Making the Production of Green Hydrogen by Electrolysers Economically Viable

Thesis report

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TU Delft

Making the Production of Green Hydrogen by Electrolysers Economically Viable

by

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Preface

Hier is het dan: mijn afstudeerrapport. Na zes jaar studeren, zal ik met dit onderzoek mijn studie Werktuigbouwkunde aan de TU Delft afsluiten. Ik wil Emmett Green bedanken voor de mogelijkheid voor dit onderzoek. Ik zie energie transitie niet langer als een noodzakelijk kwaad, maar ook als sector waar ontzettend interessante uitdagingen beschikbaar zijn en veel mooi werk te doen is.

Ik wil graag Henk Polinder bedanken voor de begeleiding van dit project vanuit de TU Delft. Henk wist met nuttige kritiek mij scherp te houden tijdens het onderzoek. Daarnaast wil ik graag Michiel Wildschut bedanken als begeleider vanuit Emmett Green. Het is uiterst interessant om het raakvlak van academisch onderzoek en de zakelijke kant van onderzoek te ontdekken en hierin balans te zoeken. Ik zou graag Timon Kopka willen bedanken voor de dagelijkse begeleiding in onderzoek en rapportage. De gesprekken werden telkens weer boeiender naarmate het onderzoek vorderde. Daarnaast wil ik Gjalt Annega bedanken voor alle hulp met het EMS en het modelleren van de elektrolyzer.

Als laatste wil ik graag mijn vrouw Myrthe bedanken en alle vrienden en familie die mijn verhaal hebben aangehoord en me hebben gesteund in de afgelopen driekwart jaar.

T.J.J. Bijl
Delft, juli 2023

Here it is: my thesis report. After studying for 6 years, I will finish my studies in Mechanical Engineering at the Delft University of Technology with this research. I would like to thank Emmett Green for the opportunity for this research. I no longer see the energy transition as a necessary evil but as a field with intriguing challenges and ambitious job opportunities.

I would like to thank Henk Polinder for his guidance in the project as the representative from the Delft University of Technology. Henk's constructive comments kept me on my toes during the research. Furthermore, I would like to thank Michiel Wildschut as the representative from Emmett Green. It is really interesting to see the balance between scientific research and the business side of research. I would like to thank Timon Kopka for the daily supervision of research and reporting. Our discussion became more vivid and fascinating every time again. Besides, I would like to thank Gjalt Annega for his help in working on the EMS and modelling the electrolyser.

Lastly, I would like to thank my wife Myrthe and all my friends and family, who have listened to my stories and supported me throughout the past 8 months.

T.J.J. Bijl
Delft, July 2023

Nomenclature

Abbreviations

AEL	Alkaline ELectrolysis
aFRR	automatic Frequency Restoration Reserves
BESS	Battery Energy Storage System
CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
DA	Day ahead (market)
EMS	Energy Management System
ETS	Emission Trading System
FCR	Frequency Containment Reserves
GHG	Greenhouse gasses
ID	Intraday (market)
ISP	Imbalance Settlement Period
LCOH	Levelised/Levelized Cost Of Hydrogen
LCOS	Levelised/Levelized Cost Of Storage
MES	Multi-Energy System
mFRRda	manual Frequency Restoration Reserves directly activated
MILP	Mixed Integer Linear Programming
MPC	Model Predictive Control
O&M	Operations and Maintenance
OPEX	Operational Expenditures
PEM	Proton Exchange Membrane (electrolysis)
PEMEL	Porton Exchange Membrane ELectrolyser
PH	Power Heat
P2G	Power-to-Gas
P2H2	Power-to-Hydrogen
PV	Photovoltaic (cell)
RES	Renewable Energy Sources
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolysis Cell
UF	Utilisation/Utilization Factor

Definitions

Contribution margin	Revenue minus the variable costs of a product (More specifically: the hydrogen revenue minus electricity costs).
Day ahead market	SPOT market for electricity. Capacity is traded on the day before consumption.
Imbalance market	Real-time electricity price. The price is equivalent to the imbalance that is created by the offtake/feedin of electricity.
Valuation	The price that the electrolyser is willing to pay for electricity, based on the hydrogen selling price.
Volatility	The rate of fluctuation and difference between the low and high extremes in prices.

Summary

Green hydrogen plays an important role in the energy transition. It can function as a storage medium, as well as a replacement for fossil fuels in transport or high-temperature heat processes. However, the economic feasibility of electrolysers has proved to be a problem. Even though a lot of research has been performed on the electrolysis technology, very little research has been done on the implementation of an electrolyser.

For this research, a physical model of an electrolyser has been developed, as well as an Energy Management System. For this system, trading strategies for electricity markets have been developed. By trading on the imbalance and day ahead market, the contribution margin (hydrogen revenue minus electricity costs) has been significantly increased by over 27%. Seasonal hydrogen storage in salt caverns has proven to be a promising solution for producing more hydrogen and increasing revenue, depending on the storage costs that are applied. For a time indefinite Levelised Cost of Storage of 1€/kg, the contribution margin has increased by an average of 23%, whereas a levelised cost of 2 to 3 €/kg results in a marginal (0.8 to 3.7%) increase to no improvement. A Battery Energy Storage System (BESS) has been added to the system for its competence in dynamic behaviour on the electricity markets. For the addition of a BESS to an electrolyser, no conclusive proof of the benefits has been found.

Contents

1 | Introduction

It was in 2015 in Paris that the United Nations made an agreement in order to gain control over climate change. This agreement has the objective to not trespass the 2 degrees Celsius increase since the start of the industrial era (United Nations, 2018). The conclusion is that renewable energy sources must replace fossil fuels. Necessary for this transition is the process of electrification: energy consumers shift to electricity as the primary energy source.

There are however some problems with renewable energy sources and electrification. An issue with renewable energy sources is that their energy production is independent of the energy demand. Where a coal-fired power plant can adapt its production to the demand for energy, sustainable energy sources will generate electricity based on external causes, for example, wind speed or sunshine. A variety of sectors have difficulty making the transition of electrification, as it is financially not attractive or technically not possible. Examples of such sectors are the high-temperature heat industry and large transport sectors. To make these sectors more sustainable, other solutions are required (Wei et al., 2019).

Green hydrogen contributes to making these sectors sustainable. As can be seen in Figure 1.1, hydrogen can reach temperatures for heat processes that are higher than all other renewable energy forms. Another benefit is that for the implementation of hydrogen in these processes, the investment is significantly smaller than for electrification.

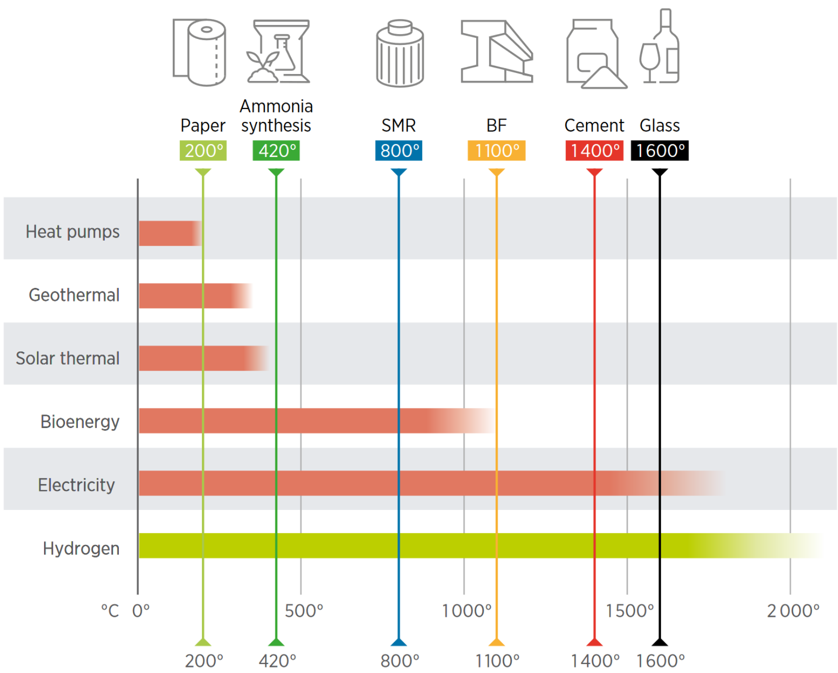


Figure 1.1. Working temperatures for renewable heat sources versus the temperature requirement of industrial processes (IRENA, 2022).

Green hydrogen is mainly produced by electrolysers. One big issue of green hydrogen is its competitiveness in comparison to non-renewable energy carriers. The application of electrolysers for green hydrogen is often not economically feasible. The conversion rates of producing hydrogen are considered too low, whereas the prices are much higher than non-renewable energy carriers. Most research is dedicated to improving electrolysers as technology, whilst almost no research has been done to improving the implementation of the electrolyser. Thus, solutions must be found that can be implemented in the short term.

This raises the research question for this thesis. Hydrogen plays an important role in the transition to the usage of renewable energies. **How can the production of green hydrogen by electrolysers be made economically viable?**
In order to be able to answer this question, the research question is subdivided into smaller questions:

1. How can an electrolyser be modelled for EMS simulations?
2. What are the different electricity markets in the Netherlands?
3. What implementation methods have the most beneficial impact on the economic viability of electrolysers?
4. How should an electrolyser be integrated in a renewable energy grid?
5. What is the effect of an energy market with higher volatility on the revenues of the production of green hydrogen?
6. What is the influence of using different electricity markets for energy trading on the revenues of the production of green hydrogen?
7. What is the effect of including hydrogen storage in the hydrogen system for the revenues of the production of green hydrogen?
8. What is the influence of combining BESS and an electrolyser on the revenues of the production of green hydrogen?

The first three questions have been answered in the literature review, which can be found in Appendix B. Research question 4 is answered in chapter 3. The rest of the questions will be answered in the chapters 4, 5, 6 and 7 and finally in the conclusion.

Chapter 2 provides an outline of the literature review and summarises the necessary knowledge for understanding this report. Chapter 3 provides an overview of the system that is modelled and optimised, as well as an introduction to the Energy Management System. Chapter 4 introduces the phenomenon of volatility and assesses its impact on hydrogen production and revenue. chapter 5 discusses trading strategies for electricity markets and presents the impact of the trading strategies. In chapter 6 it is discussed how seasonal hydrogen storage could be used to improve the business case of green hydrogen. Chapter 7 discusses the combination of an electrolyser and a battery on one site, and it proposes a method for determining the influence of the addition of the battery. For the chapters 4, 5, 6 and 7, the results are presented subsequently to the introduction of the topic. A short discussion of the results is given in those chapters as well, whereas the general discussion of all the results is provided in chapter 8. In chapter 9 the research conclusions are given.

This research is part of a current electrolyser project in the Netherlands. The project client is a large gas consumer that desires to transition to hydrogen for high-temperature heat processes. In this case, it may be assumed that there is an unlimited demand for hydrogen, as the electrolyser is comparably small to the hydrogen demand.

2 | Literature overview

Before the start of this research, the undersigned author presented a literature review of the economic viability of electrolysers (Bijl, 2023). The importance of green hydrogen was stated, the electrolysis technologies were examined and the influential factors for the economic feasibility of green hydrogen production were explained. This chapter summarises the necessary knowledge for understanding this report. The following sections introduce the proposed solutions for feasible green hydrogen. The solutions are then further specified and scrutinised in the consecutive chapters. The full Literature review can be found in Appendix B.

2.1 Purposes of green hydrogen

The presently most utilised application of hydrogen is as the feedstock of chemical processes. For these processes, the hydrogen is mainly produced by Steam Methane Reforming (SMR), which is a form of grey hydrogen (See section 2.2 for more information on the production of hydrogen). Grey hydrogen is produced by the use of fossil fuels. Green hydrogen on the other hand is produced by electricity from renewable energy sources (RES) through the process of electrolysis.

The intended purpose of green hydrogen is to simplify the transition to RES. The transition from a fossil-fueled society to a society fueled by RES introduces several problems to the usage of those RES. First of all, the RES have an intermittent nature. It has a daily intermittency, for example, solar power will peak during the day as a result of the sunshine hours. But there is also a seasonal intermittency, as for that in summer time the amount of sun hours is higher than in wintertime. The nature of RES is that the supply of energy is not demand dependent. Therefore, a storage medium is required. Batteries are useful for short-term storage, but for long-term storage, the Netherlands lacks good solutions (for example hydro-storage is not a viable option) (Parra et al., 2017). Hydrogen bears an important role in this long-term storage.

Applications with inelastic demand

Originally, the focus of research on hydrogen has been to use hydrogen as an electrochemical battery, in combination with a fuel cell. However, this idea has proved to be difficult to make economically feasible. One has to look beyond those established ideas for hydrogen to achieve this feasibility. When looking at price elasticity for different branches that envision using hydrogen in the future or present, one can determine where the true possibilities lay for economically feasible green hydrogen. In a recent research by Wietschel et al. (2023), it was determined that the high-temperature heat industry and international aviation or maritime transport are foreseen to have an inelastic demand for hydrogen, either as hydrogen or as feedstock for synthetic fuels. For these applications, there are hardly any economically-attractive or technologically possible alternatives. As these branches collectively account for a vast demand for hydrogen, other possible applications of hydrogen that have alternatives are not likely to switch to hydrogen as fuel. The demand by these branches will encourage the hydrogen price to increase to a level where electrification for certain processes is more economically attractive. In the research by Wietschel et al. (2023), it was established that over 20GW of electrolysers had to be installed in Germany to cope with the national demand for hydrogen in 2045, whereas currently worldwide only 2GW of electrolysers has been installed (IEA, 2022).

2.2 Electrolysis technologies

In electrolysis, electricity and water are used to form hydrogen and oxygen. Electrolysis is therefore, when used with green electricity, a method to produce green hydrogen. In order to produce grey or blue hydrogen, other methods can also be used, for example, Steam Methane Reforming. Grey and blue hydrogen are produced by using fossil fuels, the process for grey hydrogen emits carbon dioxide, while in the process for blue hydrogen, this carbon dioxide is captured and stored (Carbon Capture and Storage, or CCS). Currently, grey and blue hydrogen are more cost-effective than green hydrogen, which is the reason that 95% of the yearly produced hydrogen is grey hydrogen (NL Hydrogen, 2022). Still, the application of blue hydrogen should only be seen as a transition phase from grey to green. Namely, for the production of blue hydrogen fossil fuels are utilised, which is to be prevented for sustainability. Besides, redundant storage for CO2 for the coming decades is needed, which may prove to be difficult to find (Emmett Green, 2021; Friedlingstein, 2022; IEA Greenhouse Gas R&D programme, 2007).

There are several electrolysis technologies, the most important of which are: Alkaline Electrolysis (AEL), Polymer Electrolyte Membrane electrolysis (PEM) and Solid Oxide Electrolysis Cell electrolysis (SOEC). The last method is currently still under development and cannot yet be seen as a mature technology. The most important advantages and disadvantages of AEL and PEM are displayed in Table 2.1. Even though the source is somewhat old for a fast-moving technology, the characteristics still remain accurate. Further characteristics can be found in Appendix B. Currently, PEM electrolysers (PEMEL) are more expensive than AEL, due to the rare metals used in the stacks (higher CAPEX) (Proost, 2019; Frost, 2022) The OPEX of a PEMEL is higher as well, as the stacks have to be replaced every 10 years. The difference in CAPEX (and OPEX) is however decreasing (Holstein, van Gerwen, & Douma, 2018; Felgenhauer & Hamacher, 2015). The difference in total costs is yet to be analysed by simulation. Due to the different behaviours of the technologies to varying loads, the costs cannot be established by simple calculations. The expectation is that the Levelised Cost Of Hydrogen (LCOH) of a PEMEL will decrease to below that of AEL, due to the importance of electricity costs in LCOH.

Therefore, the expectation is that a PEMEL will be more beneficial to the case of producing green hydrogen than an AEL. The response to short peaks of low-priced electricity and the short start-up times will be considerably more relevant to the business case than the initial costs.

Table 2.1. *Overview of the advantages and disadvantages of Alkaline and PEM electrolysis (Carmo et al., 2013).*

	Alkaline electrolysis	**PEM electrolysis**
Advantages	- Well established technology - Non noble catalysts - Long-term stability - Stacks in the MW range - Cost effective	- High current densities - High voltage efficiency - Good partial load range - Compact system design - High gas purity - Dynamic operation
Disadvantages	- Low current densities - Crossover of gasses (degree of purity) - Low partial load range - Low dynamics - Low operational pressures - Corrosive liquid electrolyte	- High cost of components - Acidic corrosive environment - Possibly low durability - Commercialisation - Stacks below MW range

2.3 Economic feasibility of hydrogen

In Figure 2.1 the distribution of the Levelised Cost Of Hydrogen (LCOH) is displayed. This LCOH stands for the total costs to produce 1 kilogram of hydrogen. Even though this overview of predictions may already be outdated, a lot of information can be derived from the distribution of costs. In order to increase the economic feasibility of green hydrogen, the costs have to be reduced, while the revenues have to be increased. The main costs, as can be seen in the figure, for the production of hydrogen are the electricity costs. Efforts to increase the business case of green hydrogen should therefore primarily focus on reducing the electricity costs. Secondly, the CAPEX of the electrolyser plays an important role in the total costs: it is included in the initial costs as well as the stacks, as well as in the O&M. For increasing the revenue, the most important factor is to decouple the gas and electricity prices. The electricity prices are mainly driven by the gas price, as gas turbines are the most expensive dispatched generation source. Additionally, as hydrogen is often considered as a replacement for natural gas, the prices per MWh are often equated. When the prices of gas and electricity are decoupled, hydrogen can be produced at times when the electricity prices are low, and sold at the same time, while the gas prices are high. The long-term solution for decoupling the prices is by increasing the share of RES.

However, from a perspective of a company planning to install an electrolyser, factors such as the electricity price, the CAPEX of an electrolyser and the coupling between gas and electricity prices are non-influenceable. For this reason, this research proposes guidelines that increase the viability of implementing an electrolyser. These are described below.

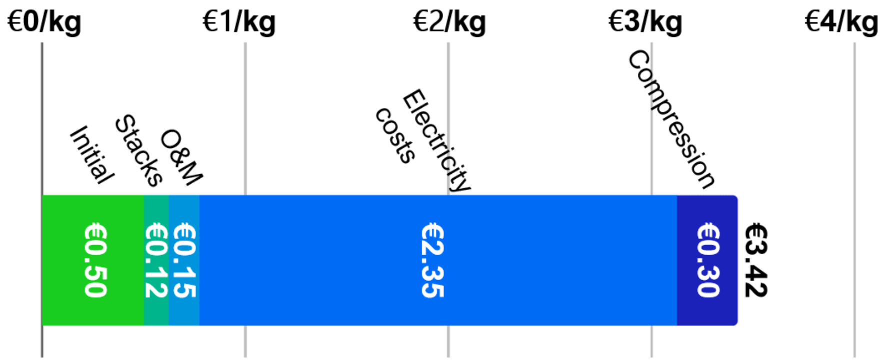


Figure 2.1. Overview of the contributions of costs to the Levelised Cost of Hydrogen (Deloitte, 2021)

Solutions for influenceable factors

Several solutions have been thought of that can be implemented in the short term to increase the viability of an electrolyser for green hydrogen. These solutions are displayed in a matrix in Figure 2.2. This matrix describes the expected impact that the solutions have on the viability, versus the complexity of implementing the solution in the Energy Management System (EMS) for the microgrid. The impact is estimated and assessed in the literature review in Appendix B. Further explanation of the solutions can be found in the appendix as well. The solutions include:

- Seasonal underground hydrogen storage. By storing hydrogen seasonally, the electricity and gas prices are decoupled from the electrolyser's owner's point of view.
- Ideal operation conditions. Electrolysers benefit from a steady operation and higher operation temperatures due to efficiency gains, resulting in lower power costs (Escobar-Yonoff et al., 2021).
- Electricity trading. Electricity is bought on the electricity market. Trading on different markets with a dedicated trading strategy can significantly reduce the electricity costs.
- Energy Management Algorithm. The algorithm of the Energy Management System (EMS) determines how the electrolyser is dispatched. As an algorithm, one can think of different optimisation or control methods.

- Financial aid. Especially in the early stages of electrolysis hydrogen production, financial aid is of the utmost importance.
- Sizing optimisation. This solution reduces the CAPEX by spending effort to have the size of the electrolyser and its equipment optimised. (Roy et al., 2021; Pan et al., 2020).
- Common equipment. Especially for larger electrolyser plants, sharing common equipment can reduce the total CAPEX. For example, one large compressor for hydrogen would be financially preferable to multiple smaller compressors when scaling up (Morgan, Manwell, & McGowan, 2013).
- Combining electrolyser with Battery Energy Storage System (BESS). As mentioned earlier, electrolysers benefit from a steady operation and have some difficulty responding quickly to load changes. Batteries have better dynamic behaviour. By combining the two, one can reduce the cost of electricity.

The actual impact is yet to be assessed by simulations, which is the main objective of this research. Based on the matrix of Figure 2.2, the most influential solutions are appointed for further research (the factors with the highest impact and lowest complexity). These include:

- trading on electricity markets;
- seasonal hydrogen storage;
- combining BESS with an electrolyser.

Included with the integration of electricity markets, the effect of electricity markets with high volatility will be assessed. The volatility of electricity markets - rapid and seemingly unpredictable changes in price - is increased with the share of RES, as these energy sources rely on external factors such as wind or solar power. The different electricity markets are explained in chapter 5. Financial aid is not assessed, as this is part of an ongoing feasibility study.

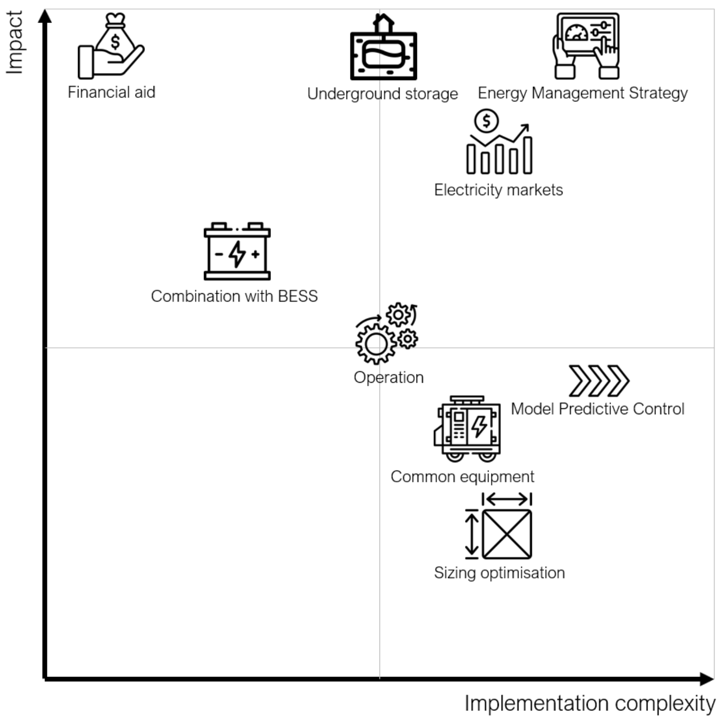


Figure 2.2. Matrix of the implementation complexity of a solution in an EMS versus the impact that the solution has on the economic viability of green hydrogen.

3 | Energy Management System

A study has been performed on the economic viability of an electrolyser. Several configurations of the system of the electrolyser should be tested on their effect on the revenues made. To investigate this, a physical model should be made of the electrolyser. However, this model should interact with other models as well, for example, a battery and an electricity grid. To make the models interact and control the data and electricity flows between them, an Energy Management System (EMS) should be used. Simulations can then be done on this EMS, in order to do research on the different configurations for the electrolyser system.

Firstly, propositions are done on what function the EMS should have. Then the system of the electrolyser is described. This system should be controlled by the EMS. These steps result in the description of the EMS and of the physical model of the electrolyser.

3.1 Functions of proposed EMS

As mentioned earlier, the EMS manages the energy flows and data between the various physical models. In order to improve the economic viability of the electrolyser, the goal of the EMS must be to optimise the revenue of the total system, not the amount of produced hydrogen. This means that not the electrolyser itself is optimised, but the full site that the electrolyser is on. For example, when a battery is combined with an electrolyser, the total profit is optimised, instead of the amount of produced hydrogen. The reason for this is that the production of green hydrogen must become economically viable. When producing a lot of green hydrogen, whilst not being financially attractive, it is not beneficial for the case of electrolysers. It is tested whether adding new elements to the system has a beneficial effect on the revenue and considered if it is worth the extra investment. Furthermore, the electricity consumed by the electrolyser is traded for on different markets, instead of offtaken from an electricity contract. The EMS has several functions to achieve this. Firstly, assets are represented as physical models in the EMS and the EMS must be able to control the assets. Secondly, the EMS should determine per time unit what the optimal solution of energy flow is for the revenues. As a third function, the EMS pseudo-trades on electricity markets, based on historic data.

3.2 System description

In Figure 3.1, an overview is given of the system that is investigated in this research. This system is connected to the grid, which means it can supply and consume electricity from the grid. The electrolyser is producing hydrogen that is sold directly to an industrial client. There is no solar park and wind park connected, in contrast to previous research in this project, as the goal for this research is the economic viability of the electrolyser. The system is therefore simplified. It is assumed that the cost of electricity from the grid has the same cost as offtaking from RES, as RES would supply to the grid for the current market price. For specific investigations, a battery can be connected to the system. This battery can directly exchange electricity with the electrolyser and the grid. For one further section of the research, seasonal hydrogen storage is added, meaning that the hydrogen is not directly sold to the industrial client, but can be kept in storage. The different elements/figures in the system description are in this project called 'assets'.

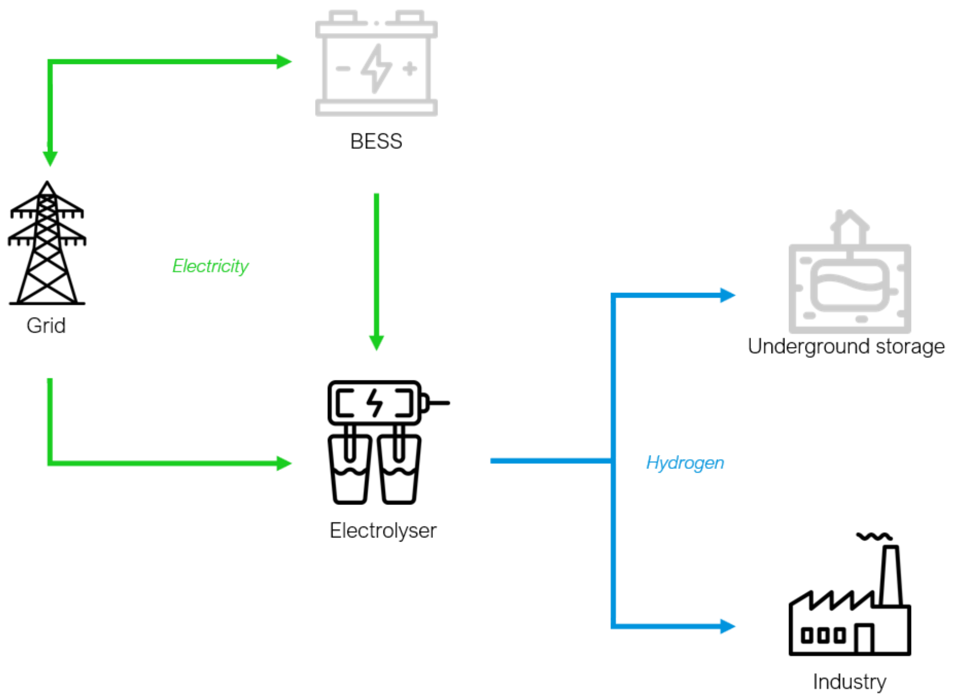


Figure 3.1. Overview of the system that is simulated in the EMS. The grey parts of the figure are added in the later stages of the research.

3.3 Description of EMS

The EMS is the software agent that controls the assets and the flow to and from the grid. In the EMS, the methodology for this research is incorporated. The EMS consists of so-called 'Assets' (i.e. physical models of the electricity grid, electrolyser, battery, hydrogen storage), the 'Controller', an 'Optimiser' and models of the electricity markets. The EMS is highly modular, meaning that only slight changes have to be made for investigating other configurations. As mentioned in the previous section, the assets 'hydrogen storage' and 'battery' are added in later stages of this research (see chapter 6 and chapter 7). The workflow, that is executed every minute, of the EMS is as follows (the explanation is given below):

1. Each asset determines **strike energy** (range) + **strike price**.
2. Central controller **receives** strike energy and strike price from assets and **instructs** optimiser to trade for electricity.
3. Optimiser **trades** on electricity market and obtains the won energy capacity at a certain price.
4. Optimiser **determines** the distribution of the won electricity over the assets **(linear optimisation)**.
5. Controller **assigns** this electricity to each asset.
6. Assets update their **power level** according to the assigned electricity capacity.

Step 1 is performed as described section 3.4. The strike energy is the electricity volume an asset is requesting for the next minute, given as a range of values. For example, when the electrolyser is turned on, the lower boundary of the strike energy range is standby power. The upper boundary of the strike energy is always lower or equal to the maximum power of the electrolyser. For more information about the power levels, see Figure D.1 in Appendix D. For a battery, two ranges are determined: for charging and discharging. For every strike energy range, a strike price is included: the maximum price that the asset is willing to pay for its electricity. For the electrolyser, this strike price is based on the hydrogen selling price (as described by section 3.4).

In step 2, the strike energy and prices from the assets are transcribed into useful information for the optimiser. The optimiser will then trade on the electricity markets, based on the strike energy and strike price that was defined by the assets (step 3) (see chapter 5 for the methods of market trading).

Then a linear optimisation is executed to distribute the won electricity bids over the assets (step 4). This linear optimisation has an economic objective: the total expected revenue that all assets will generate with the assigned electricity is maximised. The objective of this optimisation is given in Equation 3.1. In this equation, λ is the strike price of an asset (it represents the need for electricity, rather than the actual value of electricity price) and x is the assigned energy for asset i. Therefore, x_i represents the optimisation variables. Supply and consumption are in this equation defined for electricity (supply and consumption of energy must be in balance, see Equation 3.2). Furthermore, the optimisation must comply with the constraint that the assigned energy x_i is in the strike energy range requested by asset i. After the completion of the optimisation, the cost of electricity for the whole site is determined based on the market prices.

In step 5, the controller assigns this amount of electricity to the assets, after which the power level of the assets is updated. This loop is done every minute, due to the energy market's time interval.

$$\textit{MAXIMIZE} \quad f = (\sum_i \lambda_i * x_i)_{supply} - (\sum_i \lambda_i * x_i)_{consumption} \tag{3.1}$$

$$\sum_i x_i = 0 \tag{3.2}$$

The optimisation step (step 4) is a step of the utmost importance for this research. Through strike bids for the battery or adapting the strike bids for hydrogen storage, the optimisation step is utilised in all configurations. To emphasise: the optimiser has an economic objective, meaning that the total revenue of all assets is maximised.

