperature hydrogen	70 C
Pressure hydrogen	34 bar

Table 8: Specifications electrolyser (MTSA) (Schmidt et al., 2017).

The current plan is to install two electrolysers in the GROHW system. Electrolyser 1 will be located at S-Park and will have a power output of 5 MW. Electrolyser 2 will be located next to the A1 highway with a power output of 3 MW. However, because the current plan is not definitive yet and it is unclear which electrolyser will supply which customer, the electrolysers are combined into a single electrolyser unit of 8 MW in the model.

There is no data about maintenance time. However, as the models only simulate a three-week period for each season, the maintenance time is not included into the scope of the research. The GROHW project management is exploring the possibility of a pipeline from the electrolyser at the S-Park to customers. However, this plan is not confirmed yet and it will take some years to build if approved. The short-term solution is transportation with trucks. The model assumes only trucks are used for transportation, which are also out of scope for this research.

4.1.2 Electricity system

The renewable electricity sources for local green electricity from the microgrid consist of two wind turbines and two solar farms in near Deventer.

The two wind turbines next to the A1 highway are considered to deliver electricity to the electrolysers. These are Enercon E92- type wind turbines with a hub height of 89 metre (Deventer Energie

Coöperatie, n.d.). Their specifications are listed in Table 21: Specifications Enercon E92 (Enercon, 2015) and Table 22 the Appendix.

The two solar farms considered in the GROHW project planning are Wilp and Heijmans A1. The solar farm at Wilp is privately owned and encompasses 117,416 solar panels (Solar Magazine, 2020). The solar farm Heijmans A1 is built within an interchange of the A1 highway. There is no data about the number of solar panels but the estimated surface will be 8,500 m^2 (Rijkswaterstaat, 2020). Table 9: Overview solar farms near Deventer gives an overview of the solar farms used in the model.

Solar farm	**Surface size**	**Number of panels**
Wilp	147,944.16 m^2*	117,416
Heijmans A1	8,500 m^2	6746*

*Table 9: Overview solar farms near Deventer (*calculated with the standard panel size)*

The data of the specifications of the solar panels in these parks were not available at the time of writing this report. Therefore, the size and generation of both solar parks are determined with a standard solar panel module. This is further explained in Section 4.1.3.

Table 10 gives an overview of all the electricity participants in the GROHW system.

Renewable energy type	**Unit**
Wind	Wind Turbine 1 (Enercon E92)
	Wind Turbine 2 (Enercon E92)
PV	Solar farm Wilp
	Solar farm Heijmans A1

Table 10: Overview all renewable energy sources for GROHW.

The hourly electricity generation data from both the wind turbines and the solar farms in the periods in 2020, were not available at the time of writing this report. Therefore, the data is simulated.

4.1.3 Simulation of RES generation

The generation of both the wind turbines and the solar farms are simulated in Python based on local weather data. The weather data from the KNMI station in Heino is used as it is the closest weather station to Deventer. The sets of weather data from the KNMI are converted to CSV files and added as input values to the Python models.

Wind generation

The wind data from the KNMI is used in Equation 1 from Section 2.4.3 to determine the windspeed at hub height in the different time periods. The exponent factor α is assumed to be 0.28 as the locations of the turbines are on the edge of Deventer.

With the windspeed at hub height, the corresponding power output can be identified in Table 22 in the Appendix. This yields in the power generation of an Enercon E92 wind turbine during the periods.

PV generation

The KNMI data only provides the global horizontal irradiance (GHI) in joule per cm^2 per hour. Firstly, the solar data is converted to Watts per m^2 with Equation 2 from Section 2.4.3.

The second step is to determine the direct normal irradiance (DNI) and the diffused horizontal irradiance (DHI). The Python model uses the *pvlib* library for this conversion. First, the function *pvlib.solarposition.ephemeris* is used to calculate the angles of the sun at Deventer. For the coordinates of Deventer, a latitude of 52.0849 and longitude of 5.1766 are used. This results in the zenith and azimuth of the sun per hour of the day. These can be used as input for the function *pvlib.irradiance.aoi* to calculate the angle of incidence. The most accurate and available decomposition models to calculate the DNI and DHI are the Erbs or the Dirint model (Lave et al., 2015). In this research, the Erbs model is chosen. The DNI and DHI are determined with the function *pvlib.irradiance.erbs*.

The third step is to determine the DC power generation. The *pvlib.irradiance.get_total_irradiance* function is used to find the total irradiance of a m^2 plane with the most optimal orientation for the Netherlands. An optimal orientation can be used because the solar panels in the solar farms are static. The optimal tilt angle is determined to be between 35 and 40 degrees (van Sark et al., 2013). In this research, an angle of 37 degrees is used with a southward orientation. The specifications data for the solar panels used in the solar farms, were not available at the time of writing this report. Therefore, a standard solar panel is used. The specifications of this panel can be found in Table 27 in Appendix A. The function *pvlib.pvsystem.sapm_effective_irradiance* is used to determine the effective irradiance. The function *pvlib.pvsystem.sapm_celltemp* is used to determine the cell temperature in the panel. The DC power of one panel is determined by using these inputs in the function *pvlib.pvsystem.sapm*.

Table 28 in Appendix A presents an overview of the pvlib functions and the non-default inputs that are used.

In the last step, the AC power of one panel is determined by multiplying the DC power with the efficiency equation of an inverter. This is done with Equation 11, based on an inverter model described by Driesse et al. (2008). The rated power of the inverter (P_0) can be determined by multiplying the maximum voltage (Vmp0) of the solar panel with the maximum current (Imp0). The nominal efficiency (η_{Inv}) is assumed to be 0.96.

Equation 11

$$P_{AC,t} = \frac{-0.0162 * P_{DC,t} * \eta_{inv}}{P_0} - \frac{0.0059}{\frac{P_{DC,t} * \eta_{inv}}{P_0}} + 0.9858$$

The power generation of the solar farms is determined by multiplying the AC power with the number of panels. In case of Heijmans A1, the 8,500 m^2 surface is first divided by the panel size to determine the number of panels.

Results of the RES simulation

The results of the simulation of the wind and PV generation consist of 504 timesteps. Therefore, the choice is made to only give a visual presentation of the first 5 days of each period, starting at 0:00. These are presented in Figure 5, Figure 6, Figure 7 and Figure 8. Table 11 presents an overview of the total RES generation.

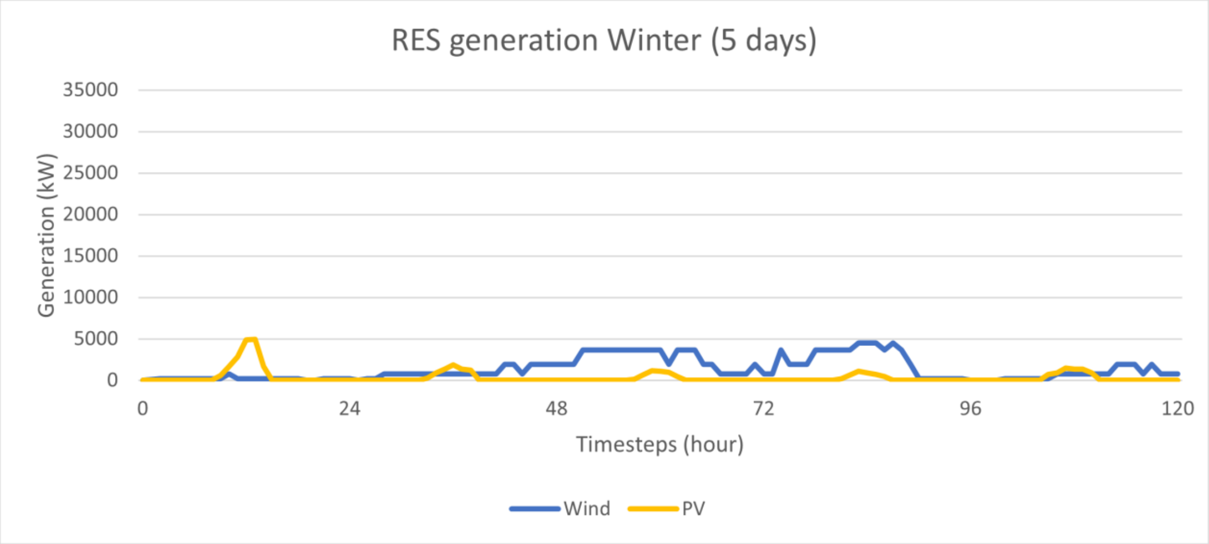


Figure 5: RES generation winter period.

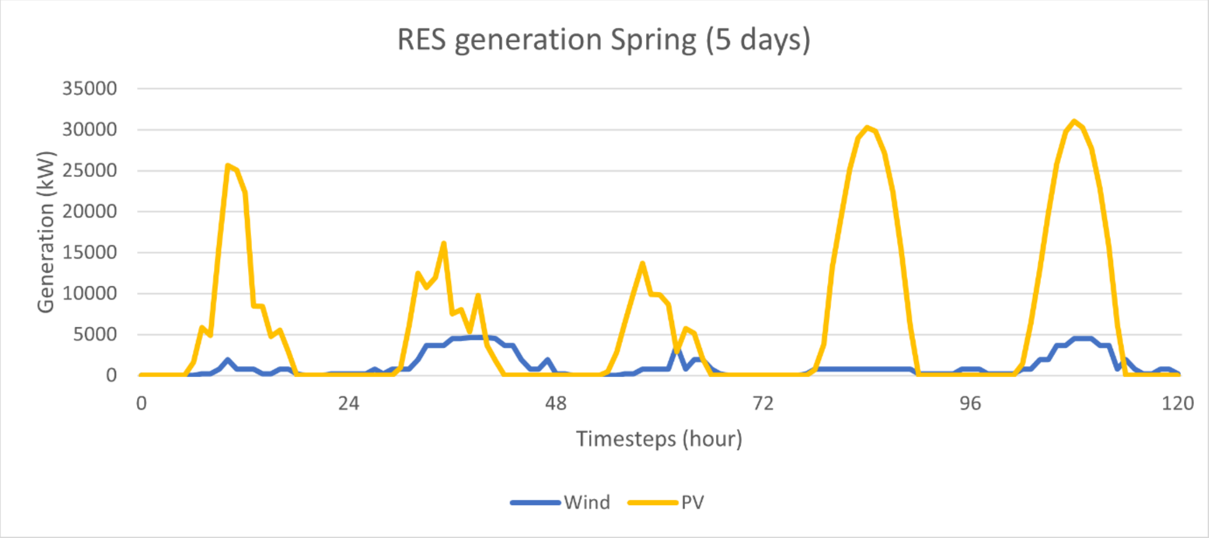


Figure 6: RES generation spring period.

