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Industrial Engineering and Management

Financial Engineering and Managment

Determining a fitting hydrogen strategy for Pure Energie

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May 8, 2023

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ABSTRACT

Combating global warming is one of the major concerns of our time. It is important to reduce greenhouse gas (GHG) emissions in all industries and social groups. The switch from traditional energy systems, which rely on fossil fuels and produce GHG pollution, to sustainable energy systems that produce GHG at a lower rate is a crucial step in reducing GHG emissions. It is assumed that hydrogen can play an important role in the energy transition. This is also recognised by Pure Energie. As a producer and supplier of sustainable energy, Pure Energie is actively working to reduce greenhouse gas emissions and accelerate the energy transition.

This thesis explores the feasibility of green hydrogen production for Pure Energie. With a focus on wind farms and solar farms, Pure Energie aims to transition to a low-carbon economy by investing in hydrogen as a key player in the clean energy sector. The thesis examines the parameters necessary for a viable business case, considering the company's renewable energy portfolio and the selection of windplan Groen as the optimal location for hydrogen expansion.

By analyzing different system setups and conducting sensitivity analyses, the study reveals that the project's success hinges on factors such as electricity and hydrogen prices rather than geographical positioning. Moreover, the research suggests that placing the electrolyser near areas with high grid congestion could create additional income streams. The importance of Power Purchase Agreements (PPAs) or fixed energy contracts is highlighted, emphasizing the need for stable pricing to mitigate risks. Comparisons between hydrogen and natural gas prices demonstrate that while hydrogen may not be cost-competitive, its renewable and green nature can appeal to companies seeking to reduce their environmental footprint. Additionally, the thesis explores how the electrolyser can be used to hedge risk for new wind turbines through long-term fixed energy contracts. This strategy helps mitigate market price fluctuations and reduces portfolio risk for Pure Energie. Overall, this thesis presents a compelling case for the feasibility of green hydrogen production, showcasing the potential market opportunities and the benefits it brings to Pure Energie's sustainability goals and portfolio diversification.

MANAGEMENT SUMMARY

In order to facilitate the generation of clean and sustainable energy, this thesis investigates the viability of combining wind energy and hydrogen electrolysis. The objective is to evaluate Pure Energie's potential for hydrogen electrolysis investment and portfolio diversification. Pure Energie is a prominent provider of renewable energy in the Netherlands. Pure Energie seeks to aid in the shift to a sustainable future by utilizing the resilience and adaptability of hydrogen as an energy source.

The importance of hydrogen as a clean energy source and its prospective uses in sectors like high-heat steel and glass manufacture are highlighted at the outset of the thesis. Exploring hydrogen electrolysis as a potential strategic investment is motivated by Pure Energie's commitment to sustainability.

The current condition of hydrogen production and the function of electrolysis are explored through a thorough literature review. The advantages of using wind energy for electrolysis are underlined, including the fact that it is renewable. However, difficulties brought on by the erratic availability of wind energy are also recognised. Although little data is available at this time because commercial hydrogen electrolysis projects are still under development, potential revenue models for hydrogen fuel sales and market competitiveness are investigated.

The methodology employed in this thesis includes assessing electrolysis technologies, engaging in interviews with electrolyser manufacturers, and conducting business case calculations. The preferred technology, PEM electrolysis, is found to be suitable for integrating with renewable energy assets due to its flexibility in handling fluctuating energy inputs.

The business case calculations focus on geographical positioning, grid connectivity, and operating costs. Three scenarios are analyzed, considering direct grid connection, a combination of grid and wind turbine power inputs, and exclusive reliance on wind energy. Sensitivity analyses highlight the importance of electricity and hydrogen prices, while indicating the potential for leveraging grid congestion as a revenue source.

In conclusion, the thesis reveals that investing in hydrogen electrolysis powered by wind energy is a financially viable option for Pure Energie. By strategically integrating hydrogen production with existing wind energy assets, the company can unlock new revenue streams and mitigate portfolio risk. The findings underscore the need for Power Purchase Agreements or fixed energy contracts to ensure long-term stability. This research recommends that Pure Energie explores the opportunities presented by hydrogen electrolysis and considers collaborations with industry stakeholders and policymakers to accelerate the adoption of hydrogen as a clean energy solution. The thesis sets the stage for further research and development in this promising field, demonstrating the potential for a sustainable and decarbonized energy system.

ACKNOWLEDGEMENTS

I would like to take this opportunity to express my deepest gratitude to all those who have supported and inspired me throughout my academic journey in the field of Industrial Engineering and Management with a specialisation in Financial Engineering and Management.

First and foremost, I am immensely grateful to Mr. Bruggink, my supervisor from the University of Twente. His guidance, expertise, and support have been instrumental in shaping this thesis. His insightful feedback and constructive criticism have challenged me to push the boundaries of my knowledge and abilities. I am truly fortunate to have had the opportunity to work under his mentorship.

I would also like to extend my sincere appreciation to Mr. Boeve, my supervisor from Pure Energie. His industry expertise, valuable insights, and continuous encouragement have played a crucial role in the successful completion of this thesis. I am grateful for his guidance and the opportunity to collaborate with Pure Energie, a company that truly embodies sustainability and innovation.

Furthermore, I would like to acknowledge the faculty members and staff of the Industrial Engineering and Management department at the University of Twente. Their dedication to education and commitment to fostering a stimulating learning environment have greatly contributed to my personal and academic growth. I am grateful for the knowledge and skills I have acquired throughout my studies, which have laid a strong foundation for my future endeavors.

Lastly, I would like to express my deepest gratitude to my family for their unwavering love, encouragement, and belief in my abilities. Their constant support and understanding have been my pillars of strength, enabling me to overcome obstacles and pursue my academic goals with determination.

This thesis is a culmination of the collective efforts, guidance, and inspiration from all those mentioned above, as well as the countless others who have contributed to my growth as a student and individual. I am truly grateful for their presence in my life, and I will carry the lessons learned and memories made throughout this academic journey with me as I embark on new adventures in the future.

Thank you all from the bottom of my heart.

Thomas W. Bos

Haaskbergen, 8 may, 2023

CONTENTS

List of Figures

1 INTRODUCTION

Hydrogen has been identified as a promising clean energy carrier due to its high energy density and versatility. It can be produced through a variety of methods, including electrolysis, which involves the splitting of water molecules into hydrogen and oxygen using an electric current. One potential source of electricity for electrolysis is wind energy, which is a renewable and plentiful resource. Pure Energie is a renewable energy company that is dedicated to providing clean, sustainable energy solutions to its customers. The company has a diverse portfolio of renewable energy sources, including wind and solar, and is constantly working to expand and improve its offerings. Whether it is through the development of new technologies or the implementation of innovative projects, Pure Energie is committed to driving the transition to a more sustainable future. Therefore, Pure Energie wishes to investigate the opportunities of extending its portfolio with hydrogen elektrolysers, since it is believed to be part of the solution towards a sustainable future.

In this report, we will research the possibilities of using hydrogen electrolysers in combination with wind energy. We will begin by reviewing the current state of hydrogen production and the potential for electrolysis to play a role in this process. Next, we will examine the benefits and challenges of using wind energy to power electrolysis. One of the potential revenue models is the sale of hydrogen fuel to consumers or to other industries. This could include the sale of hydrogen for use in fuel cell vehicles, as well as for use in stationary fuel cell systems for electricity generation. The price of hydrogen fuel would need to be competitive with other energy sources, such as gasoline or natural gas. A combination of revenue streams could be utilized, along with potential government subsidies or carbon credits. It is essential to carefully assess the costs and potential revenue streams in order to determine the financial feasibility of combining a hydrogen electrolysis and wind energy system.

Finally, we will explore the potential for integrating hydrogen electrolysis with wind energy systems in various applications, including electricity generation and transportation.
Overall, this report aims to provide a comprehensive overview of the potential for using hydrogen electrolysers in combination with wind energy and to identify key areas for further research and development.
In terms of a business case, hydrogen produced through electrolysis powered by wind energy has the potential to be a financially viable option. There are several potential revenue models that could be employed in this scenario.

2 RESEARCH SETUP

Hydrogen accounts for less than 2% of current energy use in Europe and is mostly used in the production of chemical products such as plastics and fertilizers. Natural gas generates 96% of hydrogen, resulting in significant CO2 emissions. Renewable hydrogen is produced using electrolysis, which involves splitting water into hydrogen and oxygen using renewable power. It will be critical in decarbonizing industries when other options (e.g. battery systems) are either impractical or too expensive. It has the potential to replace fossil-based hydrogen in transportation and industrial operations, as well as to launch new industrial goods such as green fertilizers and steel. Pure Energie is a Dutch company that focuses on the production of renewable energy. By investing in large wind and solar farms, Pure Energie is contributing towards a more sustainable energy grid. Since (green) hydrogen is seen as one of the key factors in the energy transition, this research will focus on the possible hydrogen strategies for Pure Energie. To see whether hydrogen could be an interesting addition to Pure Energie's portfolio, we are looking at several possibilities that the strategic addition of hydrogen could offer. Determining a useful strategy that fits the profile of Pure Energie must take various aspects into account. One of these is that, in addition to being ecologically profitable, an investment in hydrogen must also be economically profitable. Sustainable energy does not only cover the ecological and renewable aspect, but must also have an economically sustainable character. The combination of aspects can determine whether it is interesting for Pure Energie to add hydrogen to its portfolio.

2.1 Problem context

In the Netherlands, the present energy mix consists of around 20% electricity and 80% natural gas or liquid fossil fuels (petrol, diesel). Climate objectives set by the Netherlands and the EU will significantly alter the situation in the near future. Wind and solar power will generate an increasing percentage of electricity. A viable electrical solution is still absent for a variety of applications such as heavy transport, high-temperature operations in industry, and aviation, and there is still a need for a sustainable gas. Hydrogen can be advantageous in this situation. Furthermore, hydrogen is crucial for large-scale storage under windless and gloomy conditions. Due to the (still) limited amount of applications for hydrogen, investors and governments are reluctant when it comes to investing on large scale in hydrogen plants or related systems. Hydrogen is currently significantly more expensive compared to other types of fuels and incentives to use hydrogen rather than ecological, are also often not outweighing these higher costs. For investors to commit to these hydrogen systems, it is required to have a certain level of security that a significant return on investment (ROI) is obtained.

To increase incentives to invest in hydrogen, the European Union released the REPowerEU plan in may 2022 [European Commission, 2022]. In this report the European Commission states that the transition from a fossil fuels to renewable energy sources have two significant effects. One of these effects is that by transforming Europe's energy system, the EU's dependence on

Russian fossil fuels is reduced [European Commission, 2022]. By doing so, the EU becomes less economically and politically dependent on Russia. The second effect is tackling the current climate crisis. Hydrogen is one of the key factors to facilitate the REPowerEU plan. As stated in the report, the goal is to produce 10 million tonnes of renewable hydrogen in the EU by 2030. To support REPowerEU, €225 billion is alread available in loans under the Recovery and Resilience Facility(RRF). Under Multiannual Financial Framework(MFF), projects that lead to decarbonisation, and green energy transition projects can also apply for support with a total of €100 billion being available [European Commission, 2022]. All these grants, funds, stimulus packages are meant to increase the profitability and ROI of renewable energy projects such as the production of hydrogen.

The Netherlands intends to use hydrogen as an energy carrier to ensure that the country has a sustainable energy system by 2050. Hydrogen is already widely used as a raw element in the Dutch manufacturing industry. Hydrogen may also be utilized to store and transmit renewable energy to customers. The government intends to expand the production and use of sustainable hydrogen. For a long time, Dutch companies have produced and used hydrogen (derived from natural gas). This is known as grey hydrogen because it emits CO2: around 13 megatons of CO2 each year. This accounts for around 8% of total CO2 emissions in the Netherlands. As a result, it is preferable to make hydrogen production more sustainable. This can be accomplished in two ways:

1. To catch the CO2 that is released during the production of grey Hydrogen. This method is CO2 neutral and climateneutral and is referred to as blue hydrogen.
2. By producing hydrogen through electrolysis with electricity from renewable sources (e.g. solar- or wind energy)

Pure Energie already has multiple wind farms and a rapidly growing number of solar farms. The goal of Pure Energie is to offer clean and renewable energy. Therefore, the adoption of hydrogen systems could be interesting for its portfolio. Wind- and solar farms are able to produce large amounts of renewable energy. However, these systems are subject to the presence of sunlight or wind. This means that the output of such systems is less predictable compared to when energy is produced by generators powered by fossil fuels. To have a reliable and sustainable energy grid in the Netherlands, the balance of the grid has to be stable. Electric batteries or hydrogen could support renewable energy sources by creating a system with very predictable output.

2.2 Research questions

The objective of this research is to answer the following main research question:

Is the production of green hydrogen commercially interesting?

Whether Pure Energie should invest in hydrogen or not, cannot be based on general assumptions or a market analysis alone. The choice has to be supported both by theoretical and practical research and it should also align with the corporate vision of the company. To carefully support a statement concerning whether Pure Energie should invest in hydrogen systems, is therefore supported by several research questions. These research questions will focus on existing literature and theory on the energy commodities market, the systems involved, and also governmental policies both in the Netherlands and the European Union. Combining the aforementioned literature with a quantitative model, the objective is to indicate several elements that can be used to conclude whether investing in hydrogen systems is interesting for Pure Energie, or might become interesting in the future. By doing so, we can visualise the parameters which can tell us whether investing is interesting. To support the main research question, the following research questions are used:

1. **What are the possible (durable) energy systems based on hydrogen?**

   The existing literature is used to answer this research question. By answering this research question, we obtain an overview of the existing or upcoming possibilities for hydrogen systems and policies regarding investing in such systems. The literature should also cover the requirements for such systems to operate and also which already existing systems in the portfolio of Pure Energie are suited for implementation of hydrogen systems. The following sub-questions will support the answer to this research question:

   - What is hydrogen and how does green hydrogen differ from other types of hydrogen (e.g. grey or blue)?
   - What is a hydrogen electrolyser, what types of electrolysers are available and how do they interact with existing energy grids and systems?
   - What are the requirements for a hydrogen system to operate?
   - What are the developments regarding hydrogen policies in the Netherlands, neighbour countries and European Union?
   - Which of the current systems (operated by Pure Energie) are suitable for a hydrogen extension?

2. **When does a hydrogen system become economically viable for Pure Energie?**

   To support the main research question, we need to know the parameters when an investment in durable hydrogen systems will become viable for Pure Energie. This research question will therefore go in the quantitative measures that are needed to calculate an interesting business case. The goal of this research question is to create a calculation model which is able to indicate the bandwidth where the parameters should be in between, in order for the investment to be interesting for Pure Energie. The following sub-questions will support the answer to this research question:

   - What is the current situation on the hydrogen market in terms of price, innovations, and demand? And how is it expected to change in the future?
   - What grants or stimulus packages are available to stimulate investments in hydrogen?
   - Create a business model for the different hydrogen scenarios suitable for Pure Energie.
   - Perform a performance analysis on the investment in hydrogen systems
     - Consider fluctuations in resource prices.
     - Identify financial and operational risks.
     - What are the terms and conditions for Pure Energie to start investing in hydrogen?

3. **Does hydrogen fit the profile of Pure Energie, its vision, and operations?**

   For Pure Energie to invest in hydrogen is not only a financial matter. Manage has also to decide whether they think hydrogen is a good fit to the company and whether the company is ready to invest yet. By analysing the current portfolio, we will look into the fit between the already owned systems and new hydrogen systems. Interviews with the management board will be used to see if the corporate vision allows for invetments in hydrogen systems. The following sub-questions will support the answer to this research question:

   - How well does it connect to other investments and operations?
   - Does investing in hydrogen stroke with the corporate vision of Pure Energie?

2.3 Methodology

The methodology of this research involves a mixed-methods approach that combines both qualitative and quantitative research. The qualitative research will be used to build a theoretical framework for the study, while the quantitative research will be used to test the hypotheses and answer the research questions. The following is a more detailed explanation of the methodology.

1. Literature Review: The first step of this research is to conduct a comprehensive literature review on the current and expected developments for durable hydrogen and hydrogen systems. This will include an exploration of relevant policies, regulations, and grant opportunities for hydrogen systems. The literature review will also cover the energy commodities market and the requirements for hydrogen systems to operate effectively. This step will provide a foundation for the research questions and guide subsequent data collection.

   the following topics will be analysed further during the literature review:

   Research Question 1

   - The current and expected developments for hydrogen systems.
   - The current and expected developments in the energy commodities market.
   - The requirements for hydrogen systems to operate.
   - Dutch and European policies regarding hydrogen systems.
   - Portfolio analysis of systems owned by Pure Energie.

   Research Question 2

   - Available grants for investments in hydrogen systems.
   - Hydrogen supply chain analysis.
   - The fit between hydrogen systems and the vision of Pure Energie.
   - Creating a business model for a hydrogen plant.
   - Perform a stakeholder analysis.

   Research Question 3

   - The fit between hydrogen systems and the vision of Pure Energie.

2. Interviews: Following the literature review, interviews will be conducted with relevant stakeholders to gather more in-depth information. The interviews will be used to confirm the information collected during the literature review and are used to provide additional information where the literature review was not sufficiently comprehensive. These interviews will be conducted with experts in the field, in-house at Pure Energie, and potential partners in the hydrogen supply chain. The data collected from these interviews will be used to form the theoretical framework for this thesis.

3. Qualitative Data Analysis: The qualitative data collected from the literature review and interviews will be analyzed to identify key themes and patterns. This analysis will provide a comprehensive understanding of the current state of durable hydrogen and hydrogen systems, and will inform the development of the research questions and the quantitative research model.

   The data analysis is focussed primarily on the current asset portfolio of Pure Energy and the fit to the hydrogen system scenarios. For this the historic wind data of the windpark Groen Asset location. A new windfarm is currently under construction at this location, and is currently assumed to be the most suitable location to use for green hydrogen production.

4. Quantitative Research Model: The quantitative research model will be created specifically for Pure Energie, using the data collected during the qualitative research phase. This model will be designed to test the hypotheses and answer the research questions. The model will consist of several scenarios based on different percentages of ownership and positions of Pure Energie in a hydrogen system or supply chain. The expected cash flow, discounted cash flow, expected annual returns, maintenance and operational costs, transport costs, and other relevant parameters will be calculated for each scenario.

5. Evaluation: The final stage of this research is to evaluate the various scenarios using the quantitative research model's specified calculation models. These calculations will be compared to the findings in the qualitative research and the vision of the management board of Pure Energie. This stage will involve drawing conclusions, making recommendations, and disclosing the research limits. All other research questions will support the answer to the main research question.

2.4 Research scope

This thesis investigates the viability of investing in hydrogen systems for Dutch renewable energy provider Pure Energie. The objective of this study is to investigate the current and anticipated developments for durable hydrogen and hydrogen systems, as well as the policies, regulations, and funding opportunities for hydrogen systems. In addition, the study will examine the energy commodities market and the operational requirements for hydrogen systems.
The research will employ a mixed-methods approach, combining qualitative and quantitative research to test hypotheses and provide answers to research queries. The study will examine available grants for investments in hydrogen systems, conduct an analysis of the hydrogen supply chain, and develop a business model for a hydrogen facility. In addition, the research will conduct a stakeholder analysis, a risk analysis, and an investment bandwidth calculation for relevant parameters.
Using the specified calculation models of the quantitative research model, the numerous scenarios will be evaluated. The findings will be compared to Pure Energie's board of directors' vision in order to draw conclusions, make recommendations, and reveal research limitations.