3.4 Description electrolyser model

The electrolyser is a complex asset for the EMS. The largest difficulties are the start-up/stop times, the ramp rates and the minimum production power. The electrolyser has a start-up time to get from the off-state to producing state (the cold start). For the Alkaline electrolyser in this system, a cold start will take about 50 minutes. Turning the electrolyser off is a faster process, this will take about 10 minutes. There is also the possibility of standby mode. In standby, the temperature and pressure are maintained (thus some energy is consumed), whereas in off-state no energy is consumed. However, from standby no start-up time is needed, only the ramping has to be taken into account.

When the electrolyser is producing hydrogen, changing the power level of production is not instantaneous (e.g. from 100% to 60% power): the electrolyser has the characteristics of ramp-down and ramp-up rates. This means that the power level must gradually be increased or decreased. Because of these start-up times and ramp rates, the dynamic behaviour of electrolysers is more complex compared to that of for example a battery. Another factor that adds complexity to this asset is the minimal power. Below this power, the mixture of oxygen and hydrogen is unsafe, thus the mixture is fully vented. This means that a considerable amount of energy can be used, without actually producing the hydrogen that can be sold. Therefore, having an assigned energy level between standby power and minimal power is to be prevented.

As for now, constant efficiency is assumed. In practice, efficiency has a non-linear relationship with current density (see Figure 3.2).

The electrolyser is communicating its strike energy and strike price to the controller. The strike price is based on the hydrogen price, this hydrogen price is determined by the gas prices, taxes, subsidies and green premium. The strike price of the electrolyser is also called the valuation of electricity: the price that the electrolyser is willing to pay for its electricity. This valuation considers the conversion losses. Due to these losses, the amount of energy in hydrogen that is produced is

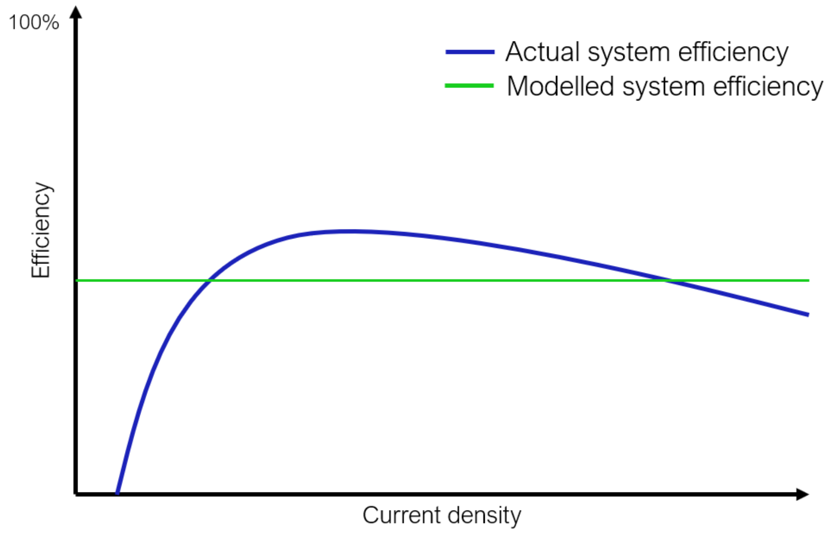


Figure 3.2. Actual, nonlinear system efficiency versus the modelled, linear efficiency (not on scale) (Lettenmeier, 2021).

not equal to the amount of energy in electricity that is utilised for this production. Therefore, the price bid for electricity must be adapted to the losses that take place. For example: if the hydrogen can be sold for €100/MWh, and the efficiency is 60%, then €60/MWh should be bid for electricity (see Equation 3.3).

$$\textit{Strike price Electrolyser} = \textit{Valuation} = \textit{hydrogen price} * \textit{conversion efficiency} \tag{3.3}$$

Deciding on the strike energy of the electrolyser is more difficult, as the power of the future and historic time steps should be taken into account, due to ramp rates and start-up/stop times. For this reason, firstly an optimisation is done on the day ahead clearing prices for the upcoming day, which decides the state of the electrolyser per minute for that day. A mathematical model of this state optimisation is displayed in Appendix C. It is then known beforehand when the start-up and stop times are activated. The lower boundary and upper boundary for the strike energy are determined based on the ramp rates. The EMS will determine what energy is most optimal.

In order to prevent the electrolyser from having a power level between standby and minimum power, a second optimisation loop is added. This loop is engaged at times when the assigned energy is between those levels. In the loop, the strike energy range is adapted to the most fitting value (either standby power or minimum power). The choice between the two of these is regulated by the aggressiveness of the asset.

The specifications of the parameters that are used in the investigations are displayed in Appendix D. In this appendix, explanatory figures of the used parameters can be found as well. Several assumptions have been made in developing the physical model of an electrolyser. These assumptions are displayed in the grey box on the next page. In Appendix E the verification and validation of the electrolyser model and EMS is performed.

List of assumptions:
For the system:

- The grid is used with a big enough grid connection, so there will always be enough power for the electrolyser.
- For establishing the selling price of hydrogen, the gas price is needed. It is assumed that the gas price of the next day is known at the moment that the day ahead bidding is done.
- Wind and solar parks are not incorporated in the investigations. For research on economic viability, configurations that use grid electricity can be easily compared. It is thus assumed that green electricity prices follow the same market prices as electricity from the grid.

For the electrolyser model:

- Efficiency of electrolyser is constant for all pressure / temperature / power levels (based on efficiency determined by Middelkoop (2022). Overall efficiency for AEL: between 60-80% (Buttler & Spliethoff, 2018) (Taibi et al., 2020)).
- Physical constraints of the electrolyser can be described by ramp rates and the start/stop times.
- Ramping of the electrolyser is a linear process.
- In the first part of the start-up phase, there is no production. In the second part of the start-up phase, there is reduced production (based on (Middelkoop, 2022)). See Figure D.2 for the behaviour of the electrolyser during start-up.
- The reduced production in the second part of the start-up phase is based on Middelkoop (2022).
- The standby power of the electrolyser is a theoretically calculated value, as described by Middelkoop (2022) (See Figure D.1).
- The start-up and stop times is based on information provided by manufacturers.
- Life cycle costs or degradation costs are not included in the model. Manufacturers do not have a clear view of the degradation of electrolysers.

4 | Electricity market volatility

As electricity costs are the highest driver of costs, utilising less expensive electricity will have a major impact. In this chapter, it is discovered what the effect of volatility in the electricity markets on hydrogen production and the hydrogen revenue is. Volatility is not a factor that can be influenced by an EMS. However, the volatility is expected to increase with the increase of the share of RES. The share of RES is increasing steadily over the years, meaning the volatility over the coming years will increase (PBL, TNO, CBS, & RIVM, 2022). Thus, it may be interesting to asses its effect on produced hydrogen revenue, for future implementation of electrolysers.

Firstly, the methods for volatility analysis are discussed. In the next section, the results are displayed and discussed.

4.1 Volatility analysis setup

Volatility is an important feature of markets. High volatility stands for rapidly fluctuating prices and large differences between low and high extremes. The numerical terminology for volatility is the standard deviation of the data set (Tashpulatov, 2011; Fernandes & Soares, 2022). In the electricity markets, the volatility can be reviewed over the yearly data set, but also daily. The daily electricity prices approximate a sinusoid. Higher daily volatility would translate to a larger difference between the lowest price and the highest price of the day (see Figure 4.1).

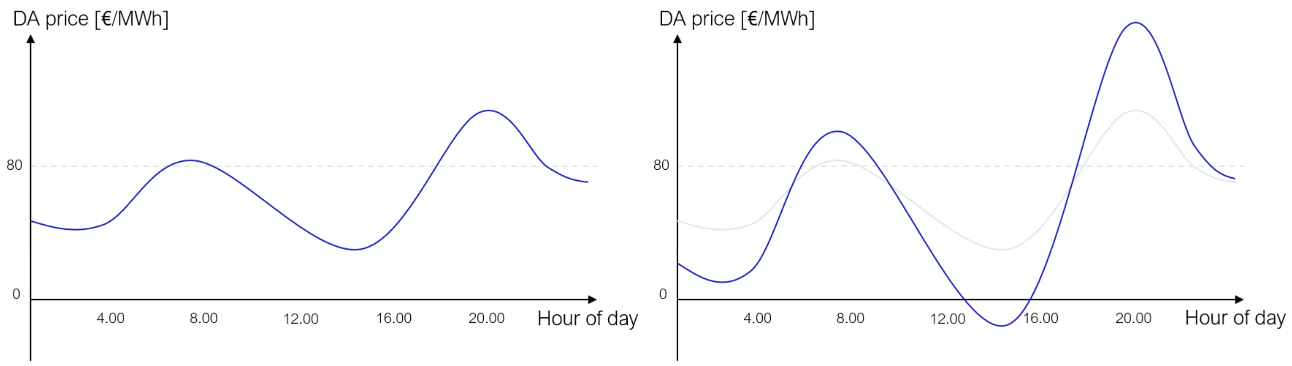


Figure 4.1. The two graphs explain the principle of daily volatility in electricity prices. The left graph represents a day with an ordinary electricity price distribution. The right graph shows a similar day but with higher volatility.

Volatility is an important phenomenon in the energy transition. Due to the increasing share of RES, the supply of energy is not conform to the demand for energy. Due to this imbalance, the prices of electricity will fluctuate more over the day and over the year. The volatility can therefore be estimated by using the share of RES in the total supply of electricity in the Netherlands, compared to years where the volatility in the electricity market is known. This data can be found as published in the "Klimaat- en Energieverkenning" by PBL et al. (2022). Solutions that help to balance the electricity markets can profit economically, for example, a battery that consumes at times of surplus of energy and delivers at times of shortage of energy.

It is expected that there is a correlation between the volatility in the electricity market and the hydrogen production. The volatility would cause daily dips to become more extreme, meaning that hydrogen could be produced at even lower electricity prices. As the hydrogen price is determined by the daily average gas price, for these hours hydrogen is produced at low cost and sold for higher prices. In this sense, the electrolyser is balancing the electricity market, as electricity is converted to another form of energy at times of surplus of electricity.

To discover a connection between volatility and hydrogen production, two steps are taken. Firstly, an analysis is done of the daily volatility and the daily hydrogen production of the years 2020, 2021 and 2022. The goal is to verify whether the volatility in electricity prices has a direct correlation to the hydrogen production. If this is not the case, other factors that have an influence should be found. In the second step, the direct influence of volatility is tested by creating new data sets. For three scenarios of high, mid and low day ahead prices, different values for the standard deviation are assigned. This must show what the direct effect of volatility can be on hydrogen production.

4.1.1 Analysis on volatility in historic data

The first analysis must show whether there is a direct correlation between volatility and hydrogen production. There may be other important factors for hydrogen production, these are to be established. As mentioned earlier, the volatility can be defined numerically as the standard deviation of the data set. In Table 4.1 an overview of the average prices and standard deviations of the day ahead market and hydrogen market are given. As can be seen, the volatility has increased dramatically over the course of the three years. For this part of the research, the correlation of the daily standard deviation to the daily hydrogen production will be determined.

Table 4.1. *Average and standard deviation of the day ahead market and hydrogen market prices (TenneT, 2023b; EEX, 2023)*

Year	Day ahead		Hydrogen market	
	Avg [€/MWh]	SD [€/MWh]	Avg [€/MWh]	SD [€/MWh]
2020	32.23	15.31	92.02	5.48
2021	102.94	74.71	130.05	36.45
2022	241.88	131.54	220.24	51.45

4.1.2 Analysis on artificial volatility data sets

In this subsection, the creation of a data set with increasing volatility is described. The artificial data set is created to have clean data to do the analysis on. By having a controlled environment for the analysis, the result will have a more decisive conclusion. The dataset shows the effect of volatility in combination with a relatively low, medium or high electricity price. The dataset is created with a well-known sinusoid formula, that is displayed below (Equation 4.1). In this formula, A is determined by the standard deviation (Equation 4.2). d determines the average electricity price. b determines the period of the sinewave. For electricity prices, there is a period of 12 hours, with two peaks and two valleys in a day. By Equation 4.3 it is determined that $b = \pi/6$ (unit: 1/hour).

$$f(x) = A * sin(b(x - c)) + d \tag{4.1}$$

$$A = \sigma_{sinusoid} * \sqrt{2} \tag{4.2}$$

$$(2 * \pi)/b = period \tag{4.3}$$

9 configurations are tested. The parameters of these configurations are displayed in Table 4.2 and visualised in Figure 4.2, Figure 4.3 and Figure 4.4. The configurations are each tested for 30 days. As the wave function is periodically for half a day, simulating for half a day would have been possible as well. However, the ramping between configurations would then start to play a role, whereas when testing for 30 days this can be neglected.

The values that are displayed in the table are based on the efficiency of the electrolyser. At times when the hydrogen has a value of 150 €/MWh, and the electrolyser has a conversion efficiency of 60%, the electricity is worth 90 €/MWh. No other costs or losses are counted in these calculations, meaning that without volatility at an average electricity price of 90 €/MWh, the electrolyser is expected not to produce.

Table 4.2. *Parameters for the artificial data set. The hydrogen price is kept constant, while the average and standard deviation of the day ahead (DA) price have 3 options. This results in 9 configurations.*

Parameter	Configuration	Value [€/MWh]
DA avg	low	70
	mid	90
	high	110
DA SD	no	0
	low	25
	high	50
Hydrogen price	constant	150

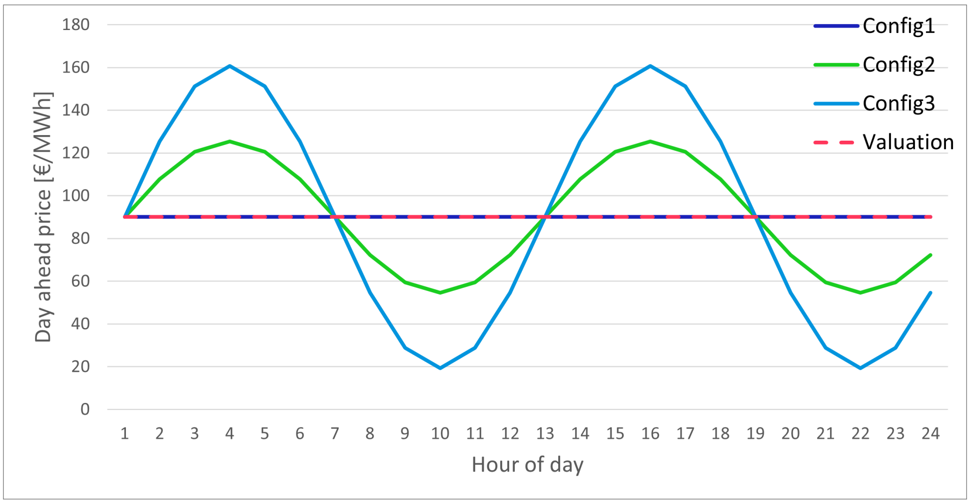


Figure 4.2. Visualisation of configuration 1, 2, 3 for volatility analysis. The red dotted line represents the valuation for electricity, the dark blue line is the electricity price without any volatility, the green graph has some volatility and the light blue graph represents an electricity price with high volatility.

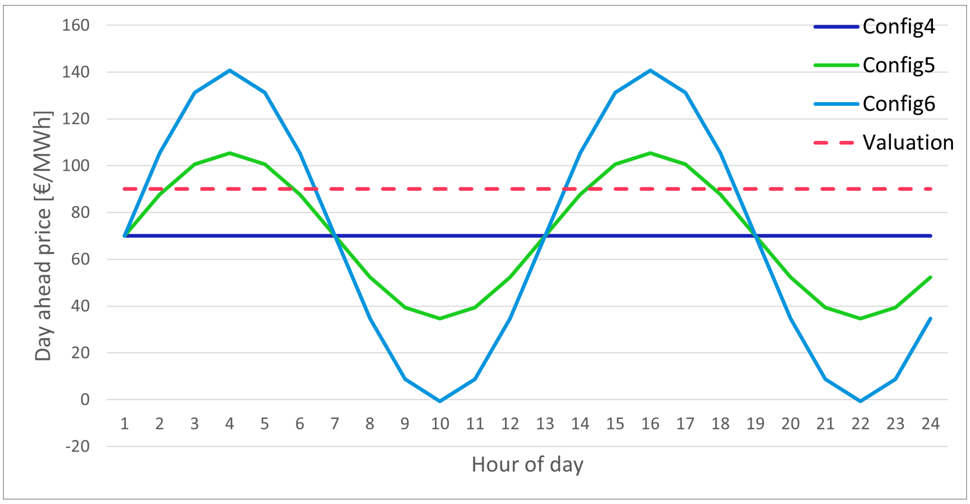


Figure 4.3. Visualisation of configuration 4, 5, 6 for volatility analysis. The red dotted line represents the valuation for electricity, the dark blue line is the electricity price without any volatility, the green graph has some volatility and the light blue graph represents an electricity price with high volatility.

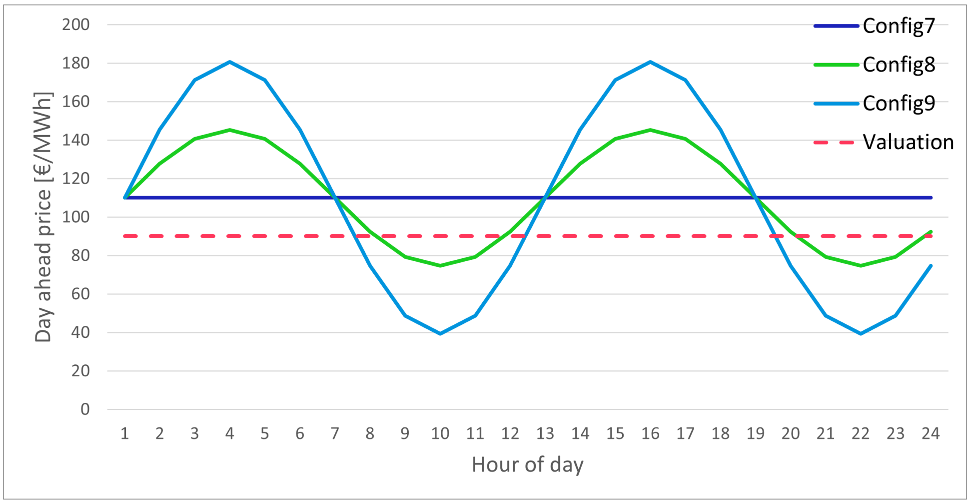


Figure 4.4. Visualisation of configuration 7, 8, 9 for volatility analysis. The red dotted line represents the valuation for electricity, the dark blue line is the electricity price without any volatility, the green graph has some volatility and the light blue graph represents an electricity price with high volatility.

4.2 Results and discussion

This section discusses the results of the research on the electricity market volatility. In the volatility analysis, two experiments have been done. The first experiment tests the influence of volatility on the economic viability in historic data sets. In the second experiment, an artificial data set is created, that must show the influence of volatility on the hydrogen revenue.

4.2.1 Analysis on volatility in historic data

This section must show the relationship between daily volatility in historic data and the hydrogen revenue for those days. As mentioned in section 4.1, the volatility has increased considerably in the years 2020, 2021 and 2022.

This analysis is done based on the configuration and trading tactics as described by Middelkoop (2022). The state of the electrolyser is determined based on the day ahead prices, after which the trading for electricity is done on the imbalance market.

Table 4.3. *Correlation of the volatility in the electricity prices and the produced hydrogen or hydrogen revenue.*

Year	Correlation volatility & produced H2	Correlation volatility & Hydrogen revenue
2020	-0.140	0.298
2021	-0.413	-0.309
2022	-0.0481	0.00712

For the analysis, it is important to consider Table 4.1. The volatility in the electricity market has increased steadily over the years 2020, 2021 and 2022. However, the averages have increased dramatically as well. The average hydrogen prices in 2020 and 2021 are higher than the electricity prices, which is needed for production due to the conversion losses. In 2022 the electricity price is higher than the hydrogen price, in that year there was not a lot of hydrogen produced, causing virtually no correlation to be found (See Table 4.3 for the volatility correlation results).

2020 is the only year that has a positive correlation between volatility and hydrogen revenue. This correlation is however fairly small. This may be due to the fact that - because of the low electricity prices - at times of high volatility less hydrogen is produced, as the electricity price is at its peaks higher than the electrolyser is willing to pay. On the same day, hydrogen is produced at lower electricity costs, due to downward extremes, giving more revenue. Therefore it seems that in 2020 the revenue remains fairly constant, even though the volatility of electricity prices may fluctuate.

Even though the correlation for 2020 and 2021 is too low to draw hard conclusions, it is important to notice that there is an apparent negative correlation between volatility and hydrogen production and revenue. This may be due to the economic objective of the research: producing a lot of hydrogen may not be economically the best option. This then requests another correlation analysis: the correlation between the volatility and the contribution margin, which can be seen in Table 4.4. **The contribution margin is determined by the hydrogen revenue minus the electricity costs.**

In Table 4.4 the correlation between the average day ahead price and contribution margin is negative: with low electricity prices, hydrogen is produced at a lower cost. The correlation between volatility and the contribution margin is inexplicable: the correlations are insignificant as well as varying per year.

The correlation between the average electricity price and the produced hydrogen or hydrogen production in Table 4.5 is negative. When the electricity prices are lower, more hydrogen is produced, generating more revenue. In 2020, the margins on producing hydrogen were smaller, meaning that with lower electricity prices more hydrogen is produced, but not that much more revenue was generated.

From this analysis, not a lot can be concluded on the correlation between the volatility and the hydrogen revenue or hydrogen production. Either the results are inconsistent or not significant. On the other hand, the average of the electricity prices seems to have a higher influence on the hydrogen production and revenue. This could be due to several reasons. The volatility in the hydrogen price is not considered in this analysis. This could possibly have an influence on the results as well. Furthermore, due to extreme events in the historic data sets (COVID-19 and the Russian-Ukranian war), external factors have influenced the markets that are unpredictable. However, the most compelling argument for the seeming absence of correlation is that the production and revenue of hydrogen are dependent on more factors than volatility alone, meaning that correlation is difficult to establish in historic data.

In order to determine the relationship between volatility and hydrogen production and revenue further research is done, by analysis of an artificial volatility data set. This data set consists of pure volatility data, meaning that no external factors can influence the results.

Table 4.4. *Correlation of the volatility in the electricity prices or average electricity prices and the contribution margin of hydrogen.*

Year	Correlation vol DA & Contr Marg	Correlation avg DA & Contr marg
2020	-0.297	-0.537
2021	-0.0828	-0.436
2022	0.225	-0.428

Table 4.5. *Correlation of the average electricity prices and the produced hydrogen or hydrogen revenue.*

Year	Correlation avg DA & produced H2	Correlation avg DA & Hydrogen revenue
2020	-0.515	-0.125
2021	-0.687	-0.649
2022	-0.555	-0.530

4.2.2 Analysis on artificial volatility data sets

In Table 4.6 an overview is given of the results of simulations that are done based on the artificial data set. Each configuration is run for 30 days. The contribution margin is calculated by subtracting the electricity costs from the hydrogen revenue. The artificial data set is created in order to display the relationship of volatility to hydrogen revenue and production, without considering additional influences on the revenue and production.

Table 4.6. *Overview of results of artificial volatility data set.*

DA price	SD value	H2 production [MWh]	H2 revenue [k€]	Contribution margin [k€]
mid	no	0	0	-9.71
mid	low	3618.32	542.75	152.50
mid	high	3618.87	542.83	310.35
low	no	8640.00	1296.00	289.40
low	low	6498.87	974.83	330.00
low	high	5047.42	757.11	477.59
high	no	0	0	-11.91
high	low	2178.87	326.83	33.85
high	high	3618.32	542.75	199.49

A lot can be deducted from these results. An important phenomenon in the discussion of these results is the value that is assigned to the electricity by the electrolyser. The value is based upon the hydrogen selling price and the efficiency, the electrolyser is utilising more electricity [MWh] than the amount of energy that is in the hydrogen [MWh]. The hydrogen price and conversion efficiency are constant for these simulations, meaning that the value of electricity for the production of hydrogen is 150 €/MWh * 0.6 equals 90 €/MWh, which was called the 'valuation' (see Equation 3.3). The valuation of electricity is compared to the actual electricity price.

For the first three configurations, the electricity price is equal to the valuation of electricity. In the valuation, only the conversion efficiency is incorporated. To prevent degradation, the electrolyser is not producing hydrogen. However, in the simulations, no state optimisation was done: the electrolyser was always turned on, meaning that standby power is consumed when there is no production. For every price lower than the average price, it is already beneficial for the comparison of hydrogen value and production costs. So, the hydrogen production for low and high volatility is roughly equal. Though, the electricity costs are lower for high volatility, as the average price of consumed electricity is lower. Thus, with high volatility, the contribution margin is higher as well.

For configurations 4 to 6 the electricity price average is low. Without any volatility, the electrolyser is producing at full power, as the electricity price is always lower than the valuation of electricity. When introduced to volatility, the production and revenue of hydrogen decrease. It now occurs that the electricity price is sometimes higher than the valuation of electricity. Still, the contribution margin increases with the increase in volatility. This can be explained by the reduction in electricity costs: the average price of the consumed electricity is lower.

For the last three configurations, the electricity price is high. Without any volatility, no hydrogen is produced, and the electrolyser is on standby for the full 30 days. The contribution margin is more negative than it was in the first configuration, due to the higher electricity prices. When introducing volatility, the electricity price will drop occasionally below the valuation of electricity. This occurs more often when having higher volatility, causing a higher hydrogen production and revenue. However, the average electricity price of the consumed electricity is lower as well when having high volatility. This induces a dramatically higher contribution margin for the high volatility configuration.

When comparing all 9 configurations, it shows that the hydrogen production and contribution are affected by the volatility. Higher volatility for an equal electricity price has always caused a higher contribution margin in these simulations. The effect of volatility on the amount of produced hydrogen does however relate to the absolute electricity price: with a low average electricity price, the amount of produced hydrogen is reduced. This is caused by the economic objective of the research. The simulations show that there is a correlation between the volatility and the contribution margin. However, it shows as well that the influence of the average electricity price is more important. When having a high average electricity price with high volatility, one will have a lower contribution margin than when having a low average electricity price with low volatility.

5 | Electricity market trading

In the literature review that has been done, an overview is given of different electricity markets in the Netherlands. This literature review can be found in Appendix B. Having a good strategy for trading on an electricity market that fits the system well, is expected to be one of the most influential factors for the economic feasibility of an electrolyser, as this will have a large effect on the electricity costs. In the literature review, it was concluded that possible electricity markets for an electrolyser are the day ahead (DA), automatic Frequency Restoration Reserves (aFRR), GOPACS and the imbalance market. As GOPACS is a new market, of which the specifics are not yet known, this market is out of scope. Another possible option for electricity usage of an electrolyser is a Dynamic Contract, which is not a market but rather a contract with a supplier. Firstly, the markets are explained shortly and considered for their suitability for an electrolyser, after which the trading tactics that will be investigated are described. Lastly, the results are presented and shortly discussed. The general discussion of all results can be found in chapter 8. All information about the electricity markets can be found at Tennet (2023).

5.1 Prospected electricity markets

Day ahead

The day ahead is one of the Spot markets, together with the long-term market and intraday market. The day ahead price is the representation of the 'electricity price'. On this market, capacity of electricity is bought and sold beforehand. Parties submit bids for either feed-in or offtake, at 12 o'clock noon the auction is held, after which the price of electricity is determined and electricity capacity is assigned to the parties for every hour of the day. The parties receive or pay the clearance price of electricity, not the price that was bid.

aFRR

The aFRR market is a balance market. A party bids capacity that is available for balancing the market. There are several restrictions on this capacity, this is explained in Appendix B. Based on these restrictions, the electrolyser should always be in standby mode, to be able to react quickly. Furthermore, the electrolyser is only able to sell offtake capacity. When a certain amount of hydrogen is required, this market is not useful. This market rewards parties that have capacity on hold for balancing activities, but this does not mean that the electrolyser will actually produce hydrogen. When being on hold, the party is not allowed to use its capacity for production with electricity from other markets. This market is therefore expected to have less impact on the business case of green hydrogen, which is the reason that this market is out of scope for now. It is however recommended that this market is investigated in further research, as including this market in a strategy may improve the business case even more.

Imbalance

The imbalance market is a real-time market, a party pays for the imbalance it creates, or it receives money for the balance it creates. Both can be done by feed-in or offtake of electricity. This means that if consuming energy restores the balance of the grid (at times when there is a surplus), one can actually earn money. The price for electricity is however determined afterwards, which indicates that price predictions are very important. Another important phenomenon is that if capacity is bought on the day ahead market, and the party does not comply with this capacity, this counts as using the imbalance market. This would mean that if capacity for offtake of electricity was bought on the day ahead market, but there is a shortage of electricity, and the feed-in imbalance market prices are very high, a party receives the money for not using the day ahead capacity as if the party is feeding electricity in the grid.

The imbalance market is one of the backup markets of the EMS, as this can solve any small deviation in the energy balance.

Dynamic contract

Another backup for the EMS is a Dynamic contract. This is in fact no market. A party pays the day ahead electricity price for offtake, plus a fee for the contract costs, without having to bid on the day ahead. This contract is often used for solar parks, meaning that the owner receives the day ahead price minus a contract fee.

5.2 Trading strategies

In this subsection, an overview of the research and simulation is given. Furthermore, the several trading strategies that are investigated are discussed.

5.2.1 Dynamic contract

The first configuration serves as a baseline for all other trading strategies. This strategy consists of buying electricity on a dynamic contract, without paying a fee to the supplier. This construction can be seen as a simplified day ahead market trading, where bids are not taken into account. The electrolyser will produce hydrogen when the selling price for hydrogen is higher than the electricity costs. This strategy therefore represents the optimal participation on the day ahead market.

5.2.2 Imbalance market trading

The next strategy is on the imbalance market trading. As the imbalance is a backup market, this is the next logical step in the research. This strategy for trading is based on imbalance market price predictions. As these predictions are only available 15 minutes on beforehand, and an electrolyser has warm-up times and ramp rates to go to full power or standby power, this strategy is based on a state optimisation. This state optimisation is based on the day ahead predictions, as the day ahead is an estimation for the imbalance prices. The predictions for the imbalance price get better every minute during the 15 minutes before the ISP (Imbalance Settlement period) and during the 15 minutes of the ISP itself. This strategy is researched by Middelkoop (2022), and will not separately be discussed in this report.

5.2.3 Full capacity day ahead trading

The day ahead trading is an additional market to the backup market, which is in this case the imbalance market. Trading on the day ahead market is done by bidding on the previous day of the one that one will consume or feedin electricity. As for the first strategy, the value of the electricity based on the selling price of hydrogen (valuation) is bid (see Equation 3.3 for the definition of valuation). The selling price of hydrogen is in the simulation determined by perfect knowledge of historic data, as a gas price estimator is not included in this research. In this first strategy, the full capacity of the electrolyser is bid as the capacity for the day ahead market.