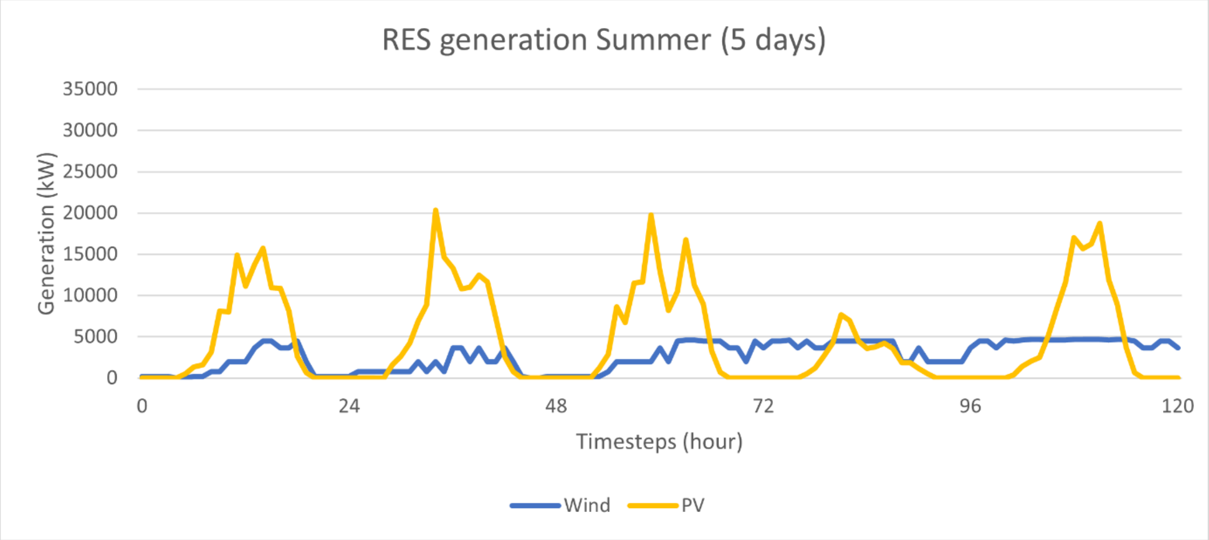


Figure 7: RES generation summer period.

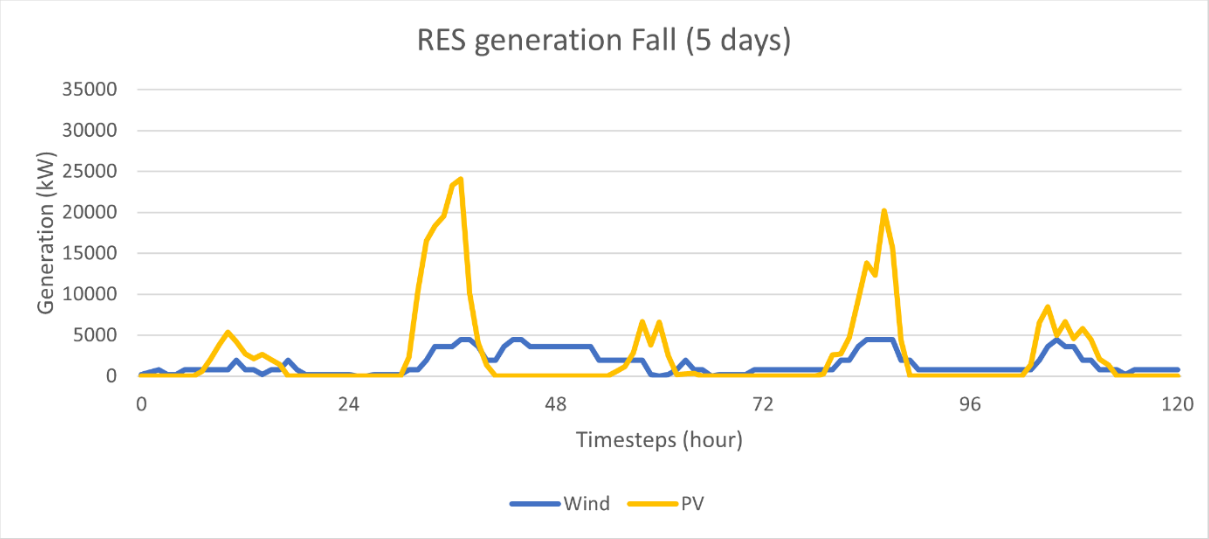


Figure 8: RES generation fall period.

Period	**Total wind generation** (kWh)	**Total PV generation** (kWh)	**Total RES generation** (kWh)	**Share Wind/PV**
Winter	866,591.60	464,660,03	1,331,251.63	65.1% / 34.9%
Spring	591,918.60	4,150,502.89	4,742,421.49	12.5% / 87.5%
Summer	530,527.20	2,899,357.43	3,429,884.63	15.5% / 84.5%
Fall	495,092.40	1,201,378.72	1,696,471.12	29.2% / 70.8%
Total	**2,484,129.80**	**8,715,899.07**	**11,200,028.87**	**22.2% / 77.8%**

Table 11: RES generation overview

The Figures 5, 6, 7 and 8 give an overview of the generation patterns of the RES. In the winter period, the wind generation is more dominant than the PV. In the other three periods, the PV generation is significantly more dominant.

As can be seen in Table 11, the PV generation contributes the most electricity to the system except in the winter. The wind generation is relatively constant through the four periods. The PV generation is very high during the spring and the summer period. A reason for the relatively high PV generation in the spring period compared to the summer period is the sunny weather in the first weeks of April 2020 (Laurent, 2020).

4.1.4 Dynamic electricity prices

The dynamic electricity prices of the EPEX day-ahead market are gathered from the ENTSOE–E transparency platform (ENTSO-E Transparency Platform, n.d.). Figure 9 gives a visual presentation of the prices in the first 5 days of each period starting at 0:00. The average price of each period is included into the figure.

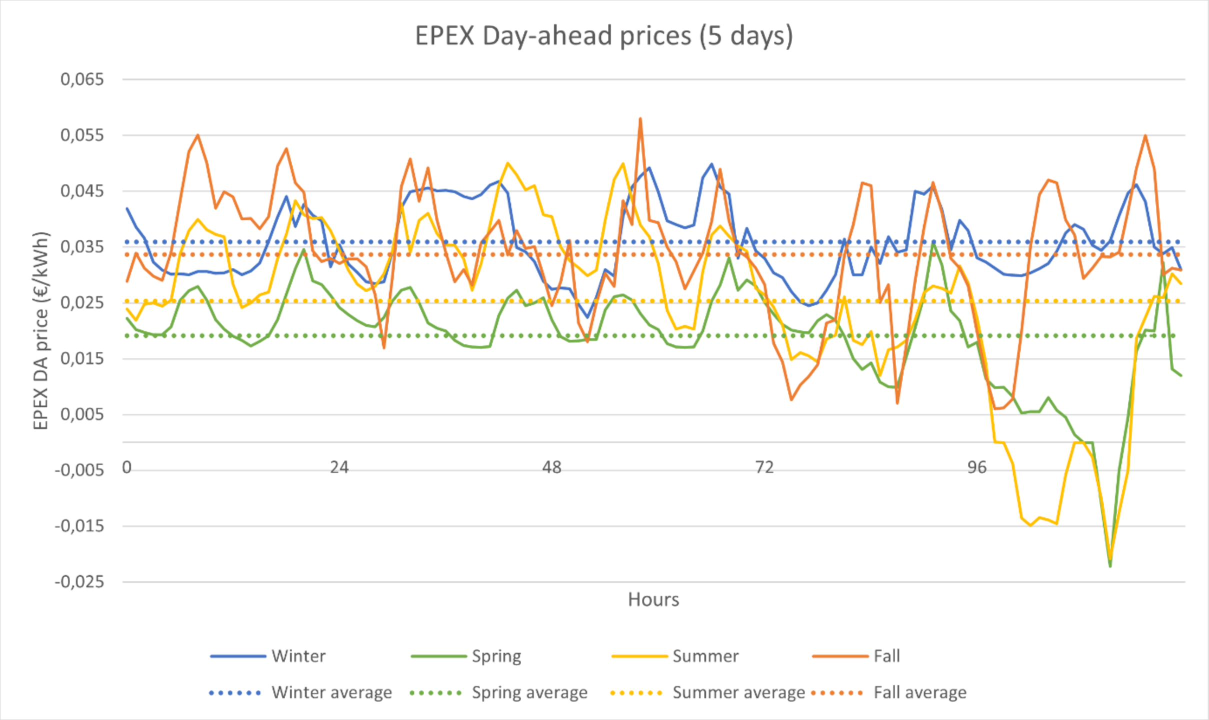


Figure 9: EPEX Day-ahead prices for a 5-day period in a season.

The winter period has a high average price and the lowest fluctuations. The spring and summer period have relatively lower average prices and high fluctuations. In some hours there are even negative prices. This is most likely caused by high RES generation in Central Western Europe at those hours. The fall period has a higher average price relative to the spring and summer period but the same high fluctuations.

4.1.5 Hydrogen system

The consumption data of hydrogen consumers from the first phase of project GROHW was acquired through Witteveen + Bos. In most cases, the acquired data is the consumption data of natural gas from 2018. Due to the lack of newer consumption data for the model, the assumption is made that the data is the same in 2020. The five hydrogen consumers are listed by their company characteristics below.

Asphalt factory

The asphalt factory in Deventer is one of the larger consumers in the GROHW system. They provided the hourly natural gas consumption for a full year. Their consumption has very high peaks and no clear pattern. This is caused by the industrial process and the demand of the road building industry.

Consumer goods factory

The consumer goods factory manufactures unspecified, non-energy intensive consumer goods. They want to fully replace natural gas for hydrogen at their production facility in Deventer. Table 25: Consumption data consumer goods manufacturer in the Appendix presents the monthly gas consumption acquired from the consumer goods factory. The recalculated hydrogen consumption is also added in the table. There is no data available from the consumption pattern, so the assumption is made that they require a constant hourly supply of hydrogen.

Industrial service provider

The industrial service provider wants to use hydrogen as a heating source for their office building. They could not give any data about their natural gas consumption. Therefore, their expected consumption was calculated based on the hourly outside temperature.

Steel manufacturer

The steel manufacturer currently has two furnaces consuming natural gas. Their aim is to rebuild these furnaces to work with hydrogen. They provided their monthly gas consumption data. This acquired data is presented in Table 26 in the Appendix. The steel manufacturer is assumed to have a constant demand.

Fuel station

The fuel station next to the A1 highway has an average daily consumption of 150 kg. Furthermore, they expect to need a constant supply between 9:00 and 17:00. This results in an hourly consumption of 12.5 kg between 9:00 and 17:00.

An overview of the hydrogen consumption made with these companies is presented in Table 12.

Company	**Hydrogen demand** (kg/year)	**Demand pattern**
Asphalt manufacturer	117,090	Irregular
Consumer goods factory	21,643	Constant
Industrial service provider	26,346	Irregular, weather based
Steel manufacturer	328,479	Constant
Fuel station	54,750	Constant between 7:00 - 19:00. No demand between 19:00 – 7:00.

Table 12: Overview of hydrogen consumers

Using Equation 3 and Equation 4 from Section 2.4.4, the consumption data is converted from kg to kWh. Figure 10, Figure 11, Figure 12 and Figure 13 give a visual presentation of the hydrogen consumption in kWh of the first five days of each period.