Ultimately, the research will shed light on the viability of investing in hydrogen systems for Pure Energie, with the potential to inform the company's investment strategy for renewable energy systems.

2.5 Deliverables

The fourth and concluding stage of the investigation is to convey the findings to the Pure Energie problem owners. To offer a good summary of the recommendations and how these recommendations were supported to the problem owner. Pure Energie will get the following deliverables.

- Business model
- Calculation model
- Report

3 THEORETICAL FRAMEWORK

In this chapter, we gain further understanding on the theory supporting the research. The theoretical framework focuses on carefully researching the literature required to do this research. In order to support the assumptions made during this research, a general literature search on the topic of (renewable) hydrogen systems was conducted. In this research the goal is to find answers to the research questions and to function as a precedent for the research. Hence, we will review the definition of durability and the various types of hydrogen. Subsequently, the types of hydrogen electrolysers are reviewed together with the requirements for such systems to be operational. Thereafter, policies regarding the production and use of hydrogen are looked into. Hydrogen policies for the Netherlands and for the European Union are reviewed. Knowledge on these policies will eventually also be supportive on the decision whether investing in hydrogen is interesting for Pure Energie.

Now knowing the methods of operating and the requirements for a hydrogen system, we can look at the already existing energy projects of Pure Energie and see which of those are suitable for hydrogen extension.

Research questions

- What is hydrogen and how does green hydrogen differ from other types of hydrogen (e.g. grey or blue)?
- What is a hydrogen electrolyser, what types of electrolysers are available and how do they interact with existing energy grids and systems?
- What are the requirements for a hydrogen system to operate?
- What are the developments regarding hydrogen policies in the Netherlands, neighbour countries and European Union?
- What is the business model for hydrogen electrolysis?

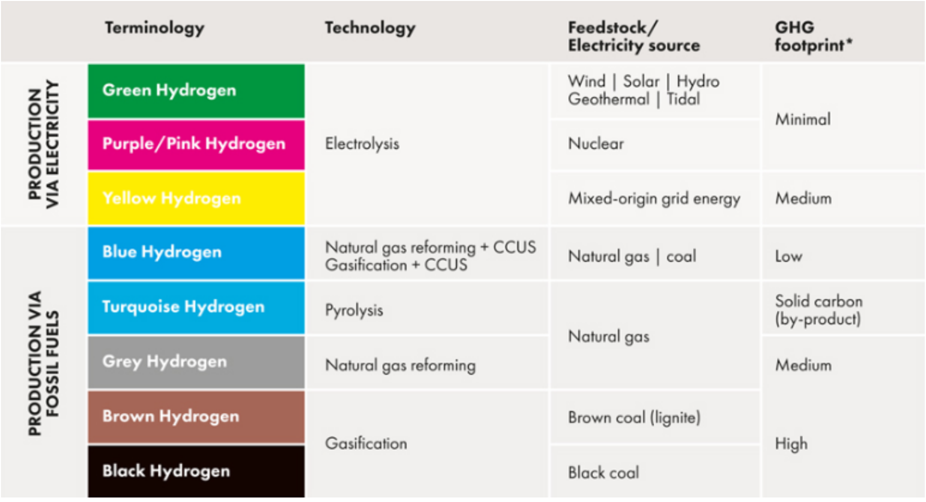
3.1 Defining hydrogen

Inexhaustibility, cleanliness, convenience, and independence from foreign influence are the primary qualities for a perfect fuel. All of these features are possessed by hydrogen, which is being investigated and pushed globally as an ecologically friendly substitute for gasoline, heating oil, natural gas, and other fuels in both transportation and non-transportation uses [Ratnakar et al., 2021].

Hydrogen, like electricity, is a high-quality energy carrier that can be used with great efficiency and near-zero emissions at the time of use. Green hydrogen extraction from renewable energy sources is a novel idea in the energy business. As an energy carrier, hydrogen is well suited to enable strong linkage between diverse energy sectors as well as the incorporation of renewable energy sources [Rabiee et al., 2021]. It has been proved technically that hydrogen can be utilized for transportation, heating, and power generation, and that it could replace current (fossil) fuels in all of their current applications [Ratnakar et al., 2021]. Therefore the use of hydrogen is believed to be one of the key factors in the energy transition.

3.1.1 Categories of hydrogen

Is green H2 superior to blue? Is grey on its way out? As the globe shifts away from oil and toward greener alternatives, several questions about hydrogen (H2) and its role in the current and future energy mix are being asked [Feder, 2021]. Hydrogen is defined in many colours along the spectrum. There are the main categories green, blue, and grey hydrogen. These categories will also be used throughout this research as reference. There are also other colours in the hydrogen spectrum like yellow hydrogen, turquoise hydrogen, and pink hydrogen. These are merely color codes or nicknames used in the energy industry to differentiate between various kinds of hydrogen. Depending on the process of production, hydrogen is assigned different hues. However, there is no universal naming convention.



	Terminology	Technology	Feedstock/ Electricity source	GHG footprint*
PRODUCTION VIA ELECTRICITY	Green Hydrogen	Electrolysis	Wind | Solar | Hydro Geothermal | Tidal	Minimal
	Purple/Pink Hydrogen		Nuclear	
	Yellow Hydrogen		Mixed-origin grid energy	Medium
PRODUCTION VIA FOSSIL FUELS	Blue Hydrogen	Natural gas reforming + CCUS Gasification + CCUS	Natural gas | coal	Low
	Turquoise Hydrogen	Pyrolysis	Natural gas	Solid carbon (by-product)
	Grey Hydrogen	Natural gas reforming		Medium
	Brown Hydrogen	Gasification	Brown coal (lignite)	High
	Black Hydrogen		Black coal	

Figure 3.1: Colour spectrum of hydrogen

Green hydrogen indicates all hydrogen that is produced with net-zero carbon emissions. It is also referred to as durable hydrogen. To fit the vision and profile of Pure Energie, we will only focus on the production of green hydrogen, as this type is the only relevant type of hydrogen. All others are not considered regardless if the business case is interesting.

3.1.2 Green hydrogen production

A variety of techniques can be used to create hydrogen. Heat and chemical reactions are used in thermochemical processes to extract hydrogen from organic sources such as fossil fuels and biomass, as well as from inorganic elements such as water [Office of Energy Efficiency & Renewable Energy, 2022]. Using electrolysis or solar energy, water (H2O) can also be split into hydrogen (H2) and oxygen (O2). Through biological processes, microorganisms such as bacteria and algae can produce hydrogen

[Office of Energy Efficiency & Renewable Energy, 2022].

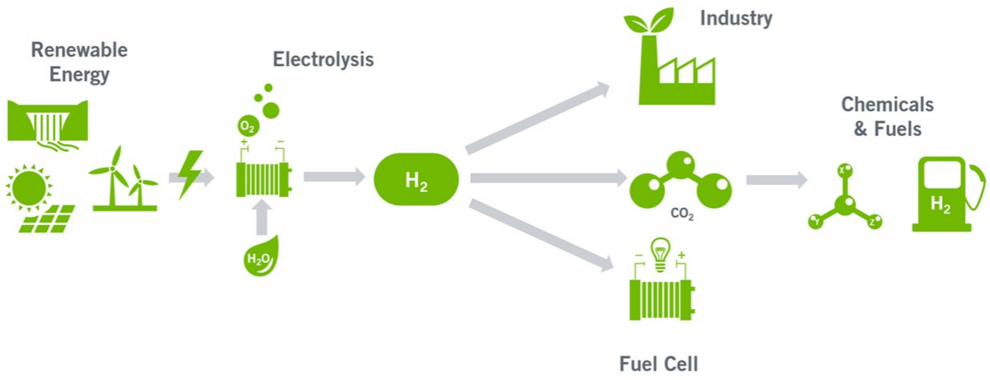


Figure 3.2: Hydrogen extension of renewable energy portfolio

Since we are focusing on extending the current portfolio of Pure Energie with hydrogen systems, we have to look at systems that are compatible with the wind- and solar-farms that are currently operational. Electrolysers divide water into hydrogen and oxygen using electricity. This technology is well established and commercially available, and systems that can utilise intermittent renewable energy efficiently are being developed.

3.2 Hydrogen electrolyser technologies

An electrolyser is a device that utilises electricity to split water into hydrogen and oxygen through a process known as electrolysis. The electrolyser generates hydrogen gas by electrolysis [Cummins Inc., 2020]. The remaining oxygen is either discharged into the environment or caught and stored to serve other purposes. The hydrogen gas may be kept either compressed or be liquefied, and because hydrogen is an energy carrier, it can be utilised to power any hydrogen fuel cell electric application, including trains, buses, vehicles, and data centres [Cummins Inc., 2020]. An electrolyser can be considered on multiple levels.

- The cell is the electrolyser's heart and the site of the electrochemical process. It's made up of two electrodes (anode and cathode) submerged in liquid electrolyte or near to a solid electrolyte membrane, two porous transport layers (which assist reactant movement and product removal), and bipolar plates that provide mechanical support and flow distribute[IRENA, 2020].
- The stack has numerous cells linked in series, spacers (insulating material between two opposing electrodes), seals, frames (mechanical support), and end plates (to eliminate leaks and collect fluids).
- The system level (or balance of plant) includes equipment for cooling, hydrogen processing (e.g., purity and compression), converting the electrical input (e.g., transformer and rectifier), treating the water supply (e.g., deionization), and gas output (e.g., oxygen) [IRENA, 2020].

Purified water is introduced into the system by circulating pumps or gravity. Water then flows through the bipolar plates and the porous transport layers to reach the electrodes. Water is divided into oxygen and hydrogen at the electrode, with ions (usually H+ or OH-) passing through a liquid or solid membrane electrolyte. The membrane or diaphragm between the two electrodes is also in charge of keeping the generated

3.2.1 Types of electrolyser technologies

Hydrogen electrolysis is a basic principle that enables the development of many technical variants depending on various physicochemical and electrochemical features. Based on their technology, electrolyzers are often categorised into four categories. Depending on the electrolyte, they are divided.

Electrolysers are classified into four types: Alkaline and polymer electrolyte membrane (PEM) systems are currently available. While anion exchange membrane (AEM) and solid oxide are now marketed, they represent a significant stride forward [IRENA, 2020]. For this research we only consider PEM and Alkaline electrolysers given that the other two types are not yet commercially available.

Alkaline electrolyser

An alkaline electrolyser uses both water and a liquid electrolyte solution. These are generally easy to build because to their straightforward stack and system architecture as well as their simplicity. They currently have electrode areas that are as high as 3 square metres (m2) in total [IRENA, 2020]. This makes it possible for the generated gases (hydrogen and oxygen – H2 and O2) that are dissolved in the electrolyte to mix together. As a result, the lower power-operating range of the battery is reduced, while its capacity to run at higher pressure levels is increased.

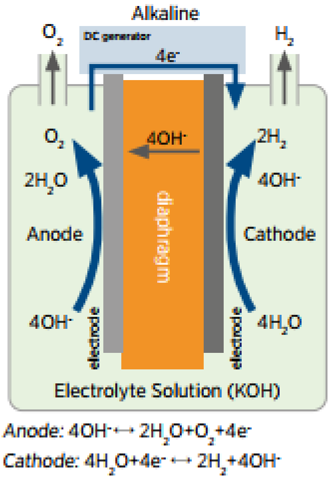


Figure 3.3: Alkaline Electrolyser design

Potassium hydroxide (KOH) and sodium hydroxide are examples of such solutions (NAOH). An ”anode,” ”cathode,” and ”membrane” are the three components that make up a ”cell,” which is where hydrogen is created. The cells are often connected in a series to form a ”cell stack,” which generates more hydrogen and oxygen as the number of cells grows [Cummins Inc., 2020]. When current is applied to the cell stack, hydroxide ions (OH-) move through the electrolyte from the cathode to the anode of each cell, forming hydrogen gas bubbles on the cathode side and oxygen gas at the anode, as seen above. [Cummins Inc., 2020]. Atmospheric Alkaline Electrolysers are a variation of alkaline electrolysers that can reach a efficiency of 3.8 kWh/Nm3 [NELhydrogen, 2022]. However, the downside of alkaline electrolysers is that they have to run at a constant output to reach high levels of efficiency. This means that scaling up or down production cannot be done as fast compared to PEM Electrolysers.

PEM Electrolyser

A Proton Exchange Membrane (PEM) uses a cathode (which has a negative charge), an anode (which has a positive charge), and a membrane. These three components make up the electrolyser in its most basic form. The comprehensive system consists of a variety of components, some of which are as follows: pumps, vents, storage tanks, a power source, and a separator [Cummins Inc., 2020]. The electrolysis of water is a kind of electrochemical reaction that takes place inside of cell stacks. On the other side of the proton exchange membrane is where the electric current is provided () to the anode and cathode, causing water (H20) to split into its component molecules, hydrogen (H2) and oxygen (O2) [Cummins Inc., 2020].

A PEM electrolyser makes use of a PFSA membrane that is only 0.2 millimetres thick and electrodes that have been redesigned to allow for increased efficiency (i.e. less resistance). In addition to its chemical and mechanical robustness [IRENA, 2020], the perfluorosulphonic acid (PFSA) membrane is capable of withstanding significant pressure differences. This enables the PEM cells to function at pressures of up to 70 bar while maintaining the ambient pressure on the oxygen side of the cell [IRENA, 2020].

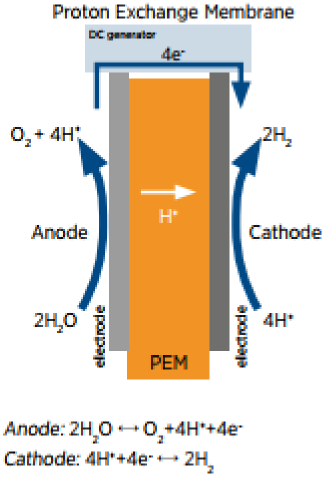


Figure 3.4: PEM Electrolyser design

Water splits into hydrogen and oxygen when current is delivered to the cell stack, and the hydrogen protons flow through the membrane to generate H2 gas on the cathode side. Electrolysers can be built in a modular design and are therefore suited for multiple applications. PEM Electrolysers also have a variable output. Meaning the system is able to adjust its production capacity in a range from 10% to 100%. Another interesting system aspect of PEM electrolysers is that scaling up or down production can be done in mere seconds. This characteristic makes PEM Electrolysers extremely suitable for fluctuating demands. PEM Electrolysers run approximately at a efficiency of 4.3 kWh/Nm3 to 6.5 kWh/Nm3, depending on the setup [NELhydrogen, 2022]

3.2.2 Electrolyser system

Each type of electrolyser has some core components that are similar fore each type, e.g. a purified water supply, transformer units, H2 storage, compressors, etc.. However, the specific balane of plant design differs per electrolyser type. For this research we only consider Alkaline and PEM electrolysers, and therefore also only their Balance of plant design.

Alkaline electrolyser systems

In contrast to the other techniques, alkaline electrolysers need an electrolyte, which is represented by KOH, to be pumped continuously into and out of the stack components [IRENA, 2020]. This results in a reduction in pressure, which in turn necessitates certain pumping characteristics and has a negative impact on the efficiency, which is normally less than 0.1% of the total power consumption of the stack but can be significantly greater for other manufacturers. There are also certain alkaline systems that can be run without the need of pumping peripherals [IRENA, 2020]. This alkaline solution, once it has exited the stack, will need to be separated from the gases that were created. This is accomplished in gas-water separators that are positioned above the stack at a certain height, and then the KOH-water mixture is returned to the stack. At the very bottom, the water phase may be extracted, and at the very top, the gas phase can be extracted. In addition to its primary function, the water column inside the separator performs the duties of a buffer store for varying load standards[IRENA, 2020]. The filling level of each gas separator is regulated by the water management system, and water penetration through the diaphragm is something that has to be taken into consideration.

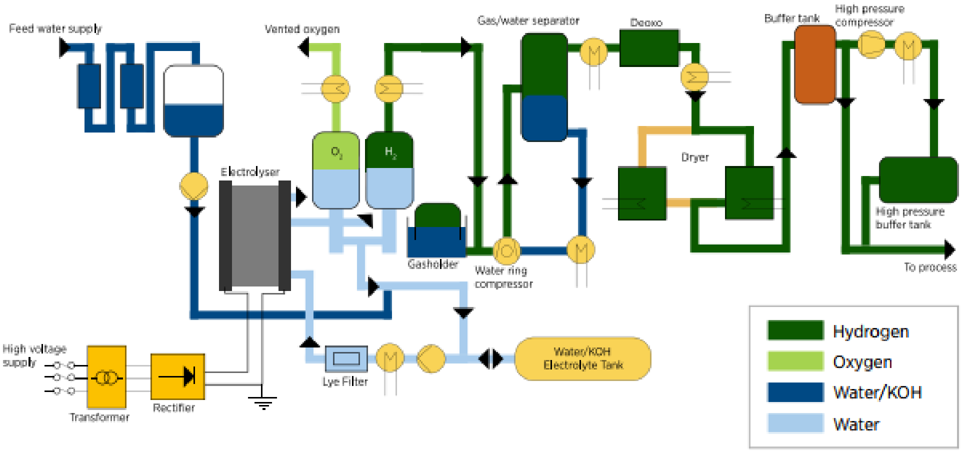


Figure 3.5: Generic Alkaline electrolyser system design for balance of plant [IRENA, 2020]

PEM electrolyser systems

PEM electrolysers are less complicated than alkaline. Only on the oxygen (anode) side do they often need for the utilisation of circulation pumps, heat exchangers, pressure control, and monitoring. A gas-separator, a de-oxygenation component to remove residue oxygen (usually not needed for differential pressure), a gas dryer, and a final compressor step are required on the cathode side of the reaction [IRENA, 2020]. PEM systems, more critically, have additional design options, including atmospheric, differential, and balanced pressure (design is locked to a single one), which reduces costs, system complexity, and the amount of maintenance required. Both the anode and the cathode are intended to function at the same amount of pressure while a balanced pressure operation is being carried out. An example of the constant pressure operating mode is the atmospheric pressure operation, which maintains a pressure of less than one standard atmosphere (atm) [IRENA, 2020]. The PEM membrane electrolyte is designed to function in differential pressure environments, generally ranging from 30 bar to 70 bar. However, in order to achieve the same level of mechanical stability, a thicker membrane is required. This, in turn, lowers the amount of gas that can pass through the membrane, which in turn lowers the level of efficiency achieved. It is possible that an extra catalyst will be necessary in order to revert any hydrogen back to water, as the greater pressures will cause more hydrogen to infiltrate the surrounding area.