The difference between the day ahead trading strategy and the dynamic contract strategy may not be obvious. The main difference in the implementation of the markets is that trading is needed for day ahead capacity, whereas a dynamic contract is purely an agreement with a supplier. Another difference is the fee that is paid to the supplier of the dynamic contract, this fee is not paid for day ahead capacity. The last and most important difference between these trading strategies is the backup market. The dynamic contract is a stand-alone solution for electricity. The day ahead market has the imbalance market as back-up, for when electricity is being used at times that no day ahead capacity was available. This gives the opportunity for intermarket trading. Intermarket trading is not possible for the dynamic contract.

5.2.4 Day ahead arbitrage

Another strategy for the day ahead market uses the difference in electricity price of the day ahead and the imbalance market. One bids for a certain amount of the total capacity (for example 15MW of the total of 20MW), for the price of the electricity value of the sold hydrogen. Then intermarket trading is used, meaning that one decides its offtake based on the predictions of the imbalance market. If the imbalance price for offtake appears to be low, then the electrolyser will consume its maximum capacity. If the imbalance price for offtake appears to be high, one just consumes the capacity bid that was won on the day ahead market. If the price for feed-in appears to be high, one consumes less than the capacity indicated on the day ahead market bid. As explained, this will be registered as a feed-in operation, meaning that money can be made without using the electrolyser.

This last strategy will not be especially beneficial for the amount of hydrogen produced. It is however expected that a higher total revenue is generated by the electrolyser. It is to be decided by its user what is a preferable operation.

Three values are used for capacity bid, 100%, 70% and 40% of the maximum capacity (which is 20MW). After this, three values are chosen based on the results to see whether there is a better capacity bid between the aforementioned values.

5.3 Results and discussion

In this section, the results of the trading strategies are presented and considered. The results follow the same order as described in section 5.2.

5.3.1 Dynamic contract

Result

The result of three full-year simulations is displayed in Table 5.1. In this configuration, all electricity was bought by a dynamic contract, without an additional fee for the supplier. This means that electricity was bought for the day ahead clearance price, without having to bid capacity on the previous day.

Table 5.1. *Summary of the results of the dynamic contract simulations.*

Year	Produced H2 [GWh]	Contribution margin [M€]	Full-power hours
2020	100.93	4.61	8402
2021	39.50	-0.071	3255
2022	13.31	-0.35	1088

In the table, it can be seen that in 2020 more hydrogen has been produced than in 2021 and 2022. The maximum amount of hydrogen that can be produced in a year with a 20MW electrolyser is 105.1 GWh. In 2020, there were 8402 full-power hours compared to a total of 8784 hours in a year. The electrolyser was never turned off: at the start of the year the electrolyser started up, and only went in standby for a little over 300 hours. Furthermore, in 2020 the contribution margin is positive, which is not the case for 2021 and 2022.

Discussion

2020 was a good year for hydrogen production, as can be seen in the comparison of Figure 5.1. The electricity price is in 2020 often below the electricity valuation for hydrogen production. This is not the case for 2021 and 2022, as can be seen in Figure 5.2 and Figure 5.3. It can be seen in the heatmap that at times when the electricity price and hydrogen price are comparable, for example at the start of 2021 or in October 2022, hydrogen is produced especially at cheaper moments of the day. The electricity price distribution is less visible in the heatmap of 2020 due to high production overall.

An important factor in 2021 and 2022 is the start-up and stopping costs of the electrolyser. In 2022 the electrolyser was on full power for about 1000 hours. Of the 1800 hours that the electrolyser was on, it was more than 600 hours in standby. That means that standby and start-up/stop costs contribute more to the total costs than in 2021, where the electrolyser had over 3300 hours of production. This can be seen in the less negative value in the contribution margin of 2021.

What makes a negative value for the contribution margin possible? The strategy that is handled in this simulation ensures that hydrogen is produced at times when the hydrogen revenues are higher than the electricity costs. This could not cause negative revenues. However, the electrolyser can still consume electricity when it is not in production: when on standby and when it is starting up or shutting down. The amount of time that the electrolyser is in those modes depends on the state optimisation. A limitation of this EMS is that it handles time exactly as if it were in application: minute per minute. The state optimisation is thus done only for the next day, as for that day the electricity prices are known. If a state optimisation was done for the whole year, this would result in a positive, or less negative, result for the contribution margin.

Furthermore, it is important to notice the absolute value of the electricity price and hydrogen value. At times when the absolute electricity price and gas price are high, the relative added value of the SDE++ subsidy and taxes is low, as the gas price determines the hydrogen value. This means that the gas price and electricity prices in 2021 and 2022 are again more coupled than in 2020, resulting in lower hydrogen production.

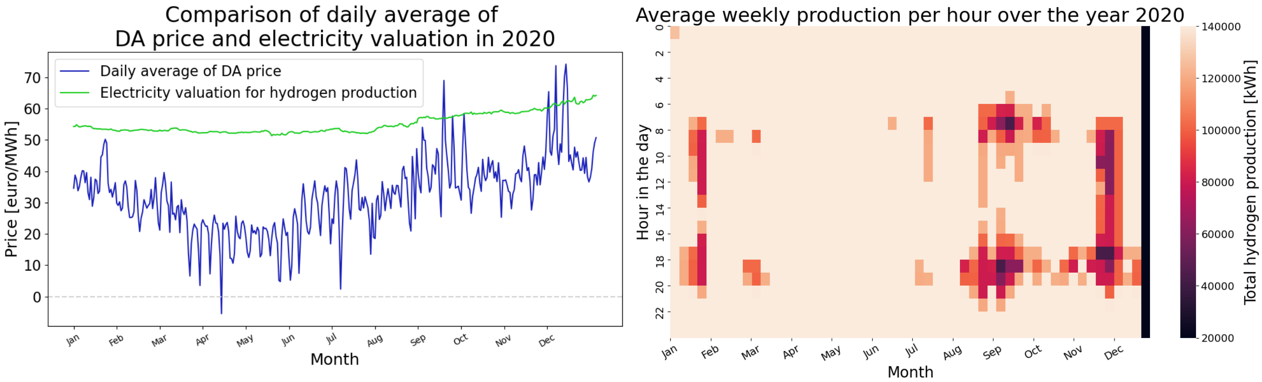


Figure 5.1. Comparison of the day ahead and electricity valuation for hydrogen production, versus a heatmap of the production of hydrogen in 2020 per week and hour.

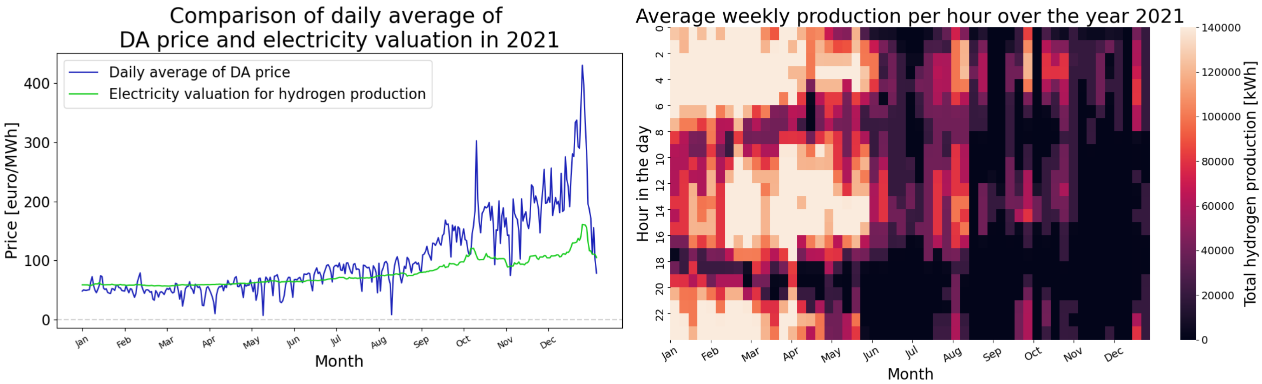


Figure 5.2. Comparison of the day ahead and electricity valuation for hydrogen production, versus a heatmap of the production of hydrogen in 2021 per week and hour.

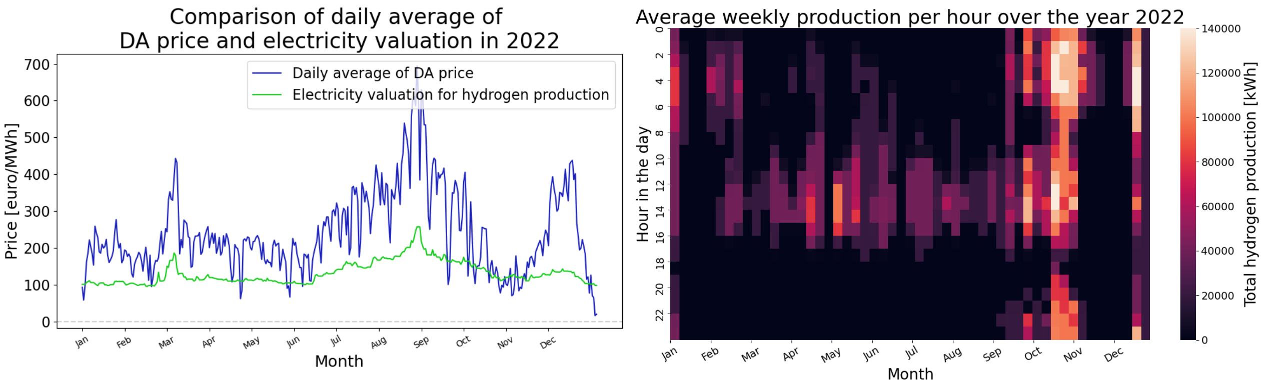


Figure 5.3. Comparison of the day ahead and electricity valuation for hydrogen production, versus a heatmap of the production of hydrogen in 2022 per week and hour.

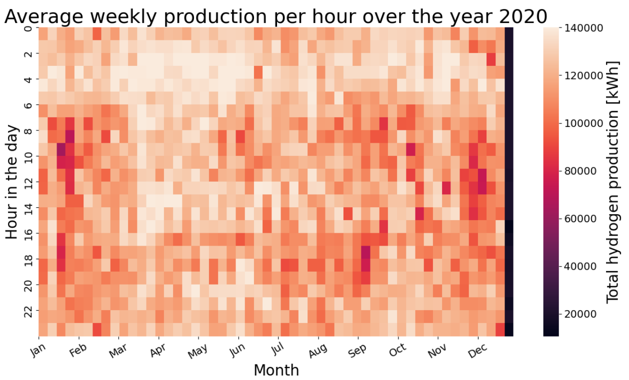
5.3.2 Imbalance market trading

Results

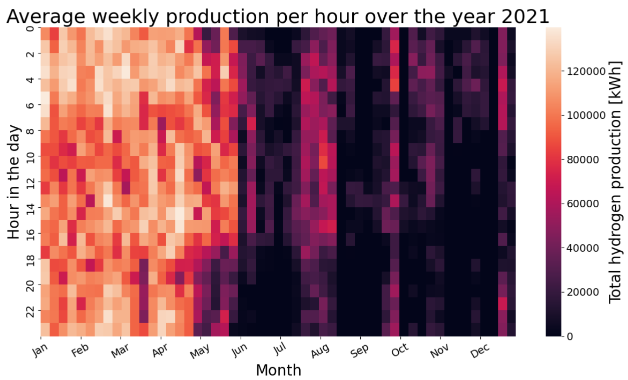
The results of the electrolyser using electricity from the imbalance market are displayed in Table 5.2. As can be seen, the contribution margins have been improved, even though in all years less hydrogen is produced.

Table 5.2. *Summary of the results of the imbalance simulations. The percentages indicate the case compared to the dynamic contract configuration.*

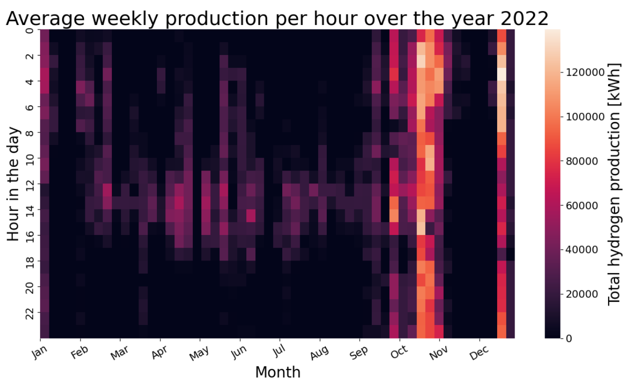
Year	Produced H2 [GWh]	Contribution margin [M€]	Full-power hours
2020	90.00 -11%	5.09 +10%	6902 -18%
2021	37.62 -4.8%	2.22 +↯%	2693 -17%
2022	11.03 -17%	1.97 +↯%	792 -27%



(a) Hydrogen production per week in 2020



(b) Hydrogen production per week in 2021



(c) Hydrogen production per week in 2022

Figure 5.4. Heatmap of hydrogen production in 2020, 2021, 2022 when using the imbalance market.

Discussion

It is noteworthy that when using the imbalance market, the electrolyser is producing fewer hours on full-power (as well as a lower amount of production hours). However, the amount of hours that the electrolyser is turned on, is equal to the amount of hours in the dynamic contract configuration, as the input for the state optimisation is equal in every configuration. This thus influences the standby hours as well as the non-full-power production hours. The reduced production of hydrogen demonstrates the economic objective of the EMS. Furthermore, these results reveal that with a more sophisticated trading strategy, the cost can be dramatically reduced. As can be seen in Figure 5.4, the hydrogen production is less correlated with the day ahead price peaks and valleys. The imbalance price fluctuates around the day ahead price, meaning that the production profile is more evenly spread over the hours. The days with a relatively high electricity price average are however still recognisable, as they were in Figure 5.2 and 5.3.

5.3.3 Full capacity day ahead trading

Results

The results of bidding the maximum capacity of the electrolyser on the day ahead market are displayed in Table 5.3. In Figure 5.5, the power of the electrolyser of one day in the year is displayed. In this figure, it can also be seen at what moments in time the day ahead biddings were won for the electrolyser (bottommost graph), this corresponds to the intersection points of the day ahead prices and hydrogen price in the uppermost graph.

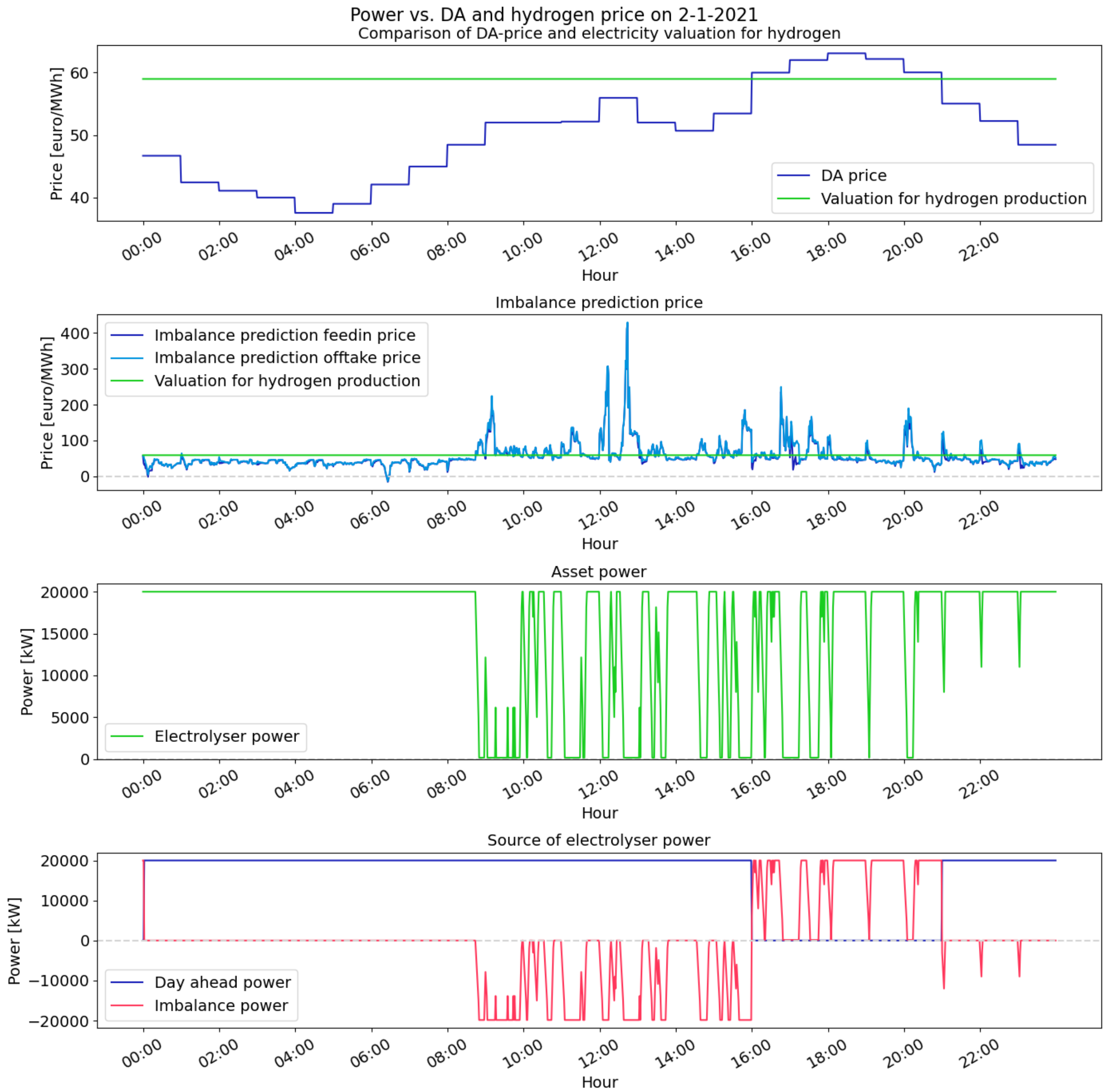


Figure 5.5. Electrolyser power on 2 January 2021 and the power that is traded on the day ahead and imbalance market, versus the day ahead and imbalance prices.

Table 5.3. *Summary of the results of the full capacity day ahead strategy. The percentages represent the comparison to the imbalance-only figures.*

Year	Produced H2 [GWh]		Contribution margin [M€]		Full-power hours	
2020	92.25	+2.5%	5.89	+16%	7177	+4.0%
2021	40.58	+7.9%	2.47	+11%	2963	+10%
2022	12.27	+11%	2.68	+36%	894	+13%

Discussion

When comparing this configuration (of the day ahead market combined with imbalance market trading) with the configuration of imbalance market only, it is noticeable that more hydrogen is produced for all three years. Besides, the contribution margin has increased considerably. This shows the potential of electricity trading: without altering the electrolyser itself, more hydrogen can be produced while having a higher revenue.

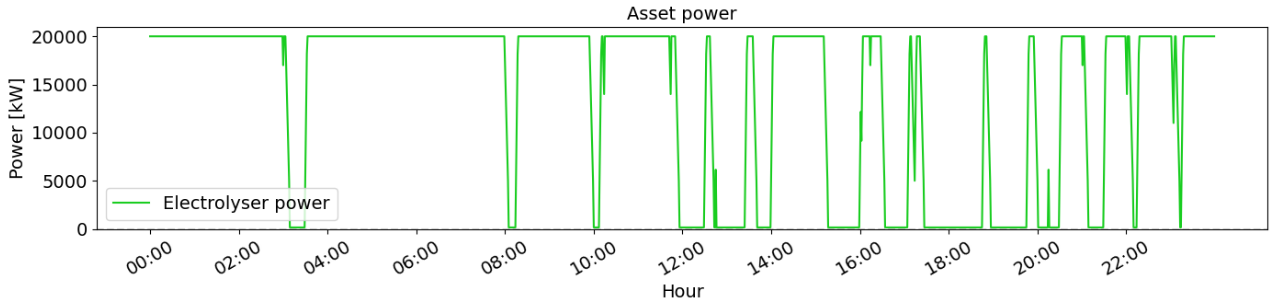
Another remarkable phenomenon can be seen in the two lower graphs of Figure 5.5. While the full power bid was won on the day ahead market, the electrolyser starts intermittently producing hydrogen around 9.00, instead of running on full power. In the meantime, there is a negative imbalance power, meaning that electricity is fed into the grid.

An important remark is that the electricity flow shown in the bottommost graph of Figure 5.5 is virtual. As explained in section 5.2, not offtaking power that was won on the day ahead market, is counted as feedin on the imbalance market. The day ahead power shown in the graph is virtual - it is the power that is available due to a won bid - unless it is actually utilised by the site (from 0.00 to 9.00). Likewise, the imbalance power is virtual, except for the times that the power is actually used by the site (for several moments between 16.00 and 21.00).

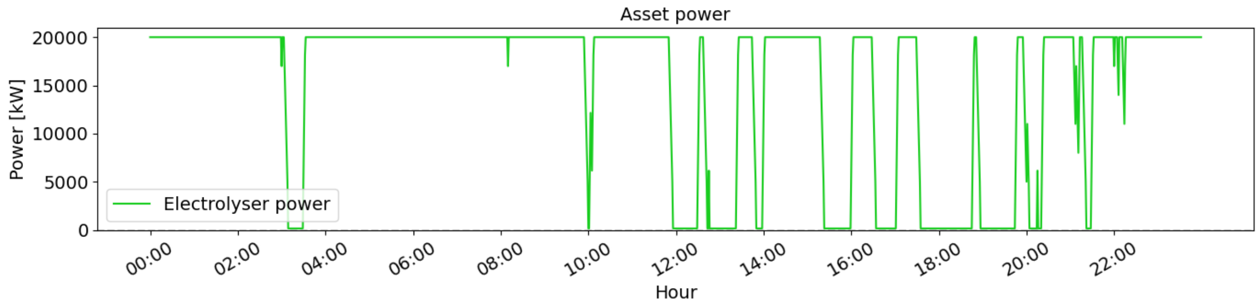
Why does the electrolyser not use the full power bids of the day ahead market? As can be seen in the second graph of Figure 5.5, the predictions for the imbalance feedin price are at times excessively high. As the EMS has an economic objective, it is decided that the electricity is not used for hydrogen production, but for imbalance feedin, as more profit is made by doing so. This aspect of market trading creates the opportunity to earn money, even though the electrolyser is not used at that time.

How can the hydrogen production be increased? In Figure 5.6, one can see the differences in power for the two trading strategies. Overall, the graphs appear similar. However, several details make a large difference in the production of hydrogen. For example: as there is day ahead capacity available at 21.00, the duration of the dip is smaller. As for the dips after 22.00, these have mostly disappeared: the fluctuations are caused by short moments of feedin to the imbalance market. The less fluctuating profile of the day ahead and imbalance markets combined causes an increase in the production of hydrogen. Even though the differences between the profiles may seem minor, the difference in production over this day is 17.5 MWh, which would extrapolate to a difference of over 6 GWh per year. Again, it is to be noted that the state optimisation is equal for both cases, meaning that the hours-on time is identical. Differences in total produced hydrogen are solely due to electricity trading.

The assumption of the constant efficiency for the electrolyser does have an impact on the power profiles. The power profile is rather erratic, as in the model there is no penalty for behaving so. Future information by manufacturers and experiments must indicate whether such behaviour is to be desired.



(a) Electrolyser power when only using the imbalance market



(b) Electrolyser power when trading on the imbalance and day ahead market.

Figure 5.6. Power comparison of (a) Only buying electricity on the imbalance market and (b) Trading on the day ahead and imbalance market (Date: 2 January 2022).

5.3.4 Day ahead arbitrage

Results

The results of the day ahead arbitrage simulations are shown in Table 5.4. The day ahead arbitrage configuration bid a share of the full capacity of the electrolyser on the day ahead market, after which more freedom is gained on the imbalance market. Instead of only being able to offtake less of the day ahead market when a bid is won, now the ability is created to consume more electricity than the bid has won.

The figures for the lower %-capacity bids are lower than the previously researched 100% capacity bid.

Table 5.4. *Summary of the results of the day ahead arbitrage strategies. The percentages indicate the case compared to the DA-100% strategy.*

Cap. bid	Year	Produced H2 [GWh]		Contribution margin [M€]		Full-power hours	
70%	2020	91.31	-1.0%	5.63	-4.4%	6983	-2.7%
	2021	39.79	-1.9%	2.44	-1.2%	2811	-5.1%
	2022	12.00	-2.2%	2.52	-6.0%	844	-5.6%
40%	2020	90.65	-1.7%	5.38	-8.7%	6942	-3.3%
	2021	39.22	-3.4%	2.39	-3.2%	2782	-6.1%
	2022	11.79	-3.9%	2.34	-13%	837	-6.4%

Discussion

As can be seen in Table 5.4, these values are all lower than the 100% capacity power bid, with a downward trend for lower %-capacity bids. No percentages are added, as for the simulated years, the 40% and 70% perform less than the 100% strategy. In order to establish the relationship of the % of the capacity in the bids, simulations have been done with 85%, 90% and 95%, but the values for contribution margin and hydrogen production were all lower than for the 100% capacity bid, with approximately a linear relationship.

The expectations for the day ahead arbitrage strategies were that by less commitment beforehand, better decisions in the short term could have been made. This would have resulted in less hydrogen produced, but also in fewer costs. However, as seen before the electrolyser does not perform well under short-term decisions. Steady control often performs better for a slow electrolyser, compared to for example batteries. All graphs show that dips in the electrolyser power at times of high imbalance prices for feedin and offtake are smaller when having bought full capacity at the day ahead market. The electrolyser is more dependent on those short high price peaks when less capacity is bought on the day ahead market.

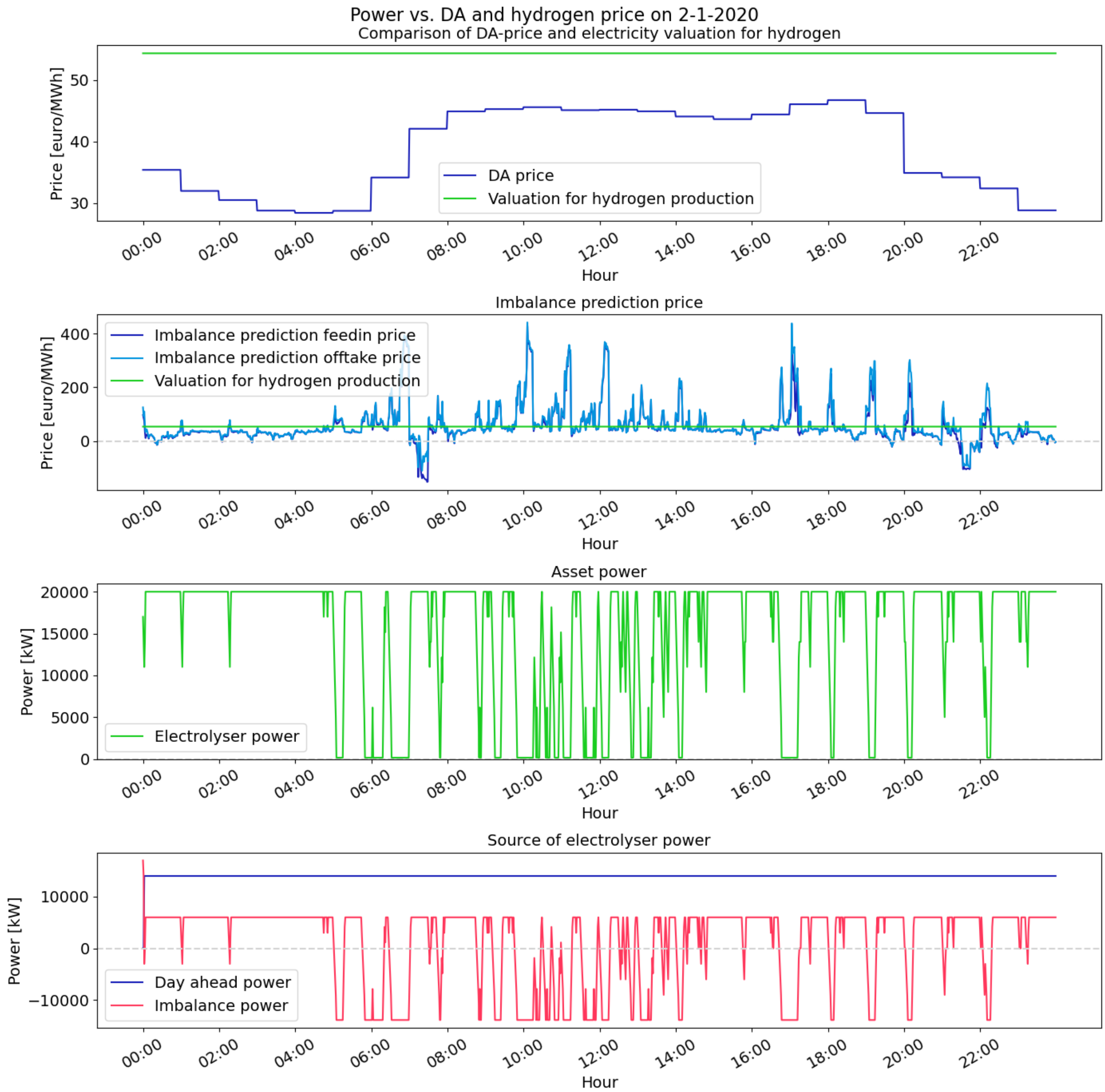


Figure 5.7. Electrolyser power on 2 January 2020 and the power that is traded on the day ahead and imbalance market. In the top two graphs the hydrogen price, the day ahead and imbalance prices are displayed.

6 | Seasonal hydrogen storage

The application of storage of hydrogen is discussed in the literature review (Appendix B). Several types of storage of hydrogen exist. Local hydrogen storage in tanks is hard to become profitable as purity is reduced and losses occur for this short-term storage option (Abomazid et al., 2022; Zhang et al., 2017). It is therefore only useful as a buffer for a steady supply of hydrogen, for daily fluctuations of production. Large-scale storage may be useful for hydrogen, especially when volatility is increased by the share of RES. It will then function as seasonal storage: meaning that hydrogen is produced at times of a lot of sunshine and wind, stored, and sold at times of expensive electricity (Rogers et al., 2014). The envisioned storage unit for the project that this research is part of, is Zuidwending. This is a salt cavern in Groningen that will be repurposed for hydrogen storage (Zuidwending, 2022). Viability depends on the costs of storage and the transportation costs to the storage site.

It will first be explained how hydrogen storage is implemented in the system of the EMS. Then the results are displayed and discussed.

6.1 Integration in the EMS

To integrate storage in the EMS, two components have to be changed. Firstly, the bidding system of the electrolyser and secondly a storage segment has to be added. By adding these segments, the electrolyser can produce for either selling or storing hydrogen, based on what is more economically attractive.

In normal operation, the model of the electrolyser submits its bid of energy and price to the optimiser of the EMS. The EMS will then trade on the electricity markets and inform the electrolyser about the electricity that it got assigned. With hydrogen storage, the price that is bid may be higher, as the selling price of stored hydrogen can be higher than that of hydrogen that is directly sold. It has to be taken into account that storage has extra costs for storage and transportation, this must be subtracted from the price bid (6.1). Thus, the highest valuation of electricity (for selling or storing hydrogen) is bid to the EMS.

$$\textit{Storage electricity valuation} = \textit{Expected hydrogen selling price - Levelised Cost of Storage} \quad (6.1)$$

Subsequently, a storage segment has to be added. This is a feature that saves the amount of hydrogen that is produced and registers the value of the hydrogen that is stored. The hydrogen in storage is not sold in this model, but its value is registered, based on the expected selling price.