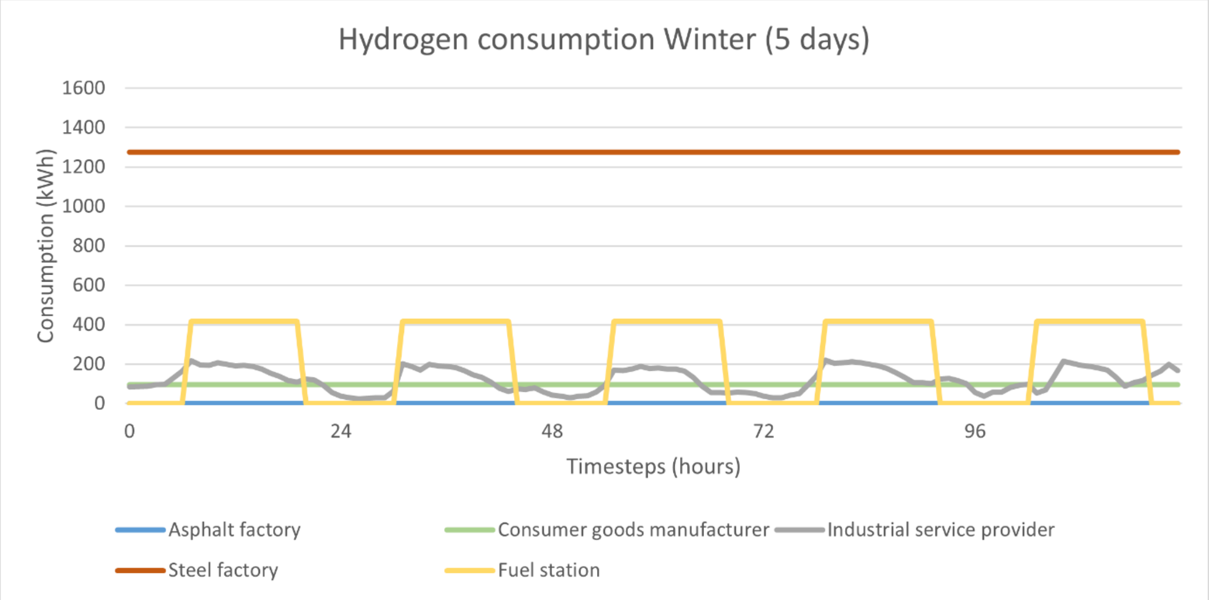


Figure 10: Hydrogen consumption winter

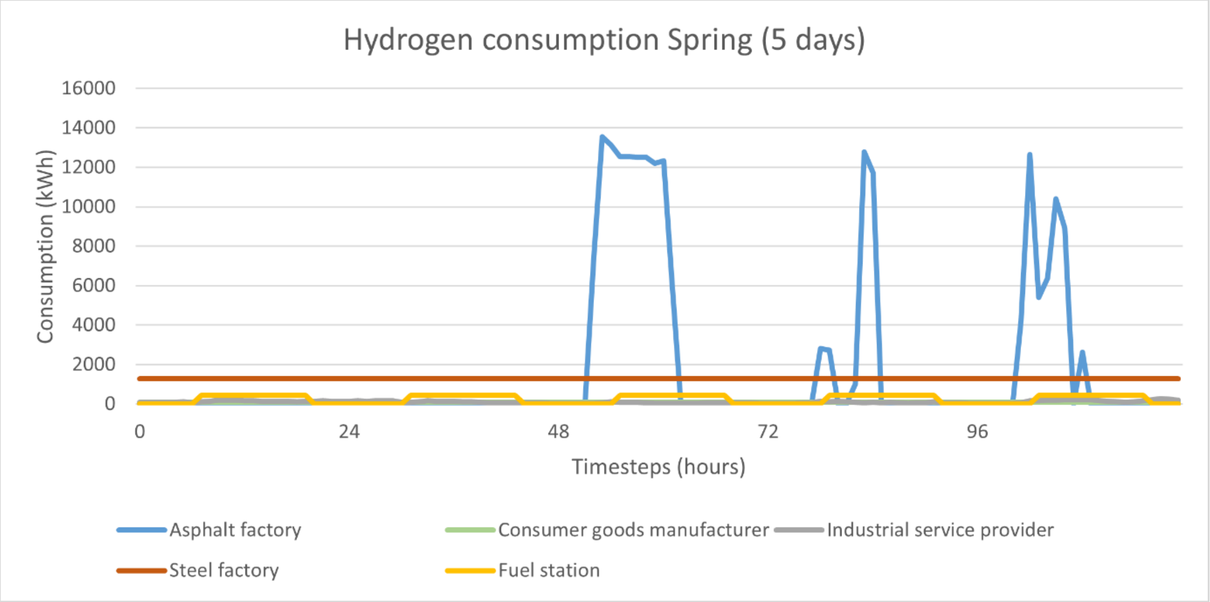


Figure 11: Hydrogen consumption spring

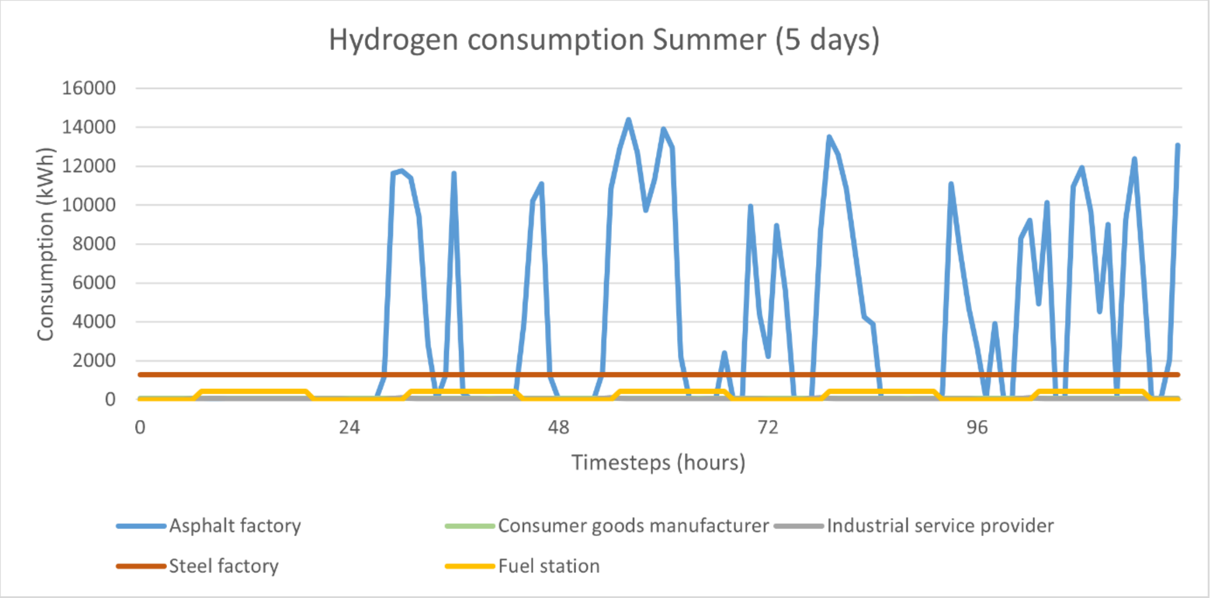


Figure 12: Hydrogen consumption summer

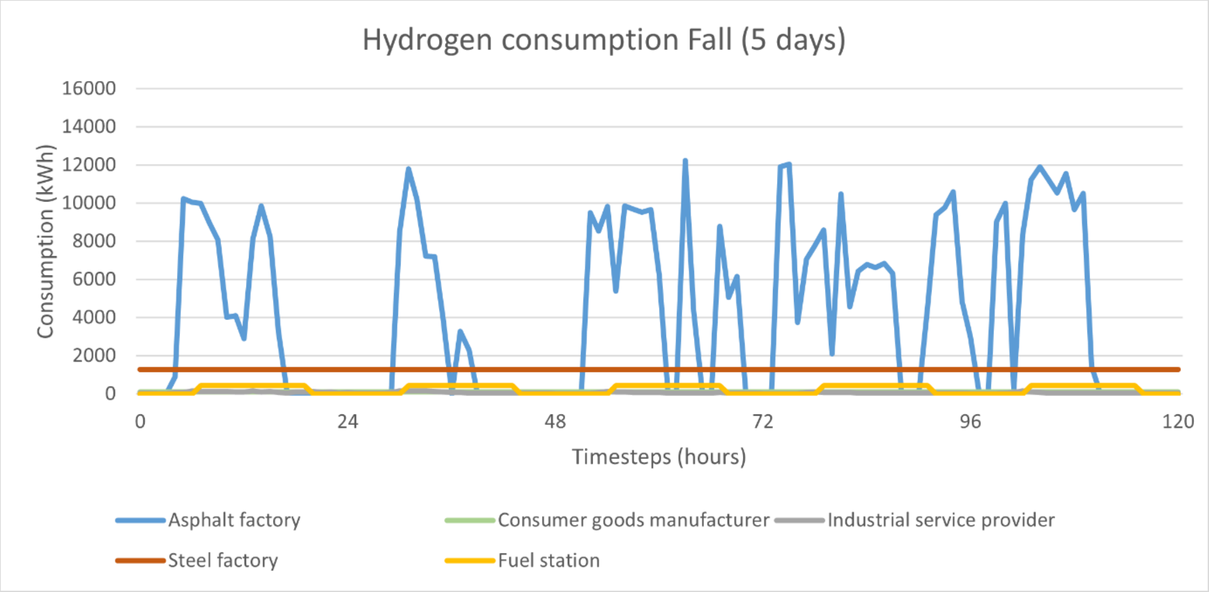


Figure 13: Hydrogen consumption fall

The data from Table 12 and Figures 10, 11, 12 and 13 shows that there are two large hydrogen consumers and three small ones. Especially the asphalt factory has a high influence on the demand pattern of the combined hydrogen consumers. This can be explained by the irregular demand for asphalt in the road building industry and the short heating period of the industrial process.

The asphalt factory was not active in the winter period as is illustrated in Figure 10. This can also be explained by the road building industry activity. Note that the y-axis of Figure 10 is not aligned with the other Figures to present the consumption pattern of the smaller hydrogen consumers.

4.1.6 Parameters

The values of the parameters elaborated in Section 2.5.2 are determined. Table 13 presents the results with the explanations below.

Parameter	Value	Unit	Definition
$E_{H,\,max}$	10810	kWh	The maximum input of the electrolyser in kWh
$E_{H,\,min}$	1081	kWh	The minimum input of the electrolyser in kWh
η_{PEM}	74	%	The efficiency of the PEM electrolyser
η_{Other}	90	%	The combined efficiency of the after treatments of the hydrogen
p_{GC}	0.001	€/kWh	Price of a green certificate per unit of electricity bought at the grid
$p_{Penalty}$	0.45	€/kWh	Penalty price of having to buy green electricity outside of the GROHW system.
$H_{s,tank}$	260.8	kWh	The size of a storage tank unit.
C_{tank}	65.12	€/unit	Price of a storage tank unit (‘annualized’ for three weeks).
p_{tank}	0.2497	€/kWh	Price per kWh of hydrogen storage capacity (‘annualized’ for three weeks).
$H_{s,t=1}$	$0.5 * H_{s,max}$	kWh	The starting value of the amount of hydrogen in the hydrogen storage

Table 13: Values of parameters.

Electrolyser

An electrolyser efficiency of 74% is used. The are no definitive plans about which after-treatments will be used. Therefore, only the energy loss required for compression is included into the model. According to the Department of Energy, compression requires 5 to 20% of the lower heating value (LHV) value (DOE, 2009). The efficiency factor of the after-treatments is therefore assumed to be 90%.

The maximum input of the electrolyser is based on the latest developments of GROHW, elaborated in Section 4.1.1. With a maximum output of 8 MW of the electrolyser, the input can be calculated by dividing the output by the efficiency. This results in a maximum input of 10.81 MW. The minimum input size is based on the minimum flow rate requirement of 10%. This results in a minimum of 1.081 MW.

Price GoO

The price of a GoO is based on data from the European prices. According to Commerg (2020), the prices dropped from 0.40 €/MWh to 0.10 €/MWh in 2020. However, 2020 was no ordinary due to a low energy demand during the Covid-19 pandemic. In a normal year ordinary European GoO's can be bought for around 1.00 €/MWh, but the price for a Dutch GoO ranges between 5.00 and 10.00 €/MWh (Mulder et al., 2019). No clear preference for a type of GoO has been stated by GROHW stakeholders. An assumed average price of 1.00 €/MWh or 0.001 €/kWh is used in the model.