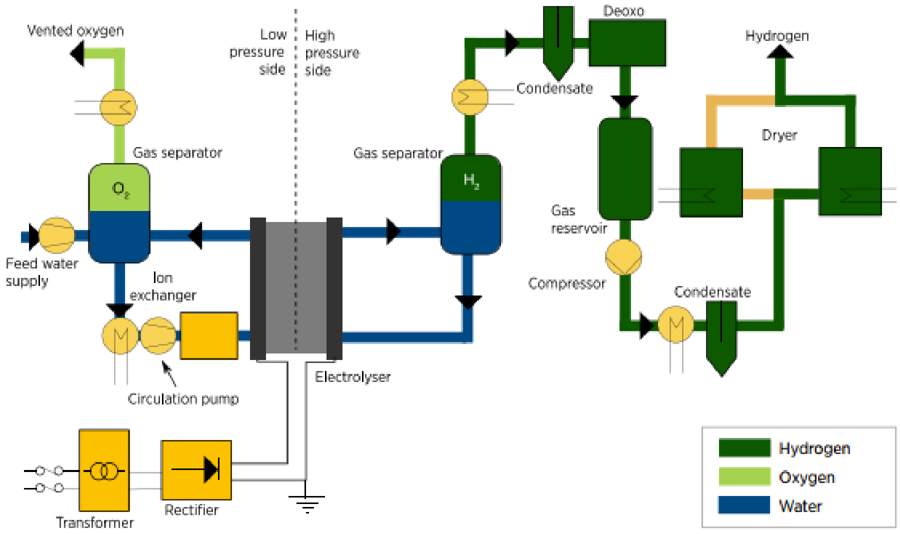


Figure 3.6: Generic PEM electrolyser system design for balance of plant [IRENA, 2020]

Flexibility in production of green hydrogen

To keep the cost of green hydrogen supply at a minimum while still operating efficiently, system design and operation must be approached differently. Depending on a number of parameters, system design may be optimised to save costs while increasing flexibility. An example is: the fluctuation of power supply, continuous grid consumption or direct feed from changeable solar or wind farms. Since this will be the case, the time that it takes to increase production, also called ramp-up time, is of significant importance.

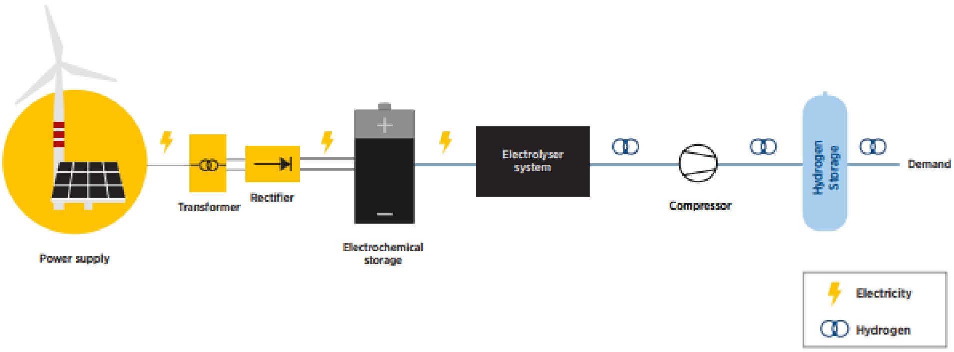


Figure 3.7: System overview for green hydrogen production with wind or solar power as energy input

The power input received from wind or solar farms is not as constant as other fossil fuel based energy sources. This is due to the variation in wind speeds, solar hours and other external influences. Where a coal-powered generator can be kept at a steady level of output, this is not true for wind an solar farms. This uncertainty in output creates several problems. One is the balance of the grid. When demand is lower than production, the grid becomes overloaded. This causes the frequency of the grid to rise, which is not desirable. When the demand is higher than the power production, the frequency of the grid reduces, again, not desirable. By implementing a variable production capacity at a wind or solar farm, in the form of an electrolyser, we are able to dampen the uncertainty in the production profile of these renewable energy sources. When production is higher than demand, the electrolyser can ramp up its production, reducing the excess energy on the grid. When demand surpasses production, the electrolyser could lower its production, therefore decreasing demand and restoring grid balance. The service of being in this balancing role, could also generate extra income for the electrolyser. This is because the national grid operator, TenneT, is willing to pay for flexible grid capacity.

Since PEM and alkaline electrolysers work through different principles, their production characteristics are different as well. Where Alkaline electrolysers can achieve higher efficiencies when provided with stable and continuous power input, PEM electrolysers are better suited for changing inputs [Khelfaoui et al., 2021]. For PEM electrolysers it is possible to ramp up/ramp down production within seconds [NELhydrogen, 2022]. According to NEL [NELhydrogen, 2022], PEM electrolysers react within seconds on changing production requirements, where alkaline electrolysers need several minutes to react.

To confirm the information on hydrogen electrolyser systems from the literature, several electrolyser manufacturers are interviewed to give an expert opinions. The companies interviewed are:

- NEL Hydrogen - Small/medium scale electrolyser systems
- Siemens Energy - Medium/large scale electrolyser systems
- Enapter - Small scale electrolyser systems

Considering the connection to renewable energy systems, all companies agreed that PEM elektrolyser systems are most suited to combine with the portfolio of Pure Energy. Where alkaline electrolyser systems are able to operate at a higher efficiency, the flexibility is limmited. THis flexibility is key for a system to be integrated with renewable energy sources. According to Siemens energy, the current most relevant information is described in the IRENA2020 report on hydrogen goals [SIEMENS ENERGY, 2022]. Specialised in smaller systems, NEL hydrogen [NEL Hydrogen, 2022] and Enapter[ENAPTER, 2022] also implied the possibilities to introduce multiple smaller scale hydrogen production units. However, this research focuses on a single investment, for further research multiple smaller-scale systems could be researched as well.

Conclusion

Whether an Alkaline or PEM electrolyser is the better choice, depends on the application. The scope of this research is to see whether a hydrogen plant is a suitable extension for the Wind Park Groen. The source of energy for a hydrogen plant at Wind Park Groen are wind turbines built and partially owned by Pure Energie. Wind turbines do not have a steady and reliable power output all of the time. Therefore, the power input for the hydrogen plant could fluctuate. As mentioned earlier, Alkaline electrolysers have the highest efficiency but do require a very steady power input. This is the result of the loss in efficiency whilst scaling up or down production capacity. Another aspect that has to be considered, is the grid balance. As mentioned in the previous section, input and output on the electricity grid are not always in balance. Renewable energy sources are decreasing the balance on the grid since their output is not always predictable. Also, the output that is created by the renewable energy sources is not always needed. This creates an opportunity for the hydrogen plant. As described in the previous section, the production could be scaled up when electricity prices are low. A PEM electrolyser is therefore the most suitable for this situation. The flexibility to up- or downscale hydrogen production quickly is a useful characteristic of a PEM electrolyser. Therefore, we can conclude that a PEM electrolyser is the most suitable for the Wind Park Groen location. The choice of a PEM elektrolyser is also confirmed by the commercial manufacturing companies during the interviews.

3.3 Requirements and methods of operating

For a hydrogen plant to be fully operational, several aspects have to be considered before investing. The physical requirements, e.g. the balance of plant, water consumption and energy consumption, have to be researched for the operations of the plant. However, in order to start building a hydrogen plant, several economical and political requirements have to checked as well. For the economical requirements we consider the various inputs for the quantitative model (the business model calculation). This involves all Monetary streams regarding the initial investment (CAPEX) of a hydrogen plant, the operational expenses (OPEX), and also the various income streams, e.g. selling the hydrogen, subsidies, grants, grid balance, etc.. In this section we will first review the physical requirements of a hydrogen plant with PEM electrolysers. Considering the physical requirements, we will look into the OPEX and CAPEX of the plant itself. At last, we consider the possible revenue streams that are accessible with such a hydrogen plant. The revenue streams eventually determine whether the investment in a hydrogen is interesting or not. The quantitative model will later on assess the parameters where the investment has a satisfactory Internal Rate of Return (IRR), and if it is feasible under the current circumstances.

3.3.1 Balance of plant

When analysing the specifications and operating techniques for a project such as an electrolyser, the interaction between various components is critical. The synergy between such components is also known as plant balance. We determined in the previous section that, because wind turbines supply the primary source of energy for the electrolysers, a PEM electrolyser is the appropriate alternative to focus on during this research. In figure 3.8 we can see a simplified overview of a PEM hydrogen electrolyser plant considering material and power flow. The main components of this hydrogen plant are the transformer and rectifier unit, the electrolyser itself, the feedwater system, H2/water separator, O2/water separator, the dryer, and a storage unit.

- **Transformer and rectifier** - Used to convert the alternating current voltage supply into the required voltage DC current input [NELhydrogen, 2022].
- **Electrolyser** - As described in section 3.2, the electrolyser facilitates the actual conversion from pure water to the separate hydrogen and oxygen molecules.
- **Feedwater system** - For the production of hydrogen it is essential that demineralised water is used. The higher the purity of the feedwater, the more efficient the electrolysis process. Higher water purity has also an effect on the maintenance and lifetime of core components of the electrolyser [IRENA, 2020].
- **H2/Water separator** - This component filters the liquid water (H20) from the high pressure hydrogen (H2) molecules. The liquid water is recycled into the system water tank [NELhydrogen, 2022].
- **O2/Water separator** - This component filters the liquid water (H20) from the gaseous oxygen (O2) molecules. The liquid water is recycled into the system water tank [NELhydrogen, 2022].
- **Dryer** - The dryer is used to dry the hydrogen gas to reach the dew point. It is made up of numerous beds that are filled with a regenerating desiccant to absorb water [NELhydrogen, 2022].

- **H2 storage** - The storage unit is, as the name suggest, to store the hydrogen for later use. it could be used as a buffer to ensure hydrogen purity and quality when production is sub-optimal [NELhydrogen, 2022].

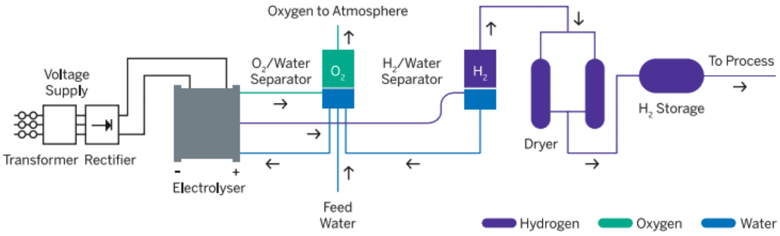


Figure 3.8: PEM Electrolyser simplistic overview [NELhydrogen, 2022]

Hydrogen compression

The hydrogen that is produced by the electrolyser is in the form of a gas, and its pressure can range anywhere from atmospheric pressure to 30 bar (although greater pressures are theoretically feasible). A smaller volume is required in order to ease the movement of hydrogen. In order to do this, the pressure must be raised, the gas must be liquefied, or the gas must be converted into liquid organic hydrogen carriers. The use of compression can have a significant impact [IRENA, 2020]. difference. It is possible to lower the volume of the gas by a factor of 65 just by increasing the pressure from atmospheric to 70 bar, which is normal for transmission pipes. When compared to atmospheric pressure, the volume can be reduced by a factor of 625 when it is compressed to a pressure of 1,000 bar (which is a normal pressure for storage in tanks), and the liquefaction factor can be reduced by a factor of 870. [Bloomberg NEF, 2020].

There are primarily three methods that compression may be accomplished: through the utilisation of a typical separate compressor; through the modification of the electrolyser's working pressure; and through the application of a separate electrochemical device. It is possible that doing both the compression and the creation of hydrogen in the electrolyser would be a desirable choice from the point of view of reducing the number of necessary pieces of equipment and the level of complexity of the process [IRENA, 2020]. The disadvantages, on the other hand, are the increased expense of developing an electrolyser capable of withstanding a greater pressure and the possibility of an increase in the amount of gas that passes through the membrane (efficiency and durability). When the pressure inside the electrolyser is increased, the permeation losses also rise. This means that a greater quantity of hydrogen is transferred to the oxygen side of the membrane rather than the product side [IRENA, 2020]. This, in turn, results in an increase in the amount of energy required for the same level of output as well as an increase in the danger posed to the anode.

There are two forms of pressurisation options for PEM electrolysers: balanced and differential. Both of these modes are pressurised. When the mode is set to balanced, there is an equal amount of pressure exerted on both the anode and cathode sides [IRENA, 2020]. Given the reduced demand for mechanical strength, this indicates that the membrane, spacers, and porous transport layer may each be made thinner. Because of this, there is less resistance within the cell on the inside, which ultimately results in a better efficiency. The pressurised mode has a number of drawbacks, the most significant of which is that it necessitates the redesign of the apparatus as a whole to accommodate a greater pressure, which not only incurs more costs but also raises concerns regarding the pressurised oxygen [IRENA, 2020]. Only the anode is susceptible to the greater pressure when operating in the differential mode. This is because the anode gets all of the pressure from the cathode side, which is where the creation of pressurised hydrogen takes place.

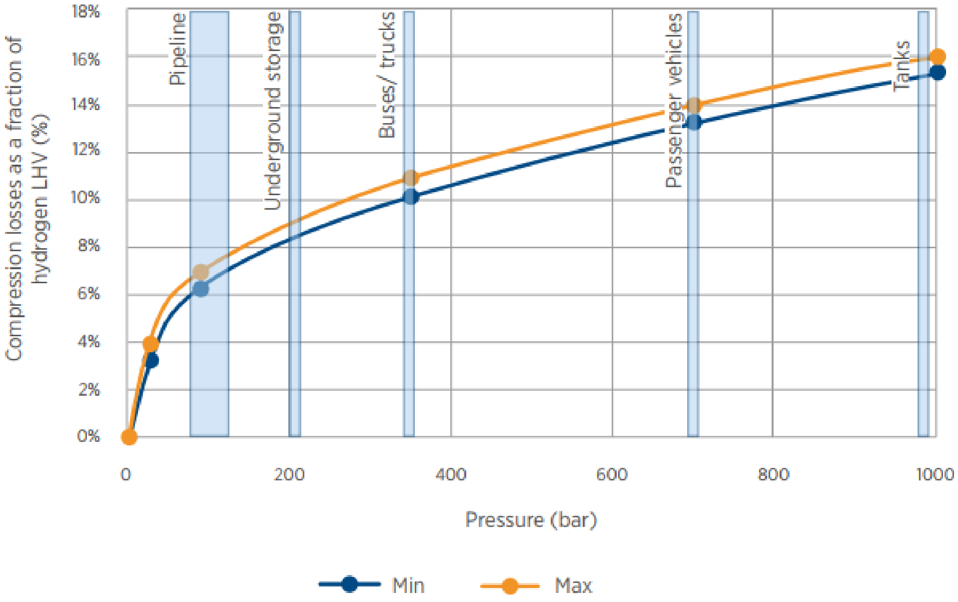


Figure 3.9: Energy losses for mechanical compression of hydrogen

Efficiency is only one aspect. A compressor of roughly 4 MW would be required to take the stream from a conventional atmospheric alkaline electrolyser to the normal working pressure of a pressurised electrolyser for a 100-MW electrolyser (30 bar). This size already enjoys economies of scale and contributes just roughly USD 0.07/kg H2 [IRENA, 2020]. The cost penalty for greater pressures would be the same for both methods. This price gap equates to around USD 50/kW, which defines the cost differential threshold for atmospheric alkaline stacks to be competitive with 30 bar (PEM) stacks. According to Saba et. al. [Saba et al., 2018], the cost increase for increasing the design pressure from 1 bar to 15 bar for an alkaline electrolyser is around USD 150/kW. Another cost-influencing element is the design of the PEM electrolyser. Differential pressure mode is preferred because it avoids high-pressure balance-of-plant components on the oxygen side. However, stack costs rise at the same time because stack components on the oxygen side must maintain the prescribed operating pressure. Depending on the business case and application, a tradeoff might range between 30 and 70 bar. Compression has an additional expense connected with the disposal of the compressor condensate, which can be as much as USD 1000 per day for a 20 MW plant.

Power supply

Power supply for electrolysers accounts for 20%-30% of overall costs, however there's room for savings. For small-scale electrolysis facilities, power supply is generally part of the package supplied by electrolyser manufacturers or a bespoke design from EPC contractors. As the facility grows, top electrical equipment manufacturers provide utility-scale power supply systems. This can cut electrolyzer power supply costs and improve performance. Further optimisation may be done by carefully integrating the electrolyser's numerous components, optimising the overall facility rather than individual components, and leveraging efficiency gains in the balance of plant, including the power supply. The water electrolysis business benefits from solar industry developments, and the power supply plays a key role in maximising electrolysis plant efficiency. While electrolyser stack efficiency decreases linearly with output, rectifiers have low efficiency at low load due to voltage rise [Kim et al., 2013]. Depending on the planned operating regime (e.g. constant output, variable input powered directly by solar or wind), the power supply can be sized and designed to maximise system efficiency, defined as minimising efficiency losses from power input to hydrogen production at the appropriate pressure. Optimized design influences efficiency and flexibility.

Land and water use

Water is used as a key feedstock in green hydrogen production, and renewable electricity is used as an energy source to separate hydrogen and oxygen from water in an electrolyzer.

Water, as pure as possible, is thus a critical input. While the amount of purity required varies depending on the technique, the cost of water purification is minimal, beginning with desalinated sea water (far below USD 1/cubic metre (m3) of water [Reddy and Ghaffour, 2007].
However, due to some process inefficiencies, taking into account the process of water demineralisation, with typical water consumption, the ratio can range between 18 kg and 24 kg of water per kilo of hydrogen.

For land use, a comparison is made with the production capacity of an electrolyser versus the production capacity of wind farms. Research has shown that using mass use of electrolysers could result in a energy density of nearly 7 500 MW/km2 (production), which is nearly 1500 times greater than a relatively good onshore wind farm coming in at an energy density of 5MW/km2[IRENA, 2020]. This indicates that the electrolyser would only take up a fraction of the space occupied by the renewable electricity input.

3.4 Costs and revenue

This section will focus on the costs and revenue streams of a green hydrogen solution. For the investment to be interesting for Pure Energie, the economical impact of the project has to be analysed. For a new project to be realised, all stakeholders have to be visualised as well. In figure 3.10 a simplified overview of the electrical grid is given. The various interactions and monetary flows are visualised. in this model, the subsidies and other types of stimulus packages from governments, have been neglected. This is due to the continuous change in government policies. The subsidies and stimulus packages are not neglected in the quantitative model and are also described later in this section.
To calculate a valid business model in the quantitative section, several parameters have to be examined. The parameters will be partially based on existing literature and on the in-house expertise at Pure Energie. The following topics will help to create a foundation for the parameters and assumptions in the quantitative section:

- Stakeholder analysis.
- Capital expenditure analysis.
- Operational expenditure analysis.
- Hydrogen price analysis.
- Energy transport and congestion costs analysis/portfolio balancing.
- Revenue form grid balancing operations.
- Subsidies and stimulus packages for green hydrogen solutions.
- Strategic road map for EU and the Netherlands.