For simulating hydrogen storage in the EMS, several assumptions have to be made. These are displayed in the grey box below.

The parameters for the seasonal hydrogen storage in the model are displayed in Appendix D. As Levelised Cost of Storage (LCOS), meaning the cost per kilogram with all costs of storage and transport included, the values 1, 2 and 3 €/kg are used. These values are not chosen with the intent to compare with each other: fewer storage costs would evidently result in a better case. However, these values represent current estimations for LCOS for storage in salt caverns. Recent predictions for LCOS are mentioned by Chen et al. (2022) ($2.3/kg), Epelle et al. (2022) ($1.51/kg) and Yousefi (2021) (€0.79/kg). As for Zuidwending, an LCOS of 2 to 3 €/kg is expected.

Assumptions for integration

- Infinite storage capacity
- Levelised Cost Of Storage based on predictions of either literature (see text above) or Zuidwending
- Levelised Cost Of Storage is independent of the amount of time in storage.

6.2 Results and discussion

Table 6.1 displays the figures of simulations with hydrogen storage. The simulations that resulted in these figures have been done with the 100%-capacity day ahead strategy. As mentioned, the €1/kg is based on literature, whereas the costs of €2/kg and €3/kg are based on current predictions for the usage of Zuidwending.

Figure 6.1 shows how the storage behaves over the year 2022 for the storage cost of €2/kg. This graph can be compared to Figure 6.2. At the start of the year, the expected price that the hydrogen can be sold for minus the storage costs is higher than the price that the hydrogen could directly be sold for. Therefore, hydrogen is produced and directly stored. In late summer, the electricity prices are rather high and not much hydrogen is produced. In October, the prices for directly selling hydrogen are advantageous compared to the electricity prices, meaning that a lot of hydrogen is produced. This is directly sold, as it is at a peak of the hydrogen prices in the year, meaning that with the storage costs included it is beneficial to directly sell. In Figure 6.2 the impact of storage costs is easily visible: with 2€/kg, the hydrogen storage selling price is rarely higher than the hydrogen sold selling price.

Table 6.1 shows that in 2020 there are no benefits in having storage. In 2020 a lot of hydrogen is already produced without hydrogen storage, the electrolyser is producing at full power the majority of the year without the addition of hydrogen storage. Furthermore, the hydrogen price is relatively consistent, meaning hydrogen cannot be sold for much higher prices at one moment than the rest of the year. Hydrogen storage does therefore not add any value to the business case in 2020. As can be seen, the influence of seasonal hydrogen storage depends largely on the storage costs. For €1/kg great improvements have been made to the contribution margin in 2021 and 2022. The improvements in the amount of produced hydrogen are an encouraging result when having the energy transition and demand for hydrogen in mind. However, €2/kg is already showing less promising results, whereas €3/kg is not adding value for all years.

In conclusion, the success of seasonal hydrogen storage will principally depend on the cost of storage. The predicted €1/kg from literature will have a great effect, while the predicted 2 or 3€/kg would probably not cause the hydrogen revenue to outweigh the additional investment costs.

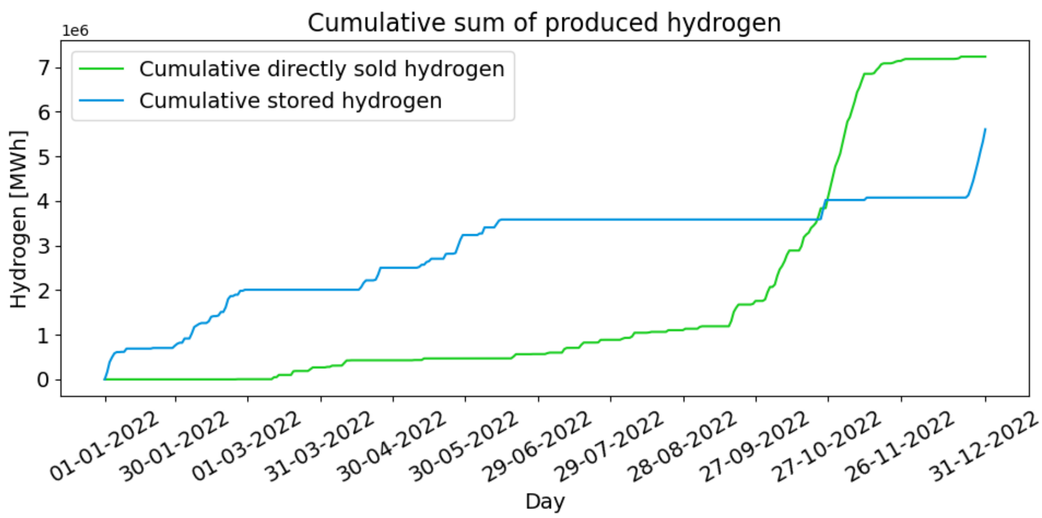


Figure 6.1. Produced hydrogen that is either directly sold or stored, in a cumulative plot.

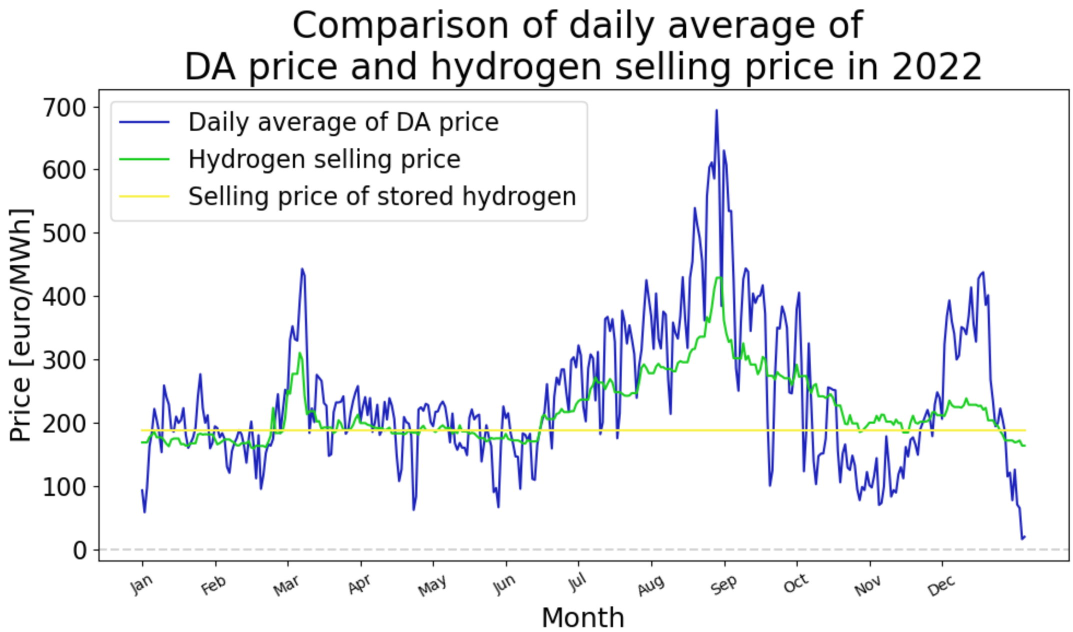


Figure 6.2. Comparison of the day ahead price with the selling prices of directly sold hydrogen and stored hydrogen.

Table 6.1. *Summary of the results of the seasonal hydrogen storage simulations. The percentages represent the comparison to the full capacity bid day ahead strategy. The storage simulations were done in combination with the 100%-capacity day ahead strategy.*

LCOS [€/kg]	Year	Produced H2 [GWh]	Contribution margin [M€]	Full-power hours
1.00	2020	92.25 0%	5.89 0%	7177 0%
	2021	49.07 +21%	3.73 +51%	3685 +24%
	2022	15.53 +27%	3.17 +18%	1138 +27%
2.00	2020	92.25 0%	5.89 0%	7177 0%
	2021	40.64 +0.15%	2.49 +0.8%	2968 +0.17%
	2022	13.11 +6.8%	2.78 +3.7%	957 +7.0%
3.00	2020	92.25 0%	5.89 0%	7177 0%
	2021	40.58 0%	2.47 0%	2963 0%
	2022	12.27 0%	2.68 0%	894 0%

Table 6.2. *Comparison of the amount of stored and sold hydrogen.*

Year	LCOS [€/kg]	H2 stored GWh	H2 sold [GWh]	H2 produced [GWh]
2020	1.00	0	92.25	92.25
	2.00	0	92.25	92.25
	3.00	0	92.25	92.25
2021	1.00	44.57	4.50	49.07
	2.00	7.78	32.86	40.64
	3.00	0	40.58	40.58
2022	1.00	12.90	2.63	15.53
	2.00	5.87	7.23	13.11
	3.00	0	12.27	12.27

7 | Electrolyser with BESS

In this section, Battery Energy Storage Systems (BESS) are introduced to the electrolyser. BESS have different characteristics than electrolysers. These characteristics have their influence on the control that is needed. Additionally, these characteristics have different benefits for adding value to a site. Firstly, the characteristics are clarified and the benefits of an appended BESS are described. Subsequently, the implementation and research method are explained. Lastly, the results are displayed, processed and discussed.

7.1 Potential benefits of combining an electrolyser with BESS

One of the main benefits of a battery for this system is the fast response time. The battery can almost instantaneously consume or supply electricity at full power. Therefore, it can respond to small peaks or valleys, whereas the electrolyser has to stay idle, as the start-up costs are too high or ramp rates to slow. Furthermore, for short periods of time that are long enough for the electrolyser to respond, electricity can be consumed more efficiently by the battery as it does not have to start up for this short period. This stored energy can afterwards be used by the electrolyser over a longer period of time.

Furthermore, additional time is needed for an electrolyser to start up to a production state from off-state. This may take up to an hour, depending on the type of electrolyser. To be able to respond more swiftly, the electrolyser can be put into standby mode, meaning that the pressure and temperature are maintained, while no hydrogen is produced. The electrolyser does however consume electricity when in standby mode. A battery can be in a static state with hardly any losses. To be on standby for these peaks, the battery can be used, after which the electrolyser can use the electricity for the production of hydrogen.

Another large difference in characteristics is the minimum power of the electrolyser. For the production of hydrogen, a certain minimum power is needed. Below this power level, a dangerous mixture of hydrogen and oxygen is produced, which has to be vented. Therefore, it is not useful to consider a power level between standby power and minimum power, as this is a waste of energy. A battery can be set to whatever power level its maximum power level allows.

At times of exceptionally low prices, both assets can be run at full power. The electrolyser can then produce hydrogen for lower electricity prices, as the electricity was stored in the battery. The moments of exceptionally low prices are expected to happen more often due to the increasing share of RES. Negative day ahead prices are not uncommon with a large share of RES.

Lastly, the battery opens up new electricity markets for the site. The distinction that is made in the literature review (Appendix B) between suitable electricity markets is not valid when a battery is added. For example, Frequency Containment Reserve (FCR), intraday and manual Frequency Restoration mFRR - which require high response times - are suddenly suitable for this site. It is to be noted that the balancing markets can only reserve the capacity of the battery if the electrolyser cannot meet the response requirements.

7.2 Integration in the EMS

The EMS is a modularised system. A battery can be added as a new asset to the EMS, after which the electrolyser and battery can collaborate. An important phenomenon is the allocation point. A site can have multiple allocation points, which allows trading on multiple markets. For collaboration of battery and electrolyser, both assets must be placed behind the same allocation point, to make sure that no costs are incurred for transferring electricity from the battery to the electrolyser.

Both assets will place a bid for consuming electricity for a certain price to the EMS. The battery will place a bid for supplying electricity as well. After trading, the EMS determines the amount of electricity that both assets will receive, or that the battery has to supply. In the case that both assets do not win their respective bids on the electricity market, the battery may supply electricity to the electrolyser. For this case, the battery must have bid a lower price for supplying electricity than the electrolyser bids for consuming electricity.

An important feature of the battery that facilitates this behaviour is that the bid price of the battery changes depending on its State Of Charge. If the battery is almost fully charged, it would rather discharge than charge, meaning that a higher price is bid for discharging than charging.

It is to be discovered by simulation whether the battery will be utilised to provide the electrolyser of power, or it will almost solely be utilised for trading.

Assumptions for integration

- A value of 700 €/kWh is assumed for the CAPEX of BESS. This price is all-inclusive (e.g. engineering and installation costs) (TenneT, 2023a).

7.3 Results and discussion

Results

Table 7.1 shows the results of having a BESS next to the electrolyser. The contribution margin of all configurations has increased. In Figure 7.1 and Figure 7.3, when the battery has positive power, it is charging. Negative power means the battery is supplying power, either as feedin to the grid or as power to the electrolyser.

Table 7.1. *Summary of the results of the simulation with an electrolyser and BESS. The percentages represent the comparison to the imbalance-only figures. The BESS-electrolyser simulations were done with the imbalance-only strategy.*

Battery cap [MW]	Year	Produced H2 [GWh]	Contribution margin [M€]	Full-power hours
20MW, 1C	2020	90.00 0%	6.17 +21%	6902 0%
	2021	37.63 +0.03%	3.79 +71%	2695 +0.07%
	2022	11.04 0%	5.28 +168%	792 0%
10MW, 1C	2020	90.00 0%	5.10 +0.2%	6902 0%
	2021	37.62 0%	2.60 +17%	2693 0%
	2022	10.90 -1.2%	3.49 +77%	777 -1.9%

Discussion

It is obvious that the addition of a battery has added value to most of the simulation configurations, as the contribution margin is substantially higher. The amount of hydrogen that is produced has hardly increased, mostly the amount of produced hydrogen has remained the same.

The configuration of 2022 with a 10MW 1C battery, in a system with a 20MW grid capacity, does not have a clearly higher contribution margin, in contrast to all other configurations. In this configuration, not a lot more revenue could have been generated than in the original configuration. The electrolyser is often using the full 20MW, meaning that the battery does not have a lot to add as there is no grid capacity left.

The question for this part of the research is however not if adding a battery provides better figures. The investment of an additional battery system must be accounted for. The battery can of course trade on the electricity markets on its own, without having to collaborate with the electrolyser. But the question is whether the battery adds value when placed next to an electrolyser. Therefore especially the cooperation of the two machines is investigated. It may be interesting to see whether an electrolyser and battery can be installed, while the revenue of both remains equally high compared to when being installed as separate systems, but this is not the intention of this research. In this research, the battery must increase the produced hydrogen or reduce the electricity costs.

As can be seen in Figure 7.1, the electrolyser and battery have different behaviours for consuming power. In this graph, it can be seen that the day ahead price is too high for hydrogen production, meaning that the electrolyser state is off (see Figure 7.2). However, the imbalance prices are fluctuating notably, meaning that the battery is able to trade on the market. This behaviour that is shown, shows the potential of a cooperation of a battery and electrolyser. However, it must be observed that the electrolyser and battery do not cooperate in this specific case.

Another important factor to notice is the fluctuating behaviour of the electrolyser as well as the battery. This is due to the price predictions of the imbalance market. Without corrections, this could mean that within the ISP the prediction can shift from profitable to nonprofitable.

When looking at the performances in both configurations, it appears that the battery rarely supplies power to the electrolyser. It appears that generally more revenue is generated when electricity from the battery is sold to the grid, instead of using it for hydrogen production.

In Figure 7.3, it can be seen that the battery does at times supply electricity to the electrolyser (for example at 19h). The electrolyser remains at full power, while the offtake of the imbalance market goes to 0. Even though, this phenomenon occurs rarely and for short periods of time. It was expected that having a restricted grid capacity (configuration 2) would induce more cooperation, but no evidence could be found to support this case. It is expected that when having a better efficiency model for the electrolyser model, the cooperation is improved. As indicated, the profile of the electrolyser power is rather erratic. For now, the electrolyser model does not have constraints to prevent this, as the effect of such a profile is not known. If a stabilised power profile is preferred, the hypothesis is that the battery will support the electrolyser for short periods of time, filling up potential gaps. This hypothesis is to be examined in further research.

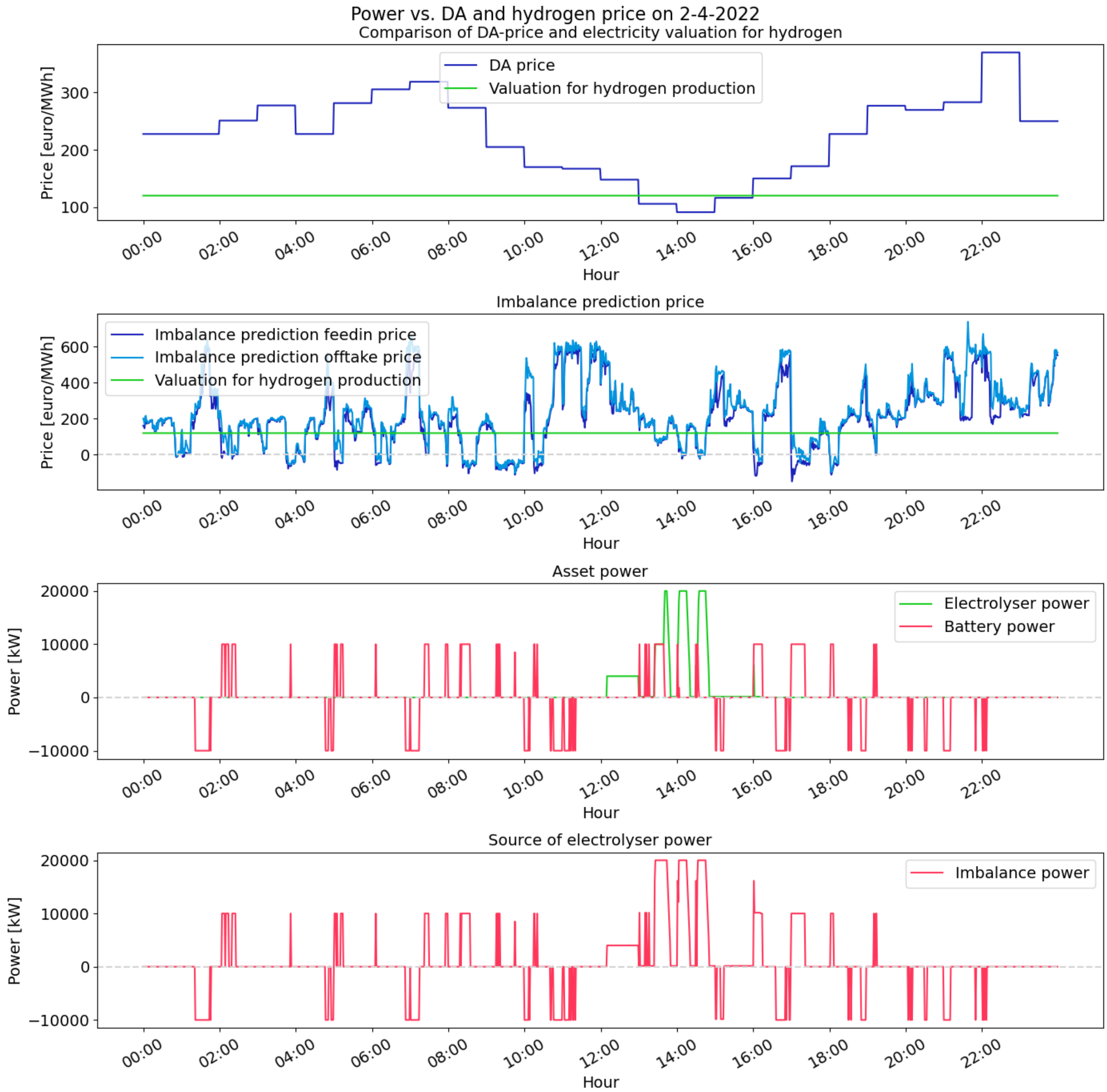


Figure 7.1. The power of the electrolyser and battery on 2 April 2022 in battery configuration 2. In graphs 1 and 2 the prices for electricity and hydrogen are displayed.

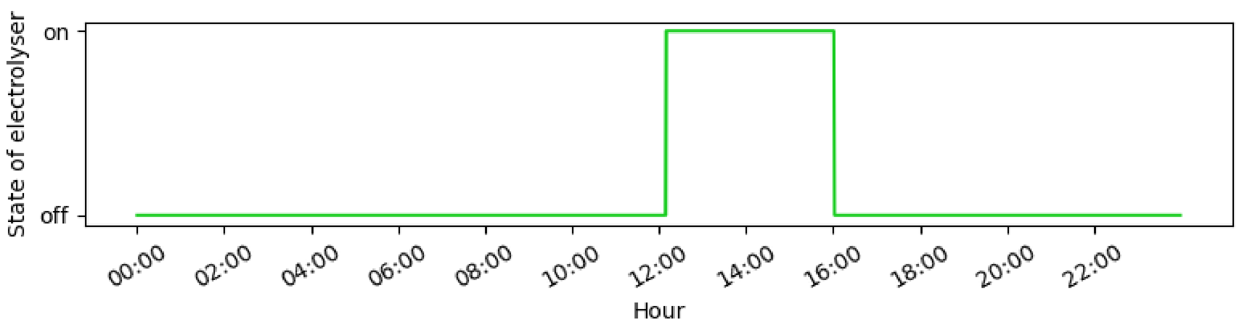


Figure 7.2. The state of the electrolyser on 2 April 2022. This state is determined by an optimisation using the day ahead prices as input.

From the graphs, it thus seems that hardly any cooperation takes place when combining an electrolyser with a battery. In order to investigate this further, the revenues of a battery are determined when being installed as a sole asset in the system. These results are displayed in Table 7.2. Furthermore, the added revenue of having a BESS next to an electrolyser is determined, compared to both units working separately (Equation 7.1). These results are displayed in Table 7.3.

When having a large battery and a large enough grid capacity, the combination of both machines does add some value to the site. 2020 was already a very good year, meaning that adding a battery does not add value to the electrolyser. It is however remarkable that the added value is negative. After analysing the data, it can be concluded that this reduced revenue is due to limitations in the battery strategy. The battery strategy, that was already existing before the start of this study, is deciding for what prices it is willing to supply or consume electricity. The difference between a battery individually or in combination with an electrolyser is that at times the battery is supplying electricity to the electrolyser. This occurs at times when the imbalance price is high, but the electrolyser is obligated to consume power, due to ramping down or being on standby. The battery will assist the electrolyser with electricity, even though it might be able to sell this electricity sometime later for a higher price. The limitations of the battery strategy are thus due to the statistical price prospect, which determines what is the expected price to be received for its electricity. For 2021 and 2022 this problem does not occur due to the high volatility in the imbalance market. The sudden high prices of electricity for the electrolyser that cannot be prevented are more extreme than in 2020, meaning that using electricity from the battery is a good method to cope: supplying electricity to the electrolyser is worth more than directly selling this electricity.

$$\begin{aligned}\textit{Added revenue} = {} & \textit{Contribution margin of combined site} \\ & - \textit{Contribution margin of site with only BESS} \\ & - \textit{Contribution margin of site with only electrolyser} \end{aligned} \tag{7.1}$$

When the site has a limited grid capacity, the battery and electrolyser are competing for electricity. Consequently, the site has less revenue than when having both systems separately. In this case, it would not be economically attractive to add BESS, especially with the high investment costs. Applying a BESS and an electrolyser separately would be more financially appealing when having restricted grid capacity.

Table 7.2. *Results of simulations of a battery trading on the imbalance market. No electrolyser is used in these simulations.*

Battery cap [MW]	Year	Revenue (imbalance only) [M€]
20MW, 1C	2020	1.11
	2021	1.52
	2022	3.28
10MW, 1C	2020	0.56
	2021	0.76
	2022	1.64

Table 7.3. *Additional revenue by the collaboration of the electrolyser and BESS. Remark: Additional revenue is in k€.*

Battery cap [MW]	Year	Additional revenue [k€]	Share of additional revenue to total revenue
20MW, 1C	2020	-29.7	-0.48 %
	2021	37.2	+0.98 %
	2022	31.3	+0.59 %
10MW, 1C	2020	-540	-11 %
	2021	-383	-15 %
	2022	-124	-3.6 %

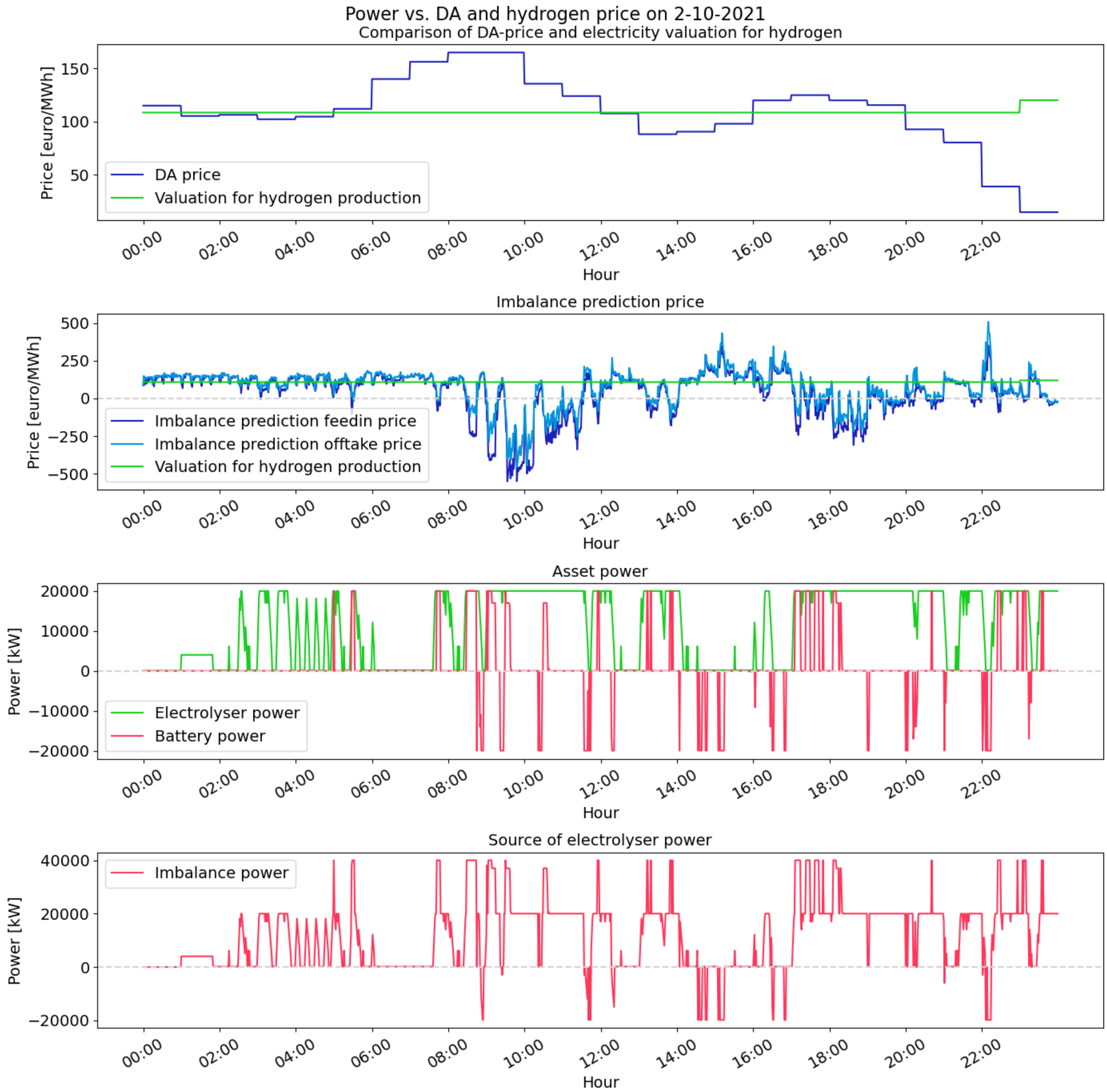


Figure 7.3. The power of the electrolyser and battery on 2 October 2021 in configuration 1. In graphs 1 and 2 the prices for electricity and hydrogen are displayed.

8 | General discussion

In this chapter, the results of the investigations are discussed. First, an overview of the simulations that are used for the investigations is given. Subsequently, the configurations are discussed all together in the general discussion. The results of the configurations and the appurtenant discussion can be found in the corresponding chapters.

8.1 Simulation overview

Table 8.1 displays the different configurations of simulations that are executed for the years 2020, 2021 and 2022.

Table 8.1. *Overview of all simulation configurations.*

Config	Summary	Back-up market	DA cap. bid	Storage cost	Battery cap.
1	Baseline	Dynamic contract	-	-	-
2	Imbalance only	Imbalance	-	-	-
3	DA 100%	Imbalance	100%	-	-
4	DA 70%	Imbalance	70%	-	-
5	DA 40 %	Imbalance	40%	-	-
6	Storage €1/kg	Imbalance	100%	1 €/kg	-
7	Storage €2/kg	Imbalance	100%	2 €/kg	-
8	Storage €3/kg	Imbalance	100%	3 €/kg	-
9	Battery 20MW	Imbalance	-	-	20MW
10	Battery 10MW	Imbalance	-	-	10MW
11	DA 85%	Imbalance	85%	-	-
12	DA 90%	Imbalance	90%	-	-
13	DA 95%	Imbalance	95%	-	-
14	Battery 20 MW only	Imbalance	-	-	20MW
15	Battery 10 MW only	Imbalance	-	-	10MW

8.2 Discussion

Having discussed the results of the different cases individually, conclusions should be deduced from the overall result. Besides, some remarks should be made on the validity of the research.

Firstly, the analysis of the influence of volatility on hydrogen revenue had a beneficial outcome. Even though it was difficult to verify this correlation in historic data, due to obscurity by other influences, the artificial data set showed a positive correlation between volatility and the hydrogen contribution margin in all cases. An important remark is that the volatility in the day ahead prices of historic data was analysed. However, a high share of renewable energy generation has an even more extreme effect on the imbalance prices and thus its volatility, meaning that possibly its impact would have been more visible in the analysis.

Secondly, it is remarkable that without expensive investments, the economic viability of the electrolyser can be increased. By trading on electricity markets, the financial feasibility is substantially increased by at least 27% (DA-100% compared to dynamic contract configuration). This shows the importance of research to the implementation of such a technology, besides the research to the technical development. For now, it is advised to utilise the day ahead with imbalance combination. The possibility for intermarket trading certainly has a positive effect on the electricity costs and revenues made. There are more markets to be researched for the electrolyser, for example, the aFRR and GOPACS. For the implementation of these markets, extra research is needed. These markets might have even more impact on the contribution margin of the electrolyser. An important remark is that with the current electrolyser model, bidding 100% of the electrolyser capacity on the day ahead market is financially favourable. However, when utilising a nonlinear model for the electrolyser efficiency, this might shift to a lower percentage capacity bid (Lettenmeier, 2021).