Price hydrogen from external supplier

The price for buying green hydrogen from outside of the system could not be obtained. There are no suppliers near Deventer to deliver large quantities of green hydrogen. Therefore, the price is an assumption based on available sources. According to Kakoulaki et al. (2021), the production cost of green hydrogen in the EU is estimated at 5.09 €/kg. The sell price of green hydrogen in the Netherlands is estimated at 15.00 €/kg by Staalkaart groene waterstof (2020). The 15.00 €/kg is used in the model because it is the closest to a realistic market price. To find the cost in €/kWh, 15.00 is divided by 120.0 (LHV value of hydrogen in MJ/kg). The resulting 0.125 is then multiplied by 3.6 to convert it from €/MJ to €/kWh. This results in a value of 0.45 €/kWh.

Storage capacity

The size of a storage tank unit is based on data acquired from MTSA. The units have a volume of 270 L and a storage pressure of 350 bar. The energy content of the hydrogen in one storage tank unit can be calculated with Equation 12.

Equation 12

$$n = \frac{p * V}{R * T}$$

With p is 350 bar or 35,000,000 Pa. R is the gas constant 8.31. V is 270 liter or 0.27 m^3. T is the temperature in kelvin, which is assumed to be 293 K. This results in a value of 3,881.17 mol. The molar mass of H_2 is 1.016 g/mol. Multiplying the number of mol with the molar mass results in a mass of 7.824 kg. The energy content of a storage tank unit can be determined by multiplying the mass with the lower heating value of hydrogen (120.0 MJ/kg). This results in an energy content of 938.88 MJ. To converse MJ to kWh, the amount of MJ is divided by 3.6. This results in 260.8 kWh of energy in a storage tank unit ($H_{s,tank}$).

The price of storage tank unit is estimated at €6,000 (MTSA). This is without auxiliary equipment and infrastructure. Auxiliary equipment is assumed to cost an additional 10% or €600. The infrastructure cost consists mainly of the containers to store the storage tank units. The price of a 20ft container ranges between €2,000 and €3,000 (CARU Containers, n.d.). Due to the high safety requirements of storing hydrogen, the higher price range of €3000 is used in this research. Each container can store 50 storage tank units, so the extra infrastructure cost per storage tank unit is €60. The total investment cost per the storage tank unit with auxiliary equipment and infrastructure is estimated to be €6,660.00.

To determine if the costs per kWh are realistic, €6,660.00 is divided by 260.8 kWh. This results in a cost of 25.54 €/kWh. As a reference, the cost of a compressed hydrogen system is estimated 450 $/kg (370 €/kg) for a pressure of 430 bar according to Elberry et al. (2021). When converting the kg to kWh, this results in a cost of 11.1 €/kWh. The higher costs of the system of MTSA could be explained by the differences between the Dutch market and the global market.

To fairly use the price of a storage tank unit in the optimization model, it is 'annualized' for a three-week period. Equation 6, Equation 7 and Equation 8 from Section 2.5.2 are filled in below to show the calculations that are made. The operating costs could not be obtained, so an assumption of 4% of the investment costs is made. To determine the annuity factor, a value of 5% is assumed for r. The lifetime of all the equipment is estimated at 10 years according to Agostini et al. (2018). This results in an annuity factor of 7.72. Using this annuity factor in the EAC equation results in a value of €1128.80. This value is converted to be used for a three-week period. The resulting value is €65.12.

$$A_{t,r} = \frac{1 - \frac{1}{(1+0.05)^{10}}}{0.05}$$

$$EAC = \frac{6660}{A_{t,r}} + 6660 * 0.04$$

$$C_{tank} = EAC * \frac{3}{52}$$

Finally, Equation 9 from Section 2.5.2 is used to determine the price of a kWh of hydrogen storage capacity.

$$p_{tank} = \frac{C_{tank}}{H_{s,tank}}$$

The amount of hydrogen in the storage at the start of the optimization ($H_{s,t=1}$) is assumed to be 50% of the maximum installed capacity.

4.2 Results

In this section, the results of the models are presented. The RES generation presented in Table 14 is the same for every optimization in order to make the results comparable.

Results Q1

First, the operational results of the MEC system of GROHW without hydrogen storage are determined with the Q1 simulation model from Section 2.5.2. Table 14 presents these results.

Season	**RES generation** (kWh)	**Electrolyser demand** (kWh)	**Total import from grid** (kWh)	**Total export to grid** (kWh)	**Total hydrogen unfulfilled** (kWh)	**Self-consumption** (%)
Winter	*1,331,251.63*	1,332,028.01	507,361.95	506,585.57	0	61.91
Spring	*4,742,421.49*	2,130,599.57	722,024.12	3,333,846.04	421,890.32	50.96
Summer	*3,429,884.63*	2,686,735.09	985,313.16	1,728,462.70	674,007.36	46.00
Fall	*1,696,471.12*	3,064,392.07	1,990,536.66	622,615.71	682,286.34	26.26

Table 14: Results of Q1 model

In the winter period, the RES generation is almost equal to the electrolyser demand. However, the self-consumption rate is only 61.91. This means that there is a supply demand mismatch on the hourly timesteps. The fact that there is no hydrogen unfulfilled is caused by the lack of activity of the asphalt factory. All the other hydrogen consumers can be supplied within the maximum flow capacity (8 MWh of hydrogen) of the electrolyser. The high price of hydrogen unfulfilled causes the model to use this option.

In the spring and summer periods, the electrolyser demand is a lot higher due to the asphalt factory being active. There is hydrogen unfulfilled in both periods. This is mainly caused by the high demand peaks of the asphalt factory. The electrolyser does not have enough maximum flow capacity to supply this demand. This can be seen in Figure 14, where the hydrogen demand of first 5 days of the spring period is plotted.

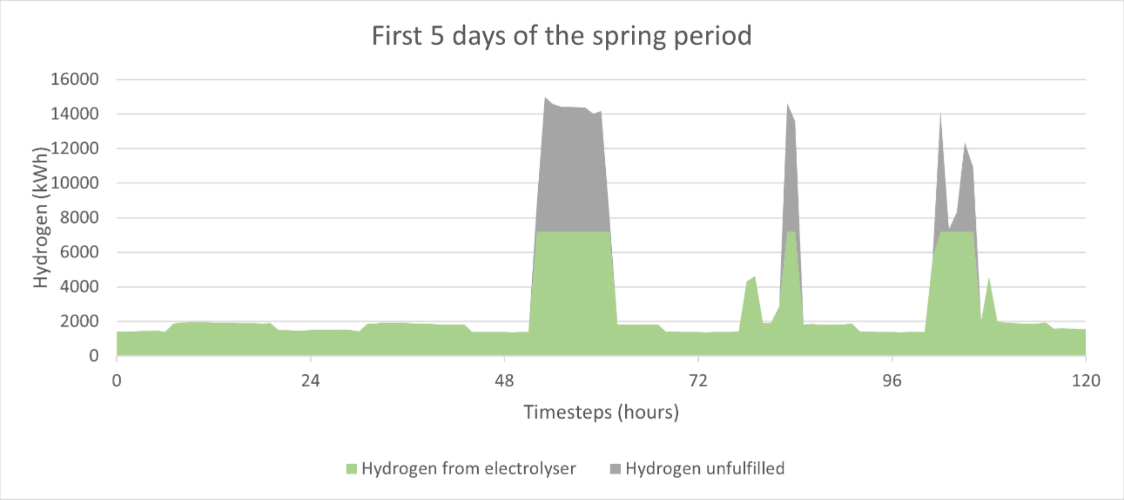


Figure 14: Green hydrogen demand from spring period

The relatively higher RES generation of the spring period does not cause a large increase in the self-consumption rate compared to the summer period. The cause of this is the supply-demand mismatch between RES generation and demand.

The fall has a relatively low self-consumption rate compared to the other seasons. This is caused by a high hydrogen demand and low RES generation. A lot of electricity is imported from the grid to compensate this.

Results Q2

The operational results of the MEC system of GROHW with hydrogen storage are determined with the Q2 optimization model from Section 2.5.2. Table 15 presents these results.

Season	**Electrolyser demand** (kWh)	**Total import from grid** (kWh)	**Total export to grid** (kWh)	**Hydrogen storage capacity** (kWh)	**Total hydrogen unfulfilled** (kWh)	**Self-consumption** (%)
Winter	1,332,028.01	507,361.95	506,585.57	0	0	61.91
Spring	2,762,996.06	535,452.46	2,514,877.89	60,187.24	0	80.62
Summer	3,697,761.00	1,267,299.86	999,423.49	109,150.84	0	65.73
Fall	4,087,827.78	2,632,362.93	241,006.27	147,888.80	0	35.60

Table 15: Results of Q2 model

The winter period has the same results as Q1 due to the lack of storage. It is cheaper to buy electricity with GoO's from the grid than to build a hydrogen storage system. It can be concluded that the price of a GoO is not high enough to justify the installation of hydrogen storage capacity.

The model installs storage capacity for the spring, summer and fall period. This motivated by the high penalty of buying hydrogen from outside the system. The storage capacity is optimized to the point that this is prevented.

The spring, summer and fall periods have a significantly higher self-consumption rate. This caused by the high RES generation in combination with the hydrogen storage. This makes it possible to store more hydrogen during times of low demand.

Another first difference with Q1 is the higher electrolyser demand. This is caused by the additional creation of hydrogen, which would otherwise be bought outside of the system.

The amount of electricity exported to the grid is higher than the amount that is imported during the spring and summer period. A closer look at the data reveals that export only occurs during times where the maximum flow capacity of the electrolyser is reached. The maximum flow capacity of the electrolyser is still the most important bottleneck for the self-consumption rate.

Results Q3

The operational results of the MEC system of GROHW with hydrogen storage and dynamic electricity prices are determined with the Q3 optimization model from Section 2.5.2. Table 16 presents the results.

Season	**Electrolyser demand** (kWh)	**Total import from grid** (kWh)	**Total export to grid** (kWh)	**Hydrogen storage capacity** (kWh)	**Total hydrogen unfulfilled** (kWh)	**Self-consumption** (%)
Winter	1,330,924.61	699,831.70	700,158.73	15,518.66	0	47.41
Spring	2,749,794.85	998,680,86	2,991,307.51	60,187.24	8792.01	63.38
Summer	3,693,111.21	1,758,550.21	1,495,323.63	109,150.84	3096.74	52.32
Fall	4,087,827.78	3,000,320.20	608,963.54	147,888.80	0	26.60

Table 16: Results of Q3 model

The hydrogen storage capacity is added in all the four periods. The only difference compared to Q2 is the winter period where a small hydrogen capacity is added. The model uses a minimal storage capacity to profit from the dynamic electricity prices. This is supported by the higher grid import and export. The fact that the size of the hydrogen storage capacity is the same in Q2 and Q3 in the spring, summer and fall periods, supports the conclusion that the capacity size is dependent on the maximum flow capacity and the electrolyser demand.

Another difference with Q2 is that there is some hydrogen unfulfilled in the spring and summer periods. A closer look at the data reveals that this occurs during negative electricity prices. The model prefers to use the negative electricity prices to fill the hydrogen storage tank instead of serving the hydrogen consumers.

The self-consumption rate is lower in all four periods compared to Q2. The combination of dynamic electricity prices and storage capacity presents the opportunity to buy electricity at times of low of prices. The electricity prices are often lower at times of high RES generation or at low electricity demand. The low electricity demand can also occur at night where there is no PV generation. Due to the relatively low cost of a GoO for green electricity, the model chooses to use these periods to buy electricity.

Table 17 presents an overview of the percentual differences between the self-consumption rates of the systems without storage (Q1), with storage (Q2) and with storage and dynamic electricity prices (Q3). The percentual difference is calculated with Equation 10.