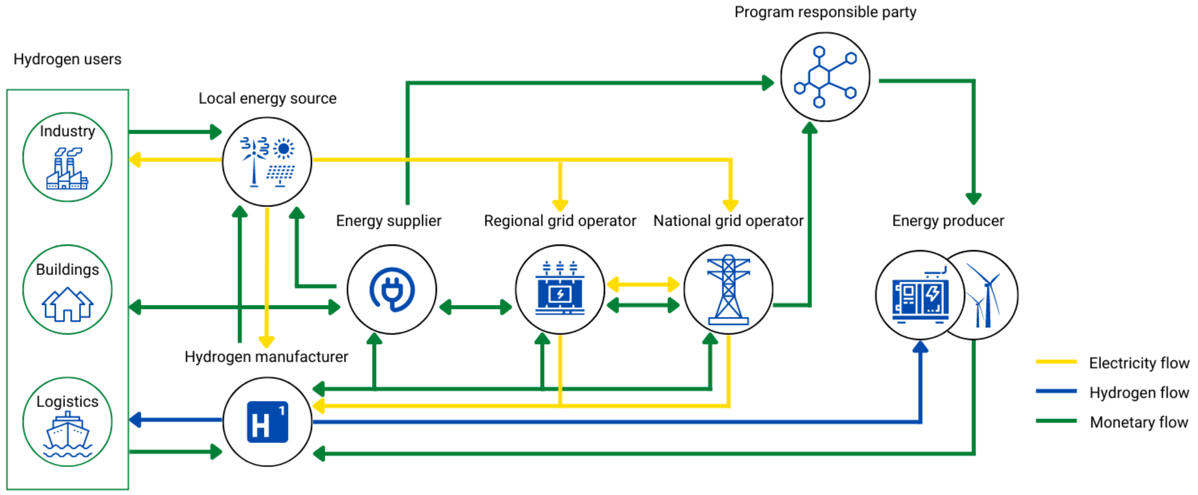


Figure 3.10: Grid overview with relevant monetary, energy, and hydrogen flows visualised

3.4.1 Stakeholders

For a project of this scale to succeed, many stakeholders must be examined. Each stakeholder has its own priorities, incentives and constraints. The goal is to use a (green) hydrogen solution to combine the interests of these stakeholders. For this research, we have selected the most important and influential stakeholders. In figure 3.11, the most important stakeholders are shown.

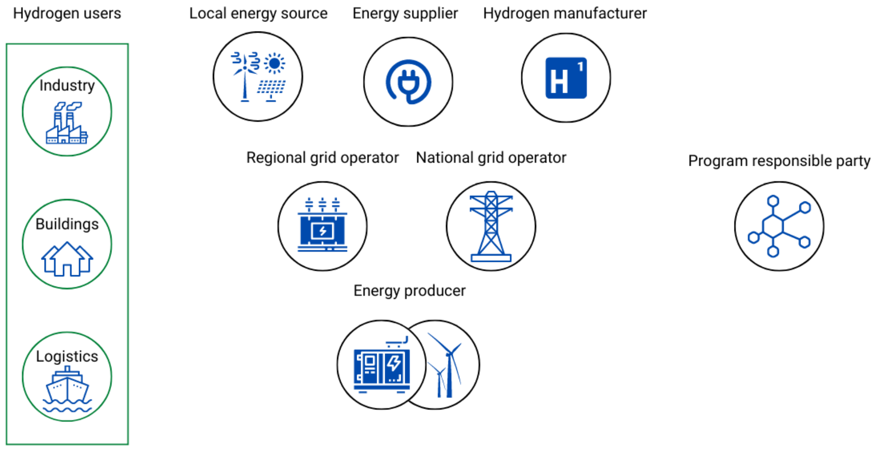


Figure 3.11: Stakeholder overview

- **Hydrogen manufacturer**

  The main interest of a hydrogen manufacturer is **a competitive price for hydrogen production**. A low electricity price is extremely necessary in order to produce as cheaply as feasible. Furthermore, the facility's investment must be "exploited."

This requires a large amount of operational hours In this case, the hydrogen producer will seek an optimum in practice: production will occur when the power price is lower than the marginal revenue. If the price of power rises, manufacturing becomes uninteresting from a commercial standpoint: the electricity costs more than the hydrogen output. The hydrogen producer is also interested in adequate pricing certainty for electricity. Volatility in power prices can benefit the hydrogen producer if he can maintain adequate operational hours and margins. Aside from power expenses, the costs of connecting to and transmitting the electrical grid, as well as the costs of transporting and storing the hydrogen generated, all play a role in the hydrogen producer's business case.

Another important factor for the hydrogen manufacturer is **a stable and reliable hydrogen market**. The hydrogen producer needs as much assurance as possible that the hydrogen it generates will be sold. A consistent or rising demand for hydrogen, as well as concrete sight of sales markets, are required for this, such as for usage in industry, mobility, the built environment, or the energy market (for conversion to electricity). In the commercial situation, the price the producer receives for its hydrogen is equally essential. The price that the producer receives is determined by the market in which he sells the hydrogen. Supply will influence pricing in some outlet markets (for example, an industrial cluster with a hydrogen network). In other marketplaces, the willingness-to-pay of the client is critical. This varies from customer to customer and is determined by the application as well as the customer's willingness to pay 'extra' for the green value of the hydrogen. The degree to which hydrogen is environmentally friendly is thus a key consideration in the business case.

- **Hydrogen users**

  Currently, hydrogen is mostly employed as an industrial feedstock

  [van Kranenburg et al., 2018]. In addition to feedstock, hydrogen is planned to be employed as a fuel in manufacturing, namely in cookers (high-temperature heat). Furthermore, hydrogen is already employed on a modest scale in the mobility sector (in vehicles with fuel cells) and for energy sector conversion to electricity. Hydrogen deployment for heating buildings is also being studied, for example, by mixing hydrogen into the gas grid. Overall, the following points are of importance for hydrogen users:

  - **The cost of hydrogen**. Electrolysis hydrogen should be reasonably priced. The price of green hydrogen is frequently compared to the price of grey (or blue) hydrogen. 7 The green value influences the amount of any potential premium that the user is prepared to pay. Furthermore, the prices will be compared to those of alternatives, such as fossil or 'biobased' fuels. In mobility, comparisons will be made between gasoline and diesel, as well as the expenses of electric automobiles. This includes not just the cost of hydrogen itself, but also the necessary investments in infrastructure and automobiles.
  - **Hydrogen's environmental benefit**. The fact that hydrogen is created using power derived from sustainable sources is extremely essential to some (possible) consumers. Green hydrogen is a sustainable alternative to natural gas and other fossil energy and/or raw material sources.
  - **Plant and infrastructure supply**. The larger the supply of plants and the provision of infrastructure for hydrogen application, the lower the threshold for user application. This might include factors such as the number of automobiles equipped with a fuel cell, the proximity of a hydrogen filling station, or the market penetration of hybrid boilers.

    - **Availability**. It is critical for the user that there is always enough hydrogen accessible. A consistent and dependable supply is required.

- **Local energy source**

  For the local energy producer, e.g. Pure Energie, or managers other of wind- or solar energy assets, the following points are of importance:

    - **Profit maximisation**. A local energy producer will aim to optimise its profitability as a business. Profitable operations of its facilities and a reasonable payback period are thus critical components of its business case. Hydrogen manufacturing behind the solar farm's meter can help to reduce costs. When hydrogen is created with direct connection to a solar or wind farm, the size of the connection to the grid is reduced, saving both the local energy generator and the hydrogen producer money. Transport fees may increase on local energy producers in the future. In that instance, expenses can be avoided by placing the hydrogen producer with a direct connection to the solar or wind farm's output.
    - **reducing sales and price uncertainty**. The local energy producer wishes to always be able to sell its electricity at the best possible price (even when there is a surplus of electricity). Making price agreements with a local electrolysis hydrogen producer can help reduce uncertainty.
    - **Quick deployment, enough network bandwidth, and minimal cost**. A regional energy production investor will wish to become operational. The needed strengthening of the energy infrastructure might be a hindrance at times. Adjustments to the high-voltage grid (by TenneT) can certainly last five years or more. In such a circumstance, migrating to a different place with sufficient grid capacity may be a viable option for getting started rapidly. Hydrogen generation via electrolysis at the local energy producer's site can also avoid delays if (time-consuming) grid strengthening is avoided. National grid operator's interests (TenneT)

- **Regional and national grid operators**

  The regional and national (TenneT) grid operators are responsible for keeping the grid balanced and operational at all times. As the name suggests, regional grid operators manage the grid on a regional level, and the national grid operator manages the regional grid operators. their main interests are:

    - **Socially responsible grid management**. The national grid operator, like the regional grid operator, is accountable for socially responsible network operation. TenneT, too, must provide high-quality grid services at reasonable rates while also facilitating the absorption of renewable energy. As a result, the parties avoid unproductive investments. TenneT, as a national grid operator, is likewise dedicated to facilitating the development of a sustainable energy market in Northwest Europe.
    - **Integrated grid reinforcement policy**. Electrification is becoming more important in the energy transition. Furthermore, renewable energy sources such as solar and wind are being used increasingly frequently, despite the fact that they are more volatile in nature than fossil fuels. This necessitates the need for greater capacity in the power network, demanding a complete reinforcement scheme. To prevent numerous network parts, such a scheme necessitates a better projection of future capacity demand per network section. Exploiting the advantages of flexibility services, together with optimal use of current capacity, permits the delay or even cancellation of substantial expenditures in reinforcement in particular scenarios. Cost optimization (upgrading and/or utilising flexibility) is important here. It is also ideal to focus on

the places where large-scale renewable energy occurs: for the grid operator, it is better to link wind and solar farms to regions where adequate grid capacity is available. Finally, organisational capacity is important: it is finite and must be used efficiently. For example, technician capacity is limited and must be used efficiently.

- **Ensure supply security and balance enforcement**. The national system operator is in charge of guaranteeing the security of power supply, which includes, among other things, ensuring that supply and demand are constantly in balance with one another (balance maintenance). TenneT employs devices such as regulating power, reserve power, and emergency capacity to maintain this balance and meet peaks and troughs in supply and demand.

3.4.2 CAPEX

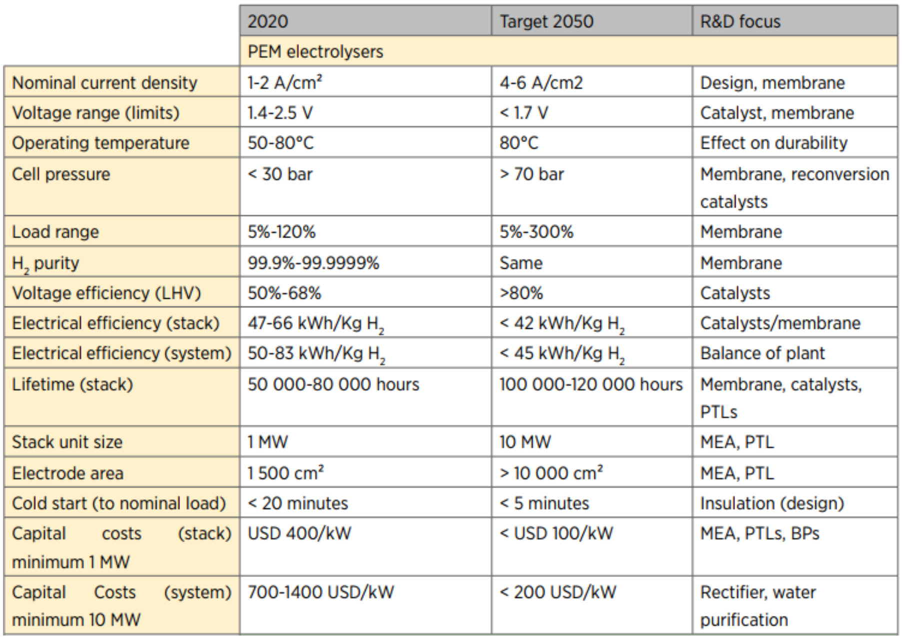
The cost of producing hydrogen via PEM electrolysis is a key factor in the commercial viability of this technology. Capital expenditures (CAPEX) are a significant component of the total cost of hydrogen production, and there has been considerable research in recent years aimed at reducing these costs in order to make PEM electrolysis more economically viable.

One of the main factors that affect the CAPEX of PEM electrolysis is the cost of the electrodes. The electrodes in a PEM electrolyzer are typically made of expensive metals such as platinum, which can represent a significant portion of the overall cost. Researchers have been working to develop alternative electrode materials that are cheaper and more efficient, such as non-precious metal catalysts [Mayyas et al., 2019]. A recent study by the National Renewable Energy Laboratory [Mayyas et al., 2019] found that the use of NPMC's could reduce the cost of the electrodes by as much as 70%, making PEM electrolysis more economically viable.

Another factor that affects the CAPEX of PEM electrolysis is the size of the electrolyzer. As the size of the electrolyzer increases, the cost per unit volume decreases, which can help to make PEM electrolysis more cost-effective at larger scale. A study by the Hydrogen Technologies and Energy Corporation [Sasiain Conde et al., 2021] found that the CAPEX of PEM electrolysis decreases exponentially with increasing scale, with a doubling of the size of the electrolyzer leading to a decrease in CAPEX of approximately 20%.

Additionally, the CAPEX of PEM electrolysis also depends on the cost of the other components of the system, such as the electrolyte membrane, the hydrogen and oxygen separation systems and the balance of plant.
One of the most recent research found that PEM electrolysis CAPEX can be reduced by 38% with the integration of renewable energy sources [Tremel, 2018] such as wind or solar power, as that can decrease the need of fossil fuel powered electricity.

The data in figure 3.12 shows the current and expected performance of PEM electrolysers as well as the capital expenditures. The figure shows that there is still much to gain on efficiency, lifetime and CAPEX on this electrolyser technology. by 2050 the goal is to reach higher efficiencies at lower costs per kW of production power.
In order to fully understand the costs associated with a PEM electrolysis hydrogen production facility, it is necessary to consider the entire plant, including all of the various components and subsystems that are required for the facility to operate. This includes not only the PEM electrolyser itself, but also any necessary equipment for hydrogen and oxygen separation, as well as any ancillary systems such as cooling, electrical, and control systems [IRENA, 2020].
A cost breakdown of a 1MW PEM electrolysis hydrogen production facility can provide valuable insight into the various cost components that make up the overall cost of the facility. A typical



	2020	Target 2050	R&D focus
	PEM electrolysers		
Nominal current density	1-2 A/cm²	4-6 A/cm2	Design, membrane
Voltage range (limits)	1.4-2.5 V	< 1.7 V	Catalyst, membrane
Operating temperature	50-80°C	80°C	Effect on durability
Cell pressure	< 30 bar	> 70 bar	Membrane, reconversion catalysts
Load range	5%-120%	5%-300%	Membrane
H_2 purity	99.9%-99.9999%	Same	Membrane
Voltage efficiency (LHV)	50%-68%	>80%	Catalysts
Electrical efficiency (stack)	47-66 kWh/Kg H_2	< 42 kWh/Kg H_2	Catalysts/membrane
Electrical efficiency (system)	50-83 kWh/Kg H_2	< 45 kWh/Kg H_2	Balance of plant
Lifetime (stack)	50 000-80 000 hours	100 000-120 000 hours	Membrane, catalysts, PTLs
Stack unit size	1 MW	10 MW	MEA, PTL
Electrode area	1 500 cm²	> 10 000 cm²	MEA, PTL
Cold start (to nominal load)	< 20 minutes	< 5 minutes	Insulation (design)
Capital costs (stack) minimum 1 MW	USD 400/kW	< USD 100/kW	MEA, PTLs, BPs
Capital Costs (system) minimum 10 MW	700-1400 USD/kW	< 200 USD/kW	Rectifier, water purification

Figure 3.12: Current and future PEM electrolyser CAPEX and performance data [IRENA, 2020]

cost breakdown may include the following major categories:

- Electrolyser: This is the core component of the hydrogen production facility and includes the PEM electrolyser itself, as well as any associated equipment such as the electrodes, the electrolyte membrane, and the bipolar plates.
- Hydrogen separation: This includes any equipment necessary to separate the hydrogen and oxygen produced by the electrolyser, such as the hydrogen compressor and the hydrogen purification system.
- Balance of Plant: This includes any ancillary systems that are necessary for the operation of the hydrogen production facility, such as the cooling system, the electrical system, and the control system.
- Site Development: This includes any costs associated with preparing the site for the construction of the hydrogen production facility, such as site clearing, grading, and foundation work.
- Engineering and design: This includes the costs of designing and engineering the facility, as well as any necessary permits and approvals.

It is important to note that the cost breakdown will also depend on the location and the specific project, for example, the cost of labor, permits, and materials can vary depending on the place. It is also important to note that these costs will not remain fixed over time and will likely change as the technology and cost of materials continue to evolve.
Figure 3.13 would visually represent the breakdown of the costs of the 1MW PEM electrolysis hydrogen production plant, with each major category represented as a separate segment of the figure and the proportion of the total cost attributed to each category represented by the size of the segment.
It would also include a detailed cost breakdown of each category with an explanation of how they were calculated.

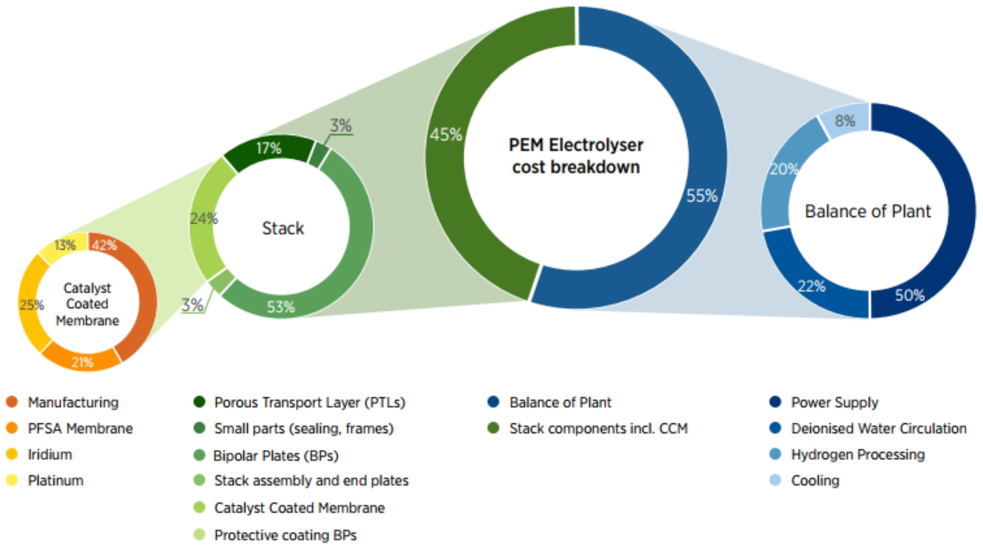


Figure 3.13: Cost breakdown for a 1 MW PEM electrolyser, moving from full system to stack.

3.4.3 OPEX

The operational expenditures, or OPEX, of a green hydrogen electrolyser are crucial in establishing the viability and competitiveness of this technology. When analysing the OPEX of a green hydrogen electrolyzer, a number of factors must be addressed, such as:

- Costs of Renewable Energy: The cost of the renewable energy utilised to power the electrolyser is a crucial element of the OPEX. This will have a substantial impact on the electrolyzer's OPEX, as the cost of renewable energy, such as wind and solar electricity, has been reducing fast in recent years and is likely to continue to do so in the future. Considering the growing renewable energy portfolio of Pure Energie, the amount of renewable energy should not be a direct problem. However, the availability of renewable energy is not as stable as fossil or nuclear power sources. Powering the electrolyser directly from a renewable energy source (without a grid connection as auxiliary input) could result in a significant decrease in operating hours.

- In addition to the cost of renewable energy, the cost of power and water required in the electrolysis process must be taken into account. Depending on the electrolyser's location and the availability of these resources, the cost of power and water can vary significantly.

- Electrolyser Efficiency: The electrolyser's efficiency is a significant aspect in determining the OPEX. Electrolysers with high efficiency require less energy to create the same amount of hydrogen, resulting in lower energy costs and decreased OPEX.