Thirdly, the success of seasonal hydrogen storage is dependent on the LCOS. For storage costs of around €1/kg, an improvement of between 0 and 51% was achieved. However, for prices higher than 2 €/kg, only a slight improvement of 0 to 3.7% in contribution margin was achieved. €1 for storage already has an enormous impact on the foresighted hydrogen cost price of 3 to 5 €/kg (Deloitte, 2021). Thus, the expected LCOS has to be monitored over the coming years. Besides, a first estimate was made on the potential of seasonal hydrogen storage. The model has to be upgraded to the actual method of determining the LCOS, for example, during the realisation of Zuidwending. The seasonal hydrogen storage model is based on large assumptions, for example, certain pricing for an indefinite time and the producer remains the owner of the hydrogen. It is however plausible that a comparable system will be implemented in Zuidwending.

For the research to the BESS, several remarks must be made. In this research, two configurations of batteries and grid capacities have been investigated. These two configurations resulted in a marginal added value (at maximum 0.98%) or negative added value (at maximum -15%). This is to be expected when having a limited grid capacity (configuration 2), as the battery and electrolyser would compete for economical electricity. For configuration 1, the results are less convincing than that probably could be expected. There is a marginal added value as the electrolyser has no reduced efficiency for inconsistent production. Thus, the assumptions made for the electrolyser may have a negative effect on the usage of the battery: the electrolyser has a constant efficiency over power levels and power changes. Therefore, the battery does not have to keep the electrolyser at a stable power level: it does not have an influence on the losses. An important upgrade to the electrolyser would thus be to have a nonlinear efficiency relationship, as this is more realistic and would influence the operation of the electrolyser, as well as the battery (see Figure 3.2). Besides, it is recommended that more research is done on different combinations of power, capacity and types of BESS, as well as the electricity markets that the battery may trade on. Batteries that are suitable for trading on electricity markets on their own are not necessarily suited for supporting an electrolyser by supplying electricity. For now, it is not recommended to invest in BESS to support an electrolyser. The previously mentioned recommendations might however change the prospect of the BESS and electrolyser combination. Furthermore, it appeared that the battery strategy, which performs greatly for an individual battery, does have some complications when combine with an electrolyser on site. At times when the electrolyser is obligated to use power (during start-up, stopping or at standby), while the imbalance price is really high, the battery will supply this electricity. This is due to insecurities about the future: it appeared that the battery could have sold its electricity on the market for more than that the electrolyser would have paid on the market. By updating the battery strategy based on the market behaviour, these extremities could be prevented. However, as this is due to a statistical price model, uncertainties will remain elements of an EMS.

When associating this new knowledge with the impact-complexity matrix that was introduced in chapter 2, a new impact-complexity matrix can be made (see Figure 8.1). The conclusion is that trading on electricity markets has more impact than was predicted, for less effort than predicted. Namely, a good strategy is needed besides the Energy Management Strategy. The impact of the Energy Management Strategy was not analysed, but cannot be underestimated. Underground hydrogen storage had less impact than was expected, at least for storage options with realistic pricing. Furthermore, the complexity of storage was found to be higher than anticipated: both for control (a prediction has to be made of the expected value of hydrogen in the future) and for infrastructure (Purification, compression, transport). This conclusion can be drawn for the BESS as well: the impact of having an additional battery without restrictions on grid capacity was marginal. Restrictions on grid capacity would even reduce the effectiveness of the electrolyser/battery combination. The implementation was thus identified to be more challenging than estimated: for each site and electrolyser, the battery should be carefully selected to make this option successful.

The state optimisation of the electrolyser has some shortcomings. This is mostly based on the short scope that the optimisation is done for. As this was designed with the application of an electrolyser in mind, optimising only the state of the next day is what is technically possible. However, the connection between days is not flawless. Improvements could be made by optimising the state not only for the next day but by optimising the end of the current day as well, in order to improve the transition.

Furthermore, some general remarks have to be made. In this research, the historic years of 2020, 2021 and 2022 are used. It is difficult to acknowledge these years as representative years, due to large events such as COVID-19 and the Russian-Ukrainian war. On the other hand, it is difficult to predict the course of the electricity and gas prices in the upcoming years, when likewise events could occur. It is expected, as explained before, that the volatility will increase, combined with more frequently occurring very low prices.

Besides, there are some restrictions to the use of this EMS. The approach to the development of this EMS is that it should resemble the application of such a system. Therefore, the optimisation cannot simply be done over a full year, even though this would produce better results. The EMS optimises each decision moment when in application mode, which most often is every minute.

The EMS has made use of the imbalance market as the backup market. It is advisable to recognise the depth of said market. When having increased the electrolyser capacity, the market prices could be influenced by running the electrolyser, causing a new optimisation problem.

As mentioned earlier, the efficiency of the electrolyser is assumed to be constant. However, in research, it was found that there is no linear relationship between power level and efficiency. This might affect the production of hydrogen. Furthermore, the degradation of the electrolyser is not taken into account. Possibly the power level influences the amount of degradation, meaning that there are preferred power levels for the electrolyser. This is to be inspected in future research.

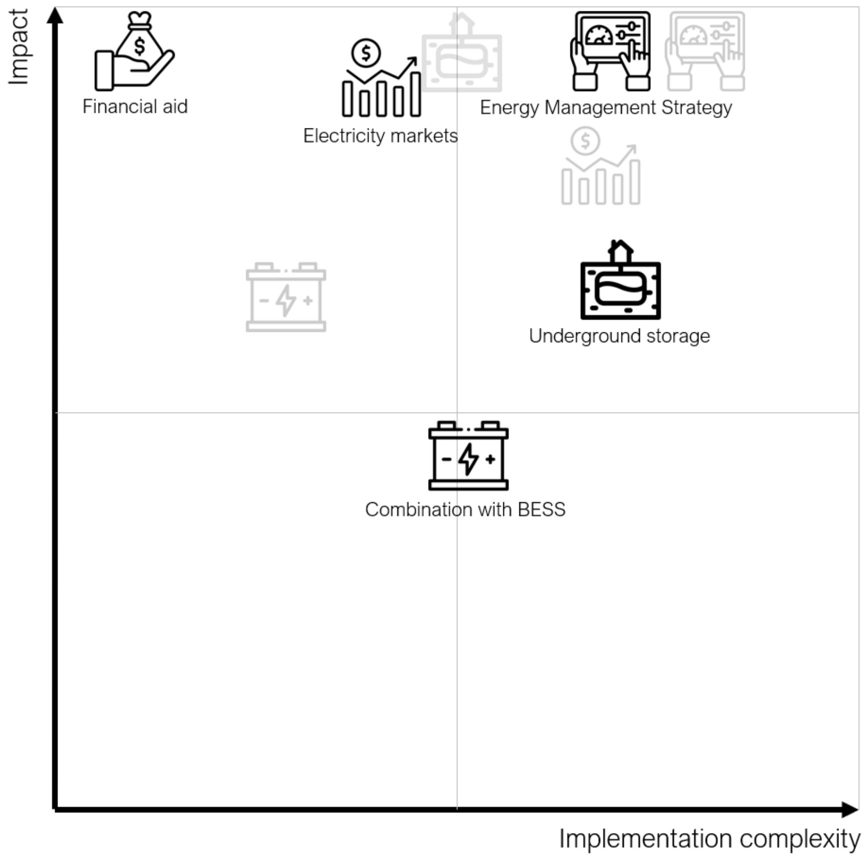


Figure 8.1. Renewed matrix of the implementation complexity versus the measured impact that the investigated solutions have. The light grey icons were the predicted location, the black icons are the resulting locations of the influenceable factors in the matrix.

9 | Conclusions

9.1 Conclusions

The question to answer in this research was: How can the implementation of an electrolyser in a renewable energy grid be made economically viable?

Firstly, sub-questions of this question are answered:

1. What is the effect of an energy market with higher volatility on the revenues of the production of green hydrogen?

In general, with increased volatility in electricity markets, the revenue and production of hydrogen increased. The volatility of electricity markets will be increased by the expansion of the share of RES. However, in historic data sets, no clear correlation between volatility and hydrogen revenue or production could be found. The production and revenue depend on considerably more factors, such as the ratio of electricity price to hydrogen price, or the volatility of the hydrogen price. The historic data years were difficult to compare due to extreme events in the data as well. By creating an artificial data set, the general effect of volatility was discovered. It can be concluded that generally volatility has a beneficial effect on the production of hydrogen. However, the production and revenue of hydrogen are dependent on more factors than volatility alone, meaning that this correlation could not be found in historic data.

2. What is the influence of using different electricity markets for energy trading on the revenues of the production of green hydrogen?

By simulation, different trading strategies have been assessed for the electrolyser. These trading strategies involved different electricity markets. Utilising the imbalance market instead of a dynamic contract already caused tremendous improvements in the contribution margin. This did however cause a lower production of hydrogen. Even larger improvements were made by implementing day ahead market trading. The combination of imbalance and day ahead market trading caused an increase in production, revenues and contribution margin. The contribution margin has increased by an additional 11% to 36% compared to imbalance market trading only. For day ahead market trading, the highest contribution margin was achieved by bidding the full capacity of the electrolyser. Overall, by trading on electricity markets instead of offtaking of a dynamic contract, the negative contribution margins of 2021 and 2022 have been corrected to almost having 2.5 M€contribution margin, and the contribution margin of 2020, which was already a very good year, has been further improved by 27%. It can be concluded that there is a considerable influence of electricity market trading on the viability of green hydrogen. For the implementation of an electrolyser, trading on electricity markets is the factor to focus on, as this solution requires, apart from the development of trading strategies, no further investments.

3. What is the effect of including hydrogen storage in the hydrogen system for the revenues of the production of green hydrogen?

The addition of seasonal hydrogen storage to the electrolyser model has shown varying results. In 2020, which was already a very good year, the storage did not influence either production, revenue or contribution margin. However, for years with a high variance of electricity price, hydrogen storage has added relatively between 18% and 51%. These figures are based on the storage costs of €1/kg that was retrieved from literature (Yousefi, 2021)(see chapter 6). When increasing the storage to €2/kg or €3/kg that is estimated voor Zuidwending, Groningen, hydrogen storage is hardly increasing the contribution margin. Where storage of the cost of €3/kg does not add value at all, storage with the costs of €2/kg only adds 0.8% for 2021 and 3.7% for 2022. The conclusion that can be drawn is that seasonal hydrogen storage can help in the viability of green hydrogen, but this is largely dependent on the costs that are indicated for storage. For implementation, it is recommended to anticipate on the developments of nearby underground storage sites, rather than taking the initiative. An exception could be research in which it is attempted to make underground storage less expensive.

4. What is the influence of combining BESS and an electrolyser on the revenues of the production of green hydrogen?

The addition of a battery system does not significantly influence the production and revenue of green hydrogen. The overall revenue has increased for all configurations, but these additional revenues are due to the battery trading on the electricity markets individually. Hardly any extra hydrogen was produced. When the grid capacity is limited and the battery and electrolyser cannot offtake electricity at full power simultaneously, the production of hydrogen is even reduced, as is the additional revenue (between -3.6% and -15%). In this case, an electrolyser and battery should be deployed separately on different sites. Research into more battery configurations should completely test the potential of the combination of a BESS with an electrolyser. For now, it is not recommended to invest in the addition of BESS to the electrolyser site. In order to open the possibility for this combination, other battery configurations should first be investigated, as well as improving the battery strategy, electricity market trading (markets that are suitable for batteries) and electrolyser model for collaboration.

Then the research question itself can be answered: "How can the implementation of an electrolyser in a renewable energy grid be made economically viable?" First of all, the importance of these results should be emphasised. BESS and seasonal hydrogen storage may induce a higher investment cost, but could improve the business case of green hydrogen. More importantly, having a valuable Energy Management Strategy and good trading strategies will reduce the production costs of hydrogen significantly, without needing higher investment costs. The development of such an EMS will add value to the electrolyser system and is absolutely worth the investment.

In this research, financial aid was included in the determination of the hydrogen selling price. The impact of this financial support should not be underestimated. In comparison to earlier research by Middelkoop (2022), significantly more revenue was generated by utilising the aid that is supplied by the government.

This research does not provide a business case proposal, meaning that it cannot yet be determined whether the innovations of this research have made a viable case. However, the results demonstrate that a lot of improvements in the case can be made by research on the implementation and control of the electrolyser.

9.2 Recommendations

Based on this research, several recommendations are deducted for future research. Firstly, it is unknown whether the behaviour that the physical model of the electrolyser shows is suitable for a physical electrolyser. The erratic profile is possible by the constraints that describe the physical model, and these constraints were retrieved from manufacturers. More information should be retrieved on the actual performance of electrolysers under inconsistent power levels.

Secondly, the efficiency of the electrolyser is kept constant throughout the simulations. In reality, it is established that the efficiency of the electrolyser is nonlinear with the power level and temperature. Such an efficiency model would influence the trading behaviour of the electrolyser, which would in turn influence its contribution margin. It is therefore important to implement a realistic efficiency model.

Furthermore, the degradation of the electrolyser was neglected in this research. The degradation of the electrolyser is not only expressed in the loss of value, but it affects the performance and efficiency of the electrolyser as well. A more detailed degradation model would improve the credibility of the business model of an electrolyser.

To improve the business case of green hydrogen even further, more electricity markets should be added to the EMS. Several suitable electricity markets, such as aFRR or GOPACS, could have a beneficial influence on the electricity costs for green hydrogen.

The state optimisation of the electrolyser is executed every day, based on the updated day ahead prices. The transition of the state of the current day to the subsequent day is however based on only the last state of the current day. A better transition would be to optimise the rest of the current day, as well as the next day. This would make the model able to make better decisions for the state based on the electricity prices.

The last recommendations are for the combination with battery systems. As mentioned, batteries that are suitable for trading on electricity markets on their own are not necessarily suited for supporting an electrolyser by supplying electricity. Only two battery configurations have been tested. More research should be done on different combinations of power, capacity and types of BESS in combination with an electrolyser in order to completely test the potential of this combination. Furthermore, batteries are suitable for trading on electricity markets that cannot be used by electrolysers, due to response time and dynamic behaviour. The combination of the electrolyser with a battery that performs such electricity trading should be investigated further.

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A Scientific paper

See next page.

Making the production of green hydrogen by an electrolyser economically viable

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Abstract—Green hydrogen plays an important role in the energy transition. It can function as a storage medium, as well as a replacement for fossil fuels in transport or high-temperature heat processes. However, the economic feasibility of electrolysers has proved to be a problem. Even though a lot of research has been done to the electrolysis technology, very few research has been done to the implementation of an electrolyser.

For this research, a physical model of an electrolyser has been developed, as well as an Energy Management System (EMS). For this system, trading strategies for electricity markets have been developed. By trading on the imbalance and day ahead market, the contribution margin (hydrogen revenue minus electricity costs) has been significantly increased by over 27%. Seasonal hydrogen storage in salt caverns has proven to be a promising solution for producing more hydrogen and increasing revenue, depending on the storage costs that are applied. A Battery Energy Storage System (BESS) has been added to the system for its competence in dynamic behaviour on the electricity markets. For the addition of a BESS to an electrolyser, no conclusive proof of the benefits for the economic viability of green hydrogen has been found.

1 Introduction

Shifting from fossil fuels to the usage of Renewable Energy Sources is an important step for sustainability. This shift is often done by electrification. However, for some sectors, electrification is not an option: it is either economically unattractive or technically not possible. For example, the heavy transport sector; or the high-temperature heat sectors, such as steel, cement or glass, that need temperatures well above 1000 °C that are not reachable for renewable heat sources and not financially attractive for electrification. In these sectors, green hydrogen can play an important role to substitute fossil fuels.

A lot of research on hydrogen has already been done, from the 19th century onwards. However, hydrogen has not been a success yet and is not implemented as a world standard for sustainability purposes. This is due to the focus of the research. Research on the implementation of electrolysers is required, rather than research on the technology of electrolysis. Instead of a focus on technological advancement, the focus should be on economic viability.

Firstly, the revenue of green hydrogen can be influenced as mentioned before: by focusing on sectors with inelastic demand and no alternatives [1][2]. This study focuses on reducing the production costs of green hydrogen. A breakdown of these costs is displayed in Figure 1. The highest costs reduction is expected by focusing on reducing the electricity costs and the capital expenditure (which is incorporated in the Initial and O&M costs).

As described in the preparatory literature review [4], it is expected that utilising financial aid and having a good EMS have the highest impact. The development of such a strategy may involve a certain implementation complexity. Financial aid is in this study covered by the calculation of the hydrogen price. Underground seasonal storage of hydrogen is expected to have a high impact while having a medium implementation complexity. Trading on electricity markets requires a good strategy but will have a high impact.

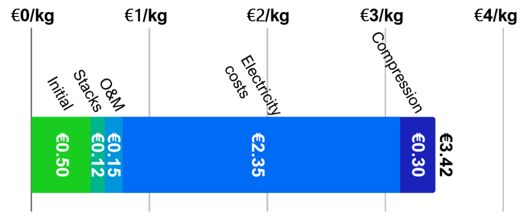

Fig. 1. Breakdown of the costs of the production of green hydrogen per kilogram, as estimated by Deloitte [3].

Combining the electrolyser with a Battery Energy Storage System (BESS) involves less implementation complexity, as these can be implemented as stand-alone units. However, the impact of such a BESS is predicted to be moderate as well.

Each of these influenceable factors is investigated on their impact. Firstly, the physical model of the electrolyser (as well as the electricity grid/battery/hydrogen storage et cetera) is designed, after which an Energy Management System is constructed with which simulations can be executed. In the system (see Figure 2) new assets can be added (the battery and the seasonal hydrogen storage), which opens the possibility for simulations on the new configurations. Furthermore, different electricity markets are added to verify whether good trading strategies would reduce electricity costs.

The goal of this paper is to assess what influenceable factors have the most impact on the economic viability of green hydrogen. This paper is organised as follows: in section 2, the EMS and electrolyser model are discussed, section 3 describes the different configurations that are tested on their influence, in section 4 the results are presented and discussed. Lastly, the conclusions of the research are drawn.

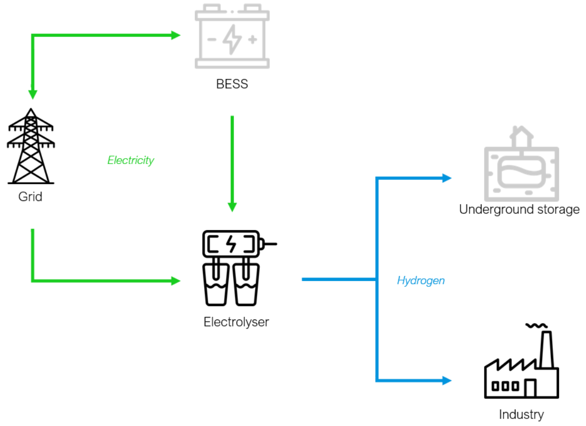

Fig. 2. Overview of the system that is simulated in the EMS. All subsystems are called assets. The grey assets are added in the later stages of the research.

2 System Description

The system is displayed in Figure 2. Of this system, the electrolyser model is the model that is focused on. After the electrolyser model is discussed, the EMS is demonstrated.

2.1 Electrolyser model

Before any experiments through simulations can be performed, a physical model of an electrolyser is constructed. The electrolyser is an asset with many restrictions on production. These limitations influence the dynamic behaviour of the electrolyser. The parameters of this model are displayed in Table 1.

The first influence on the dynamic behaviour is the cold start: before the electrolyser can produce hydrogen, a cold start is performed from off-state. For the Alkaline electrolyser in this system, a cold start will take about 50 minutes. Turning the electrolyser off is a faster process, this will take about 10 minutes. There is also the possibility of standby mode. In standby, the temperature and pressure are maintained (thus some energy is consumed), whereas in off-state no energy is consumed. However, from standby no start-up time is needed, only the ramping has to be taken into account.

Ramping is the next influence on the dynamic behaviour of the electrolyser. Changing the power level of production is not instantaneous (e.g. from 100% to 60% power), but the power level must gradually be increased or decreased.

Due to these restrictions, the operation of the electrolyser on an electricity market that has a resolution of 1 minute is not evident. The EMS has to determine a strategy in advance. Therefore, a state optimisation of the electrolyser is executed every day based on the already known day ahead market prices (these are published at noon on the previous day) [5].

An important phenomenon of the electrolyser is the phenomenon of Minimum power. If hydrogen is produced below this power level, it would result in a dangerous mixture of oxygen and hydrogen. This mixture would therefore be vented, meaning that the electricity utilisation was wasteful.

In the electrolyser model, constant efficiency is assumed. In practice, efficiency has a non-linear relationship with current density (see Figure 3).

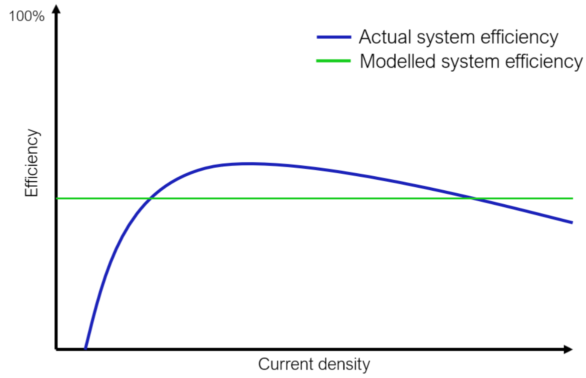

Fig. 3. Actual, nonlinear system efficiency versus the modelled, linear efficiency (not on scale) [6].

The output of the electrolyser model is a strike energy bid for the next minute, combined with the strike price bid (what the model is prepared to pay for its electricity, also called the 'Valuation'). So, the model communicates a range of all power levels that are physically possible to reach to the controller, combined with the price it is willing to pay for this electricity. This strike price bid is based on the hydrogen selling price and the conversion efficiency, in order to determine what the electricity that is used for production is worth. The range of power levels is based on the ramp rates of the electrolyser. For example, when the electrolyser is on standby, the lowest possible energy level it can reach the next minute is standby power (under the condition that the state optimisation has not determined the electrolyser to shut off), whereas the higher boundary is equal to the standby power level plus the ramp-up rate.

TABLE 1
Parameter values of the electrolyser

Parameter	Value	Unit
Maximum power	20000	kW
Standby power	150	kW
Minimum power	4000	kw
efficiency	60	%
Start up time	50	minutes
Start up power	4000	kW
Start up time first phase	20	minutes
Start up time second phase	30	minutes
Start up losses	200	kW
Stop time	10	minutes
Stop power	150	kW
Ramp up rate	30	%/minute
Ramp down rate	15	%/minute
Life cycle costs	0	€/minute

2.2 Energy Management System

The EMS is the software agent that controls the assets and the flows of energy. It consists of the models of the assets, the controller of the assets, the optimiser and the model of the electricity markets. The steps of the EMS are executed every minute due to the electricity market time interval. These steps are as follows:

1) Each asset determines **strike energy** (range) + **strike price**. The strike energy is the electricity volume an asset is requesting for the next minute, given as a range

of values. For every strike energy range, a strike price is included: the price that the asset is willing to pay for its electricity at maximum.
2) Central controller **receives** desired energy ranges and strike price from assets and **instructs** optimiser to trade for electricity.
3) Optimiser **trades** on electricity market.
4) Optimiser **determines** the distribution of the won electricity over the assets **(linear optimisation)**. This linear optimisation has an economic objective: the total expected revenue that all assets will generate with the assigned electricity is maximised. The objective of this optimisation is given in Equation 1. In this equation, λ is the strike price of an asset and x is the assigned energy of asset i. The most important constraint is the energy balance: the total sum of the assigned energy values is 0 (Equation 2). Besides, the assigned energy must be in the range given by the strike energy for every asset.

$$MAXIMIZE \quad (\sum_i \lambda_i * x_i)_{production} - (\sum_i \lambda_i * x_i)_{consumption} \tag{1}$$

$$\sum_i x_i = 0 \tag{2}$$

5) Controller **assigns** this electricity to each asset.
6) **Power level** of each asset is updated.

3 Experimental set-up

This section describes the different configurations that are investigated through simulation in the EMS, in order to verify their respective impact on the economic viability of green hydrogen. The configurations cover the topics of electricity market trading, underground hydrogen storage and the addition of a BESS to the site. All simulation configurations are displayed in Table 2. The simulations have been executed based on historic data for the years 2020,2021 and 2022.

3.1 Electricity market trading

For electricity market trading, three different electricity market sources have been examined: the dynamic contract, the imbalance market and the day ahead market [7]. The Dynamic contract is in fact not an electricity market, but a contract with the supplier. The electricity prices for this contract follow the day ahead prices, in addition to a fee for the supplier. The imbalance market is a real-time market. A party pays for the imbalance that it creates (or equally receives money for the balance that it creates). The electricity prices for this market are published after the closing of the ISP (Imbalance Settlement Period), meaning that parties rely on predictions for the pricing when utilising the market. The strategy for the imbalance market is based on research by Middelkoop [5]. For both the imbalance market and dynamic contract, the strategy can simply be summarised by: purchasing electricity at times when more money can be made by selling the produced hydrogen. The day ahead trading is combined with the imbalance market. On this market, capacity of electricity is bought and sold beforehand. Parties submit bids for either feed-in or offtake, at 12 o'clock noon the auction is held, after which the price of electricity is determined and electricity capacity is assigned to the parties for every hour of the day. The parties receive or pay the clearance price of electricity, not the price that was bid. The combination of the day ahead market with the imbalance market introduces an important feature of the imbalance market: a capacity that was won on the day ahead market but is not offtaken, is considered feedin on the imbalance market. As this may result in a financially more attractive result, the EMS might decide for this tactic, due to the economic objective of the optimiser.

3.2 Seasonal hydrogen storage

The subsequent configurations examine the effect of seasonal underground hydrogen storage on the economic viability of green hydrogen. Several types of storage of hydrogen exist. For local hydrogen storage in tanks, it is already proved to be a challenge to become profitable as purity is reduced and losses occur for this short-term storage option [8, 9]. It would therefore only be useful as a buffer for a steady supply of hydrogen, for daily fluctuations of production. Underground storage would function as seasonal storage: hydrogen is produced at times of a lot of sunshine and wind, stored, and sold at times of expensive electricity [10]. The envisioned storage unit for the project that this research is part of, is Zuidwending. This is a salt cavern in Groningen that will be repurposed for hydrogen storage [11].

To implement seasonal hydrogen storage in the EMS, the strike price bid of the electrolyser is altered. The highest bid for either selling the hydrogen directly or for storing the hydrogen first, will be communicated with the optimiser. The strike price bid for storing hydrogen is calculated by the expected value of the hydrogen minus the Levelised Cost Of Storage (LCOS). The expected value of hydrogen is determined by taking 25% of the highest hydrogen values in the year, meaning that there is a fairly large window where this hydrogen could be sold. Selling the stored hydrogen is out of scope. The determination of the expected hydrogen value from storage adopts the assumption of preknowledge of the hydrogen prices over the year.

For the LCOS, three different parameter values are chosen: 1, 2 and 3€/kg. These values represent current estimations for LCOS for storage in salt caverns and are all-inclusive and indefinite of storage time. Recent predictions for LCOS are mentioned by Chen et al. [12] ($2.3/kg), Epelle et al. [13] ($1.51/kg) and Yousefi [14] (€0.79/kg). As for Zuidwending, an LCOS of 2 to 3 €/kg is expected.

3.3 Addition of BESS

With the addition of BESS to the site of the electrolyser, an asset is added with different characteristics. The battery can almost instantaneously consume or supply electricity at full power. Therefore, it can respond to small peaks or valleys, whereas the electrolyser has to stay idle, as the start-up costs are too high or ramp rates to slow. Furthermore, for short periods of time that are long enough for the electrolyser to respond, electricity can be consumed more efficiently by the battery as it does not have to start up for this short period. This stored energy can afterwards be used by the electrolyser over a longer period of time. Besides, there is a start-up time or stop time required. Moreover, the battery can be in a static state with hardly any losses, whereas the electrolyser would consume standby power. The more dynamic characteristics of the battery open the possibility for new electricity markets that require a low response time, which were not suitable for the electrolyser.

For the integration of the BESS in the EMS, a new asset is added to the system. This asset will also place strike energy bids and strike price bids, however, this is now done for both charging and discharging the battery. These bids are dependent on the State Of Charge of the battery. The optimiser will determine which asset will operate at what power level. For the experiments, two sizes of BESS were chosen, one with the same capacity and maximum power as the electrolyser, and one with a smaller capacity and power. Additionally, the first configuration will have an unlimited grid capacity, whereas the second configuration will have a limited grid capacity of 20MW, meaning that the battery and electrolyser will have to compete for their electricity.

TABLE 2
Overview of all simulation configurations.

	Summary	Back-up market	DA cap. bid
1	Baseline	Dynamic contract	-
2	Imbalance only	Imbalance	-
3	DA 100%	Imbalance	100%
4	DA 70%	Imbalance	70%
5	DA 40 %	Imbalance	40%
6	Storage €1/kg	Imbalance	100%
7	Storage €2/kg	Imbalance	100%
8	Storage €3/kg	Imbalance	100%
9	Battery 20MW, grid 40MW	Imbalance	-
10	Battery 10MW, grid 20MW	Imbalance	-
11	DA 85%	Imbalance	85%
12	DA 90%	Imbalance	90%
13	DA 95%	Imbalance	95%
14	Battery 20 MW only	Imbalance	-
15	Battery 10 MW only	Imbalance	-

4 Results and Discussion

This section presents the results of the investigations of the configurations through simulation and provides a discussion of the results. The section is divided in Electricity market trading, the addition of Underground seasonal hydrogen storage and the addition of BESS.

4.1 Electricity market trading

For the electricity supply, three options have been considered: the dynamic contract, the imbalance market and the day ahead market (in combination with the imbalance market).

4.1.1 Dynamic contract

Table 3 presents the results of simulations with the dynamic contract. The contribution margin is calculated by subtracting the electricity costs from the hydrogen revenue.

Several details attract attention. Firstly, in 2020 more than 100 GWh of hydrogen is produced, which is over 96& of what could have been produced (105.1GWh). Secondly, 2021 and 2022 were considerably worse years for hydrogen production. More importantly: the respective contribution margins are actually negative. Even though optimisation is used for controlling the power level of the electrolyser, negative values are possible. As the resolution of the day ahead market is one day, the state optimisation can only be performed over one day. The transition of the days is therefore flawed. Having several characteristics that obligate the consumption of electricity (e.g. startup, stopping procedure, standby), it is possible that the electrolyser is consuming a lot of electricity without actually producing hydrogen or making a profit.

TABLE 3
Summary of the results of the dynamic contract simulations.

Year	Produced H2 [GWh]	Contribution margin [M€]
2020	100.93	4.61
2021	39.50	-0.071
2022	13.31	-0.35

4.1.2 Imbalance market

The results of the simulations that make use of the imbalance market are presented in Table 4. The figures are compared to the previous electricity source, dynamic contract, through percentages.

These figures represent the economic objective of the EMS. Even though less hydrogen is produced, the contribution margin is increased considerably. The negative contribution margins of 2021 and 2022 have been improved massively. The results of this investigation demonstrate the effectiveness of adequate trading strategies.