	Winter	Spring	Summer	Fall	Average
Difference self-consumption rate Q2 to Q1	0%	+58.20%	+42.89%	+35.57%	**+34.17%**
Difference self-consumption rate Q3 to Q1	-23.42%	+24.37%	+13.74%	+1.29%	**+4.00%**
Difference self-consumption rate Q3 to Q2	-23.42%	-21.38%	-20.40%	-25.28%	**-22.62%**

Table 17: Differences in self-consumption

An important result is the difference between the system with storage (Q2) and the system with storage and dynamic electricity prices(Q3). The addition of dynamic electricity prices causes a consistent reduction in the self-consumption rate, with an average of -22.62% over the four periods.

Results Q4

The results of the determining the ‘fuel cost’ for the electrolyser and the hydrogen consumers are presented in Figure 15 and Figure 16. The percentual price differences between the systems Q1, Q2 and Q3 are calculated with Equation 10 and presented in Table 18: Electricity price differences between systems and Table 19: Hydrogen price differences between systems.

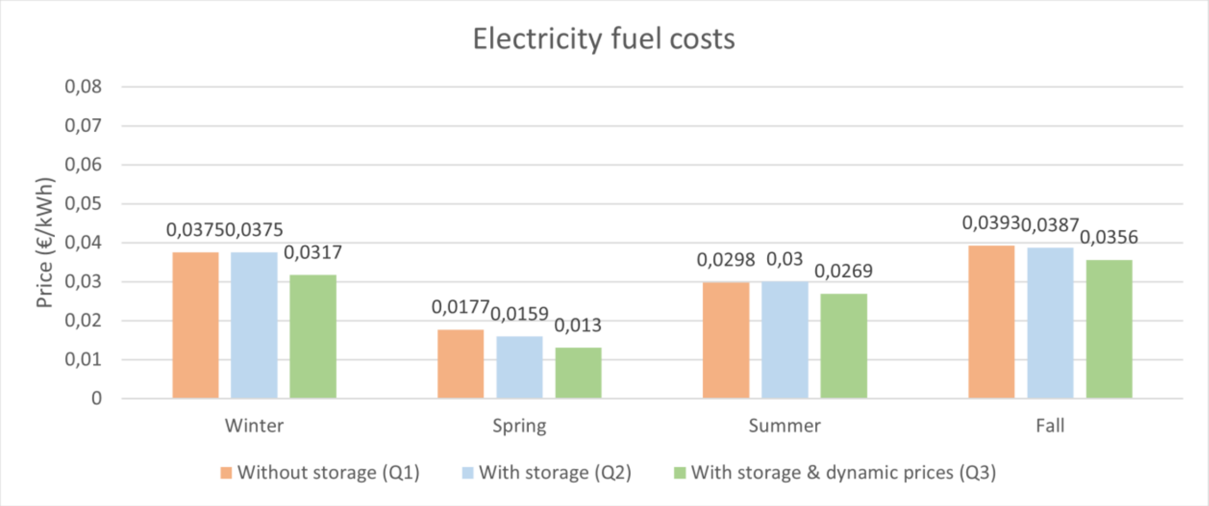


Figure 15: Electricity prices of different systems

	Winter	Spring	Summer	Fall	Average
Price difference Q2 to Q1	0%	-10.17%	+0.67%	-1.53%	**-2.88%**
Price difference Q3 to Q2	-15.47%	-18.24%	-10.33%	-8.01%	**-13.01%**
Price difference Q3 to Q1	-15.47%	-26.55%	-9.73%	-9.41%	**-15.29%**

Table 18: Electricity price differences between systems

The fuel costs for the electrolysers are not significantly lower on average (-2.88%) when hydrogen storage capacity is added. Only the spring period stands out with -10.17%. This is caused by the excess of RES generation compared to the demand.

The option to use dynamic prices in combination with hydrogen storage reduces the fuel cost with -15.29% on average from a system without hydrogen storage and -13.01% on average from a system with only hydrogen storage. Access to dynamic can offer electrolysers a significant cost reduction for electricity. The effect is again the highest in the spring period.

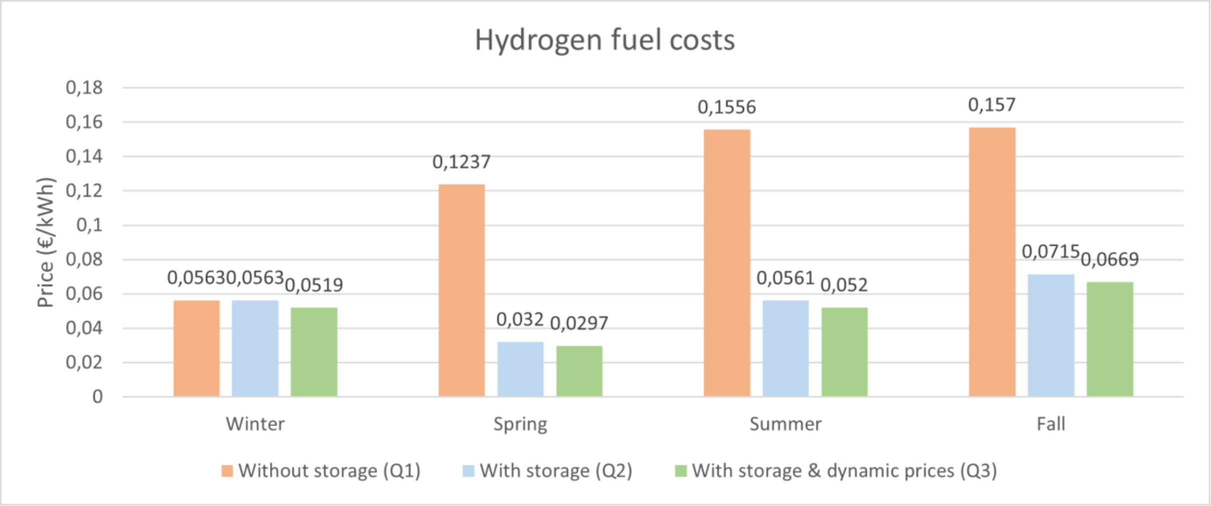


Figure 16: Hydrogen prices of different systems

	Winter	**Spring**	**Summer**	**Fall**	**Average**
Price difference Q2 to Q1	0%	-74.13%	-63.95%	-54.48%	**-48.14%**
Price difference Q3 to Q2	-7.82%	-7.19%	-7.31%	-6.43%	**-7.19%**
Price difference Q3 to Q1	-7.82%	-75.99%	-66.58%	-60.65%	**-52.76%**

Table 19: Hydrogen price differences between systems

The addition of hydrogen storage significantly lowers the fuel cost for the hydrogen consumers in the spring, summer and fall period. This is because less hydrogen is bought from outside the system. The option to use dynamic electricity prices in the optimization problem lowers the fuel cost for hydrogen further with 7.19% on average. This percentage is relatively consistent between the four periods.

5. Discussion

In the first part of this section, the results of both the design requirements as well as the techno-economic analysis of the proposed MEC system are discussed. In the second part, the limitations which were encountered when conducting this research and how it could affect the outcome, are discussed. Lastly, recommendations for further research are given.

Recommendations for design MEC system

The first part of the research investigated the regulatory and system requirements as the design options for both the electricity and the hydrogen part of the MEC system.

The pre-determined regulatory framework and the system requirements are assessed through a literature review and interviews with stakeholders. This resulted in several recommendations for a MEC system in the Netherlands. These recommendations are used to assess the proposed design options.

In the design of the electricity part of a MEC system, an administrative connection to RES is necessary. This is caused by the intermittent RES generation and technical constraint of the PEM electrolyser having to run on at least 10%. To fulfil the green electricity requirement, GoO certificates must be bought for each MWh of grid imported electricity. A microgrid can be created with the regulatory and system requirements in consideration. Depending on the available partners in the area and the oversaturation of the local grid, this could be beneficiary to both the electrolysers as the producers of renewables electricity. A good option for the electrolysers to consider is to contract an aggregator. This provides access to the dynamic electricity prices, balancing service options and GoO trading through one company. An aggregator could also control the whole electricity part of the MEC system. This would remove the necessity of having to create a trading strategy based on the forecasts of the weather and electricity prices. Only a buying scheme based on the hydrogen demand and price requirements needs to be created. The best choice for an aggregator in the Netherlands is dependent on the available parties on the market and their business models.

For the hydrogen part of the MEC system, it is advisable to find a third party as owner for the electrolysers. This removes the chance of conflict between hydrogen consumers if the ownership was shared between them. The decision between bilateral contracts and an open marketplace to facilitate the hydrogen trading is dependent on the composition and the wishes of the participants. Bilateral contracts are the easiest to facilitate and will pose less financial uncertainty. They are therefore most likely preferred by the hydrogen consumers. If an open marketplace is chosen, the advised requirements from the explorative report of the Dutch government should be taken into consideration for the design (Ouden, 2020).

The second part of the research investigated the added value of hydrogen storage capacity and dynamic electricity prices in a MEC system with a microgrid. This was done by conducting a case study on the plans for the MEC system of GROHW. The case study identified the hydrogen demand pattern and the maximum flow capacity as bottlenecks for the self-consumption rate. In the system without storage (Q1), shortages in hydrogen only occurred due to high hourly peaks in hydrogen demand. In the systems with storage (Q2 & Q3), the model maximizes the hydrogen storage capacity to prevent the shortages, as acquiring hydrogen from outside the system is very expensive.

The self-consumption rate of the system is the highest when only hydrogen storage capacity is added. The difference with the system without storage is dependent on the RES generation compared to the electrolyser demand. A more pressing bottleneck to more self-consumption is the maximum flow capacity of the electrolyser. This limits the ability to store high peaks in RES generation.

The addition of dynamic electricity prices has a negative effect on the self-consumption rate of the system, with an average reduction of 22.62%. This is caused by the low price of a GoO compared to the fluctuations of the electricity price. The model prefers to buy cheap grid electricity with GoO's at times of low prices to local renewable electricity from the microgrid. During some hours with negative electricity prices, the model even allows a very small hydrogen shortage. These hours are used to fill the hydrogen storage system.

The average fuel cost for electrolysers is the lowest in a system with hydrogen storage capacity and dynamic prices (Q3). The hydrogen storage gives the electrolysers more opportunity to buy at a lower price. The use of dynamic electricity prices also can significantly lower the fuel cost for the hydrogen consumers, even with the inclusion of the cost of the hydrogen storage system. Therefore, it is important that the electrolysers have access to the electricity markets through an aggregator or BRP.

Limitations due to the development phase GROHW

A difficult part of conducting this research is that GROHW is still in development. The definitive plan, cost data and participants are not fully determined or committed as of June 2021 yet. This prevented the chance to do a techno-economic analysis on the actual system with infrastructure and electrolyser costs. It also results in several factors that can affect the validity of the results of the current techno-economic analysis.

The first factor that could decrease the validity of the results, is that the models involve hydrogen customers that still have the option to quit the project. This is realistic as companies could have fewer financial options to take risks with new innovations, such as switching natural gas for hydrogen, due to the Covid-19 crisis of 2020. It is also uncertain what companies can pay for hydrogen while staying competitive in their market sectors. On the other side, new potential hydrogen customers can also join. This could change the hydrogen demand and consumption pattern. As can be seen in the results of Chapter 4, the size of the hydrogen storage capacity is partly dependent on the hydrogen consumption demand and pattern.

A second factor that could decrease the validity of the results, is that the electricity system is based on the initial plans for GROHW. The size and ratio of wind and PV units in the microgrid could still change. This could affect the self-consumption rate. The economic effect on the results will not be as significant as the first uncertainty factor, because the electrolyser can rely on the grid for the electricity supply and the price of a GoO is not significant on the current level.