- Regular maintenance is essential to ensure that the electrolyser operates at peak efficiency. When calculating the electrolyser's OPEX, the cost of maintenance, including component replacement and technological improvements, must be accounted for. The labour necessary to operate and maintain the electrolyser must also be factored into the OPEX evaluation. This includes the cost of experienced technicians as well as management and training expenses.

- The cost of depreciation, or the decline in value of the electrolyser over time, must also be taken into account. This expense can be considerable, particularly for large-scale electrolysers with extended lives.

	OPEX
Year	*Cost (EUR/kg)*
2020	0.61
2030	0.35
2040	0.30
2050	0.20

Table 3.1: Expected OPEX costs [Pascal, 2022]

In conclusion, the OPEX of a green hydrogen electrolyzer is a complicated and multifaceted issue that must be thoroughly evaluated when determining the practicability and competitiveness of this technology. When calculating the OPEX of a green hydrogen electrolyzer, a number of elements, including the cost of renewable energy, the efficiency of the electrolyzer, maintenance expenses, labour costs, power and water costs, and depreciation, must be considered. In table 3.1 the expected OPEX costs per kilogramme of hydrogen are projected over a timeline until 2050 [Pascal, 2022]. These do only consider the maintenance, water and labour costs of operating the hydrogen plant. Information regarding operating efficiency and technical aspects of the OPEX calculation, can be found in 3.12

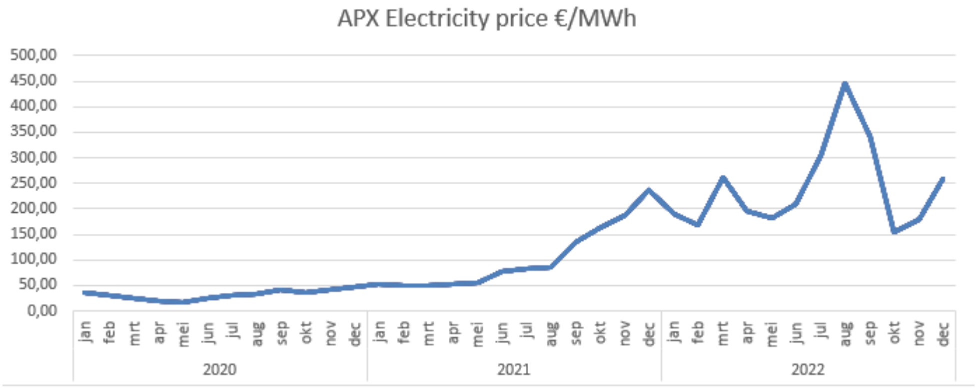


Figure 3.14: APX Energy prices of 2020, 2021 and 2022

Forecasting energy costs for the next 15 to 20 years is difficult, especially given the current market volatility. The energy market is influenced by a complex interaction of economic, political, and technological factors, which makes it impossible to accurately estimate future energy costs. In previous research, the energy prices were assumed to be between 35 and 55 €/MWh [IRENA, 2020]. However, after consulting the expertise of Pure Energie's energy trading department, higher energy costs could be the case in the future. As energy prices have reached an all-time high in 2022, it can be assumed that the average price over the investment horizon of the next 15-20 years, will be lower. But how much lower depends on many factors. Currently, "long term" energy contracts are scarce but indicate a price of 130 €/MWh until 2025 and approximately 105 €/MWh until 2027 [VanHelder, 2022]. As current prices (early 2023) are between 150-200 €/MWh [VanHelder, 2022], the consensus is that the energy price will decrease slowly over time.

For the purposes of the business case's calculations, we shall thus assume three electricity pricing scenarios. Three price scenarios: high (115€/MWh), moderate (80€/MWh), and low (56€/MWh). The high price scenario reflects a slightly lower price than the current price, where prices will remain high in the future. The low-price scenario reflects a situation where electricity prices return to the level of early 2021, and similar to the current level of SDE subsidy for wind turbines [RVO - Rijksdienst voor Ondernemend Nederland, 2022]

3.4.4 Hydrogen price

Selling hydrogen is the main source of income for the Green hydrogen business case. It is therefore a crucial aspect it is therefroe a crucial aspect to consider while calculating the possibilities. The business case should consider the price of per kilogram green hydrogen and also the volume at which it is sold.

Currently, green hydrogen generation is more expensive than traditional hydrogen production from fossil sources. As the renewable energy sector continues to expand, the cost of producing green hydrogen is anticipated to fall. In addition, technical developments in areas like electrolysis, the method used to create hydrogen from water, are anticipated to boost efficiency and decrease prices [Mike Scott, 2020]

Governments throughout the globe are also developing policies to encourage the expansion of the green hydrogen sector, including financing for research and development, subsidies for production and consumption, and laws to eliminate hydrogen derived from fossil fuels. In the next years, these activities are anticipated to reduce the price of green hydrogen and make it more competitive with standard hydrogen [UN Environment Programme, 2023].

Unfortunately, the majority of evaluations of hydrogen's potential are published prior to 2021. As is common knowledge, Europe's energy prices have been extremely volatile due to socioeconomic and political events (e.g. Ukraine war) [UN Environment Programme, 2023]. This shows that the reports are based on assumptions regarding the cost of electricity and gas in Europe that are currently regarded as implausible. Since then, the average cost of energy has increased by more than threefold and remained very volatile. This presents the difficulty of recalculating an investment plan in light of the present energy market conditions.

During the quantitative calculation phase of this research, a visualisation will be made to plot the threshold at which volume and price the green hydrogen has to be sold in order to return an interesting profit.

3.4.5 Energy transport and congestion/portfolio balancing

Energy generated at a wind farm is usually delivered to the (local) energy grid where the regional and national grid operators make sure the power is delivered to the end customer. Like stated earlier, Pure Energie has a fast portfolio containing renewable energy sources like wind and solar farms. If electricity is delivered from a energy source to the grid, the producing party does not pay for the transport of electricity. The customer of the electricity pays for these transportation costs. This research focuses on the addition of a hydrogen electrolyser, which will consume energy. Therefore, the transportation costs of energy can become a large factor in the business case analysis of the hydrogen electrolyser.
Two scenarios are possible considering the investment in a hydrogen electrolyser. One is where the electrolyser is considered as normal energy consumer, paying for all the electricity transport fees and costs. The other scenario considers the option of placing the electrolyser between the renewable energy and the energy grid. The second scenario is more complicated to achieve since one should (partially) own the energy source. However, if the electrolyser is placed between the renewable energy source and the grid connection, all electricity that flows directly from the renewable energy source into the electrolyser will be free of transportation costs and fees. this scenario is visualised in figure 3.15

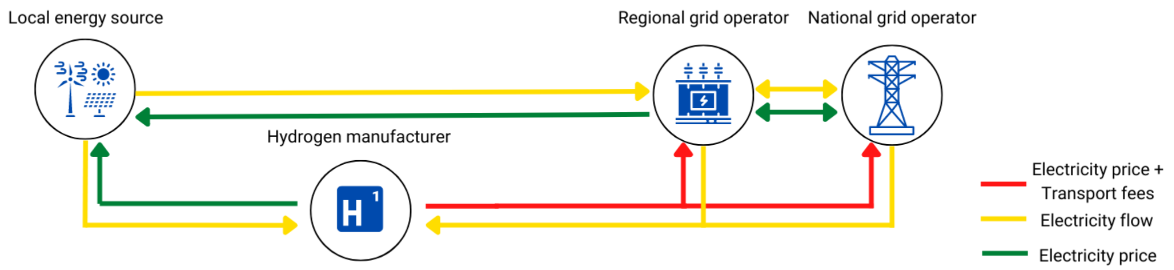


Figure 3.15: electrolyser placed between renewable energy source and grid

The placement of the electrolyser in between the renewable energy source and the grid, could improve the business case tremendously. During the quantitative part of the research, this difference of placement will be elaborated upon and the difference in costs are visualised as well.

3.5 Grid balance and congestion

TenneT is the energy transmission system operator (TSO) in the Netherlands, managing the country's high-voltage grid and guaranteeing the equilibrium between supply and demand. This involves managing grid congestion and maintaining the stability of the power system by directing the flow of electricity in real time and guaranteeing sufficient capacity to satisfy fluctuating demand. TenneT collaborates closely with other European TSOs to manage the linked grid and ease the cross-border flow of electricity. TenneT plays a vital role in guaranteeing the security and dependability of the energy supply in the Netherlands and contributing to the stability of the European power system as a whole.

As renewable energy sources, such as wind and solar power, make up a growing portion of the energy mix, preserving grid balance and minimising congestion become increasingly crucial. Unlike conventional power plants, which can be readily managed and changed to suit demand, renewable energy sources are frequently weather-dependent and their output might fluctuate. This can lead to times of overproduction and undersupply, resulting in grid imbalances.
In addition, the integration of renewable energy sources might cause congestion on the transmission grid, as electricity generated in some places may not be consumed locally and must be moved to areas with a larger demand. Managing congestion and maintaining the safe and efficient transmission of power becomes crucial under such circumstances.

TenneT and other TSOs play a critical role in balancing the grid and managing congestion by closely monitoring the power system and altering the flow of energy in real time to guarantee that supply and demand are in balance and there is sufficient capacity to satisfy changing demand patterns. This demands complex control systems, links with other TSOs, and efficient transmission grid planning and management. TenneT and other TSOs contribute to the stabil-

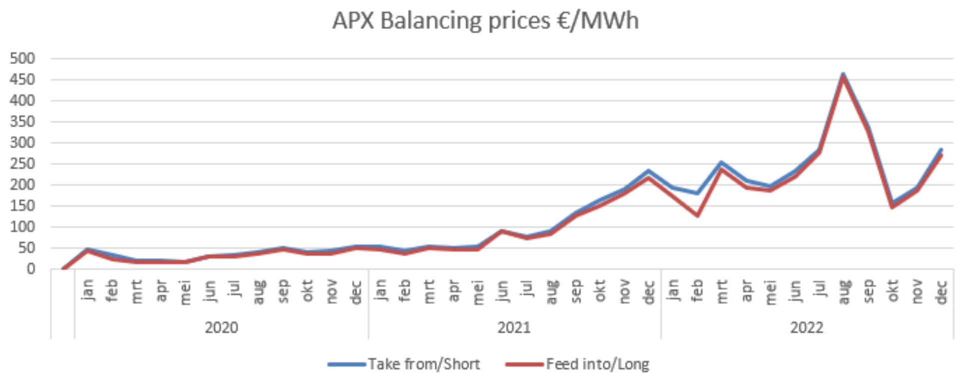


Figure 3.16: APX Balancing prices of 2020, 2021 and 2022

ity and dependability of the electrical supply in this manner, notwithstanding the rising use of renewable energy sources.

By installing a hydrogen factory near renewable energy sources like Windpark Groen, the electrolysers can scale up production when the energy grid is overloaded. For balancing the grid, TenneT is willing to pay. Having a grid balance problem, also leads to fluctuating energy prices over a day. It could be interesting to scale up production during times of low energy demand, producing H2 at lower costs as well as resolving a grid balance problem. Combining these to mechanisms, we are able to stack the business model and retrieve a lower price per kg of h2 produced.

3.6 Subsidies and regulations

The National Hydrogen Programme has been operational since early 2021. There is also information about funding, specifically national hydrogen awards and European funds. To stimulate the production and usage of green hydrogen, the IPCEI is an important document. IPCEI is a European scheme. It stands for 'Important Project of Common European Interest'. In this document is stated that to be able to reach the climate goals of 2050, hydrogen is crucial[RVO - Rijksdienst voor Ondernemend Nederland, 2022]. According to the European Commission's strategic vision for a climate-neutral EU, released in November 2018, the amount of hydrogen in Europe's energy mix is expected to rise from less than 2% now, to 13-14% by 2050 [European Commission, 2020]. Hydrogen will play a part in the future integrated energy system, with renewable electrification and more efficient and circular resource utilisation. Rapid deployment of clean hydrogen is critical for the EU to meet its greater climate ambitions of decreasing greenhouse gas emissions by at least 50% and up to 55% by 2030 in a cost-effective manner[European Commission, 2020].

With effect from 2020, much has changed in the grant instruments made available by the Ministry of Economic Affairs and Climate Change (EZK) through RVO. The introduction of a mission-driven innovation policy resulted in five missions for the Electricity Generation, Built Environment, Industry, Mobility, and Agriculture and Nature sectors. Linked to these are 13 multi-year mission-driven innovation programmes (MMIPs).

This sectoral approach has led to hydrogen becoming a cross-cutting theme as it has intersections with all missions and with at least 9 MMIPs. There is, unfortunately, no separate grant programme for hydrogen from 2020, as there was in the years 2017-2019. The following explains what grant opportunities are available for hydrogen within this new constellation. The basic idea is that hydrogen is included in multiple missions and MMIPs, with the specific topic leading where projects can fit. For example, hydrogen production for industry falls under mission C, MMIP 8. Application in mobility fits within mission D, MMIP 9.

To stimulate green hydrogen projects, several subsidies have been made available in the Netherlands. Each subsidy will be analysed on its requirements and its applicability. This should support the choices and the calculations made later in the quantitative analysis of this report. The following subsidies are available for (green) hydrogen projects in the Netherlands:

- **MOOI** - Since 2020, a new scheme has been in place for projects in the middle TRLs(technology Readiness Level) (TRL 4-6, industrial and experimental research): the MOOI (Mission-Driven Research, Development, and Innovation) scheme. The plan encourages integrated solutions that help to achieve climate targets. This strategy is important to the consortia. The strategy prioritises projects in the categories of ”offshore wind,” ”renewable energy on land,” ”built environment,” and ”industry.” This system is described in further detail below.
- **DKTI** - The DKTI programme (Demonstration of Climate Technologies and Innovations in Transport) is of interest for mobility-focused projects.
- **DEI+** - The DEI+ scheme (Demonstration Energy and Climate Innovation), among others, is suited for projects concentrating on higher TRL phases (TRL 7-9, practical experiments, pilots, and demonstrations).
- **TSE** - The Top Sector Energy Studies Industry scheme is offered for projects concentrating on the feasibility of an innovative pilot or demonstration project.
- **MIT** - The MIT (Innovation Stimulation Region and Top Sectors) programme is offered specifically for SMEs.
- **MIA/VAMIL** - Tax tools such as MIA/VAMIL can be utilised in addition to these innovation subsidies.

Technology Readiness Level

The technology readiness Level is a term used to describe the level of development maturity for a specific product. An engineered product is typically developed in stages, beginning with rapid prototyping and progressing to series production readiness. In order for industries and verticals to speak the same language, a rating system with several levels has been defined to assess the technology readiness level of products.

The broader diversity of items developed for the hydrogen sector is not yet produced at the scale found in other parts of the energy economy. The manufacturing quantities of fuel cell engines and the components necessary to produce current hydrogen systems are not yet comparable to those of traditional internal combustion engines or battery systems. Given this situation, it is critical for systems engineers to understand the maturity level of the goods being integrated into their systems, both in terms of development and manufacture.
In an ideal world, a fuel cell or hydrogen system would be designed using only components with a technological readiness Level of 9 (TRL 9) and a manufacturing readiness Level of 10. (MRL 10). This would imply that, while the system created does not yet match any of these criteria, it does have integrated components and technologies that have been tested in the defined operational environment and are made in series, and utilising lean manufacturing techniques.

- A technological readiness level (TRL) of 9 indicates that the technology has been **polished and accepted**.
- A technological readiness Level 8 (TRL 8) indicates that an engineering product has been **tested in its operating setting**.
- A technological readiness level of 7 (TRL 7) typically indicates that a product prototype has been **proven in an operating setting**.
- A Technology Readiness Level (TRL) of 6 indicates that a product prototype has been **demonstrated** in the relevant environment.
- A Technology Readiness Level (TRL) of 5 or less indicates that the product development has **not yet reached the prototype stage**.

Since this research is focused on implementing existing hydrogen solutions in an already existing energy portfolio, the TRLs can be assumed to be at least 7 or higher for a solution to be considered. Since Pure Energie will be buying the technology from a manufacturer, most research should on operations has already been concluded. Only minor improvements or alterations are acceptable.

3.6.1 Strategic roadmap of EU and the Netherlands

The European Union (EU) has highlighted the production of green hydrogen as a top priority for meeting its long-term climate goals. In accordance with this objective, the EU has produced a strategic roadmap for green hydrogen production, which provides a comprehensive plan for the expansion of hydrogen production, the deployment of hydrogen infrastructure, and the promotion of research in this field[Clifford Chance, 2020].

Being a prominent actor in the hydrogen industry, the Netherlands has also developed its own strategy plan for the development of green hydrogen. The nation has set lofty goals for the production and consumption of hydrogen in an effort to become a world leader in this field[**?**]

The strategic roadmap for green hydrogen production in the European Union and the Netherlands is founded on scientific principles, including a thorough evaluation of the technical, economic, and social aspects of hydrogen production and consumption. It highlights the significance of collaboration and cooperation among diverse stakeholders, such as governments, industry entities, and research institutes.

Several major factors comprise the strategic road map for green hydrogen generation in the EU and the Netherlands. Among these are the establishment of a regulatory framework to support the development of hydrogen infrastructure, the implementation of incentives to encourage investment in hydrogen technology, the promotion of research and development in this area, and the deployment of large-scale hydrogen production facilities to scale up hydrogen production [Clifford Chance, 2020]. In addition, the strategic road map calls for the implementation of hydrogen in multiple areas, including transportation, manufacturing, and energy generation. This is anticipated to greatly contribute to the reduction of carbon emissions and the achievement of climate goals in these areas.

The strategic roadmap for green hydrogen generation in the EU and the Netherlands is founded on scientific principles and seeks to provide a comprehensive framework for the advancement of hydrogen technology. The implementation of this road map will necessitate the collaboration and cooperation of numerous stakeholders, and its success will be contingent on the successful implementation of the policies and initiatives specified in it.

3.7 Conclusion

This section will reflect on the theoretical framework and answers the research questions that are set during the research setup. The theoretical framework section provides an overview of the various concepts, policies, and technologies related to hydrogen production through electrolysis. This section reflects on the fundamental principles of hydrogen production as well as the technicalities involved in the design and implementation of hydrogen energy systems. Additionally, this section examines the policies and regulations that have been put in place to promote the adoption of hydrogen as an alternative energy source. Through an in-depth analysis of these topics, this section aims to provide a comprehensive understanding of the key factors that are critical to the successful implementation of hydrogen-based energy systems.
The following research questions were answered in this chapter:

Research questions answered

- *What is hydrogen and how does green hydrogen differ from other types of hydrogen (e.g. grey or blue)?*

  Section 3.1 explains the difference between the types of hydrogen and also the environmental impact of the different categories [Feder, 2021]. Since Pure Energie solely focusses on renewable energy sources, the only possible category of hydrogen is green hydrogen [Pure Energie, 2022]. Green hydrogen can only be produced through electrolysis powered by renewable energy sources.

- *What is a hydrogen electrolyser, what types of electrolysers are available and how do they interact with existing energy grids and systems?*

  Hydrogen Electrolysis is explained in section 3.2. Different techniques and systems are discussed, but the choice was made to make use of PEM electrolysers. PEM electrolysers are better suited for rapid up- and down scaling of production [van der Burg, 2022]. This characteristic is necessary when dealing with unstable or unpredictable power sources like wind- and solar farms. Since the portfolio of Pure Energie consists of only wind and solar assets, the choice for a PEM electrolyser is made.