TABLE 4
Summary of the results of the imbalance simulations. The percentages indicate the case compared to the dynamic contract configuration.

Year	Produced H2 [GWh]	Contribution margin [M€]
2020	90.00 -11%	5.09 +10%
2021	37.62 -4.8%	2.22 +↯%
2022	11.03 -17%	1.97 +↯%

4.1.3 Day ahead market

The results of the simulations that make use of day ahead trading are displayed in Table 5.

The results for the day ahead trading exhibit the potential of trading on multiple electricity markets. The output data showed that at times the electrolyser would not consume electricity, even though day ahead capacity was won. Not offtaking this electricity is to the net operator equal to feedin on the imbalance market. This again demonstrates the economic objective of the EMS: it may be financially more attractive to not do anything at times that the imbalance prices for feedin are rather high. This results in a drastic increase of contribution margin between 11 and 36%. Even though the focus of the EMS is on having a high contribution margin, the hydrogen production was increased for all years. This is due to a more steady operation than is achieved when trading only on the imbalance market.

Nonetheless, the profile of the power level of the electrolyser is still rather erratic (see Figure 5). The characteristics of the electrolyser as described by the physical model allow for such behaviour. It is to be discovered in future research what the effect on the electrolyser is of such a power pattern.

The results displayed in Table 5 are based on a configuration in which the EMS bids 100% of the power capacity of the electrolyser on the day ahead market. Several experiments have been done to verify whether bidding a lower capacity on the day ahead market would result in more adaptability for the electrolyser to the imbalance market. The day ahead experiments have been done for 40%, 70%, 85%, 90% and 95% of the electrolyser capacity. All results revealed a decrease in performance compared to the 100% strategy, with an approximately linear relationship between the size of the capacity bid and the contribution margin.

TABLE 5
Summary of the results of the full capacity day ahead strategy. The percentages represent the comparison to the imbalance-only figures.

Year	Produced H2 [GWh]		Contribution margin [M€]	
2020	92.25	+2.5%	5.89	+16%
2021	40.58	+7.9%	2.47	+11%
2022	12.27	+11%	2.68	+36%

4.2 Seasonal hydrogen storage

The results of the investigation to seasonal hydrogen storage are displayed in Table 6. In Figure 4 the operation of the hydrogen storage is displayed: the highest 25% of the hydrogen selling price is taken, after which the LCOS is subtracted (in this case €2/kg).

In 2020, there are no benefits to having underground storage. The hydrogen prices in 2020 are relatively high and consistent. There is no real peak in these prices, meaning that the hydrogen cannot be sold for a higher price. In 2021 and 2022 only for the LCOS of €1/kg great improvements have been achieved, for €2/kg this is already remarkably worse. In Figure 4 it can be noticed that only in the start of the year (and several times throughout the rest of the year) the storage price is better. The impact of a higher LCOS is clearly visible. With the amount of €3/kg LCOS, no improvements have been made.

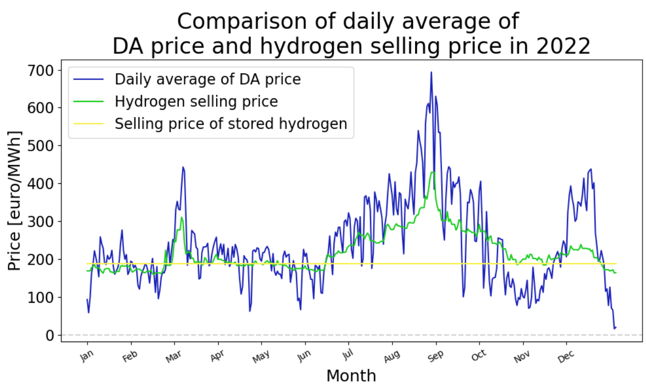

Fig. 4. Comparison of the day ahead price with the selling prices of directly sold hydrogen and stored hydrogen, in the case of the LCOS of €2/kg.

TABLE 6
Summary of the results of the seasonal hydrogen storage simulations. The percentages represent the comparison to the full capacity bid day ahead strategy. The storage simulations were done in combination with the 100%-capacity day ahead strategy.

LCOS [€/kg]	Year	Produced H2 [GWh]		Contr. margin [M€]	
1.00	2020	92.25	0%	5.89	0%
	2021	49.07	+21%	3.73	+51%
	2022	15.53	+27%	3.17	+18%
2.00	2020	92.25	0%	5.89	0%
	2021	40.64	+0.15%	2.49	+0.8%
	2022	13.11	+6.8%	2.78	+3.7%
3.00	2020	92.25	0%	5.89	0%
	2021	40.58	0%	2.47	0%
	2022	12.27	0%	2.68	0%

4.3 Addition of BESS

Table 7 displays the results of the addition of a battery to the electrolyser. The contribution margin in the results is high, due to having an extra asset that can trade individually. The difference in dynamic behaviour between BESS and electrolyser is visible in the results: 2022 is concluded with a significantly higher revenue.

However, the contribution margin is in this case not important. The objective is to verify whether a BESS impacts the economic viability of green hydrogen. It seems through the amount of produced hydrogen, hardly any impact was made by the BESS. For a better perspective, the additional revenue is calculated as in Equation 3. The results from this equation are displayed in Table 8.

$$\textit{Additional revenue} = \textit{revenue combined site - revenue sole electrolyser on site - revenue sole battery on site} \quad (3)$$

TABLE 7
Summary of the results of the simulation with an electrolyser and BESS. The percentages represent the comparison to the imbalance-only figures. The BESS-electrolyser simulations were done with the imbalance-only strategy.

Battery	Year	Produced H2 [GWh]		Contr. margin [M€]	
20MW, 20MWh	2020	90.00	0%	6.17	+21%
	2021	37.63	+0.03%	3.79	+71%
	2022	11.04	0%	5.28	+168%
10MW, 10MWh	2020	90.00	0%	5.10	+0.2%
	2021	37.62	0%	2.60	+17%
	2022	10.90	-1.2%	3.49	+77%

When having a large battery and a large enough grid capacity, the combination of both machines does add some value to the site. 2020 was already a very good year, meaning that adding a battery does not add value to the electrolyser. It is however remarkable that the added value is negative. After analysing the data, it can be concluded that this reduced revenue is due to limitations in the battery strategy. The battery strategy, which is focused on individual performance, is deciding for what prices it is willing to supply or consume electricity. The difference between a battery individually or in combination with an electrolyser is that at times the battery is supplying electricity to the electrolyser. This occurs at times when the imbalance price is high, but the electrolyser is obligated to consume power, due to ramping down or being on standby. The battery will assist the electrolyser with electricity, even though it might be able to sell this electricity sometime later for a higher price. The limitations of the battery strategy are thus due to the statistical price prospect, which determines the expected price to be received for electricity. For 2021 and 2022 this problem does not occur due to the high volatility in the imbalance market. The sudden high prices for the usage of electricity that cannot be prevented by the electrolyser are more extreme than in 2020, meaning that using electricity from the battery is a good method to cope: supplying electricity to the electrolyser is worth more than directly selling this electricity.

When the site has a limited grid capacity, the battery and electrolyser are competing for electricity. Consequently, the site has less revenue than when having both systems separately. In this case, it would not be economically attractive to add BESS, especially with the high investment costs. Applying a BESS and an electrolyser separately would be more financially appealing when having restricted grid capacity.

TABLE 8
Additional revenue by the collaboration of the electrolyser and BESS. The percentage represents the share of the additional revenue to the total revenue made by the combined site. Remark: Additional revenue is in k€.

Battery	Year	Additional revenue [k€]	
20MW, 20MWh	2020	-29.7	-0.48 %
	2021	37.2	+0.98 %
	2022	31.3	+0.59 %
10MW, 10MWh	2020	-540	-11 %
	2021	-383	-15 %
	2022	-124	-3.6 %

4.4 General discussion

Having discussed the results of the different cases individually, more general remarks will be made.

Firstly, electricity market trading seems to be a vital factor for the economic viability of green hydrogen. The development of a good strategy is important, but besides, there are no additional investments. The contribution margin has increased by at least 27% (DA-100% versus dynamic contract), showing the potential of the solution.

The success of hydrogen storage depends on the LCOS. The additional revenue that is made must weigh out the investment costs of transport, purification and compression. Besides, through this research, a first estimate is made on the potential of seasonal hydrogen storage. The model has to be upgraded to the actual method of determining the LCOS (in this study, the LCOS was all-inclusive and time indefinite), for example, during the realisation of Zuidwending, in order to verify the validity of the assumptions.

The added value of BESS is questionable: in this study, only a marginally positive or a negative added value was achieved. The assumptions made in the model of the electrolyser may have an influence on the cooperation of the BESS and electrolyser. As the efficiency of the electrolyser was assumed to be constant, there was nothing to be gained from a smooth power level profile of the electrolyser. As demonstrated in Figure 3, the efficiency is proved to be nonlinear and electrolysers do benefit from steady operation [15]. Due to the assumption, the battery had no intent to support the electrolyser, apart from when more money is made through hydrogen than through selling electricity. Several improvements are required for the research on the BESS/electrolyser combination. There are more parameters to investigate in this combination, meaning that more configurations should be examined, for example, the type of battery, the C-value of the battery and grid capacity. Furthermore, the battery strategy that was utilised was optimised for individual operation. The effect is that for example in 2020 with an unlimited grid capacity, less revenue was made, due to an inaccurate electricity price prediction model.

Furthermore, some general remarks have to be made. In this research, the historic years of 2020, 2021 and 2022 are utilised. It is difficult to acknowledge these years as representative years, due to large events such as COVID-19 and the Russian-Ukrainian war.

Moreover, the EMS has made use of the imbalance market as the backup market. It is advisable to recognise the depth of said market. When having increased the electrolyser capacity, the market prices could be influenced by running the electrolyser, causing a new optimisation problem.

5 Conclusion

The goal of this research was to improve the economic viability of green hydrogen and to assess what influenceable factors have the most impact on this economic viability. The economic viability is assessed by the contribution margin, which is calculated by subtracting the electricity costs from the hydrogen revenue. In this study, an electrolyser model was developed, as well as an Energy Management system, through which the production, revenue and costs of hydrogen production for different configurations could be determined over the years 2020, 2021 and 2022.

- Through electricity market trading, the contribution margin was significantly increased for all years. Trading on the imbalance market has increased the contribution margin by over 27% compared to the dynamic contract, whereas the day ahead market trading has improved this by another 11% to 36%.
- Underground seasonal hydrogen storage is showing potential for improving the green hydrogen business case. The LCOS will determine the success of this method. In this study, it was concluded that for the LCOS of €3/kg, there is no value in underground hydrogen storage. For €2/kg, the consideration of the increased investment costs versus the additional revenue has to be made, this study has shown an increase of between 0.8% to 3.7% in contribution margin. The configuration of €1/kg resulted in a large increase in contribution margin, that would justify the investment in infrastructure for underground storage.
- The addition of BESS to the electrolyser site has not resulted in added value. There was no additional hydrogen production, and the added value of the BESS was 0.98% at maximum. This would not weigh out the extra investment costs, meaning that it would financially be more attractive to utilise a battery and an electrolyser on different sites.

APPENDIX A
PLOT DAY AHEAD STRATEGY

In this appendix, a figure is presented that demonstrates the operation of the EMS and electrolyser for the day ahead strategy. This day ahead strategy is combined with the imbalance market, opening the possibility for intermarket arbitrage.

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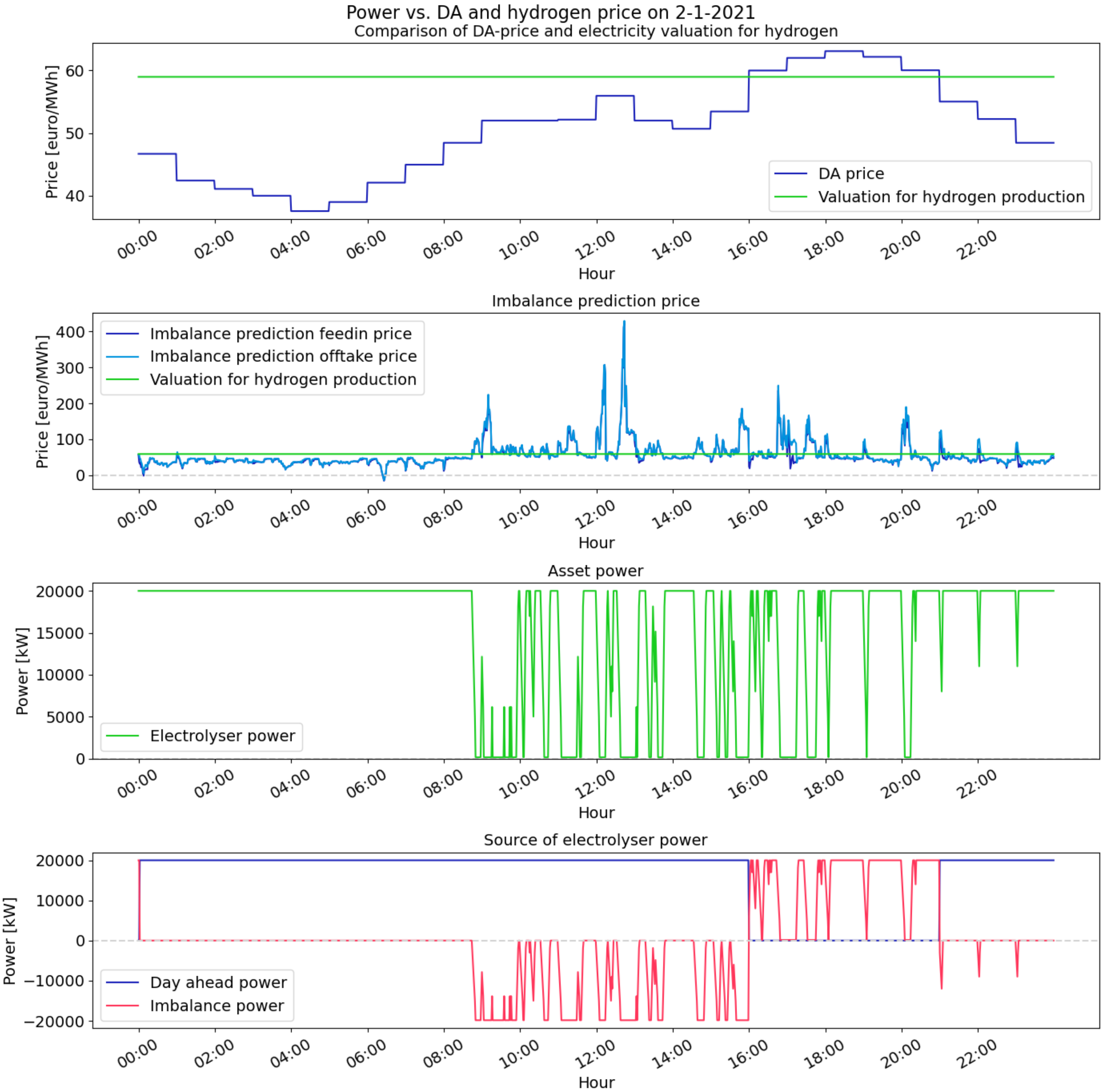

Fig. 5. The performance of the day ahead trading strategy on January 2nd 2021. Notice the feedin on the imbalance market (negative power) in the bottom graph, which is the virtual flow due to not using this electricity for powering the electrolyser. The energy balance will always accumulate to nought: the day ahead power plus the imbalance power minus electrolyser power equal zero.

B | Literature Review

See next page.

Abstract

Green hydrogen is an important concept in the energy transition. It can function as storage medium, as well as replacement for fossil fuels in high temperature heat processes. However, the economic feasibility of electrolysers has proved to be a problem. This paper gives an overview of literature that focuses on improving the business case of green hydrogen. This literature is specifically on the implementation of an electrolyser, instead of on the technological development of electrolysers. This resulted in several main factors that should be researched for the implementation of an electrolyser: the effect of usage of different electricity markets, the effect of hydrogen storage in salt caverns, the combination with BESS, and the integration of these solutions in an Energy Management System.

1 Introduction

It was in 2015 in Paris that the United Nations made an agreement in order to gain control over climate change. This agreement has the objective to not trespass the 2 degrees Celsius increase since the start of the industrial era. The rising temperatures have a strict correlation with the emission of greenhouse gasses (GHG), as can be seen in Figure 1. The agreement states that the usage of fossil fuels has to be diminished and in the end suspended in order to lower the amount of GHG (United Nations, 2018).

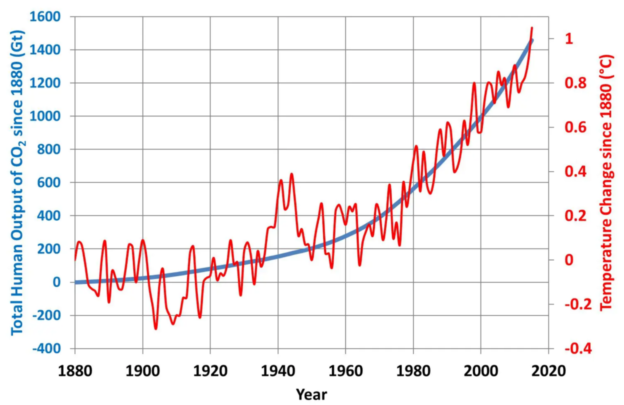

Figure 1. Correlation between the CO2 emission and global temperature change (Waltham, 2019).

However, as can be seen in Figure 2, the usage of fossil fuels since 2015 has not decreased, but is still increasing. 2021 was the year with the highest fossil fuel consumption in one year.

In order to reduce and stop the use of fossil fuels, the world should start relying on renewable energy. Currently, the generation of green energy is increasing more rapidly than that of fossil fuels (as can be seen in Figure 3), though the production of energy from fossil fuels is still rising. This is due to several complications in the use of renewable energy, of which most importantly: the intermittent nature of sources and the need for high temperature heat in industries. Where a coal-fired power plant is able to adapt its production to the demand of energy, sustainable energy sources will generate electricity based on external causes, for example wind speed or sunshine, unrelated to the demand. Besides, high temperature heat processes are running on fossil fuels and electrification of these processes is an expensive endeavour. Green hydrogen is a big part of the solution here, as energy storage medium and as fossil fuel replacement.

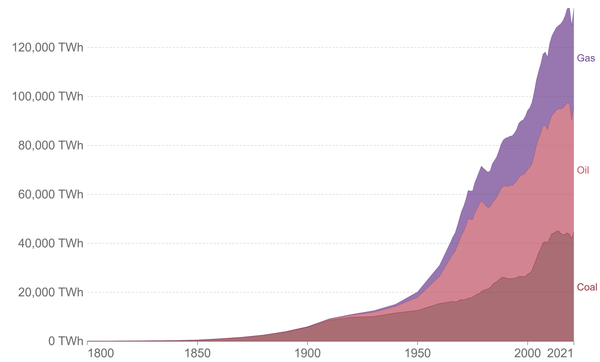

Figure 2. Global fossil fuel usage from 1800 to the present (Ritchie et al., 2022).

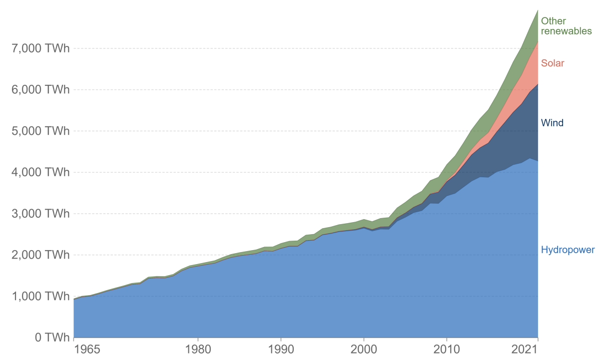

Figure 3. Global renewable energy consumption from 1965 to the present (Ritchie et al., 2022).

Green hydrogen is made by electrolysers. The application of electrolysers for green hydrogen is however often not economically feasible. Most research is dedicated to improving electrolysers as technology, while almost no research is done to improving the implementation of the electrolyser. Thus, solutions must be found, that can be implemented short-term.

The case for which the application of an electrolyser is considered, is a large gas consumer that desires to transition to hydrogen for high temperature heat processes. In that case, there are no alternatives to hydrogen for transitioning to renewable energy. In this case, it may be assumed that there is an unlimited demand for hydrogen. The consumer is located in the Netherlands, however, inspiration may come from other regions.

This raises the research question for this literature review. Hydrogen plays an important role in the transition to the usage of renewable energies. The usage of hydrogen has to become economically viable. **How can the implementation of an electrolyser in a renewable energy grid be made economically viable?**

In section 2 the purpose of green hydrogen is explained. In section 3 different electrolysers are compared in characteristics and costs in order to elect the most suiting type. In section 4, the three most important factors for economically feasible green hydrogen are discovered. Thereafter in section 5, short-term solutions are considered in order to satisfy the factors for economically feasible green hydrogen. In section 6 the complexity and the impact of these solutions are assessed, in order to determine the priorities for future research.

2 Importance of green hydrogen

In this chapter, the question that must be answered is: why is the application of green hydrogen important? Firstly, the different uses of hydrogen are explained, whereafter the importance of green hydrogen production is emphasised.

2.1 Purposes of green hydrogen

Green hydrogen can be used for different purposes. Yet, the false starts of hydrogen technology in the last decades show the difficulties to develop economically efficient hydrogen technology. The emphasis in the vision of hydrogen is its purpose as electrochemical battery, in combination with a fuel cell. However, fuel cells are currently not energy efficient, expensive to implement and have a low lifespan. The conversion rate of green electricity to hydrogen and back to green electricity is still too low. Therefore the purpose in this paper is not to generate electricity from hydrogen storage, and to deviate from this vision. What is then the purpose of green hydrogen?

The global annual hydrogen demand is about 90Mt, which is used for iron and steelmaking; methanol; ammonia and refineries, as displayed in Figure 4 (IRENA, 2022; IEA, 2022a). These processes run currently mostly on grey hydrogen. In this chart, hydrogen is used as feedstock for Methanol and Ammonia, as gas for Power Heat (PH) in iron and steel industry and used for the chemical process in refining.

The first application of hydrogen is feedstock of certain processes. Feedstock consists of more than 51% of the hydrogen demand, according to Figure 4.

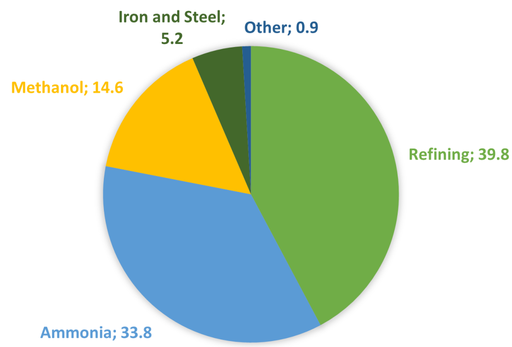

Figure 4. Amount of hydrogen (Mt) used globally per sector in 2021 (IEA, 2022a).

Another application, that is not yet implemented widely, is a consequence to the high demand of high temperature heat from the industry. The heat industry covers 24% of the total energy consumption, of which the majority is being generated by fossil fuels (Solar Payback, 2017). In order to make this process become more sustainable, renewable heat sources could be used, or the process could be electrified in combination with green electricity. However, the high temperature heat industry - consisting of 48% of the heat industries - covers temperatures well above 400 °C, whereas renewable heat sources are only able to reach 350 °C (See Figure 5. Furthermore, electrification requires high investment costs and is therefore often not executed (Lechtenböhmer et al., 2016; Wei et al., 2019). Hydrogen may be the solution to this problem as direct replacement for the fossil fuels: the processes do not have to be altered, the investment on upgrading the infrastructure are relatively low, and hydrogen can easily generate the required high temperatures in the process. This application is called power-to-gas (P2G) or power-to-hydrogen (P2H2), meaning that power from renewable sources is used for the production of gasses that can be used for Power Heat (PH). P2G for PH is a costly application, but not impossible to implement profitably (Naegler et al., 2015).

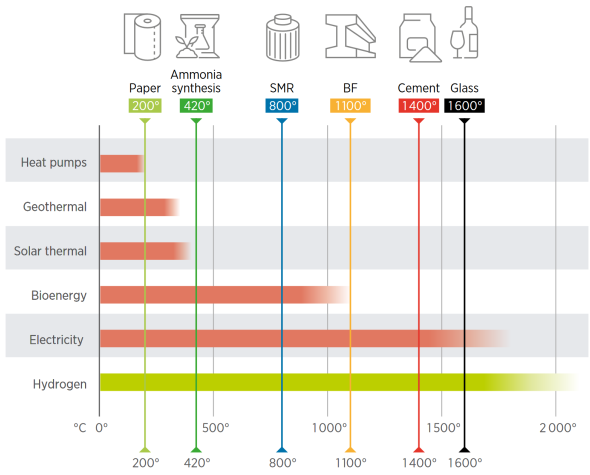

Figure 5. Working temperatures for renewable heat sources versus the temperature requirement of industrial processes. (IRENA, 2022)

Lastly, hydrogen can be used as storage medium of energy. This is not in contrast with what is said about fuel cells. Storing hydrogen for feedstock or PH-fuel is a method of handle excess electricity, without considering the low conversion rates of a fuel cell. The consequence is that less electricity has to be used for hydrogen production in times of shortage of energy. The hydrogen gas is thus used as gas, instead of converting this back to electricity again. Fuel cells are solely economically beneficial at the moment that green hydrogen storage is full, green hydrogen for feedstock is used fully and all industrial processes that use hydrogen are supplied with green hydrogen (Frost, 2022).

2.2 Green hydrogen production

Then the question to answer is: why should the produced hydrogen be green? Hydrogen can be produced via several processes. Currently, the most used process for hydrogen production in the world is SMR: Steam Methane Reforming. This is a very cost-effective method, methane is used with steam under high pressure to produce hydrogen, whereafter the CO2 is emitted. Hydrogen from fossil fuels is therefore called grey hydrogen. Currently, 95% of the produced hydrogen in the world is grey hydrogen (NL Hydrogen, 2022). If these GHG are captured and stored (Carbon Capture and Storage, CCS), this is called blue hydrogen. Another production method for hydrogen is electrolysis. Electrolysis is a process that can also be called grey, blue or green, depending on the source of the electricity needed for the electrolysis.

Blue hydrogen through SMR is a more environmentally friendly solution that is less difficult to implement and become profitable. However, as for the production fossil fuels are utilised and redundant storage for CO2 is needed, blue hydrogen should only be utilised as transition phase (Emmett Green, 2021). The storage capacity of hydrocarbon reservoirs is currently estimated at 800 gigatonnes CO2, whereas the total emission in 2021 by burning fossil fuels was 36 gigatonnes of CO2, meaning the storage would be sufficient for only several decades, assuming that all CO2 would be captured (Friedlingstein, 2022; IEA Greenhouse Gas R&D programme, 2007). Thus, investments for the use of hydrogen to help the energy transition should resolutely be placed in green hydrogen.

3 Electrolyser analysis

As stated in the previous section: investments in hydrogen should be placed in green hydrogen. Green hydrogen is produced by the chemical process of electrolysis. This section informs about the current state of different electrolysers. The focus is on the application of the technologies and partly the economic viability of the technologies, instead of on the technological principals on which its performance is based. In the end, this paper functions as preparatory literature review in a project where a 20MW electrolyser will be implemented. Therefore, energy efficiency or other characteristics of the electrolyser cannot be altered. Instead, the best electrolyser in this scenario should be applied. In the foreseen scenario of the electrolyser, the electrolyser is producing hydrogen of electricity that is directly derived from a solar park. The solar park will also have a grid connection, meaning that the electrolyser must compete with all other power consumers. The electrolyser could possible be utilised for peak-shaving.

3.1 Electrolysis technologies

Electrolysis is a well-known technology that exists since the start of the 19^{th} century. There are, however, different electrolysing technologies, the most important of which:

- **Alkaline electrolysis (AEL)** This is the most implemented technology and it is considered the most mature, as it originates from the early electrolysing researches. It

Table 2. *Overview of the advantages and disadvantages of Alkaline and PEM electrolysis (Carmo et al., 2013).*

	Alkaline electrolysis	PEM electrolysis
Advantages	- Well established technology - Non noble catalysts - Long-term stability - Stacks in the MW range - Cost effective	- High current densities - High voltage efficiency - Good partial load range - Compact system design - High gas purity - Dynamic operation
Disadvantages	- Low current densities - Crossover of gases (degree of purity) - Low partial load range - Low dynamics - Low operational pressures - Corrosive liquid electrolyte	- High cost of components - Acidic corrosive environment - Possibly low durability - Commercialisation - Stacks below MW range

is thus seen as reliable and robust, but it is sometimes stated as a lumbering, old-fashioned technology.

- **PEM electrolysis (PEM)** This is a relatively newer technology, the state and the progress of this technology is precisely documented by Carmo et al. (Carmo et al., 2013) The development of this technology had stopped between 1970 and 1990, but it was continued at the time that the necessity for hydrogen was rediscovered.

- **Solid Oxide Electrolysis Cell electrolysis (SOEC)** This is not a mature technology, as it is still in the development stages. It cannot therefore not accurately be compared with the other two technologies.

3.2 Characteristics of electrolysers

The Alkaline and PEM electrolysis technologies have different characteristics under operation. The most important advantages and disadvantages are displayed in Table 2, which was retrieved from (Carmo et al., 2013). The source that is used for this table is dated, as the hydrogen technology develops currently at high rates. Even though the differences between alkaline and PEM may have decreased, the advantages and disadvantages are still accurate. Some aspects deserve an extra highlight, for example the dynamic operation of a PEM electrolyser. This means that in matter of seconds a PEM electrolyser can start from stand-by or several minutes from a cold start to maximum power. With an alkaline electrolyser, this is not possible, this will take several minutes from stand-by to 20 minutes from cold start(Tuinema et al., 2020; Matute et al., 2021; Deloitte, 2021). Another important aspect which is still being examined is the high output pressure of PEM, meaning that the compressed hydrogen can immediately be used for storage (Mathiesen et al., 2013). This lowers the CAPEX as no gas compressor is needed, but this also diminishes the required total power (Salehmin et al., 2022). For the prospected European Hydrogen Backbone, or delivery at site, the estimated pressure is between 30 to 80 bar, which is widely available under PEM electrolysers (Wang et al., 2020).

3.3 Financial analysis of electrolysers

When comparing AEL and PEM technology, it can be concluded that PEM still has a higher CAPEX (Proost, 2019; Frost, 2022). Especially the stack costs, that also have to be replaced after about 10 years, are more expensive than that of alkaline, due to the rare metals used. The difference in CAPEX and OPEX of the two technologies is however decreasing (Holstein et al., 2018; Felgenhauer & Hamacher, 2015). Furthermore, in the case of choosing an electrolyser, the application of the electrolyser is far more important than the CAPEX. This is further explained in section 4. The CAPEX only count up to a small share of the Levelised Cost Of Hydrogen (LCOH), electricity costs are considerably more important. Therefore, the operation and energy efficiency under this operation is financially more relevant than the expenses on the electrolysers.