Model limitations

The models have two main limitations which are addressed here below.

Firstly, the models cannot give a good indication of the economic viability of the whole project as the CAPEX and OPEX of the electrolyser are not included in the model. The CAPEX is not included because the project is largely subsidized by the Dutch government. The OPEX is not included because it has not been decided on what kind of legal and commercial construction will be used for the ownership of the electrolyser. Therefore, the models are only used to determine the self-consumption rate and the fuel costs.

Secondly, the model has perfect knowledge about the whole three-week period for which is solves the optimization. Especially in case of the EPEX day-ahead prices, this is not realistic. A trading platform will have to function with more uncertainty, which can result in higher fuel costs.

Recommendations further research

This research can be used a base for more in-depth research into MEC systems. Four recommendations are given for further research.

A first recommendation for further research would be a more extensive techno-economic analysis when the definitive plan of GROHW is finalized. This could provide more accurate results for the participants on important aspects, like the final price of hydrogen for the hydrogen consumers.

A second recommendation would be to conduct an extensive uncertainty analysis to determine the bottlenecks and optimal structure of the MEC systems. The following parameters could be interesting to explore:

- Electrolyser size: The maximum flow capacity is a limiting factor for the MEC system. It would be interesting to determine the extent of this factor with an uncertainty analysis.
- Price of a GoO: Another interesting parameter to change would be the price of a GoO. At this point, the model uses a European price average. However, the MEC system could choose to use only Dutch GoO's. The price of a Dutch GoO is 5 to 10 times higher. This could affect the operational results of the system and improve the self-consumption rate.
- Wind/PV ratio: The effect of the ratio between wind and PV generation on the self-consumption rate of the microgrid could be explored. The MEC system of GROHW is now mostly reliant on electricity from PV. With an uncertainty analysis, a more optimal ratio could be found.

A third recommendation would be to explore the option is to install a battery system in the electricity microgrid of the MEC system. This could improve the self-consumption of the system as it is now constrained by the maximum flow capacity of the electrolyser.

Lastly, the option to create a marketplace between electrolysers and hydrogen consumers could be further explored. As stated in Section 3.4.2, there are several requirements that first need to be met. If these are met, several market structures can be explored to find the most suitable structure for a MEC system. Examples for market structures are an open marketplace with peer-to-peer trading or an auction system.

6. Conclusion

This research was conducted as an explorative effort to assess the requirements and design options for building a multi-energy carrier (MEC) system with electrolysers, local RES and local industries in the Netherlands. The main research question was therefore stated as follows:

How to integrate a renewable-powered electrolyser in a local energy system consisting of large energy producers and consumers and how could the sustainability of the system and economic welfare of the participants be improved?

To provide an answer, the research question was divided into four sub-questions, which each cover a part of the main research question.

The regulatory and system requirements for the MEC system were determined through a literature review and interviews with stakeholders. This resulted in several recommendations for the MEC system. With these recommendations in consideration, the design options for electricity and hydrogen part of the MEC system were evaluated. Although no optimal design was determined, the advantages and disadvantages of each option were presented. The results could serve as a base for designing future MEC systems.

A case-study with a techno-economic analysis was conducted on the MEC system of the GROHW project to determine the effect of hydrogen storage capacity and dynamic electricity prices. This was done with optimization and simulation models in Python. First, the inputs from the participants in the MEC system of GROHW were determined. The RES generation was simulated with Python to determine the local electricity input. The hydrogen demand of potential consumers was determined by converting the energy consumption in natural gas to hydrogen.

The models provided several insights in the effects of addition of hydrogen storage and dynamic electricity prices. The addition of only hydrogen storage capacity increased the self-consumption rate of an MEC system significantly, dependent on the RES generation. However, bottlenecks for further improvement of the self-consumption rate are the flow capacity of the electrolyser and the hydrogen demand pattern.

The addition of dynamic prices reduces the self-consumption rate of the MEC system with 22.62% on average. This is caused by the possibility to trade the fluctuations of the EPEX SPOT price and the low price of a European GoO. Dynamic electricity prices are determined to have a 7.19% average cost reduction on the fuel cost for hydrogen compared to a system with only storage. As this can make a difference for hydrogen consumers, MEC systems should therefore aim to gain access to the electricity markets.

Acknowledgements

I would like to thank my supervisor Prof. Dr. Madeleine Gibescu for the extensive feedback and the support during the lockdown. This helped to keep my focus and motivation. The feedback also helped me to continue during the times that I was stuck in the beginning. I would also like to thank my second reader Dr. Sanne Akerboom for the feedback and reviews on regulatory frameworks. This has really improved the quality of those parts of the thesis in my own opinion. Furthermore, I would like to thank Jan Wiegner for the feedback and help he provided during the modelling phase. Without his help, I would have struggled a lot more with creating the desired models. Lastly, I would like to thank the people at Coinversable for their input, data and social contact, which importance must not be underestimated during a lockdown.

References

Agostini, A., Belmonte, N., Masala, A., Hu, J., Rizzi, P., Fichtner, M., Moretto, P., Luetto, C., Sgroi, M., & Baricco, M. (2018). Role of hydrogen tanks in the life cycle assessment of fuel cell-based auxiliary power units. *Applied Energy*, *215*(June 2017), 1–12. https://doi.org/10.1016/j.apenergy.2018.01.095

Andersson, J., & Grönkvist, S. (2019). Large-scale storage of hydrogen. *International Journal of Hydrogen Energy*, *44*(23), 11901–11919. https://doi.org/10.1016/j.ijhydene.2019.03.063

Barbir, F. (2005). PEM electrolysis for production of hydrogen from renewable energy sources. *Solar Energy*, *78*(5), 661–669. https://doi.org/10.1016/j.solener.2004.09.003

Bauelos-Ruedas, F., Angeles-Camacho, C., & Sebastin. (2011). Methodologies Used in the Extrapolation of Wind Speed Data at Different Heights and Its Impact in the Wind Energy Resource Assessment in a Region. *Wind Farm - Technical Regulations, Potential Estimation and Siting Assessment*, *June 2011*. https://doi.org/10.5772/20669

CARU Containers. (n.d.). *Wat kost een zeecontainer? | CARU Containers*. Retrieved May 7, 2021, from https://www.carucontainers.com/nl-nl/faq/wat-kost-een-zeecontainer

CBS. (2020). *Productie groene elektriciteit in stroomversnelling*. https://www.cbs.nl/nl-nl/nieuws/2020/10/productie-groene-elektriciteit-in-stroomversnelling

CertiQ. (n.d.). *Handelaar*. Retrieved April 29, 2021, from https://www.certiq.nl/handelaar/

Commerg. (2020). *Guarantees of Origin in 2020 – Seemingly higher demand but ever lower prices | Commerg*. https://commerg.com/insights/guarantees-of-origin-in-2020-seemingly-higher-demand-but-ever-lower-prices/

Cui, B., Wang, S., & Xue, X. (2014). Effects and performance of a demand response strategy for active and passive building cold storage. *Energy Procedia*, *61*, 564–567. https://doi.org/10.1016/j.egypro.2014.11.1171

Deventer Energie Coöperatie. (n.d.). *Windpark Kloosterlanden - Deventer Energie Coöperatie*. Retrieved January 7, 2021, from https://www.deventerenergie.nl/projecten/111-windpark-kloosterlanden-een-duurzame-aanwinst

DNV GL. (2020). *GROENE WATERSTOF EN HERGEBRUIK BESTAANDE GASLEIDINGEN ALS OPLOSSING VOOR CONGESTIEPROBLEMATIEK*. *april*, 1–17.

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

Driesse, A., Jain, P., & Harrison, S. (2008). Beyond the curves: Modeling the electrical efficiency of photovoltaic inverters. *Conference Record of the IEEE Photovoltaic Specialists Conference*. https://doi.org/10.1109/PVSC.2008.4922827

Dutch Ministry of Economic Affairs and Climate Policy. (2016). *Energieagenda: Naar een CO_2-arme energievoorziening*. 120.

EEX Group. (n.d.). *EPEX SPOT*. Retrieved March 30, 2021, from https://www.eex-group.com/en/epex-spot

EEX Group. (2019). *Trading on EPEX SPOT 2019-2020 (Trading brochure)*.

Elberry, A. M., Thakur, J., & Santasalo-aarnio, A. (2021). Large-scale compressed hydrogen storage as part of renewable electricity storage systems. *International Journal of Hydrogen Energy*, *46*(29), 15671–15690. https://doi.org/10.1016/j.ijhydene.2021.02.080

Enercon. (2015). *Enercon Wind Turbine - Product Overview*. 1–19. http://www.enercon.de/fileadmin/Redakteur/Medien-

Portal/broschueren/pdf/en/ENERCON_Produkt_en_06_2015.pdf

ENTSO-E Transparency Platform. (n.d.). Retrieved February 17, 2021, from https://transparency.entsoe.eu/dashboard/show#

Estermann, T., Newborough, M., & Sterner, M. (2016). Power-to-gas systems for absorbing excess solar power in electricity distribution networks. *International Journal of Hydrogen Energy*, *41*(32), 13950–13959. https://doi.org/10.1016/j.ijhydene.2016.05.278

European Commision. (2017). *VERORDENING (EU) 2017/2195 VAN DE COMMISSIE van 23 november 2017 tot vaststelling van richtsnoeren voor elektriciteitsbalancering*. *2017*(november), 6–53.

European Parliament. (2009). DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. *European Wind Energy Conference and Exhibition 2008*, *1*, 32–38.

European Parliament. (2018). Directive (EU) 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. *Official Journal of the European Union*, *2018*(L 328), 82–209. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN

European Parliament. (2019). Richtlijn (EU) 2019/944 van het Europees Parlement en de Raad van 5 juni 2019 betreffende gemeenschappelijke regels voor de interne markt voor elektriciteit en tot wijziging van Richtlijn 2012/27/EU. *Publicatieblad van de Europese Unie*, 55.

European Smart Grids Task Force EG3. (2019). *Demand Side Flexibility - Perceived barriers and proposed recommendations*. *April*, 1–50.

Fares, R. (2015). *Renewable Energy Intermittency Explained: Challenges, Solutions, and Opportunities - Scientific American Blog Network*. https://blogs.scientificamerican.com/plugged-in/renewable-energy-intermittency-explained-challenges-solutions-and-opportunities/

Gallandat, N., Romanowicz, K., & Züttel, A. (2017). An Analytical Model for the Electrolyser Performance Derived from Materials Parameters. *Journal of Power and Energy Engineering*, *05*(10), 34–49. https://doi.org/10.4236/jpee.2017.510003

Hone, B. (2020). *Advies van het Europees Comité van de Regio's — Naar een stappenplan voor schone waterstof — De bijdrage van lokale en regionale overheden aan een klimaatneutraal Europa*. *1999*, 41–47.

Hulshof, D., Jepma, C., & Mulder, M. (2019). Performance of markets for European renewable energy certificates. *Energy Policy*, *128*(February), 697–710. https://doi.org/10.1016/j.enpol.2019.01.051

IRENA. (2020). *ADVANCED FORECASTING OF VARIABLE RENEWABLE POWER GENERATION*.

Jain, I. P. (2009). *Hydrogen the fuel for 21st century*.

Juffermans, J. K. J. (2018). *Aggregators and flexibility in the Dutch electricity system Aggregators and flexibility in the Dutch electricity system in partial fulfilment for the degree of Master of Science in Innovation Sciences*.