- *What are the requirements for a hydrogen system to operate?*

  System requirements for PEM electrolyser systems are discussed and reviewed in section 3.3. The main components are shown in a schematic overview in figure 3.6. For operational requirements the most important aspects are a stable feedwater supply. Electrolysis consumes 18 to 25 litres of water for each kilogram of hydrogen [Cummins Inc., 2020]. A renewable energy source, and a plot of land for the plant to be build on are also of essence.

- *What are the developments regarding hydrogen policies in the Netherlands, neighbour countries and European Union?*

  In section 3.6 the subsidies and regulations within the European Union and the Netherlands have been highlighted. To goal is to incerase the amount of hydrogen in Europes energy mix from 2% to 14% by 2050. At the same time, the goal is to reduce greenhouse gasses by at least 50% by 2030 [European Commission, 2020]. to reach these goals, green hydrogen production has to be scaled up quickly. In section 3.6 several possible subsidies have been elaborated as well as some of the technical requirements to qualify for these subsidies. During the business model calculations, the case is calculated without the help of subsidies. This can be compared to the market, and then it can be decided how much subsidy is needed for the project to become feasible. This is done since subsidies are project dependent and are assessed for each project independently.

- *What is the business model for hydrogen electrolysis?*

  The lack of a single, ideal business paradigm for hydrogen electrolysis is a key finding of this research. This discovery challenges the notion that a standardised approach can be applied in all cases, regardless of local or regional conditions. The three distinct business models presented in Chapter 4 reflect the distinctive characteristics of the Dutch market, such as the local renewable energy sources and regulations, and provide a road map for future research in other regions.

  Unfortunately, there is no ”one perfect business model” for hydrogen electrolysis that fits every case. In chapter 4, three business models and scenarios are given. These three models are later calculated in chapter 5 and the results are compared.

4 BUSINESS MODEL FOR GREEN HYDROGEN PRODUCTION

This study combines a comprehensive literature evaluation with expert interviews in the field of electrolysis-based hydrogen production. By conducting a comprehensive analysis of the current state of hydrogen production and the governing policies and regulations, this study has provided a theoretical framework for understanding the key factors that are essential for the successful implementation of hydrogen-based energy systems.

Furthermore, the three distinct business models presented in Chapter 4 reflect the distinctive characteristics of the Dutch market, such as the local renewable energy sources and regulations, and provide a roadmap for future research in other regions. The detailed analysis of these models allows for an exploration of the strengths and weaknesses of each, as well as a comparison of their potential profitability and sustainability.

This chapter will explain and assess three potential investment scenarios for Pure Energie's hydrogen production solution investments. The selection of these scenarios is predicated on the company's commitment to sustainability and its goal to cut expenses and maximise efficacy. Various considerations, including technical feasibility, economic viability, and environmental impact, will be used to evaluate the scenarios.

4.1 Scenario explanation

Hydrogen is becoming an attractive energy source due to its high energy density, simplicity of storage and transport, and absence of greenhouse gas emissions during usage. Consequently, there is a growing interest in designing and executing hydrogen generation systems that can facilitate the commercialization of this attractive energy source.

There are numerous strategies for designing a hydrogen production plan, each with its own pros and downsides. For instance, one method is to rely on the grid for electricity, and another strategy is to incorporate renewable energy sources. A third method is to rely solely on renewable energy sources, thereby decreasing reliance on the grid and lowering energy costs.

Regardless of the exact technique, the development of a dependable and cost-effective hydrogen production system is essential for achieving the entire energy source potential of hydrogen. This demands the incorporation of cutting-edge technologies, meticulous planning, and investment in infrastructure and energy systems.

It is essential to emphasise that all of these methods for producing hydrogen are essential for satisfying the rising need for clean energy. Each technique has its own advantages and disadvantages, and the business or organization's objectives, resources, and limits will choose which strategy to follow. Nonetheless, the significance of each of these techniques cannot be emphasised, as they will play a pivotal part in determining the future of hydrogen energy and its global influence.

4.1.1 Scenario 1: Stand-alone Hydrogen electrolyser

In this scenario, the electrolyser functions as a stand-alone commercial entity that draws all of its electricity from the grid. This indicates that it will cover the total cost of electricity, including any transportation fees. This scenario is ideal for firms that lack access to a renewable energy source or do not wish to engage in the construction and maintenance of a renewable energy system. However, the cost of electricity from the grid may be higher than that of a renewable energy source, reducing the cost-effectiveness of this scenario.

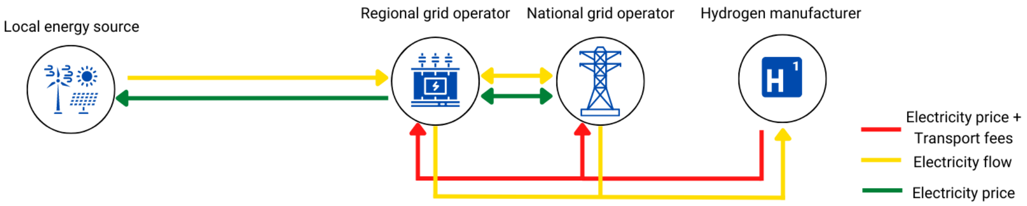


Figure 4.1: Visualisation of a standalone hydrogen production scenario

4.1.2 Scenario 2: Hydrogen production with renewable and grid energy as input

In this scenario, the electrolyser is powered in part by a renewable energy source and in part by the grid. This can lower energy costs and lessen dependency on grid-sourced electricity, but involves a substantial investment in the construction and maintenance of the renewable energy source. In addition, the electrolyser may continue to incur transit costs for the grid-sourced electricity.

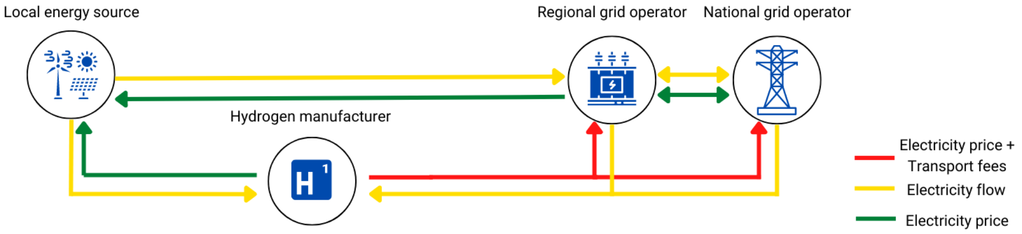


Figure 4.2: Visualisation of hydrogen production with a grid connection and renewable energy source

4.1.3 Scenario 3: Hydrogen production only with direct input from renewable energy sources

In this case, the electrolyser is entirely powered by a renewable energy source and receives no electricity from the grid. This eliminates transportation fees and decreases energy costs. This scenario is, however, constrained by the availability of renewable energy. As stated previously, renewable energy sources rely on wind or the sun to generate electricity. This means that the availability of renewable energy is not as consistent and predictable as fossil or nuclear energy.

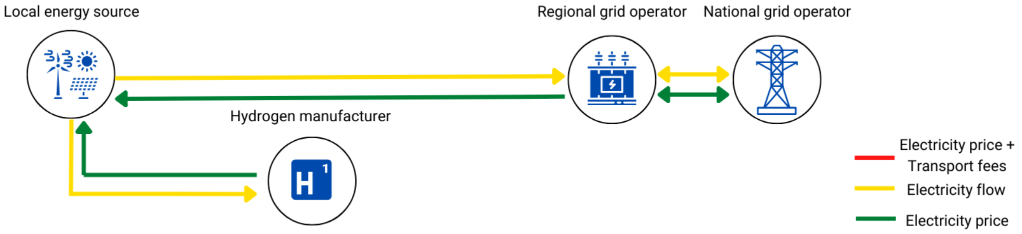


Figure 4.3: Visualisation of hydrogen production with only renewable energy as input

4.2 Requirements for the production of green hydrogen

Proton Exchange Membrane (PEM) electrolysers are essential to the creation of green hydrogen, which is hydrogen produced using renewable energy. The PEM electrolyser employs a proton exchange membrane to separate hydrogen and oxygen from water by electrolysis, resulting in the creation of hydrogen gas. The entire Hydrogen production plant is visualised earlier in chapter three. This section will describe the various inputs, conditions, and specific costs of the system in each scenario.

Several conditions must be followed in order for a PEM electrolyser to produce green hydrogen. These consist of:

- The PEM electrolyser requires a consistent and dependable supply of electrical energy from renewable sources such as solar, wind, or hydropower. During electrolysis, this energy is used to separate water into hydrogen and oxygen. For each scenario the input of electricity is different. For scenarios one and two, energy is also fed into the system from the grid. To ensure that this energy comes from a renewable energy source, A Guarantee of Origin (GoO) is needed for every MWh of energy bought from the grid. Another option is to construct a Power Purchase Agreement (PPA) with a renewable energy source, that states that all energy bought, originates from that specific renewable energy source. For scenario three, we already know that all input energy is directly coming from the renewable energy source. No GoO is needed for this. A PPA could be helpful when negotiating a long-term price for energy, similar to a long-term energy contract. Described in chapter three, we assume three scenarios for long-term energy prices, high (125€/MWh), middle (100€/MWh), and low (80€/MWh) average price expectancy.
- Operating conditions (OPEX): The PEM electrolyser must be operated within a certain range of temperature and pressure for optimal performance. Additionally, the working conditions must be carefully managed to prevent membrane and component corrosion and degradation. Maintenance, water supply and other resources are for each scenario the same. The OPEX costs are described in chapter 3 and can be found in 3.1.
- Investment costs (CAPEX): The cost of producing hydrogen via PEM electrolysis is a key factor in the commercial viability of this technology. Capital expenditures (CAPEX) are a significant component of the total cost of hydrogen production, and there has been considerable research in recent years aimed at reducing these costs in order to make PEM electrolysis more economically viable. The cost breakdown according to [IRENA, 2020] and Confirmed by SIEMENS ENERGY, is shown in 3.12.
- Transport of hydrogen: In this research, the transport of hydrogen is neglected. It is not know in what state or under which pressure the consumer wishes to receive the hydrogen. Therefore, the hydrogen is calculated per kilogram and the pressure or state of the product has to be analysed for each costumer specific.
- Transport of energy: For scenarios one and two, where energy bought from the grid, transport fees have to be paid over the energy that is taken from the grid. transport fees are depending on the amount of energy that is taken from the grid and can increase significantly when the amount of energy bought from the grid increases. The electricity transport costs have been calculated in chapter 5.
- Subsidies: The Netherlands offers per-kilogram subsidies or one-time investment grants for green hydrogen generation. These subsidies encourage the Netherlands' green hydrogen sector, which is crucial to its energy transition to a low-carbon, sustainable energy system. In the business model calculations, the CAPEX investment grants are calculated per 25% increase in subsidy. The subsidy per kilogram of hydrogen is less relevant for the calculations. A levelized cost of hydrogen is calculated as a minimum.

  The per-kilogram subsidy funds green hydrogen production. This subsidy covers the electrolyser, renewable energy source, and infrastructure costs of green hydrogen production.

The per-kilogram subsidy aims to make green hydrogen generation profitable and lower product costs by providing a continuous funding source.

A one-time investment incentive covers the startup expenditures of green hydrogen production. This subsidy helps companies and organisations overcome the high cost of electrolyzers and other equipment to enter the green hydrogen market. The one-time investment grant encourages new green hydrogen projects and sector growth by lowering upfront costs.

- Integration of the PEM electrolyser into the larger energy system, including the renewable energy source, electrical grid, and hydrogen storage and distribution systems. This demands meticulous preparation and organisation to ensure effective and flawless operation.

4.3 Scenarios for green hydrogen production at Windpark Groen

Windplan Groen is part of the Wind Energy Regioplan of the Flevoland province. The province is divided into four subareas according to the Regioplan. The initiators in a subarea collaborate to create one plan that matches the Regioplan's objectives. Windplan Groen is the project area East's plan. This lies in the province's east, in the municipalities of Dronten and Lelystad. The area east of Colijnweg, Roodbeenweg, Zeebiesweg, and Vogelweg is known as the project area East. In figure 4.4, each dot represents a wind turbine [Windplan Groen, 2022].

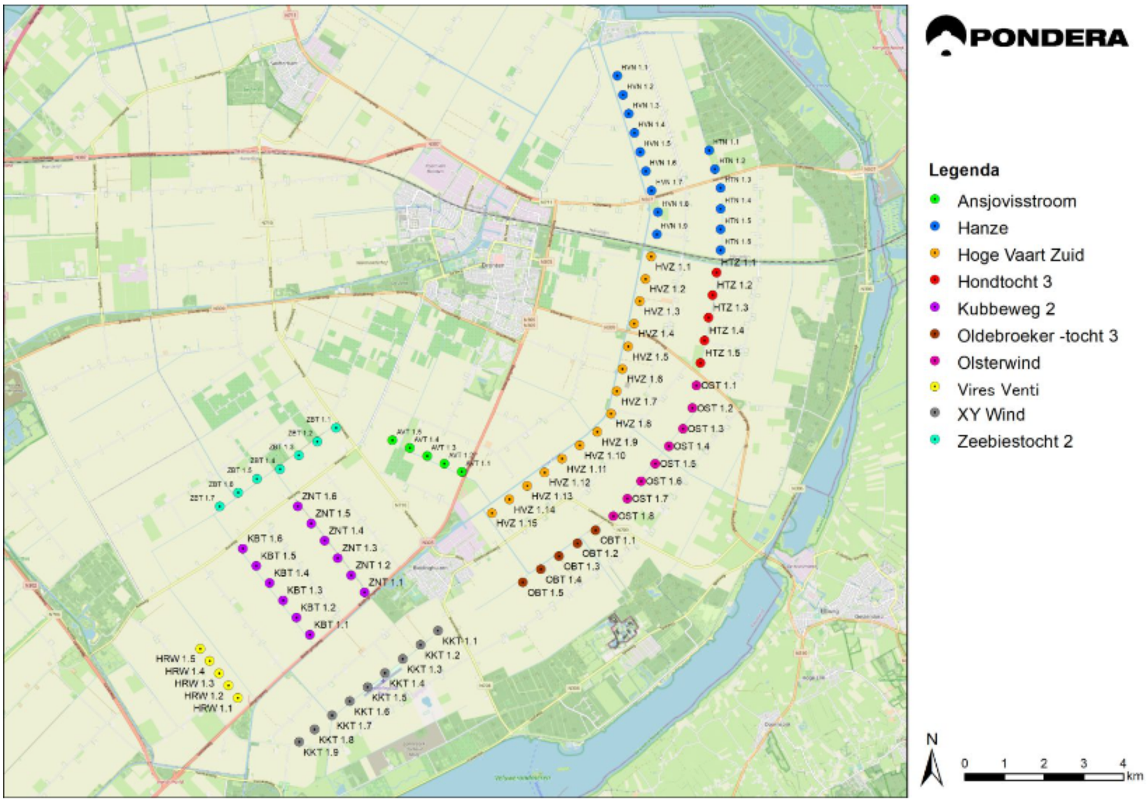


Figure 4.4: Windpland Groen site layout

Windplan Groen is a project that calls for the construction of 90 new wind turbines, 86 of which will be completed in the first phase. The overall proposal is for around 500 MW of new installed capacity. These 86 wind turbines are estimated to generate roughly 1.8 billion kWh per year when combined. That is the amount of electricity utilised in the entire province of Flevoland in a year.

Pure Energie is one of the stakeholders in the Windplan Groen Project, (partially) owning 20 of the wind turbines built at the project site. The interest in investing in green hydrogen production could be combined with this large-scale wind project. The windpark could be used to supply the electrolyser with renewable energy used to produced green hydrogen. This could be interesting for scenarios two and three, placing the electrolyser between the wind turbines and the energy grid, therefore reducing the transport fees of electricity. The windpark could also provide the electrolyser of scenario one with energy, however, the electrolyser has to have a PPA with the wind park and also has to pay transport fees in full.

4.4 Key elements of each scenario

This section summarises the key elements and general assumptions of each specific scenario. The fit with Windpark Groen will also be described.

4.4.1 Scenario 1: stand-alone hydrogen electrolyser

Positive aspects

- (Possible) Reduction in location costs due to the increased flexibility in the choice of location.
- Reduction in hydrogen transport costs due to the increased flexibility in the choice of location. e.g. The electrolyser could be placed near the end-cosumer or a large pipeline.
- Increased flexibility in energy partners. The electrolyser could close a PPA with all renewable energy producers and is not limited to only one source.
- Optimised operating hours. In this scenario, the electrolyser is not limited by the output uncertainty of the renewable energy source.

Negative aspects

- Increase in energy transport costs due to all energy being transported over the national grid network.

4.4.2 Scenario 2: Hydrogen production with renewable and grid energy as input

Positive aspects

- Reduction in energy transport costs since the input energy is partially fed directly from the renewable energy source, therefore not subject to grid transport costs.
- Optimised operating hours. In this scenario, the electrolyser is not limited by the output uncertainty of the renewable energy source, it also has the grid as an auxiliary input possibility.

Negative aspects

- Increase in energy transport costs due to a part of the energy being transported over the national grid network.
- Reduced flexibility in the choice of energy partner. The input directly from the renewable energy source is fixed, and the energy from the grid has more flexibility in the choice of PPA partner.

4.4.3 Scenario 3: Hydrogen production only with direct input from renewable energy sources

Positive aspects

- No energy transport costs since the input energy is completely fed directly from the renewable energy source, therefore not subject to grid transport costs.
- Just one PPA partner since all energy is directly sourced from the renewable energy source.

Negative aspects

- No flexibility in operating hours. The electrolyser can only be powered when sufficient renewable energy is produced by the source.

5 BUSINESS CASE CALCULATIONS

During this chapter, the research will focus on the quantitative results of each scenario and strategy connected to the study. In this section, the assumptions, the implications, the results, and the sensitivity analysis will be performed. Based on the results of this section, the key factors for the success of these investment strategies can be calculated. It can be used by Pure Energie to decide whether investing in hydrogen is interesting for their portfolio.

5.1 Assumptions

The success of these business cases largely depends on the accuracy of the assumptions made during the business case analysis. Business case analysis involves the estimation of costs, benefits, risks, and returns on investment. Assumptions are an essential component of the analysis as they provide the basis for forecasting future outcomes. This thesis aims to examine the assumptions used in the business case analysis for hydrogen projects and their impact on the accuracy of the analysis. By doing so, the thesis aims to contribute to the development of effective business case analysis frameworks for hydrogen projects, which can support decision-makers (Pure Energie) in identifying and financing sustainable energy investments.

5.1.1 Energy price

The cost of energy is a significant factor in the economic feasibility of renewable energy projects. The profitability of hydrogen electrolyser projects, for instance, is dependent on the energy prices used as inputs in the business case analysis. As stated in section 3.4.3 OPEX, we will examine the assumptions made on energy prices for a hydrogen electrolyser project using high, middle, and low energy prices of €115, €80, and €56 euros per MWh, respectively. The objective of this thesis is to evaluate the sensitivity of the business case analysis to these energy price assumptions and to explore their implications for the economic viability of the project.