3.4 Conclusion

In conclusion, as AEL has received more attention for research and development over the past decades, this is a more robust and less expensive option. However, the expenses for the electrolyser are inconsequential compared to the electricity costs, meaning that the operation of the electrolyser is of higher importance. A PEM electrolyser will then be a more viable option due to its dynamic operation.

4 Influential factors to feasibility of electrolysers for green hydrogen production

In the previous sections, the importance of green hydrogen is explained and the distinction between the different methods of producing hydrogen is made. In subsection 3.3 it was claimed that the CAPEX play a less important role in the cost of hydrogen than electricity costs. The costs of the production of a kilogram hydrogen is called the Levelised Cost Of Hydrogen (LCOH). First, it is explained what the costs mainly consists of. Then the composition of the revenues of selling the hydrogen is explained. From these compositions, the factors that influences the economic viability of green hydrogen are deduced. When having a higher revenue than the LCOH, economic viability is established.

4.1 Levelised Cost Of Hydrogen

In Figure 6 the decomposition of the LCOH is displayed for Alkaline and PEM electrolysis. The displayed LCOH is the total value in 2020 and the predicted value for 2030. The actual values of the sections in this diagram are not important, as the innovations and developments in the field of green hydrogen are changing the predictions rapidly. The decomposition is however interesting. As can be seen, between 60% to 70% of the LCOH consists of the power that is needed for the electrolysis. Furthermore, as the CAPEX decreases, the share of electricity costs increases to 70% to 80% of the total LCOH. As the CAPEX of the electrolyser decreases, the total LCOH in 2030 also decreases compared to 2020. The definition of CAPEX and OPEX in literature varies a lot. Generally, the CAPEX consists of the initial investment costs, and the OPEX consists of the O&M, replacement of stacks and the power (Power may also have been assigned its own section of expenses). In this paper, the CAPEX consists of the initial investment costs of building the electrolyser, and the stack replacements that are needed during the lifetime of the machine. The O&M is here counted to the CAPEX, this is around 2 to 4% of the initial investment. As mentioned, compression for certain PEM electrolysers is not needed when distributing the hydrogen immediately. For centralised storage (for example in the salt caverns of Zuidwende), a compressor is needed to bring the pressure to 200 bar (Farahani et al., 2020; Zuidwending, 2022; Luscuere & van Wijk, 2021).

The cost of the hydrogen produced by electrolysis is thus primarily based on the **electricity pricing**. This is caused by the fact that the electrolyser competes with other energy consumers. The merit order effect, the principle that determines the ranking for energy delivery in ascending order of price, induces an increase in electricity price (Deloitte, 2021). Furthermore, the energy efficiency of the electrolysis is important, that is the losses that occur during the process. This efficiency determines in the end the amount of energy that is turned into hydrogen to sell and is thus included in the power segment of the LCOH decomposition.

In the LCOH the Utilisation Factor (UF) is meaningful. For the electrolyser, the utilisation factor must be above 30%, to guarantee that the CAPEX and fixed costs are marginal. Additionally, the UF must be lower than 90% to prevent the merit order effect reducing its competitiveness (Deloitte, 2021). Only then the assumption of the decomposition of LCOH holds. **CAPEX** may thus be an important factor for a positive business case, depending on the UF.

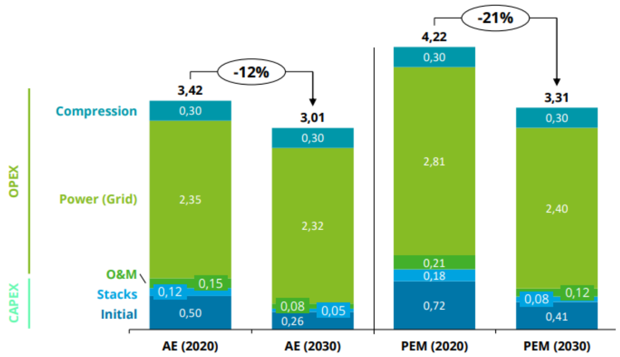

Figure 6. Realisation of the decomposition of the Levelised Cost Of Hydrogen in 2020 versus the prediction of 2030 based on a 70% utilisation factor(Deloitte, 2021).

4.2 Influential factors on revenue of hydrogen

In the previous subsection, the most important factors of the costs were discussed. Now the most important factors in the revenue of hydrogen should be discussed. The revenue of selling hydrogen is based on the local marketpotential or demand, the willingness-to-pay and the gas pricing (van Kranenburg et al., 2018). Firstly, the demand for hydrogen will increase the selling price of hydrogen. Secondly, the willingness-to-pay is applicable for green hydrogen: these are additional costs that the client is prepared to pay for green energy. Lastly and most importantly: the selling price is mostly based on the natural gas price. Currently, the gas price and electricity prices are coupled as large gas turbines determine the electricity market. It is the goal to decouple the natural gas price and electricity price, as generation of green hydrogen would then be cheap, while the hydrogen would generate relatively more revenue. The long-term method for decoupling the gas and electricity prices is a **larger share of Renewable Energy Sources** (RES) (Rijlaarsdam & Bijlsma, 2006).

4.3 Conclusion

In the previous paragraphs, the three most important methods for economically viable green hydrogen are mentioned. These are: an abundance of green electricity, low cost electricity and a low cost electrolyser (Taibi et al., 2020).

However, when implementing an electrolyser in a system, these three factors are all not influencable. Hence, other parameters that are influencable at the application of an electrolyser have to be discovered. These solutions have the same goals as the three factors for economic viability. The three goals are: Decoupling the gas and electricity pricing; Decreasing the cost of electricity in the LCOH; Reducing the CAPEX of the electrolyser. Short-term and influenceable solutions are explained in section 5.

5 Guidelines for implementation of electrolysers

As mentioned in section 4, there are three main factors that influence the cost and revenue of green hydrogen: low cost electricity, an abundance of green electricity and low cost electrolysers. These factors are however non influenceable for investors when implementing an electrolyser. Thus, the response from the industry is: waiting for lower costs of electrolysers, waiting for better performance, and waiting for the build of solar and wind parks.

This is the chicken and egg story as told by Sun et al. (2022). The industry is waiting for low cost electricity through a lot of RES before electrolysers are built. Yet, with a congested grid, these renewables cannot be implemented. To decongest the grid, batteries and electrolysers are required. Ultimately, a loop is formed of waiting industries.

Most research is dedicated to improving electrolysers as technology, while almost no research is done to improving the implementation of the electrolyser. Consequentially, other solutions must be found, that can be implemented short-term (Patonia & Poudineh, 2022). These solutions have the same purposes as the factors mentioned above, the possible solutions are mentioned in a subsection per purpose.

5.1 Decoupling gas and electricity pricing

The first factor for economically viable green hydrogen is an abundance of green electricity, thus building new renewable energy sources. This would decouple the gas and electricity prices, meaning that the cost of hydrogen goes down, while the revenue increases. A short-term solution for this purpose is hydrogen storage.

5.1.1 Hydrogen storage

A solution for abundance of green electricity is hydrogen storage. Currently, curtailment must solve the instability of the grid. Curtailment is restricting the supply of (green) energy at the times that there is a redundancy of supply. RES often come with peaks in power, for solar PV at noon, for wind parks during day time. As the demand at those times is limited, these sources must generate lower power than that is available (see the convenant on Flatten the solar curve by Molengraaf and Voorhorst (2020)). Restricting the supply still means that at times of low renewable supply grey energy is needed to compensate. Storing this redundancy of energy in hydrogen will result in a constant demand of green energy, as in hours of lower supply, hydrogen from storage can be utilised.

Storage of hydrogen for short time is not economically viable due to the conversion rates. For this, batteries are more effective (Abomazid et al., 2022; Zhang et al., 2017). For longer periods, for example in different seasons, centralised hydrogen storage is a viable option (Rogers et al., 2014), under the operation of buying electricity at low prices and selling at high prices.

Different types of storage of hydrogen are available, though underground salt caverns have the lowest Levelised Cost Of Storage. A full overview of storage options can be found in the review by IEA (2022b). In the Netherlands, salt caverns near Zuidwending is purposed for hydrogen storage at 200 bar by EnergyStock (Zuidwending, 2022). A techno-economic analysis was given by Eradus (2022) on using off-shore salt caverns in the North Sea, which was proven profitable in combination with subsidies and an advantageous pricing of hydrogen alternatives. Schwartz and Menefee (2022) found in a techno-economic analysis that the addition of underground storage will increase the Rate Of Return of a windpark by a potential 7%.

5.2 Decreasing electricity costs

As mentioned, electricity costs are the main contributor to the LCOH. The electricity price has increased dramatically in 2022. As implementer of an electrolyser, one has no influence on this price. There are however solutions to reduce the electricity costs in the LCOH.

5.2.1 Electrolyser operation

The amount of electricity needed per kg of hydrogen is determined by the electrolyser's energy efficiency. This conversion rate is highly affected by the operation.

As researched by Kiaee et al. (2015) and Escobar-Yonoff et al. (2021) the energy efficiency of an electrolyser will improve when running at low current densities, thus an inverse correlation. This is displayed in Figure 7 for a PEM electrolyser. The voltage that is needed to overcome the losses ("Cell performance") increases with the current density. But there is also a minimum power that is needed to overcome the thermoneutral voltage.

Another aspect that affects the performance of an AEL is the start-up time and ramp rates for increasing or decreasing the power. Switching between powers and turning on and off does have a high influence on this electrolyser in terms of produced hydrogen, thus stable control of the electrolyser is beneficial. A PEMEL is much more flexible, the power can be altered considerably more dynamically. Even so, a stable control would be beneficial for the PEMEL as well.

Additionally, a PEMEL is able to operate at higher temperature and pressure. In a recent research, it was found that an AEL can also be operated at higher temperatures than was established before (Lohmann-Richters et al., 2021). The performance of an electrolyser is also influenced by the cell temperature: the energy efficiency of the electrolyser is higher at high temperature. This does, however, have a negative affect on the lifespan of the stack, and a lower lifespan results in higher OPEX. The consideration between higher energy efficiency (and higher OPEX) and lower energy efficiency (and lower OPEX) must be made per individual electrolyser. (Escobar-Yonoff et al., 2021).

Another source of revenue can then be added. By selling the residual heat when running the electrolyser at higher temperature, the apparent energy efficiency is increased (this is often used for SOEC electrolysers that operate at high temperatures). This is solely interesting if there is a local demand for heat.

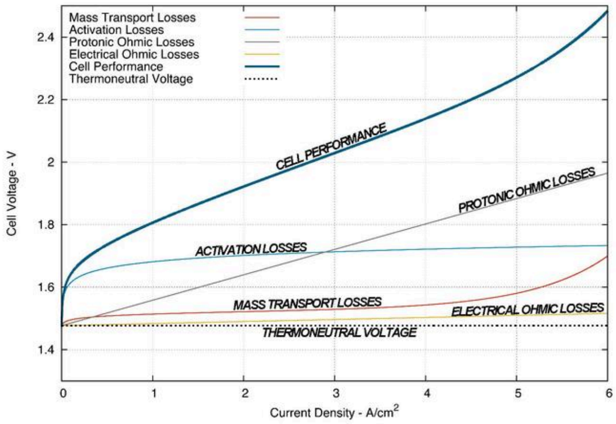

Figure 7. Breakdown of losses of PEM electrolysis (Fritz, 2013).

5.2.2 Electricity market trading

Market trading may be one of the most important factors for the feasibility of an electrolyser. In the case that this literature overview is utilised for, electricity is directly bought from a solar park. As the solar park has a grid connection, the electrolyser is competing with other power consumers. The electricity from the solar park is therefore not directly sold to the electrolyser, it is traded for. This electricity trading is done on different electricity markets. All information about electricity markets in the Netherlands can be found on the website of Tennet (2023) (see Figure 8). A great overview of implementations of electricity markets in an EMS is given by DNV (2021).

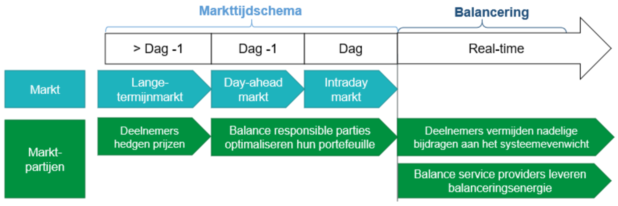

Figure 8. Time diagram of different electricity markets. Balancing markets contain the FCR, aFRR and mFRR markets (Tennet, 2023).

The first possible market to trade on is the Day-Ahead (DA) market. The auction stops at 12 o'clock at noon, where the electricity is bought and sold for the next day, in intervals of 1 hour. Based on the supply and demand, the electricity pricing and the volume is determined. This market represents best the actual value of electricity per hour per day. At times that there is an abundance of electricity, for example at noon with plenty of sun light and wind, this price will approach €0/MWh. The EMS should therefore be able to predict this low pricing and buy at the correct times. The pricing of renewable energy would not subsede €0/MWh, which could normally happen at times due to slow response of the high inertia gas turbines, as the RES will then simply be turned off.

The next possible electricity market is the Intraday (ID) market. This trading happens in almost real-time: the transactions are made 5 minutes on beforehand. The intervals on which electricity is bought or sold is 15 minutes or longer. Trading for the electrolyser is a possibility if only the warm-up time is less than 5 minutes in cold start (for PEMEL) or the electrolyser was already in standby (for AEL and PEMEL). The ID market is a method to keep the balance of the grid, closer to real-time.

Actual real-time balancing is done on the balance market. On this market, capacity for balancing activities are procured. There are three balance markets to trade on: FCR, aFRR and mFRRda.

- FCR stands for Frequency Containment Reserves. This is the primary reserve power, which should be able to switch on or off in 30 seconds. As this operation is fluctuating and highly volatile, this market is not useful for an electrolyser (Eichhorn, 2021).

- aFRR is an abbreviations for automatic Frequency Restoration Reserves. On this market, demand or supply for capacity should be ready within 15 minutes. This is however to be diminished to a Full Activation Time of 5 minutes in 2024. The ramprate of using power should be at least 7 %/min, which is achievable for an electrolyser. This is therefore a suitable market for an electrolyser. There is however the restriction of only being able to utilise power rather than also supplying, as a fuel cell will not be incorporated in this system. aFRR may be done voluntarily or by contract, which gives the obligation for a minimal frequency of bids. For a hydrogen system where plenty of trading is expected, contracted is more beneficial. An important note is that for an AEL, the electrolyser should remain in standby mode to have the requested reaction speed; the standby costs should then weigh up to the contract price or a possibility for a 15 minute electricity storage should be implemented (Holstein et al., 2018).

- mFRRda is an abbreviations for manual Frequency Restoration Reserves directly activated. This consists of emergency power for incidents or expected long-lasting surpluses and shortages. As this capacity should directly be available and the prospected revenues are low, this is not suitable for the electrolyser. An exception would be the case of additional electricity storage, where a battery would store the first energy until the electrolyser is running, especially in the case of expected long-lasting surplus.

A fairly new market is the GOPACS market. This market was designed to solve local grid congestions, while maintaining the balance of the grid. A balancing partner demand locally, while another balancing partner supplies the demand at another location, meaning that the grid operator only pays the difference of these prices. These purchases occur however sporadically and can therefore not provide a solid business case for the electrolyser.

The last market is the Imbalance market. This market is a real-time, uncontracted supply market for electricity, where electricity is bought or sold for the imbalance price. This price is based upon the imbalance that a party causes, when demanding or supplying energy. The imbalance price varies every 15 minutes. Predictions of this price are provided by several parties 15 minutes on beforehand, this estimation is improved every minute during this 15 minutes. Due to the fluctuating behaviour and due to the high extremes, this market may proof very profitable (Middelkoop, 2022).

5.2.3 Financial aid

Another short-term solution for low cost electricity is in policy-making. This is in fact not something that is influenceable at the implementation, but it is something that should be accounted for when implementing an electrolyser. Induced by the chicken and egg story, IRENA (2022) pleads for better subsidies and taxes. These must motivate investors, the initial investment is lower and the position of hydrogen versus natural gas should be enhanced. As this case is focused on the Netherlands, these subsidies and taxes are specific for the Netherlands.

As mentioned in Middelkoop (2022) the hydrogen price is determined by the gas price, as hydrogen is in a competitive position to gas. The formula can then be extended to:

H_2 price [€/kWh] = NG price [€/kWh] + taxes [€/kWh NG] - subsidies [€/kWh H_2] + green premium [€/kWh H_2]

Subsidies lower the cost of production of hydrogen (LCOH). The most important subsidie is the SDE++, which works on the OPEX of the LCOH. This subsidy may count up to €100/MWh and lasts for 15 years. But there are more subsidies than this. In the Netherlands, there are for example the subsidies: HER+, 'Subsidieregeling opschaling hernieuwbare waterstofproductie', EIA, VEKI and MOOI, most of them are available simultaneously. In Europe, the Innovation fund and Horizon Europe can be used. All of these may either lower the cost of the OPEX or CAPEX, but either way this lowers the LCOH.

Another factor that can encourage the production of green hydrogen is tax regulations on natural gas usage. The influence of these taxes for the hydrogen business case depend on the share of RES. Again, this section is not purposed for policy-makers as guide, but provides an overview of factors that can boost the implementation of electrolysers. There is for example the CO_2 tax, which works on the volumes of used natural gas. The CO_2 tax consists of the EU Emission Trading System (ETS) and Dutch CO_2 tax. At times that the Dutch tax is more expensive than the ETS, the ETS and the difference between the ETS and Dutch tax should be paid. At times that the ETS is more expensive than the Dutch tax, only the ETS should be paid. The ETS price averaged 85 €/t CO_2 for 2022 and was 58.3 €/t at lowest. The Dutch tax was 41,57 €/t, meaning that in the past year only ETS was paid. Taxes with a smaller contribution are the 'Energiebelasting' (Energy taxes) and the ODE, which would have contributed for about 1,50 €/MWh in 2022 on this case.

The last factor in the calculation of the price of hydrogen is the green premium. This is in fact the additional costs paid for energy form renewable sources, it therefore represents the willingness-to-pay additional costs for green energy (Gonzalez-Aparicio et al., 2022). Currently, this willingness is very low. The EU has announced a fund called 'the Hydrogen Bank' with a budget of €3B to cover the green premium, making the usage of green hydrogen more attractive for consumers (Allsop & Bortolotti, 2022).

5.2.4 Energy management systems

The goal of an Energy Management System (EMS) is to optimally control different components in a renewable system. All previous solutions come together in the EMS. The EMS determines the electrolyser operation and market trading, but also whether hydrogen is sold or stored. Besides, the financial aids will influence the variable costs of producing hydrogen, meaning that this also influences the outcome of the EMS. The EMS has the following responsibilities: it receives demands from the different assets in the microgrid, trades on the electricity market with a certain strategy, and then determines and controls the operation of the assets. This may be done in several ways, for example by optimisation or rule-based strategies. The EMS is thus the brain of the microgrid, this brain determines the profitability of the Multi-Energy System (MES). A smarter EMS may for example look at weather forecasts to determine whether the electrolyser should be turned off or should be placed in standby instead, based on the solar power; or incorporate seasonal yield and consumption for a hydrogen storage strategy. Variables that should be included in the optimization problem of the EMS are thus: electrolyser state, energy market predictions, hydrogen market predictions, solar forecast, possibly hydrogen storage state and seasonal trends, possibly battery state et cetera. The outcome of the optimization problem is the control of the different assets (electrolyser, hydrogen storage, battery) and bids on the electricity market.

Several researches on EMS for hydrogen systems have already been executed. Vivas et al. (2018) provides an overview of literature up until 2018. Middelkoop (2022) provides a complete overview of control methods up until 2022 and features an implementation of an EMS. This implemented EMS is innovative as it is a real-time EMS described in an article that can be combined with simulation. The main differences is in the prediction of DA prices instead of using the actual value of historic data for simulation. In the research, Mixed Integer Linear Programming (MILP) was used. In October 2022, Alzahrani et al. (2022) provided an overview of the most effective energy management strategies. There is however no unanimous correct strategy, this depends on the scenario and its parameters. A method that has been implemented in more recent researches is Model Predictive Control (MPC). These are described extensively by Sen and Kumar (2018) and Sharma et al. (2022). Besides, in these articles an overview is given of researches to EMS where MPC is used, which differ from complex to fairly simple control systems.

A lot of research has thus already been done into the implementation of the different optimisation methods and the implementation of different markets. The challenge is however to find the best fitting strategy for this scenario. The scenario includes the components available in the MES, but also the application of the electricity markets. A research with comparable components to this research is by Bartolucci et al. (2021), a Multi Energy System was designed which was controlled by an EMS. In a later research, it was attempted to increase utility of RES by using this EMS, which succeeded but was not yet made economically viable. The EMS was solved using Mixed Integer Linear Programming. A research where the DA market trading is implemented was written by van Dalen (2022). In a research by Candra et al. (2018), an extensive analysis was done on the implementation of the SPOT markets (DA and ID) in Energy Management Systems. In a research by Merten et al. (2020), a bidding strategy for a battery energy storage system on the aFRR market is proposed. As trading tactics are confidential material for companies, few information is published on the implementation of trading tactics.

5.3 Reducing CAPEX of the electrolyser

The final aspect is the low cost electrolyser. Considerable developments have been made in the past years in the cost of the electrolyser. For the application of an electrolyser, there are several factors that should be taken into consideration when deciding on an electrolyser, in order to reduce its CAPEX.

Roy et al. (2021) have done a research on a sizing optimisation of the required equipment. Morgan et al. (2013) have done a research on reduction of the CAPEX by using common equipment. These are examples how fairly simple methods could reduce the CAPEX of electrolysers.

It is necessary to base a solution on its characteristics. Batteries are clearly better of Fast Frequency Response (FFR) than electrolysers (Taibi et al., 2020). Hydrogen is better for long term storage than batteries. Parra et al. (2017) finds that only large electrolyser systems on grid scale are possible to become viable, for smaller solutions batteries should be used.
The battolyser by Mulder et al. (2017) makes use of characteristics, by a battery that generates hydrogen when fully charged with a high energy efficiency.

This battolyser does however not solve the problem when there is a constant high demand for especially green hydrogen. An possible solution that is to be researched is a low power always-on electrolyser, by combining the electrolyser with a battery for peak shaving. The battery copes with the peaks in green electricity surplus (Battery Energy Storage System (BESS), see Holstein et al. (2018)), the electrolyser runs constantly on the battery power and would therefore not have the necessity for a high maximum power. This would lower the CAPEX of the electrolyser and lower the power needed for the Balance Of the Plant, while improving the energy efficiency of the electrolysing process. The added value of an additional investment of a battery is to be researched. The conversion rates may cause difficulties in this system. This system with an electrolyser and electrochemical storage is proposed by Taibi et al. (2020), although it is mentioned that no research has yet be done on this topic.

6 Impact of proposed solutions

In the previous section, several solutions for improving the economic feasibility of hydrogen are proposed. In order to prioritize these solutions in new research, the impact and complexity of the solutions must be established. For this, the estimation of the LCOH by Deloitte (2021) is used (See Figure 9). A reduction in CAPEX has an influence on the costs for 'initial', possibly 'stacks' and lastly 'O&M', which is dependent on the initial costs. A large reduction on power costs is desired, as this attributes to the largest cost share. A reduction in power costs is done by using less electricity (thus higher efficiency or better operation) or by using cheaper electricity (trading, better algorithms, using a battery). A solution that cannot be templated in the LCOH is increasing the revenues of selling hydrogen.

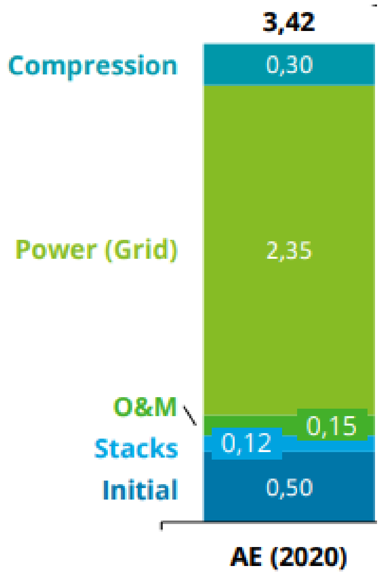

Figure 9. Estimation of Levelized Cost Of Hydrogen by production of an Alkaline electrolyser (Deloitte, 2021).

Hydrogen storage

Hydrogen storage increases the revenues of hydrogen, by producing hydrogen at times of low electricity prices and selling at times that the gas price is high. There is a Levelized Cost Of Storage (LCOS) that is added to the total LCOH. In case of storing hydrogen in salt caverns this is estimated at 1.70 €/kg (for an undefined time span) (Epelle et al., 2022). The selling prices of natural gas differ between 1.50 €/kg and 4.50 €/kg (first and third quartile). Combined with the LCOS, this accumulates to an increase of revenue of 1.30 €/kg, meaning the impact is about 38% based on the 3.42€/kg LCOH.

The complexity of this solution depends on the location of the electrolysing plant. In the case study of this literature review, this added complexity is limited, due to a storage location being nearby.

Operation

An electrolyser benefits from steady operation and higher operation temperatures, as its energy efficiency will increase. According to Escobar-Yonoff et al. (2021), this would result in an increase in energy efficiency of 5-20%. When the power costs are decreased by 5-20%, this results in a decrease of LCOH of 4-14%.

The complexity of this solution depends on the electrolyser's deployment. In combination with a battery steady operation is possible, but a battery would increase the initial costs again. Without battery this operation is more complex. The operation is determined as per the Energy Management Strategy.

Electricity markets

The correct usage of electricity markets is of the utmost importance. For economic viability of an electrolyser for green hydrogen, one can only use electricity at a low price. As the electricity prices varies considerably, depending on the market, correct application of markets is the most influential solution for feasible green hydrogen. The complexity of this solution is in the EMS and trading algorithms.

EMS algorithm

This solution is a combination of multiple (previously mentioned) solutions. The algorithm determines the operation of the electrolyser and the market trading. Effort should therefore be put into constructing the EMS algorithm, that optimises the process.

Financial aid

Making use of financial aid is, especially in the early stages, one of the most important factors for feasibility of a green electrolyser. The most important subsidy in the Netherlands for electrolysers, the SDE++ accounts for 73% of the LCOH in the first 15 years. The CO_2-tax accounts for another 25% increase of revenue for hydrogen as compared to natural gas. The financial aid is for the upcoming research however out of scope, due to parallel running researches.

Sizing optimisation

This solutions reduces the CAPEX. As stated by Roy et al. (2021); Pan et al. (2020), the expected reduction in CAPEX is a maximum of 20%. This would account for a total of less than 5% LCOH reduction. Due to the effort and complexity of this solution, it should be considered whether this is worth the added development time.

Common equipment

This solution affects the CAPEX of the electrolyser. According to Morgan et al. (2013), the expected reduction is between 25 to 60%. This accounts for a 5 to 11% reduction of LCOH. As for the complexity, it is advised to prioritize other solutions before considering these additional R&D requirements.

Combining BESS and electrolyser
Including a battery in the electrolyser system will have an influence on the costs that is associated with the electricity. Due to the dynamic capabilities of the battery, the lack of dynamic capabilities of an (Alkaline) electrolyser and the constantly varying balancing markets, a battery is more suited for balancing activities than an electrolyser. When using BESS for your electrolyser, the CAPEX of the total system will rise, along with the O&M. However, the electricity costs for hydrogen production will decrease. In combination with several assumptions made (CAPEX of the battery is 1/4 of the CAPEX of the electrolyser, reduction of 30% for electricity costs, only battery usage for the dynamic behaviour that the electrolyser does not have), this results in a reduction of 15%. However, simulation must demonstrate the actual savings that could be made. The complexity of this solution is again in the EMS, as in the current development of micro grids batteries are often already included besides an electrolyser.

7 Conclusion

Green hydrogen is the medium that must make the high heat industry sustainable, whilst coping with the volatility of RES. With the originally envisioned purpose of green hydrogen, as electrochemical battery in combination with a fuel cell, green hydrogen is very difficult to become economically feasible. A lot of research is done to improving the performance of the electrolysers as asset, yet improving economic feasibility through correct implementation in a RES microgrid has received almost no attention. The main factors for economic viability have been explained: abundance of green energy, low-cost electricity and a low-cost electrolyser.

These are all non-influenceable factors for a company that wants to implement an electrolyser. Hence, the three factors have been rewritten to goals, for which short-term solutions have been found. The goals and short-term solutions are displayed in Table 3.

The expected impact and complexity of the solutions have been assessed. The main conclusions are the importance of a satisfactory EMS algorithm, the electricity market trading strategy, making use of financial aid, and the application of hydrogen storage. In future research the short-term solutions should be simulated, to assess whether these make a significant and beneficial difference to the economic viability of green hydrogen.

The EMS is the integral solution, in what most other solutions are combined. The EMS communicates with the assets, trades on the electricity markets and optimizes these steps. A suitable EMS strategy is therefore of utmost importance.

Table 3. *Overview of goals for establishing the economic viability of green hydrogen and their short-term, influenceable solutions.*

Goals	**Solutions**
Decoupling the gas and electricity pricing	- Hydrogen storage
Decreasing electricity costs in the LCOH	- Correct operation of the electrolysers - Using the correct electricity market strategy for trading - Making use of the financial aid that is available - Having a good energy management strategy
Reducing the CAPEX of electrolysers	- Using a sizing optimisation - Using common equipment - Running tests on a low power always-on electrolyser in combination with a battery

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C | State optimisation

Introduction

This appendix describes the day ahead state optimisation of the electrolyser. More specifically: the state of the electrolyser is decided for the whole day, based on the day ahead clearance prices. This optimisation is thus run every day, at 13:00, after the hourly clearance prices of the day ahead are made public. The electrolyser is not fast enough to respond on the day ahead prices when the electrolyser is turned off. Furthermore, costs are involved for starting up and stopping. A relation of low price equals on and high price equals off is thus too simplistic.

The day ahead price is an estimation of the imbalance price: the hourly average is roughly equal to the hourly clearance price of the day ahead. As the day ahead price is already known, and the imbalance prices are only published after the ISP is done, using the day ahead prices is the best option for the state optimisation.

The following sections are subdivided into the Objective function, Indices and sets and Constraints. The indices and sets are only used for time units (time steps).