Kakoulaki, G., Kougias, I., Taylor, N., Dolci, F., Moya, J., & Jäger-Waldau, A. (2021). Green hydrogen in Europe – A regional assessment: Substituting existing production with electrolysis powered by renewables. *Energy Conversion and Management*, *228*(November 2020). https://doi.org/10.1016/j.enconman.2020.113649

KNMI. (n.d.). *Wind*. Retrieved February 14, 2021, from https://www.knmi.nl/kennis-en-datacentrum/uitleg/wind

Kole, M. (2020). *Cable pooling zon en wind*. https://www.dirkzwager.nl/kennis/artikelen/cable-pooling-zon-en-wind-1/

Laurent, V. (2020). *A New Dutch Milestone During the Coronavirus Outbreak | Genscape*. https://www.genscape.com/blog/new-dutch-milestone-during-coronavirus-outbreak

Lave, M., Hayes, W., Pohl, A., & Hansen, C. W. (2015). Evaluation of global horizontal irradiance to plane-of-array irradiance models at locations across the United States. *IEEE Journal of Photovoltaics*, *5*(2), 597–606. https://doi.org/10.1109/JPHOTOV.2015.2392938

Mesfun, S., Sanchez, D. L., Leduc, S., Wetterlund, E., Lundgren, J., Biberacher, M., & Kraxner, F. (2017). Power-to-gas and power-to-liquid for managing renewable electricity intermittency in the Alpine Region. *Renewable Energy*, *107*, 361–372. https://doi.org/10.1016/j.renene.2017.02.020

Ministerie van Economische Zaken. (2014). *Besluit van de Minister van Economische Zaken van 9 december 2014, nr. WJZ/14197582, houdende regels inzake mandaat, volmacht en machtiging voor de bestuurder van CertiQ B.V., Tennet TSO B.V., inzake garanties van oorsprong*. *35714*, 1–2.

Ministerie van Economische Zaken en Klimaat. (2020). Wet van 10 juni 2020 tot wijziging van de Elektriciteitswet 1998 en Gaswet (implementatie wijziging Gasrichtlijn en een aantal verordeningen op het gebied van elektriciteit en gas). *Staatsblad 236*, *Juli*, 1–10.

Mulder, M., Perey, P., & Jose, M. L. (2019). Outlook for a Dutch hydrogen market: Economic conditions and scenarios. In *Centre for Energy Economics Research, CEER* (Issue 5).

Natuur & Milieu. (2019). *Verkennend Onderzoek Certificering Waterstof*. 1–12.

Netherlands Ministry of Economic Affairs. (2016). *Energierapport - Transitie naar Duurzaam*. 148. https://www.rijksoverheid.nl/documenten/rapporten/2016/01/18/energierapport-transitie-naar-duurzaam

Nojavan, S., Zare, K., & Mohammadi-Ivatloo, B. (2017). Selling price determination by electricity retailer in the smart grid under demand side management in the presence of the electrolyser and fuel cell as hydrogen storage system. *International Journal of Hydrogen Energy*, *42*(5), 3294–3308. https://doi.org/10.1016/j.ijhydene.2016.10.070

Ostadi, M., Paso, K. G., Rodriguez-fabia, S., & Øi, L. E. (2020). *Process Integration of Green Hydrogen : Decarbonization of Chemical Industries*.

Ouden, B. Den. (2020). *Een Waterstofbeurs voor het Klimaat*. 1–24.

Parra, D., Gillott, M., & Walker, G. S. (2016). Design , testing and evaluation of a community hydrogen storage system for end user applications. *International Journal of Hydrogen Energy*, *41*(10), 5215–5229. https://doi.org/10.1016/j.ijhydene.2016.01.098

Prasad, A. A., Taylor, R. A., & Kay, M. (2017). Assessment of solar and wind resource synergy in Australia. *Applied Energy*, *190*, 354–367. https://doi.org/10.1016/j.apenergy.2016.12.135

PV Free. (n.d.). *PV Modules*. Retrieved May 9, 2021, from https://pvfree.herokuapp.com/pvmodules/

Rijksoverheid. (n.d.). *Overheid stimuleert de inzet van meer waterstof | Duurzame energie | Rijksoverheid.nl*. Retrieved November 16, 2020, from https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/overheid-stimuleert-de-inzet-van-meer-waterstof

Rijksoverheid. (2019). Klimaatakkoord. *Klimaatakkoord*, 250. https://www.klimaatakkoord.nl/binaries/klimaatakkoord/documenten/publicaties/2019/06/28/klimaatakkoord/klimaatakkoord.pdf

Rijkswaterstaat. (2020). *Zonnepark/Aansluiting 23 - Uitbreiding A1 Apeldoorn - Azelo*.

https://www.a1oost.nl/actuele+werkzaamheden+heijmans/wegwerkzaamheden+omgeving+deventer/1686138.aspx

Sadeghi, S., Ghandehariun, S., & Rosen, M. A. (2020). Comparative economic and life cycle assessment of solar-based hydrogen production for oil and gas industries. *Energy*, *208*, 118347. https://doi.org/10.1016/j.energy.2020.118347

Saraber, M. J. (2016). *Negative Electricity Prices in the German Electricity Market AUTHOR. 366867*.

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

Solar Magazine. (2020). *Solar Magazine - Familie Gooiker neemt grootste particuliere zonnepark van Nederland in gebruik*. https://solarmagazine.nl/nieuws-zonne-energie/i22368/familie-gooiker-neemt-grootste-particuliere-zonnepark-van-nederland-in-gebruik

Sovacool, B. K. (2009). The intermittency of wind, solar, and renewable electricity generators: Technical barrier or rhetorical excuse? *Utilities Policy*, *17*(3–4), 288–296. https://doi.org/10.1016/j.jup.2008.07.001

Staalkaart groene waterstof. (2020). *Kosten waterstof*. https://staalkaartwaterstof.nl/achtergrond/kosten/

TenneT. (n.d.). *Balancing responsibility*. Retrieved April 6, 2021, from https://www.tennet.eu/electricity-market/dutch-market/balancing-responsibility/

TenneT. (2021a). *FCR Manual for BSP ' s Requirements and procedures for supply of FCR*.

TenneT. (2021b). *Manual aFRR voor BSPs , English version Rules and procedures for aFRR delivery*.

van der Veen, R. A. C., & Hakvoort, R. A. (2016). The electricity balancing market: Exploring the design challenge. *Utilities Policy*, *43*, 186–194. https://doi.org/10.1016/j.jup.2016.10.008

van Sark, W. G. J. H. M., Bosselaar, L., Gerrissen, P., Esmeijer, K., Moraitis, P., Donker, M. van den, & Emsbroek, G. (2013). Update of the Dutch PV specific yield for determination of PV contribution to renewable energy producion: 25% more. *29th European Photovoltaic Solar Energy Conference and Exhibition*, 4095–4097.

Wimmers, A., & Madlener, R. (2020). *The European Market for Guarantees of Origin for Green Electricity : A Scenario-Based Evaluation of Trading under Uncertainty Institute for Future Energy Consumer Needs and Behavior (FCN). 17*.

Appendices

Appendix A: Data

Landscape type	Friction coefficient α
Lakes, ocean and smooth hard ground	0.10
Grasslands (ground level)	0.15
Tall crops, hedges and shrubs	0.20
Heavily forested land	0.25
Small town with some trees and shrubs	0.30
City areas with high rise buildings	0.40

Table 20: Hellman's exponent for different landscapes (Bauelos-Ruedas et al., 2011)

Enercon E92 data

Turbine type	Enercon E92
Hub height (Deventer)	89 m
Diameter	92 m
Rated power output	2.35 MW
Cut-in windspeed	2 m/s
Rated windspeed	14 m/s
Cut-off windspeed	25 m/s

Table 21: Specifications Enercon E92 (Enercon, 2015)

Enercon E92 power curve

Windspeed (ms)	**Power output** (kW)	**Power Coefficient**
1	0.0	0.00
2	3.6	0.11
3	29.9	0.27
4	98.2	0.38
5	208.3	0.41
6	384.3	0.44
7	637.0	0.46
8	975.8	0.47
9	1,403.6	0.47
10	1,817.8	0.45
11	2,088.7	0.39
12	2,237.0	0.32
13	2,300.0	0.26
14	2,350.0	0.21
15	2,350.0	0.17
16	2,350.0	0.14
17	2,350.0	0.12
18	2,350.0	0.10
19	2,350.0	0.08
20	2,350.0	0.07
21	2,350.0	0.06
22	2,350.0	0.05
23	2,350.0	0.05
24	2,350.0	0.04
25	2,350.0	0.04

Table 22: Power output and coefficient of Enercon E92 (Enercon, 2015)

MTSA data

Electrolyser (1 MW)	
Specification	*Value*
Efficiency (LHV)	74%
Nominal output	1.0 MW
Max input	1.35 MW
Min input	0,135 MW
Response time	Within seconds
Start-up time	Within minutes
Temperature hydrogen	70 C
Pressure hydrogen	34 bar

Table 23: MTSA data of electrolyser (1 MW unit) (Schmidt et al., 2017)

Storage unit	
Specification	*Value*
Pressure	350 bar
Volume unit	270 L
Units per container	50
Price per unit	€6000 +/-

Table 24: MTSA data of storage unit

Hydrogen consumers data

The natural gas and hydrogen consumption data is provided by Witteveen + Bos for the GROHW research. The tables below give a summarized overview of the data.

Month	**Natural gas consumption per month (m^3)**	**Hydrogen consumption per month (kg)**	**Hydrogen consumption per hour (kg)**
January	8000	2107.66	2.833
February	7000	1844.20	2.650
March	7100	1870.54	2.514
April	6800	1791.51	2.488
May	4200	1106.52	1.487
June	6000	1580.74	2.195
July	7000	1844.20	2.479
August	6600	1738.82	2.337
September	7400	1949.58	2.708
October	7950	2094.48	2.815
November	7900	2081.31	2.891
December	6200	1633.43	2.195
Total	**82150**	**21643.00**	

Table 25: Consumption data consumer goods manufacturer

Month	**Natural gas consumption furnace 1 (m3)**	**Natural gas consumption furnace 2 (m3)**	**Total natural gas consumption (m3)**	**Total hydrogen consumption per month (kg)**	**Total hydrogen consumption per hour (kg)**
January	74237	33645	107882	28422.26	38.20
February	66224	28780	95004	25029.46	37.25
March	81433	34353	115786	30504.63	41.00

April	73114	31710	104824	27616.61	38.36
May	78509	33928	112437	29622.31	39.81
June	71545	29763	101308	26690.30	37.07
July	73019	28640	101659	26782.77	36.00
August	46852*	29192	76044	20034.32	55.65
September	77830	30966	108796	28663.06	39.81
October	73349	31234	104583	27553.12	37.03
November	78399	32563	110962	29233.71	40.60
December	76599	30904	107503	28322.41	38.07
Total	871110	375678	1246788	328474.96	

*Table 26: Consumption data steel manufacturer (*Furnace was in maintenance during this month)*

Solar panel data

Solar panel model	Suniva OPT300-72-4-100 [2013]
Area	1.26 m
Material	Mono-si
Cells in series	72
Paralel strings	1
Fd	1.0
Isc0	5.9
Voc0	52.0
Imp0	5.5
Vmp0	43.1

Table 27: Standard solar panel data Solar panel module (PV Free, n.d.)

Pvlib functions used in Python.