5.1.2 Wind analysis

Since two of the business cases are relying on the input of green energy directly from a wind farm, the electricity output and availability of the wind farm have to be assessed. Since the wind farm used for the calculations, Windplan Groen, is not operational as of this moment, assumptions are made to calculate the power available for the electrolyser. At the location of Windplan Groen, Pure Energie already exploits a smaller-scale wind farm. This wind farm will be deconstructed in order to make room for the new and larger turbines of Windplan Groen. However, since Pure Energie has already exploited the during the past decade, there is wind data available for every 15 minutes that the turbine has been operational. Using this wind data and the power curve of the new and improved wind turbines, we are able to simulate the performance of the new wind farm. For the calculations, the data is used to simulate the output every 15 minutes of this wind farm. By using this as input for the business case, we are able to estimate the amount of electricity that will be generated, and make an estimation of how much electricity is available for the electrolyser

It is assumed that the historical wind data is representative of the future performance of Windplan Groen. The total wind capacity of this farm is calculated at approximately 300MW and it is assumed in these calculations that the entirety of this capacity can be used to power the hydrogen electrolyser.

5.1.3 OPEX and CAPEX costs

As described earlier in sections 3.4.1 OPEX and 3.4.2 CAPEX, the assumptions on these costs are based on earlier research of external bureaus and also the confirmation of the results by commercial parties in this branch. CAPEX for a complete system is set at € 1400 per kW of installed capacity. Replacement of the cell stacks after 8 years is set at €400 per KW of installed capacity. General O&M costs are set at 2% of the initial investment. For the CAPEX costs, a economy of scale factor 0.98 has been implemented. This implicates that the size of the electrolyser is multiplied by the power of 0.98 and therefore decreases the CAPEX if the size increases. For a 50 MW electrolyser, the economy of scale factor reduces the price per kW of installed capacity from € 1400 to €1296.72.

5.1.4 Expected Internal Rate of Return

For the investment to become interesting for Pure Energie, an Internal Rate of Return (IRR) should be at least 10%. The economical feasibility of the project succeeding is therefore of importance. In this section, The Levelized Cost Of Hydrogen (LCOH) is calculated for each scenario. The LCOH depicts the price at which the hydrogen should at least be sold in order to obtain this IRR of 10%.

Pure Energie's hydrogen project investment criteria is 10% IRR. Due to market unpredictability, regulatory changes, and technology developments, investing in a hydrogen project is risky.

Large-scale energy industry investments require a long-term view. Pure Energie's long-term hydrogen project investment requires a minimum 10% IRR to justify the risk.

5.1.5 Size of the electrolyser

The PEM electrolyser is set at a size of 50MW of production capacity. This is done to reach an economy of scale that has mass and traction. For Pure Energie, it is not interesting to invest in production units with a much lower capacity due to the complexity of such a project. By increasing capacity, the complexity of the project is not increasing at the same rate at which the economics of the project scale. Therefore, the size of 50 MW was set as a target. Essential to note is that this is not calculated to be optimal but more stated as an objective.

5.1.6 Operating efficiency and resource consumption

Assumed is that the PEM electrolyser operates at an efficiency of 60 kWh/kg H2. This means that for every kilogram of hydrogen output, 60 kWh of electricity is consumed. Other resource expenses are set at 10% of the initial investment size multiplied by the capacity factor. Resource expenses include the purified water that is consumed during the hydrogen production process, as well as other types of resources that are consumed.

5.2 Results

5.2.1 Scenario 1: Stand-alone hydrogen electrolyser

This section shows the business case calculations of the scenario where the PEM electrolyser is connected directly to the energy grid. In figure 5.1 a simplified sketch of the system is given.

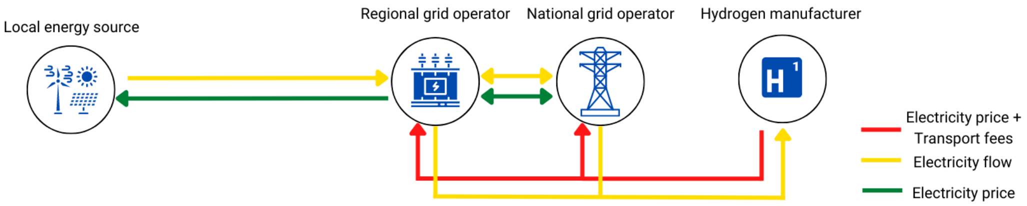
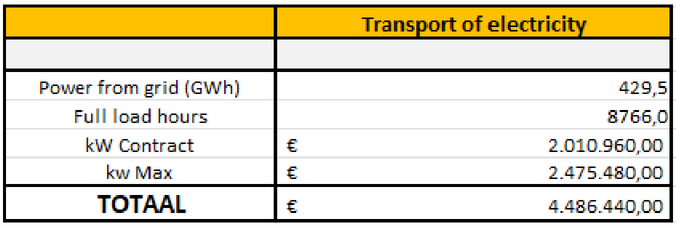


Figure 5.1: Visualisation of hydrogen production with a grid connection and renewable energy source

In this scenario, the energy grid, is the only source of power for the electrolyser. This means that the power input is predictable and the plant is able to run at full capacity all the time. To correct unforeseen downtime and maintenance, the maximum rate of operating is set at 98%.. By using this projection, we are able to calculate the transport cost of the electricity to power the 50 MW PEM electrolyser.

The transport cost of electricity can become significant if large amounts of electricity are withdrawn from the grid. The transport costs for this scenario are shown in 5.2.



	Transport of electricity
Power from grid (GWh)	429,5
Full load hours	8766,0
kW Contract	€ 2.010.960,00
kw Max	€ 2.475.480,00
TOTAAL	€ 4.486.440,00

Figure 5.2: Electricity transport costs scenario 1

For scenario 1, the Cumulative discounted cash flow of the investment is shown in figure 5.3. Visible are the Cumulative discounted cash flows under the three possible price scenarios. This shows the sensitivity of the business case to changes in electricity price. In the figure, a hydrogen price of 7.49 €/kg H2 and no CAPEX grant is used. For the electricity price of 80 €/MWh, the business case returns an IRR of 10%. For the high electricity price, the investment is not feasible. For the low energy price scenario, the project is very profitable with an IRR of 39.5%.

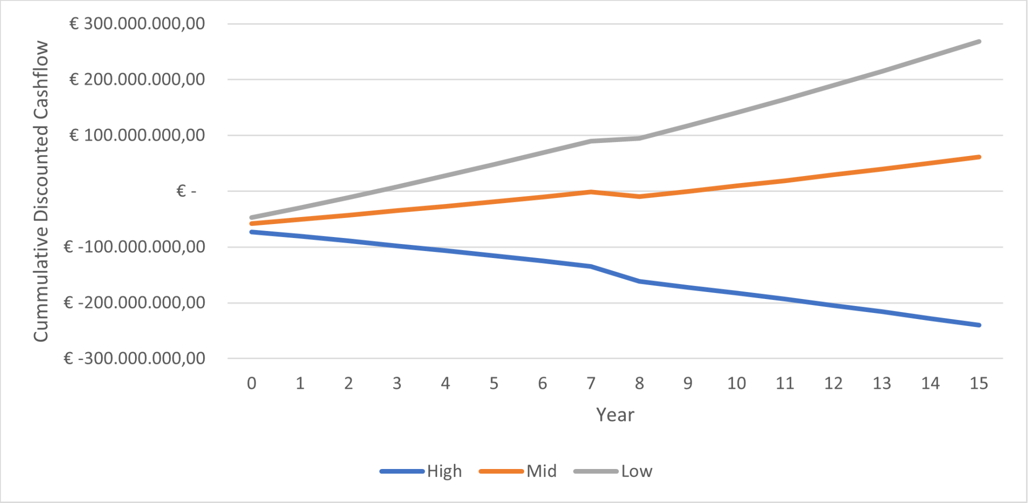


Figure 5.3: Cummulative discounted cashflow for three price scenarios for scenario 1

The revenue for scenario 1 is based on the hydrogen price, which is set at 7.49 €/kg H2. The revenue for all three price scenarios is therefore the same. In figure 5.11 the revenue is plotted over the years. The revenue is increasing over time since it is indexed against inflation, with the inflation rate set at 5%.

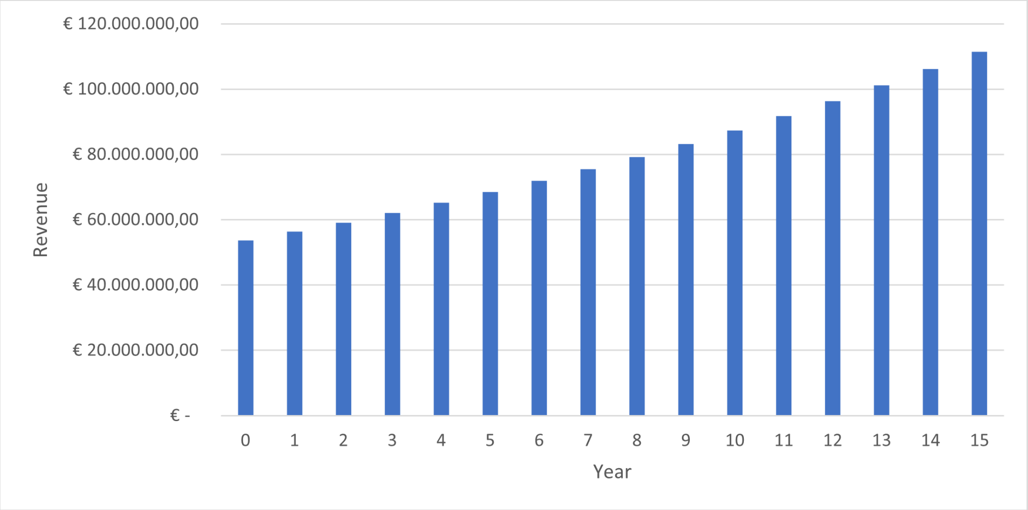


Figure 5.4: Revenue for scenario 1

In figure 5.12, the levelized cost of hydrogen is plotted against the amount of CAPEX subsidy on the project. The LCOH is plotted up until a CAPEX subsidy of 75%. However, as stated in section 3.5.1 Subsidies, it is not usual for subsidies to exceed 50% of the initial CAPEX investment for this kind of project. Therefore, the most realistic scenarios would be those with a CAPEX subsidy between 25% and 50%.

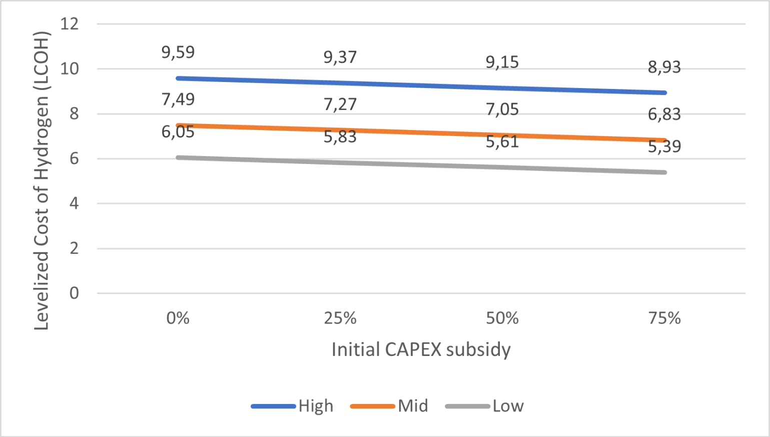


Figure 5.5: Levelized Cost of Hydrogen (LCOH) scenario 1

The cost breakdown for every electricity price scenario can be found in appendix A. Since the electricity price is the only variable between these scenarios, the expenses on electricity are the only changing factor. This again shows the high sensitivity of the business case to changing electricity prices.

Conclusion

The calculations of this scenario show that it is only possible to reach a 10% IRR if the hydrogen price is set at 6.05 €/kg H2 and with an electricity price of 56 €/MWh (low price scenario). For the price scenario at 80 €/MWh, a hydrogen price of 7.49 €/kg H2 is needed to reach an IRR of 10%. Using a CAPEX grant of 25% we could reduce the hydrogen price to 7.27 €/kg H2. A 50% CAPEX grant could result in a 10% IRR with a hydrogen price of 7.05 €/kg H2. For the high-price scenario of 115 €/MWh, a 10% IRR can be reached with a hydrogen price of 9.59 €/kg H2. A 25% CAPEX grant reduces the hydrogen price to 9.37 €/kg H2 and still returns the desired 10% IRR.

5.2.2 Scenario 2: Hydrogen production with renewable and grid energy as input

This section shows the business case calculations of the scenario where the PEM electrolyser is connected directly to the wind park, and also to the energy grid. In figure 5.6 a simplified sketch of the system is given.

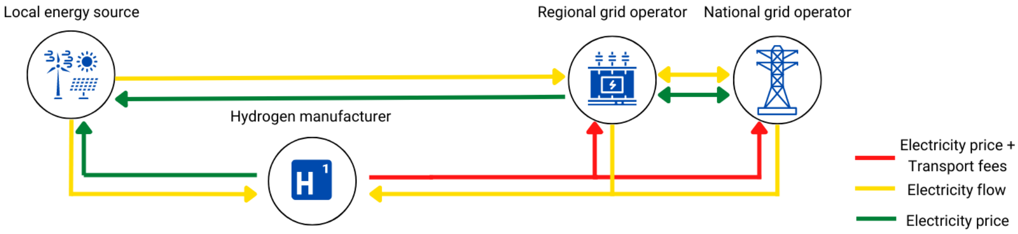
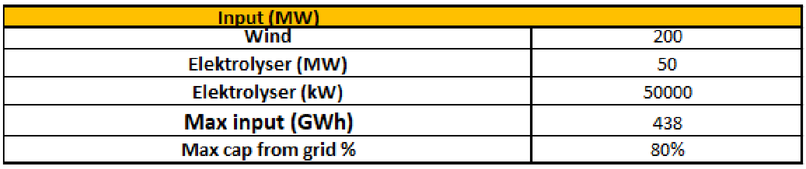


Figure 5.6: Visualisation of hydrogen production with a grid connection and renewable energy source

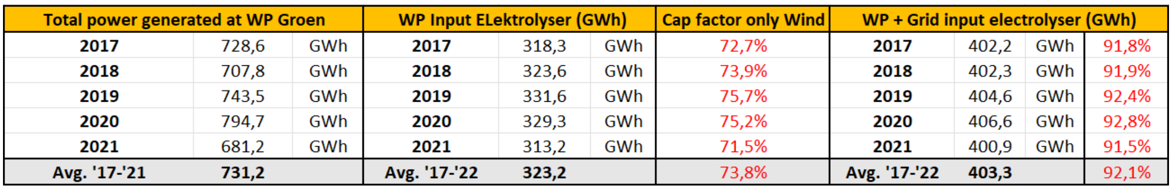
Since this scenario is dependent on both the input from the wind park as well as the energy grid, the input from the wind park is calculated and energy from the grid is added to reach the desired capacity factor. The wind data that is used in the calculations are based on the collected wind data at the windplan Groen location from 2017 until 2022. This data shows the wind speed every 15 minutes. These wind speeds are multiplied by the power curve of the new wind turbines. This gives a realistic projection of the power output that the new wind turbines could have reached if they were installed before 2017. By using this projection, we are able to calculate the capacity factor of the 50 MW PEM electrolyser with or without additional power input from the grid. In figure 5.7 the input parameters of the wind data calculations are given.



Input (MW)	
Wind	200
Elektrolyser (MW)	50
Elektrolyser (kW)	50000
Max input (GWh)	438
Max cap from grid %	80%

Figure 5.7: Input parameters scenario 2

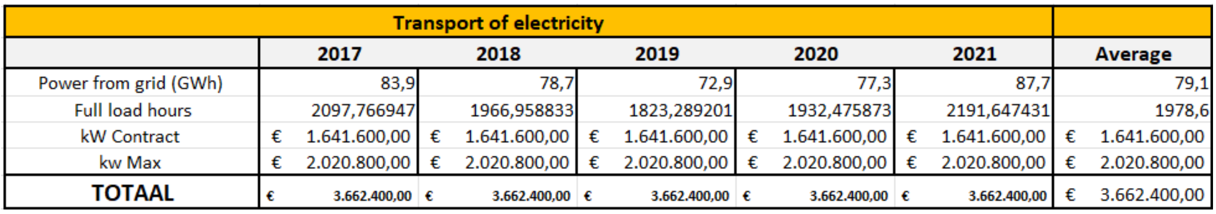
The results of the wind data analysis are shown in figure 5.8. based on the wind data, we can conclude that a 50 MW PEM electrolyser, connected to windplan Groen, is able to reach a capacity factor of 73.8% on average. In other words, the electrolyser can run on full power 73.8% of the time or 6464 hours per year. This capacity factor is reached by solely powering the electrolyser directly from the available renewable energy at that specific moment. However, A higher capacity factor could be beneficial for the business case. Therefore, if there is not sufficient renewable wind energy available from windplan Groen, the system is allowed to take energy from the grid. This means that the system is always operating at, at least 80% of its possible capacity, or higher if there is sufficient renewable wind energy available from the wind park. By adding this grid connection, the system is able to reach a capacity factor of 92.1% on average. This is an increase of 18.3%.



Total power generated at WP Groen			WP Input ELektrolyser (GWh)			Cap factor only Wind	WP + Grid input electrolyser (GWh)			
2017	728,6	GWh	**2017**	318,3	GWh	72,7%	**2017**	402,2	GWh	91,8%
2018	707,8	GWh	**2018**	323,6	GWh	73,9%	**2018**	402,3	GWh	91,9%
2019	743,5	GWh	**2019**	331,6	GWh	75,7%	**2019**	404,6	GWh	92,4%
2020	794,7	GWh	**2020**	329,3	GWh	75,2%	**2020**	406,6	GWh	92,8%
2021	681,2	GWh	**2021**	313,2	GWh	71,5%	**2021**	400,9	GWh	91,5%
Avg. '17-'21	**731,2**		**Avg. '17-'22**	**323,2**		73,8%	**Avg. '17-'22**	**403,3**		92,1%

Figure 5.8: Capacity factor scenario 2

The transport cost of electricity can become significant if large amounts of electricity are withdrawn from the grid. The transport costs for this scenario are shown in 5.9.



Transport of electricity						
	2017	**2018**	**2019**	**2020**	**2021**	**Average**
Power from grid (GWh)	83,9	78,7	72,9	77,3	87,7	79,1
Full load hours	2097,766947	1966,958833	1823,289201	1932,475873	2191,647431	1978,6
kW Contract	€ 1.641.600,00	€ 1.641.600,00	€ 1.641.600,00	€ 1.641.600,00	€ 1.641.600,00	€ 1.641.600,00
kw Max	€ 2.020.800,00	€ 2.020.800,00	€ 2.020.800,00	€ 2.020.800,00	€ 2.020.800,00	€ 2.020.800,00
TOTAAL	€ 3.662.400,00	€ 3.662.400,00	€ 3.662.400,00	€ 3.662.400,00	€ 3.662.400,00	€ 3.662.400,00

Figure 5.9: Electricity transport costs scenario 2

For scenario 2, the Cumulative discounted cash flow of the investment is shown in figure 5.10. Visible are the Cumulative discounted cash flows under the three possible price scenarios. This shows the sensitivity of the business case to changes in electricity price. In the figure, a hydrogen price of 7.49 €/kg H2 and no CAPEX subsidy grant is used. For the electricity price of 80 €/MWh, the business case returns an IRR of 10%. For the high electricity price, the investment is not feasible. For the low energy price scenario, the project is very profitable with an IRR of 37.6%.