Parameters

Table C.1. *Parameters used in the day ahead state optimisation*

Parameter	**Description**
c_t^{DA}	Costs of electricity, based on the day ahead market [€/ kWh]
c_t^{H2}	Hydrogen price [€/kWh], based on the gas price. Constant for the day.
$c^{lifecycle}$	Cost of usage of electrolyser [€/min]
$P^{Maximum}$	Maximum power of the electrolyser [kW]
$P^{Minimum}$	Minimum power for production of the electrolyser [kw]
efficiency	Efficiency of the electrolyser [-]
starting_losses	Losses that occur in the second phase of start-up, additionally to standard production losses [kW]
last_state_of_day	Last state of the day before [on/off]
last_power_of_day	Last power of the day before [kW]
startup_time	Time needed for the electrolyser to start-up from off state [min]
startup_without_prod	Time in the first phase of start-up [min]
stop_time	Time needed to turn off the electrolyser [min]

Decision Variables

Table C.2. *Decision variables in the day ahead state optimisation*

Variable	Category	Description
$gridofftake_t$	Continuous variable	The total electricity consumption from the grid in minute t [kWh]
$H2Production_t$	Continuous variable	The total hydrogen production in minute t [kWh]
$P_t^{electrolyser}$	Continuous variable	The power level of the electrolyser in minute t [kW]
$state_t$	Binary variable	Equals 1 when the electrolyser is on, equals 0 when turned off.
$start\_state_t$	Binary variable	Equals 1 when the electrolyser is starting up, equals 0 when the electrolyser is not starting up
$start\_moment_t$	Binary variable	Equals 1 when t is the first moment of the start up stage
$start\_state\_phase1_t$	Binary variable	Equals 1 when the electrolyser is in the first phase of starting up
$stop\_state_t$	Binary variable	Equals 1 when the electrolyser is in the stopping stage
$stop\_moment_t$	Binary variable	Equals 1 when t is the first moment of the stopping stage

Objective function

$$MINIMISE \qquad \sum_{t\in T}(-H2production_t * c_t^{H2} + gridofftake_t * c_t^{DA} + c^{lifecycle} * state_t) \tag{C.1}$$

The goal of the optimisation is to maximise the revenues of selling hydrogen, minus the electricity costs and life cycle costs. In this research, the life cycle is assumed 0 €/min, meaning that this part is unused. The optimisation objective is altered to fit the Minimise standard of the optimiser.

Indices and sets

In this problem, indices t, k, g, j are used, these are displayed in Table C.3. The indices are used in sets, the values of the sets are displayed in Table C.4.

Table C.3. *Indices used in the day ahead state optimisation*

Index	Description	Set
t	Minutes in the optimisation	$t \in T, S1, S2, R1, R2, R3, R4$
k	Minute of start-up time	$k \in K$
j	Minute of the first phase of the start-up time	$j \in J$
g	Minute of the stop time	$g \in G$

Table C.4. *Sets used in the day ahead state optimisation*

Sets
T is the default set for t: T = {0,1, ..., 1440}
S is used when the last values of the set T have been changed: S1 = {0,1, ..., 1440 - startup_time, 1440 - startup_time + 1} S2 = {0,1, ..., 1440 - stop_time, 1440 - stop_time + 1}
R is used when the first values of the set T have been changed: R1 = {1,2, ..., 1440} R2 = {startup_time, startup_time + 1, ..., 1440} R3 = {stop_time, stop_time + 1, ..., 1440} R4 = {1440 - startup_time, 1440 - startup_time + 1, ..., 1440}
Sets for the start-up and stop times: K = {0, 1, ..., startup_time - 1, startup_time} J = {0, 1, ..., startup_without_prod - 1, startup_without_prod} G = {0, 1, ..., stop_time - 1, stop_time}

Constraints

C.2-C.4. Nonnegativity contstraints. These are incorporated in the initialisation of the variables.

$$gridofftake_t \geq 0 \qquad \forall t \in T \tag{C.2}$$

$$H2Production_t \geq 0 \qquad \forall t \in T \tag{C.3}$$

$$P^{electrolyser} \geq 0 \qquad \forall t \in T \tag{C.4}$$

Grid offtake constraints

C.5-C.6. Constraints on and definition of the grid offtake: kW to kWh that is consumed every minute. Grid offtake cannot be higher than what the electrolyser can maximally consume every minute (C.5), and it is equal to the electricity that the electrolyser consumes in a minute (C.6).

$$gridofftake_t \leq P^{maximum}/60 \qquad \forall t \in T \tag{C.5}$$

$$gridofftake_t = P^{electrolyser}/60 \qquad \forall t \in T \tag{C.6}$$

Hydrogen production constraints

C.7-C.9. Constraints on and definition of the hydrogen production: Conversion of consumed power [kW] to produced hydrogen [kWh]. If the electrolyser is in start state phase 1, no hydrogen can be produced (C.8). If the electrolyser is in start state (in phase 2, but as the constraints pick the largest value for hydrogen production due to the objective, it is automatically phase 2, if the electrolyser is not in phase 1) there is a certain hydrogen production with reduced efficiency (starting losses) (C.9).

$$H2Production_t \leq P^{Maximum}/60 * efficiency \qquad \forall t \in T \tag{C.7}$$

$$H2Production_t \leq (1 - start\_state\_phase1_t) * M^{start} \qquad \forall t \in T \tag{C.8}$$

$$H2Production_t \leq efficiency * P_t^{electrolyser}/60 - (start\_state * starting\_losses)/60 \qquad \forall t \in T \tag{C.9}$$

State constraints

C.10-C.13. These constraints control the start and stop moments and the state of the electrolyser.

C.10 determines the state of the electrolyser at the start of the day, this is equal to the state of the last day. C.11 makes the connection between the state and the starting and stopping stages of the electrolyser. C.12 makes sure that the electrolyser cannot be starting up and stopping at the same time, C.13 ensures that the start and stop moment cannot happen at the same time.

$$state_0 = last\_state\_of\_day \tag{C.10}$$

$$start\_moment_t - stop\_moment_t = state_t + state_{t-1} \qquad \forall t \in R1 \tag{C.11}$$

$$start\_state_t + stop\_state_t \leq 1 \qquad \forall t \in T \tag{C.12}$$

$$start\_moment_t + stop\_moment_t \leq 1 \qquad \forall t \in T \tag{C.13}$$

Power constraints

C.14-C.15. These constraints control the power of the electrolyser at the start of the day, this is equal to the last power level of the day before.

$$P_0^{electrolyser} - last\_power\_of\_day \leq P\_ramp\_up * state_0 \tag{C.14}$$

$$P_0^{electrolyser} - last\_power\_of\_day \geq -P\_ramp\_down * state_0 \tag{C.15}$$

C.16-C.18. These constraints control the power of the electrolyser for the rest of the day. The power levels cannot make bigger steps than the ramp rates allow. C.18 constraints that the electrolyser cannot consume electricity when it is turned off.

$$P_t^{electrolyser} - P_{t-1}^{electrolyser} \leq P\_ramp\_up * state_t \qquad \forall t \in R1 \tag{C.16}$$

$$P_t^{electrolyser} - P_{t-1}^{electrolyser} \geq P\_ramp\_down * state_t \qquad \forall t \in R1 \tag{C.17}$$

$$P_t^{electrolyser} \leq P^{maximum} * state_t \qquad \forall t \in R1 \tag{C.18}$$

C.19-C.20. In these constraints, the power level of the electrolyser is determined when the electrolyser is in start_state, namely $P^{minimum}$.

$$-M * (1 - start\_state_t \leq P_t^{electrolyser} - P^{minimum} \qquad \forall t \in T \tag{C.19}$$

$$M * (1 - start\_state_t \geq P_t^{electrolyser} - P^{minimum} \qquad \forall t \in T \tag{C.20}$$

State transition constraints

C.21-C.23. In the following constraints, the connection between the start state and the start moment is made. C.21 ensures that start_state is equal to 1 when the start_moment has happened in the past amount of minutes that the electrolyser needs for start-up. C.22 regulates that for the entire start-up time, the start_state is filled with ones when the start happens in the last few minutes of the day. C.23 ensures that the start_state cannot be 1 when no start_moment has happened in the past amount of minutes that the electrolyser needs for start-up.

$$\sum_{k \in K} start\_state_{t+k} \geq startup\_time - M * (1 - start\_moment_t) \qquad \forall t \in S1 \tag{C.21}$$

$$\sum_{k \in K} start\_state_{t+k} = start\_moment_t * (startup\_time - t) \qquad \forall t \in R4 \tag{C.22}$$

$$\sum_{k \in K} start\_moment_{t-k} * M \geq start\_state_t \qquad \forall t \in R2 \tag{C.23}$$

C.24-C.26. These constraints make the connection between start state phase1 and start moment. The constraints are analogue to C.21-C.23.

$$\sum_{j \in J} start\_state\_phase1_{t+j} \geq startup\_without\_prod - M * (1 - start\_moment_t) \qquad \forall t \in S1 \quad \text{(C.24)}$$

$$\sum_{j \in J} startstate\_phase1_{t+j} = start\_moment_t * (startup\_without\_prod - t) \qquad \forall t \in R4 \quad \text{(C.25)}$$

$$\sum_{j \in J} start\_moment_{t-j} * M \geq start\_state\_phase1_t \qquad \forall t \in R2 \quad \text{(C.26)}$$

C.27-C.28. These constraints make the connection between the stop state and stop moment. C.27 is analog to C.21, C.28 is analog to C.23.

$$\sum_{g \in G} stop\_state_{t+g} \geq stop\_time - M * (1 - stop\_moment_t) \qquad \forall t \in S2 \quad \text{(C.27)}$$

$$\sum_{g \in G} stop\_moment_{t-g} * M \geq stop\_state_t \qquad \forall t \in R3 \quad \text{(C.28)}$$

Additional Constraint for DA-bidding

C.29. When the electrolyser can use day ahead capacity, it has to be ensured that the electrolyser is turned on when the capacity is available.

$$state_t * M \geq DA\_won\_capacity_t \qquad \forall t \in R_1 \quad \text{(C.29)}$$

D | Specifications of the system

D.1 Parameter specification of electrolyser

Figure D.2 shows the power levels of the electrolyser during startup. The parameters of Table D.1 related to the startup are explained in Figure D.2. Figure D.1 explains the different power levels of an electrolyser.

Table D.1. *Parameter values of the electrolyser*

Parameter	Value	Unit
Maximum power	20000	kW
Standby power	150	kW
Minimum power	4000	kw
efficiency	60	%
Start up time	50	minutes
Start up power	4000	kW
Start up time first phase	20	minutes
Start up time second phase	30	minutes
Start up losses	200	kW
Stop time	10	minutes
Stop power	150	kW
Ramp up rate	30	%/minute
Ramp down rate	15	%/minute
Life cycle costs	0	€/minute

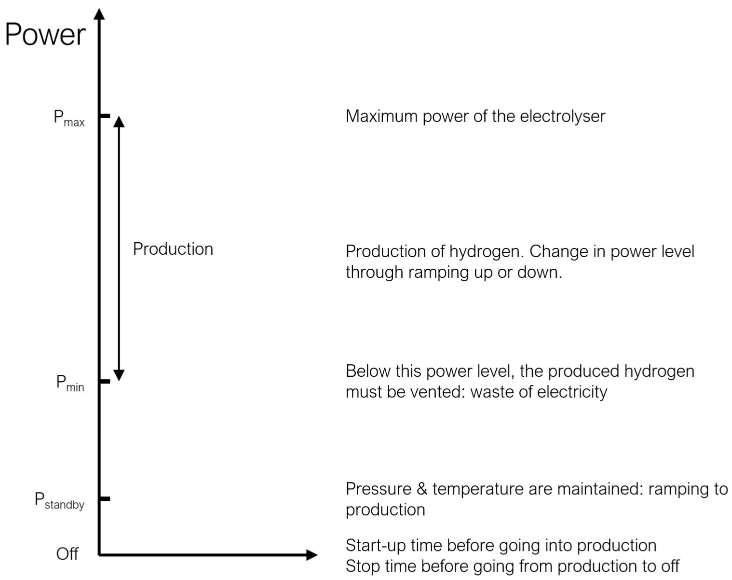

Figure D.1. Different power levels that are possible in an electrolyser. The text on the right side explains the meaning for the electrolyser for the production of hydrogen.

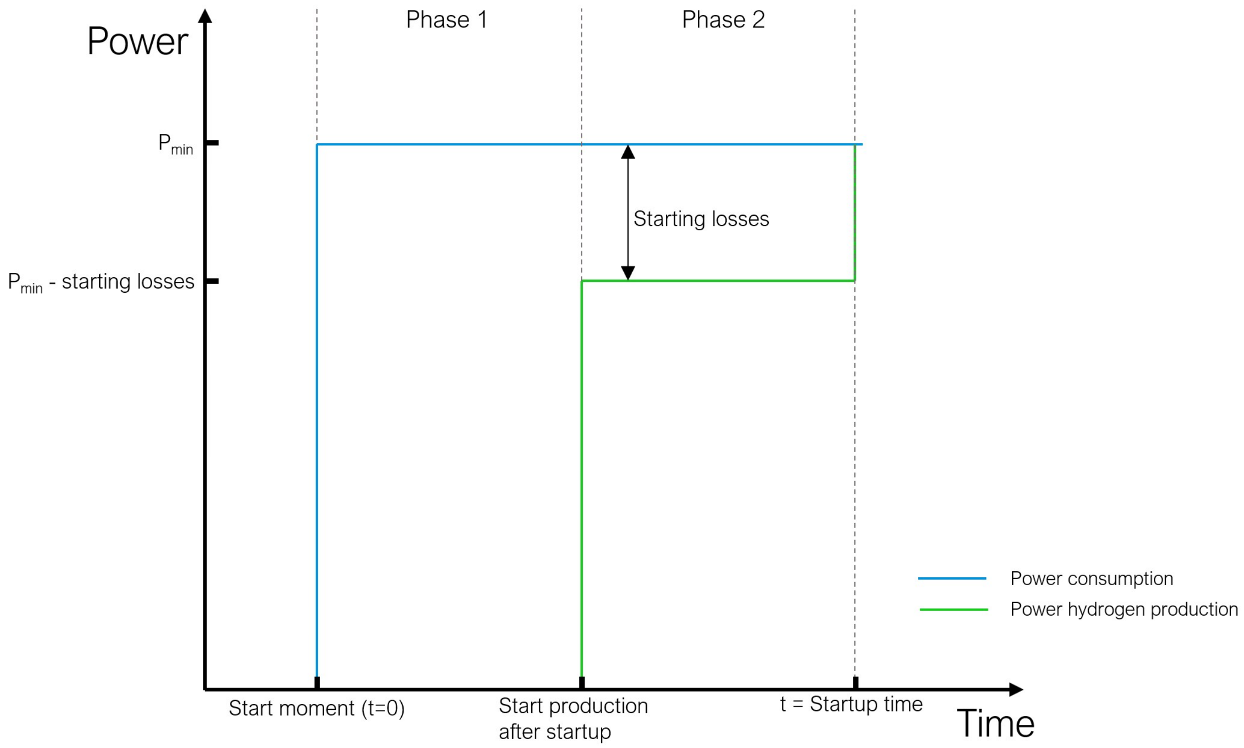

Figure D.2. Graph that shows the power of the electrolyser during startup. The power consumption of the electrolyser is equal to the minimum power of the electrolyser for the duration of startup. In the first phase of startup, no power is used for the production of hydrogen. In the second phase, a reduced power level is used for the production of hydrogen.

D.2 Parameter specification of hydrogen storage

Table D.2. *Parameter values of the hydrogen storage*

Parameter	Value	Unit
Electricity bid based on top _ of hydrogen price in the year	25	%
Storage cost sim1	1.00	€/kg
Storage cost sim2	2.00	€/kg
Storage cost sim3	3.00	€/kg

D.3 Parameter specification of BESS

In the first simulation, the grid connection and allocation point have a technical limit of 40000kW for offtake and feedin. This means that the electrolyser and battery can offtake at full power at the same time.

In the second simulation, the grid connection and allocation point have a technical limit of 20000kW for offtake and feedin. This means that the battery and electrolyser cannot offtake at full power at the same time.

Table D.3. *Parameter values of the first BESS simulation*

Parameter	Value	Unit
Maximum power	20000	kW
Maximum capacity	20000	kWh
Charge efficiency	94	%
Discharge efficiency	94	%
Maximum State Of Charge	90	%
Minimum State Of Charge	10	%
Life time cycles	3650	[-]
Battery CAPEX	14	M€

Table D.4. *Parameter values of the second BESS simulation*

Parameter	Value	Unit
Maximum power	10000	kW
Maximum capacity	10000	kWh
Charge efficiency	94	%
Discharge efficiency	94	%
Maximum State Of Charge	90	%
Minimum State Of Charge	10	%
Life time cycles	3650	[-]
Battery CAPEX	7	M€

E | Verification and Validation

In this appendix, the verification and validation of the electrolyser model and EMS is shown. Verification must ensure that the implementation of the model is done correctly (”Is the model right?”). Validation confirms the coherence with the real-life application of the physical model and that the EMS fulfils its intended goal (”Is it the right model?”). During development, the model and EMS were extensively verified by unittests, visualisations and special input testing. Furthermore, several principles for development were taken into account to avoid errors, such as modular programming, top-down approach, debugging and intermediate simulation outputs (as described by Kleijnen (1995) and Sargent (2010)).

Several verification and validation methods will be explained and displayed in this section. This must convince beyond reasonable doubt of the correctness of the system. The verification and validation methods that are used are more extensively explained by Sargent (2010); Roungas, Meijer, and Verbraeck (2018).

Visualisation

One of the most important verification methods that were utilised is visualisation. For all 39 simulations, 25 graphs were plotted and visually checked for their coherence with what is expected. The behaviour of the EMS and electrolyser must become clear for all simulations made.

In Figure E.1, an example of such a graph is displayed. This graph is a product of the configuration where 40% of the maximum electrolyser power is bid on the day ahead market and shows the result of 2 January 2021. A lot can be discovered from this graph. The day ahead power (dark blue line in the bottom graph) conforms to the price comparison of the day ahead and hydrogen in the top graph: where the electricity price (dark blue line in the top graph) is higher than the electricity valuation for hydrogen production (green line in the top graph), no day ahead power is available. The electricity valuation is the price that the electrolyser is willing to pay for electricity. Furthermore, in the first 9 hours of the day, the imbalance price is low relative to the electricity valuation (visible in the second graph). In those hours, the imbalance power is equal to the other 60% of the maximum electrolyser power, meaning the electrolyser is running at full power. Even for small deviations such as the small peak in imbalance price at 1.00, the result is visible in the offtake power and electrolyser power, where a small dip is visible. Another phenomenon is visible between 16.00 and 21.00, where no day ahead power is available. The imbalance prices fluctuate around the electricity valuation, meaning that at times hydrogen is produced. The peaks in electricity price exactly conform to the dips in electrolyser power.

Another visualisation is that of the state optimisation. An example is given in Figure E.2. As can be seen, for the hours that the day ahead price is lower than the electrolyser is willing to pay for electricity, the electrolyser is turned on. However, several minutes past 12.00, the electrolyser is already turned on as well. This can be explained by the startup time of the electrolyser: more money is made by starting up the electrolyser earlier, so hydrogen can be produced at times of low electricity prices. In this case, the startup time of the electrolyser is 50 minutes. In the output data, it can be seen that the electrolyser is turned on at 12.10, which would mean that the electrolyser can produce at full power at exactly 13.00. The behaviour of the state optimisation can therefore be explained by the characteristics of the system.

In the previous plots, the behaviour of the electrolyser was tested on a day-to-day level. In Figure E.3 the behaviour of the electrolyser over a full year is displayed in a heatmap. This heatmap is based on the same case as that of Figure E.1 and Figure E.2, so the configuration with 40% day ahead bids in 2021. The colour in the heatmap (right graph) represents the amount of hydrogen that is produced in that hour for the whole week. In the left graph, the comparison of the day ahead electricity price is compared to the valuation of electricity. At times when this valuation is higher than the electricity price, one can see in the right plat that a lot of hydrogen is produced. Later in the year, when the electricity price is higher, a lot less hydrogen is produced. The exception in this case is for two dips in the electricity price in October and December, which is also visible in the heatmap.

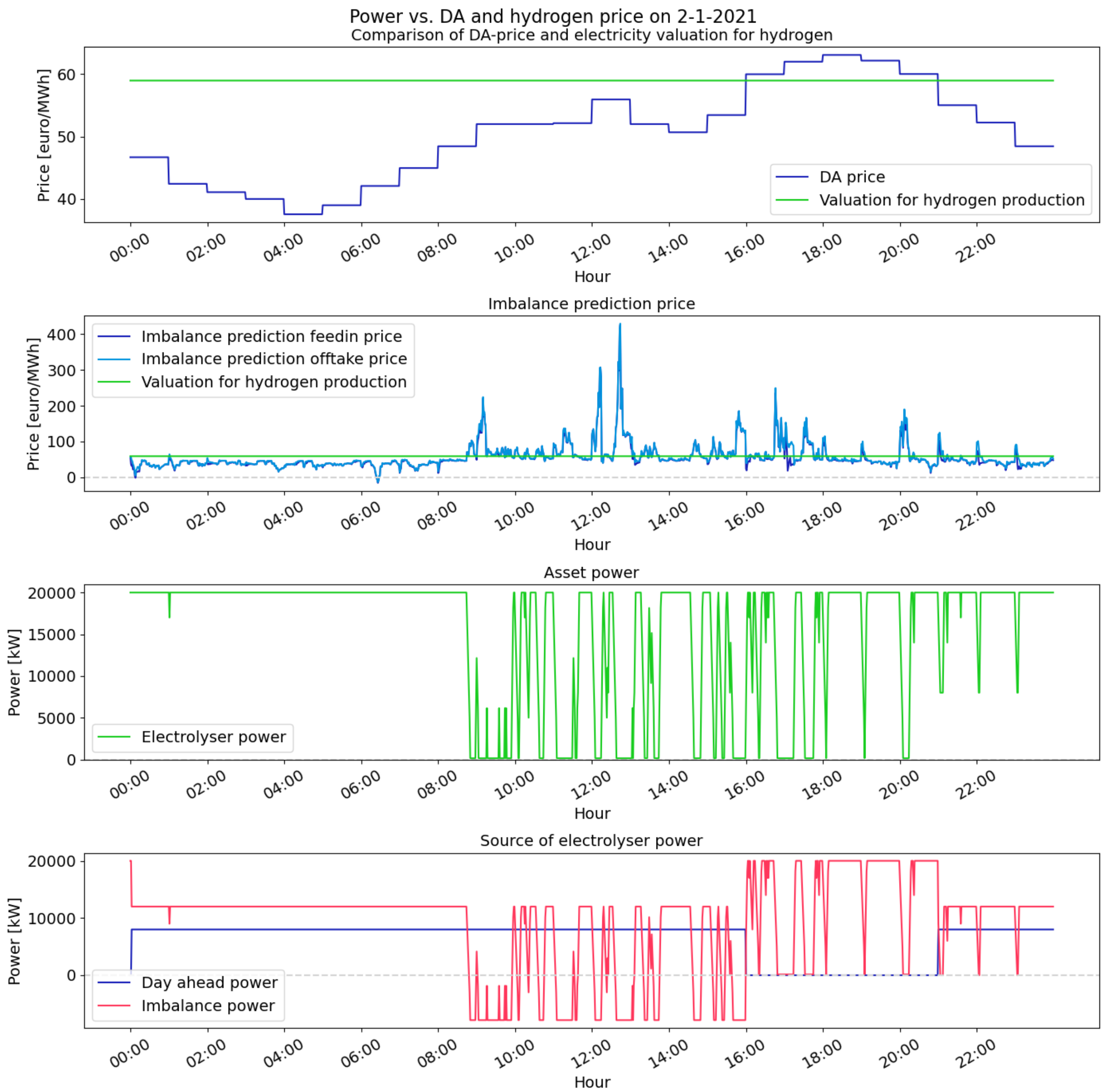

Figure E.1. Overview of electricity and hydrogen prices, compared with the power that is offtaken and assigned to the electrolyser.

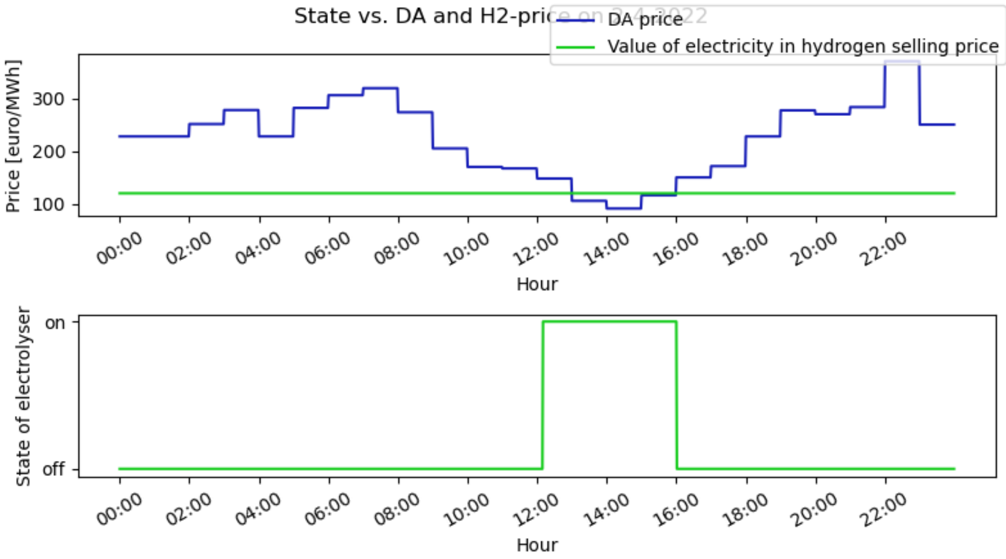

Figure E.2. State optimisation of the electrolyser for 2 April 2022, based on the day ahead price.

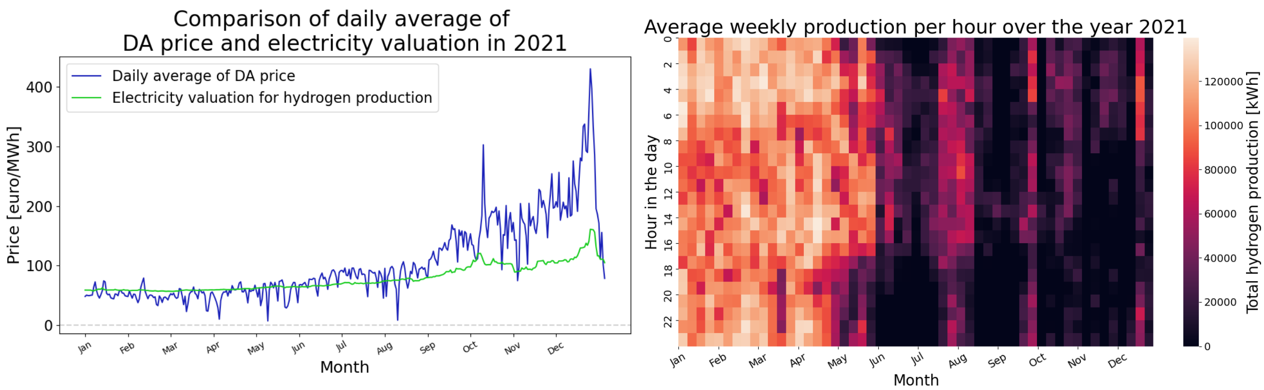

Figure E.3. (left) Comparison of the daily average price of electricity and the price that the electrolyser is willing to pay for the electricity. (right) Heatmap of the produced hydrogen per week in the year and per hour in the day.

Balance checks

In the balance check, the flow conservation over the input and output is established. In the case of the EMS, there must be a conservation of energy. This is in fact a constraint in the optimiser in the EMS. For every simulation (apart from the simulation with BESS), the energy that is offtaken from the grid is compared to the energy that is utilised by the electrolyser. These values must be equal. The produced hydrogen cannot be equalised to these values, due to the conversion losses and startup/stop/standby power, which are considered losses as well.

Example: for the imbalance-only strategy of 2020, the total amount of energy offtaken from the grid is 150135090 kWh, and the electrolyser utilises 150135090 kWh.

Product testing

Product testing assesses whether all specified requirements are satisfied. For the electrolyser model, this mainly includes the power levels and ramp rates. For the rest of the system, the power levels should be according to the capacity (e.g. the grid capacity).

For all simulations, the maximum power of the electrolyser is tested to be 20000kW, there is no negative consumption of power by the electrolyser, and there is no power level between the standby power and minimum power for production by the electrolyser (as such a power level would produce a dangerous mixture of hydrogen and oxygen, all produce is vented, meaning a waste of energy), as clarified in Figure D.1. Additionally, the physical model of the electrolyser has defined constraints to prevent such occurrences. The requirements for the EMS are defined in constraints in the optimiser. The ramp rates are tested by manually checking data, as well as visualisation (see Section Visualisation).

Special input testing

For special input testing, input values are changed to values for which the results can be predicted. The prediction is then compared to the output of the simulations.

An example of this is when the electrolyser is turned off (state optimisation is turned off and state is set to OFF). The expectation is that no hydrogen is produced, as well as no electricity offtaken from the grid. For all three simulation years, this hypothesis was found to be true.

Another test is when the state optimisation is off, the electrolyser is always turned on, and the electricity prices (imbalance prices, no day ahead is used) are set to high (1000€/MWh). The hypothesis is that no hydrogen is produced, but that still electricity is used for the standby mode. Again, for the three simulation years, this hypothesis was confirmed. With **hand calculations** the amount of electricity used is established and verified with the simulation. As the standby power is 150kW, and the electrolyser was already turned on at the start of the year, the electrolyser is consuming 1.31 GWh of electricity. Simulations confirmed this value.

A third test is for a case in which the state optimisation is on and the electricity prices are set to low (1€/MWh). The hypothesis is that the electrolyser is always producing. For this test the hypothesis was true, the electrolyser produced at full power the whole year, for all three years.

For the next test, the standby power was set to 0 kW. The hypothesis is that the electrolyser will never turn off, but will remain in standby mode when not producing. This hypothesis was found to be true: at the start of the year, the electrolyser turns on and does not turn off again.

A last test for verification was for having high startup costs and for a long startup time, whilst having only a phase 1 of startup (so no phase 2, meaning no hydrogen production during startup, see Appendix D). The hypothesis is that for a startup cost of 20000 kW during 12.5 hours, it would never be financially attractive to turn on the electrolyser. This hypothesis was confirmed by the simulations. It shows one of the flaws of the electrolyser model: for 2020 - a year with a high amount of full power hours - it could be worth it to start up the electrolyser once, after which the electrolyser could run for multiple days. But as the state optimisation can only optimise one day at a time, the beneficial electricity prices of the next day have no influence.

The Energy Management System is in previous research extensively tested and verified by the usage of a battery.

As mentioned, validation must show if the model is a good representation of the real system and if the model is serving its intended purpose. As a lot of data for implemented electrolyser is kept private, it is difficult to validate the accuracy of the representation of the model.

For the simulations, historic data on electricity prices (imbalance and day ahead market) were used for the years 2020, 2021 and 2022. In these years large events happened that influenced the electricity pricing (COVID-19 and the Ukrainian-Russian war with the embargo on Russian oil and natural gas). It is therefore questionable whether these years are representative for years to come. However, the opposite is also true: it is questionable whether a perfect year without events would result in more representative simulation data. It is difficult to predict future gas and electricity prices, especially due to such external influences, meaning that historic data is the best option for viability tests.

From the results, it can be assured to a high degree that the physical model of the electrolyser can correctly be used for simulations. Verifying the electrolyser parameters with manufacturers would increase the credibility of the simulations that were executed, these parameters currently increase the uncertainty of the system.