Python function	**Input**	**Result**
pvlib.solarposition.ephemeris	Latitude = 52.0849 Longitude = 5.1766 DateTime [t]	Apparent solar elevation [t] Actual solar elevation [t] Apparent solar zenith [t] Solar zenith [t] Solar azimuth [t]
pvlib.irradiance.aoi	Solar zenith [t] Solar azimuth [t]	Aoi (angle of incidence) [t]
pvlib.irradiance.erbs	GHI (KNMI input) [t] Solar zenith [t] Max zenith = 85	DNI (direct normal irradiance) [t] DHI (diffused horizontal irradiance) [t]
pvlib.irradiance.get_total_irradiance	Surface tilt = 37 Surface azimuth = 180 Solar zenith [t] Solar azimuth [t] GHI [t] DNI [t] DHI [t]	Poa global (total in plane irradiance) [t] Poa direct [t] Poa diffused [t]
pvlib.atmosphere.get_relative_airmass	Solar zenith [t]	Relative airmass [t]
pvlib.atmosphere.get_absolute_airmass	Relative airmass [t]	Absolute airmass [t]
pvlib.pvsystem.sapm_effective_irradiance	Poa direct [t] Poa diffused [t] Absolute airmass [t] Aoi [t] PV module	Effective irradiance [t]
pvlib.pvsystem.sapm_celltemp	Poa global [t] Wind speed (KNMI input) [t]	Cell temperature [t]
pvlib.pvsystem.sapm	Effective irradiance [t]	DC power output [t]

	Cell temperature [t] PV module	

Table 28: pvlib functions and inputs used in Python.

Appendix B: Interviews

TSO interview (Dutch)

Interviewee - Anton Tijdink

What are the entry level requirements for an electrolyser to buy electricity on the wholesale market?

Alleen programma verantwoordelijke partijen (BRP) kunnen handelen op de EPEX spot markt.

What are the requirements to become a BRP?

Er zitten verschillende eisen aan. Zelf een BRP worden is waarschijnlijk geen goed idee vanwege het lage MW vermogen. Zelfs met 2 electrolysers van 5 MW zit je nog aan de lage kant om er echt voordeel van te hebben een BRP te zijn. Ook moet je financieel sterk zijn om mogelijke onbalans onkosten te betalen

Je kan wel aansluiten bij een bestaande BRP. Hiermee kan je een inkoopprogramma maken voor de BRP die dan naar de markt gaat om dit in te kopen. Dit lijkt mij voor de electrolysers van GROHW het beste plan.

Ga naar kleine aggregator partijen toe en kijk wat je kan doen qua direct koppelen met lokale energiebronnen. Aggregator partijen zijn vaak zelf ook BRP's en kunnen dus op de EPEX spot markt handelen. Ook kunnen zij je onderling koppelen met groene energiebronnen binnen hun aggregatie. Hierdoor zou het certificaat handelen ook gefaciliteerd kunnen worden.

Is it legally possible to make a direct connection from solar farms and wind parks to the electrolyser without going to the grid?

Ja, je kan een zonnepark achter je netaansluiting zetten. Alleen dit kan wel duurder zijn aangezien het mogelijk geen certificaat geld krijgt voor op het net te zitten. De stroomprijs die je aan een zonnepark moet betalen zal waarschijnlijk hetzelfde zijn als die van de EPEX markt (+ waarschijnlijk nog een premium vanwege het mislopen van certificaatinkomsten)

Aan de andere kant heeft het wel het voordeel dat je de aansluiting deelt, waardoor er minder kosten zijn. Ook is het voor zonneparken een voordeel om de aansluiting zo te delen aangezien het moeilijker wordt voor zonneparken om zich aan te sluiten op het net.

Are there legal differences with connecting an electrolyser to the low or mid-voltage grid?

Verschillen zitten er vooral tussen kleine (<3x80A) en industriele aansluitingen (>3x80A).

What kind of contracts do the electrolyser operators have to sign?

Je moet je aansluiten bij een BRP en dan een inkoopprogramma doorgeven. Hier zitten ook eisen aan. Deze moeten opgezocht worden. Een idee is vooral te kijken naar BRP's die al electrolysers in hun portofolio hebben.

Could an electrolyser be used in the balancing markets?

Ja, kijk naar een aggregator partij. Dit soort partijen zijn vaak ook BRP's. Als je je hierbij aansluit kan je extra verdienen door mee te doen aan de balanceringsmarkt. Dit is dan natuurlijk wel op de voorwaarden van de aggregator. Als zelfstandige electrolyser is het niet mogelijk.

What are the requirements to get green certificates for electricity?

Er zijn niet heel veel eisen. Het handelen in certificaten gebeurd administratief. 1 certificaat voor 1 MWh in 2021 kan op ieder moment in 2021 geproduceerd worden en mag op een compleet ander moment ingezet worden.

Do certificates have to be traded separate from the electricity/EPEX market?

Ja, het makkelijkste zou een billaterale afspraken zijn in plaats van via een handelsplatform inkopen. Zoek naar oplossingen binnen je BRP/aggregator.

Interview hydrogen consumers (Dutch)

The hydrogen consumers interviewed are representatives from the asphalt factory, the industrial service provider and a transportation company near the fuel station.

Interviewees
Interview AsfaltNu – J.D. Sloos.
Interview Van Dorp – W. Beltman
Interview Vos Transport – R. van Verseveld

Company profile & plans

AsfaltNU
Het is ook een pilot project voor dit bedrijf. Ze gaan voor een bijbrander waterstof gebruiken om ervaring ermee op te doen en zich voor te bereiden op een grotere overstap in de toekomst. Op lange termijn (2030) zien ze graag een pijpleiding aangelegd worden om waterstof van af te nemen. Voor de korte termijn zal het transport waarschijnlijker via tubes vanaf S park/gasfabriek gedaan worden. Het hebben van meerdere vrachtwagens met tubes geeft ze enige flexibiliteit aangezien waterstof in tubes onder hoge druk staat. Hoeveel flexibiliteit is echter nog niet te zeggen.

Van Dorp
Van Dorp is een technische installateur met een breed scala aan werkzaamheden. Zij zijn in het GROHW project gestapt om informatie op te doen over het werken met waterstof. Zelf voorzien zij geen grote afnemer te zijn aangezien zij alleen waterstof willen gebruiken voor het verwarmen van hun bedrijfspand. Overstappen op waterstof is ook nog geen noodzaak voor hun.

Vos Transport
Vos Transport is zoals de naam al weggeeft een transportbedrijf. Ze hebben 400 trucks die voor verschillende opdrachtgevers werken. Om bekend te worden met waterstof willen ze 1 a 2 trucks kopen die op waterstof gaan rijden. Afhankelijk van de ontwikkelingen op gebied van schoon rijden (concurrentie van trucks op Li-ion batterijen) willen ze dit misschien nog uit gaan breiden. Hiervoor moeten de kosten echter nog wel flink omlaag zowel van de trucks zelf als de waterstof. Ook zijn ze aan het praten met een partij buiten GROHW voor het aanleggen van een waterstoftankstation.

Questions:

Hoe constant is jullie energievraag?

- AsfaltNu: Niet, afhankelijk van de klantenportfolio. Ongeveer 3 weken vantevoren wordt er een planning gemaakt met welke soorten asfaltklanten op welke dagen willen hebben. 1 dag van tevoren is er meestal bekend om welk tijdstip er een hoeveelheid asfalt geproduceerd moet worden.
- Van Dorp: Voorspelbaar en seizoensafhankelijk: Waterstof wordt alleen ingezet voor verwarming. Dit is dus niet constant maar redelijk goed te voorspellen afhankelijk van het weer. Potentieel een aantal voertuigen maar dit wordt pas later.
- Vos Transport: 1 waterstof truck op dit moment in de planning. Ze willen op termijn de rest van hun vloot van 400 trucks op waterstof of batterijaandrijving omzetten. Dit is afhankelijk van de ontwikkelingen op het gebied van trucks.

Wat is jullie geplande opslagcapaciteit, zover dat bekend is?

- AsfaltNu: Nog niet bekend. J.D. Sloos kan zich voorstellen dat ze in de pilot fase wel enkel trucks met tubes paraat hebben staan. Aangezien de waterstof hier onder hoge druk zit, geeft dit ze wel enige flexibiliteit.
- Van Dorp: Totaal niet over nagedacht. Misschien een vrachtwagenlading aan reserve.
- Vos Transport: Geen opslag capaciteit in de planning.

Hoe ver van tevoren is jullie verbruik van waterstof te plannen/te voorspellen?

- AsfaltNu: 3 weken van tevoren wordt de planning gemaakt. Dit is echter nog niet specifiek genoeg om het precieze verbruik op te plannen. Een dag van te voren is het met redelijke zekerheid per uur bekend. Op de dag zelf zal er misschien nog wat gefinetuned moeten worden.
- Van Dorp: Als het weer bekend is, kan je een planning maken op basis daarvan.
- Vos Transport: Een week van te voren is dit in redelijke lijnen bekend. Een dag van te voren is dit preciezer.

Zouden jullie het overwegen om flexibeler om te gaan met de waterstofvraag als het economische voordelen oplevert?

- AsfaltNu: Omdat het heel klantafhankelijk is, is dit best moeilijk. In de contracten moet er gewoon geleverd kunnen worden als de klanten dat vragen. Er hangt dus veel af van het hebben van opslagcapaciteit.
- Van Dorp: Ja, maar ze zien zichzelf niet als significante afnemer. Het hele project voor hun is voornamelijk om waterstof te testen.
- Vos Transport: Ja, als het geen procesvertraging oplevert.

Zouden jullie het overwegen om flexibeler om te gaan met de waterstofvraag als het duurzaamheid voordelen oplevert?

- AsfaltNu: Hetzelfde antwoord als hierboven.
- Van Dorp: Hetzelfde antwoord als hierboven.
- Vos Transport: Ja - Duurzaamheid is wel een belangrijk punt, maar ook moet het nog steeds geen procesvertraging opleveren.

Wat is het belangrijkste aspect voor jullie om over te stappen op waterstof?

- AsfaltNu: Duurzaamheid is belangrijk omdat aanbestedingen steeds vaker uitbesteed worden aan duurzame bedrijven. AsfaltNu wil daarom ook marktleider zijn in het duurzaam produceren van asfalt in Nederland. Vandaar ook de deelname aan dit project. Verder dient dit project vooral voor het leren kennen van de brandstof waterstof.

Door ervaringen op te doen op kleine schaal kunnen ze rond 2030 makkelijker op grote schaal overstappen naar waterstof.

- Van Dorp: Duurzaamheid. Dit project is ook met name om kennis op te doen. En imago. Het is geen noodzaak voor Van Dorp om over te stappen op waterstof.
- Vos Transport: Puur pionieren, vooroplopen. Ervaring opdoen. Positieve publiciteit eromheen. Ze kunnen er geen winst mee behalen.

Welk bedrag zou voor jullie economisch haalbaar zijn om voor groene waterstof te betalen?

- AsfaltNu: Niet bekend.
- Van Dorp: Niet bekend.
- Vos Transport: Er wordt gedacht aan maximaal 11 cent extra per liter energie equiavalent aan HVO. Stijgingen tot op deze schaal zijn bespreekbaar met de klant.

Hoe ziet jullie nieuwe brandstofmix voor bedrijfsprocessen eruit?

- AsfaltNu: Vooral aardgas aangevuld met waterstof. Waterstof gaat gebruikt worden voor een van de bijbranders.
- Van Dorp: Vooral waterstof aangevuld met gas. Ze willen het pand zoveel mogelijk verwarmen met waterstof alleen dan hebben ze wel een reserve aardgas CV.
- Van alle trucks (400 stuks) rijden nu 95% op diesel en 5% op LNG. Ze willen met 1 of 2 trucks overstappen.

Is er ook interesse om grijze waterstof te gebruiken als dat beschikbaar is?

- AsfaltNu: Nee, enkel groene waterstof.
- Van Dorp: Nee. Als waterstof niet groen is dan heeft het geen zin
- Vos Transport: Nee, dan is er geen duurzaamheidsaspect meer.