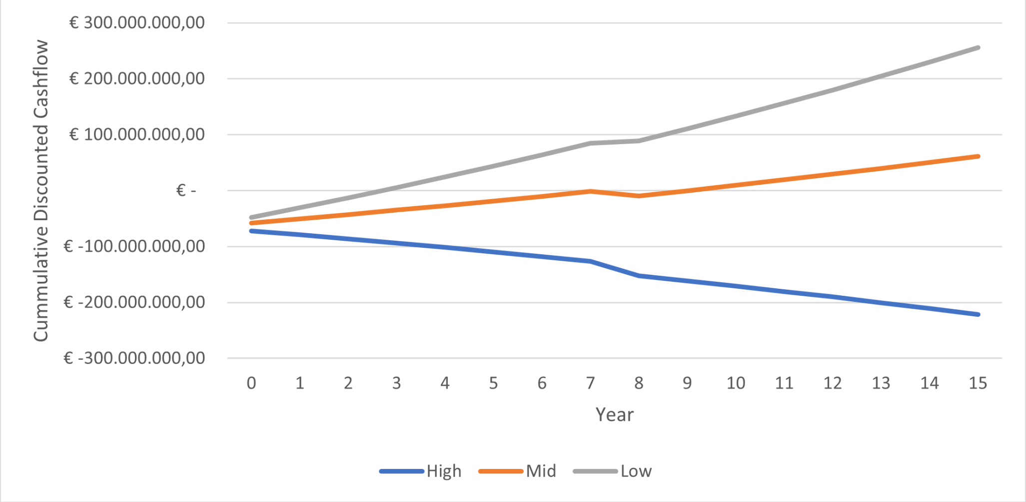


Figure 5.10: Cummulative discounted cashflow for three price scenarios for scenario 2

The revenue for scenario 2 is based on the hydrogen price, which is set at 7.49 €/kg H2. The revenue for all three price scenarios is therefore the same. In figure 5.11 the revenue is plotted over the years. The revenue is increasing over time since it is indexed against inflation, with the inflation rate set at 5%.

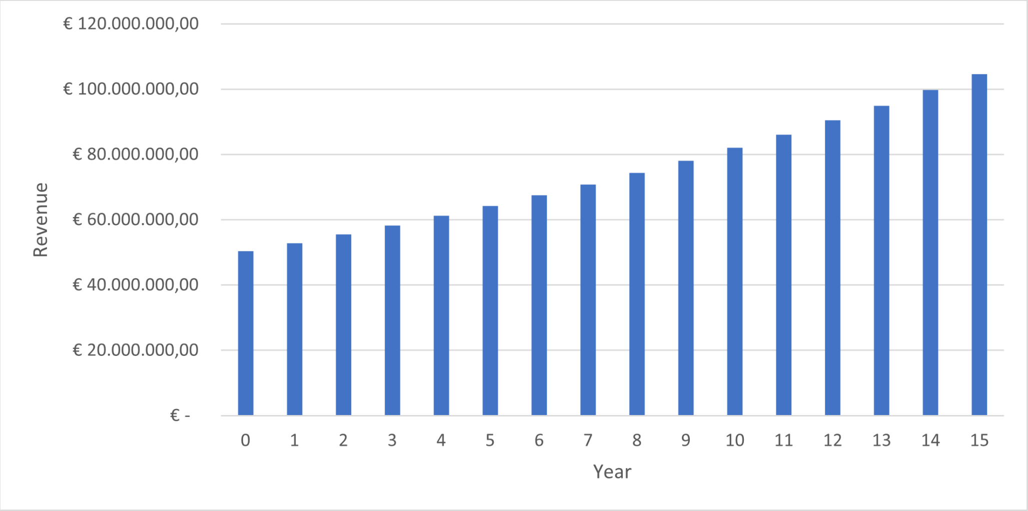


Figure 5.11: Revenue for scenario 2

In figure 5.12, the levelized cost of hydrogen is plotted against the amount of CAPEX subsidy on the project. The LCOH is plotted up until a CAPEX subsidy of 75%. However, as stated in section 3.5.1 Subsidies, it is not usual for subsidies to exceed 50% of the initial CAPEX investment for this kind of project. Therefore, the most realistic scenarios would be those with a CAPEX subsidy between 25% and 50%.

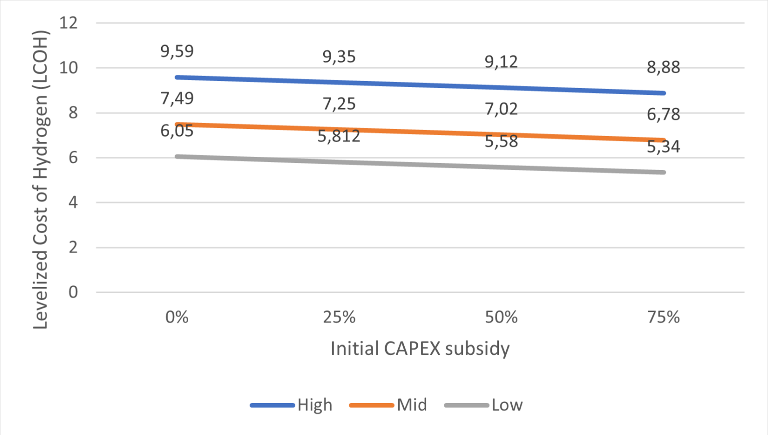


Figure 5.12: Levelized Cost of Hydrogen (LCOH) scenario 2

The cost breakdown for every electricity price scenario can be found in appendix B. Since the electricity price is the only variable between these scenarios, the expenses on electricity are the only changing factor. This again shows the high sensitivity of the business case to changing electricity prices.

Conclusion

The calculations of this scenario show that it is only possible to reach a 10% IRR if the hydrogen price is set at 6.05 €/kg H2 and with an electricity price of 56 €/MWh (low price scenario). For the price scenario at 80 €/MWh, a hydrogen price of 7.49 €/kg H2 is needed to reach an IRR of 10%. Using a CAPEX grant of 25% we could reduce the hydrogen price to 7.25 €/kg H2. A 50% CAPEX grant could result in a 10% IRR with a hydrogen price of 7.02 €/kg H2. For the high-price scenario of 115 €/MWh, a 10% IRR can be reached with a hydrogen price of 9.59

€/kg H2. A 25% CAPEX grant reduces the hydrogen price to 9.35 €/kg H2 and still returns the desired 10% IRR.

5.2.3 Scenario 3: Hydrogen production only with direct input from renewable energy sources

This section shows the business case calculations of the scenario where the PEM electrolyser is connected directly to the wind park. In figure 5.13 a simplified sketch of the system is given. The system is connected to the grid as well. However, this is done as a safety measure since hydrogen gas is a highly flammable, and complete loss of power could result in catastrophic failure. Therefore, there is a grid connection that is able to power the plant at 10% of its operational capacity. This small grid connection is not shown in the schematic overview since it is only installed as a safety measure.

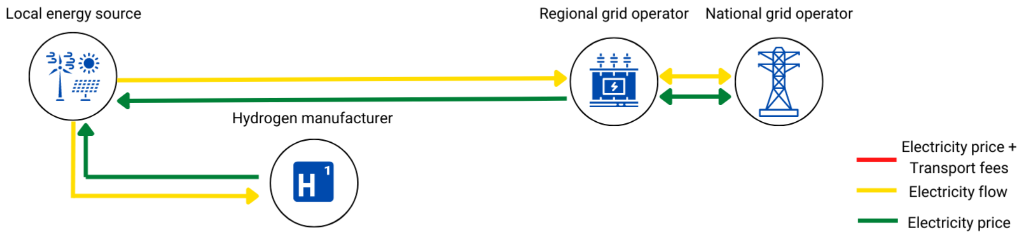
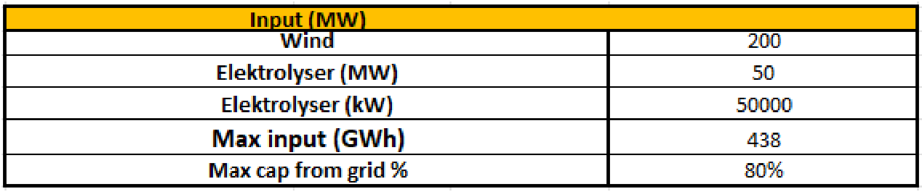


Figure 5.13: Visualisation of hydrogen production with a grid connection and renewable energy source

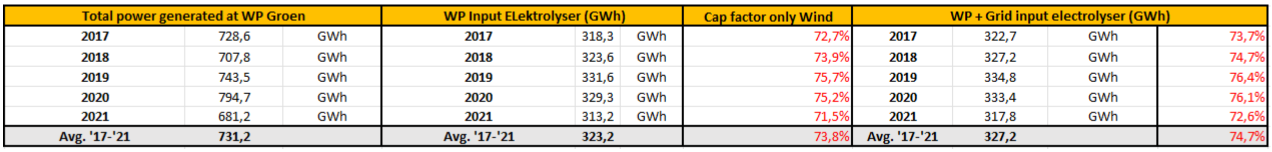
Since this scenario is solely dependent on the input from the wind park. The output from the wind park is estimated and the capacity factor of the electrolyser is calculated. The wind data that is used in the calculations are based on the collected wind data at the windplan Groen location from 2017 until 2022. This data shows the wind speed every 15 minutes. These wind speeds are multiplied by the power curve of the new wind turbines. This gives a realistic projection of the power output that the new wind turbines could have reached if they were installed before 2017. By using this projection, we are able to calculate the capacity factor of the 50 MW PEM electrolyser with or without additional power input from the grid. In figure 5.14 the input parameters of the wind data calculations are given.



Input (MW)	
Wind	200
Elektrolyser (MW)	50
Elektrolyser (kW)	50000
Max input (GWh)	438
Max cap from grid %	80%

Figure 5.14: Input parameters scenario 3

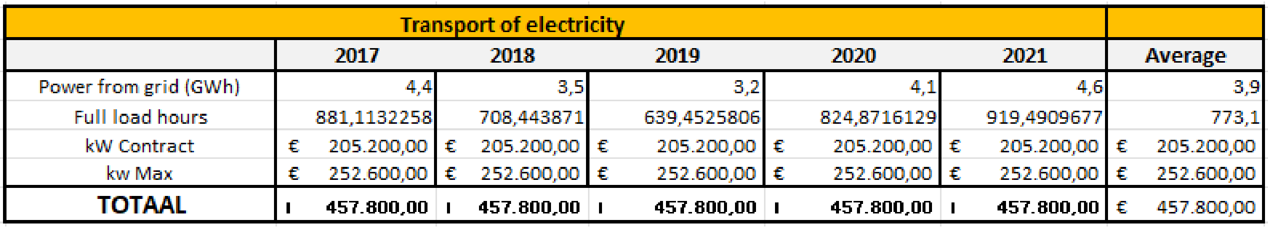
The results of the wind data analysis are shown in figure 5.15. based on the wind data, we can conclude that a 50 MW PEM electrolyser, connected to windplan Groen, is able to reach a capacity factor of 73.8% on average. In other words, the electrolyser can run on full power 73.8% of the time or 6464 hours per year. This capacity factor is reached by solely powering the electrolyser directly from the available renewable energy at that specific moment. As safety measure, if there is not sufficient renewable wind energy available from windplan Groen, the system is allowed to take energy from the grid. This means that the system is always running at, at least 10% of its possible capacity, or higher if there is sufficient renewable wind energy available from the wind park. By adding this grid connection, the system is able to reach a slightly higher capacity factor of 74.7% on average. This is an increase of 0.9%.



Total power generated at WP Groen			WP Input ELektrolyser (GWh)			Cap factor only Wind	WP + Grid input electrolyser (GWh)			
2017	728,6	GWh	**2017**	318,3	GWh	72,7%	**2017**	322,7	GWh	73,7%
2018	707,8	GWh	**2018**	323,6	GWh	73,9%	**2018**	327,2	GWh	74,7%
2019	743,5	GWh	**2019**	331,6	GWh	75,7%	**2019**	334,8	GWh	76,4%
2020	794,7	GWh	**2020**	329,3	GWh	75,2%	**2020**	333,4	GWh	76,1%
2021	681,2	GWh	**2021**	313,2	GWh	71,5%	**2021**	317,8	GWh	72,6%
Avg. '17-'21	**731,2**		**Avg. '17-'21**	**323,2**		73,8%	**Avg. '17-'21**	**327,2**		74,7%

Figure 5.15: Capacity factor scenario 3

Even with a minor grid connection similar to the one used in this scenario, the transport cost of electricity cannot be neglected. The estimated costs are shown in figure 5.16.



Transport of electricity						
	2017	**2018**	**2019**	**2020**	**2021**	**Average**
Power from grid (GWh)	4,4	3,5	3,2	4,1	4,6	3,9
Full load hours	881,1132258	708,443871	639,4525806	824,8716129	919,4909677	773,1
kW Contract	€ 205.200,00	€ 205.200,00	€ 205.200,00	€ 205.200,00	€ 205.200,00	€ 205.200,00
kw Max	€ 252.600,00	€ 252.600,00	€ 252.600,00	€ 252.600,00	€ 252.600,00	€ 252.600,00
TOTAAL	**ı 457.800,00**	**ı 457.800,00**	**ı 457.800,00**	**ı 457.800,00**	**ı 457.800,00**	€ 457.800,00

Figure 5.16: Electricity transport costs scenario 3

For scenario 2, the Cumulative discounted cash flow of the investment is shown in figure 5.17. Visible are the Cumulative discounted cash flows under the three possible price scenarios. This shows the sensitivity of the business case to changes in electricity price. In the figure, a hydrogen price of 7.32 €/kg H2 and no CAPEX subsidy grant is used. For the electricity price of 80 €/MWh, the business case returns an IRR of 10%. For the high electricity price, the investment is not feasible. For the low energy price scenario, the project is very profitable with an IRR of 32.1%.

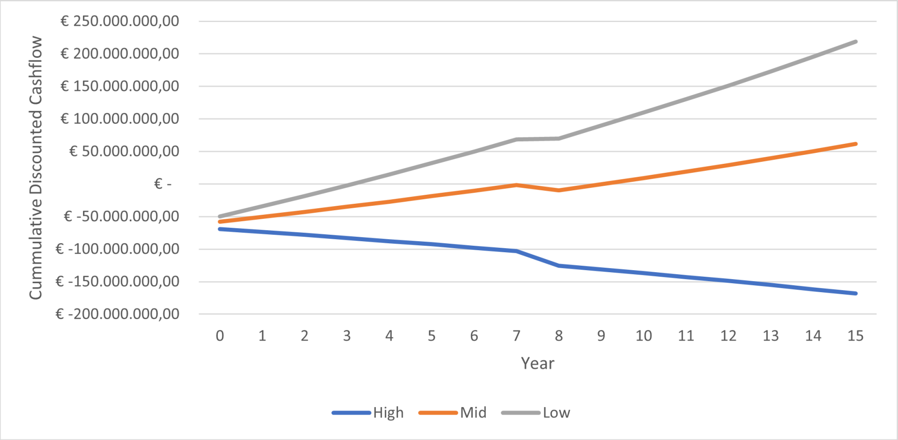


Figure 5.17: Cummulative discounted cashflow for three price scenarios for scenario 2

The revenue for scenario 2 is based on the hydrogen price, which is set at 7.32 €/kg H2. The revenue for all three price scenarios is therefore the same. In figure 5.11 the revenue is plotted over the years. The revenue is increasing over time since it is indexed against inflation, with the inflation rate set at 5%.

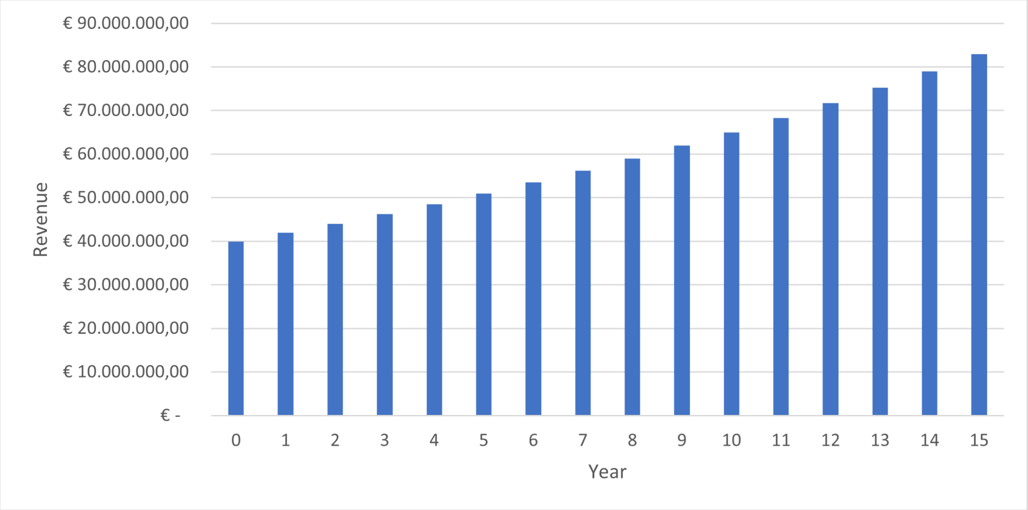


Figure 5.18: Revenue for scenario 3

In figure 5.19, the levelized cost of hydrogen is plotted against the amount of CAPEX subsidy on the project. The LCOH is plotted up until a CAPEX subsidy of 75%. However, as stated in section 3.5.1 Subsidies, it is not usual for subsidies to exceed 50% of the initial CAPEX investment for this kind of project. Therefore, the most realistic scenarios would be those with a CAPEX subsidy between 25% and 50%.

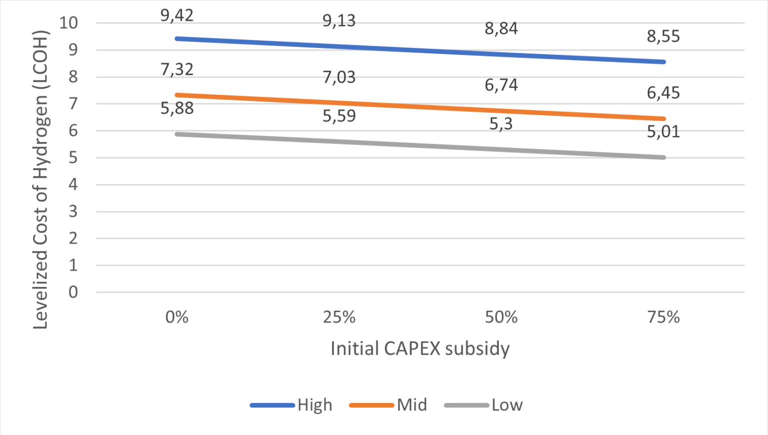


Figure 5.19: Levelized Cost of Hydrogen (LCOH) scenario 3

The cost breakdown for every electricity price scenario can be found in appendix C. Since the electricity price is the only variable between these scenarios, the expenses on electricity are the only changing factor. This again shows the high sensitivity of the business case to changing electricity prices.

Conclusion

The calculations of this scenario show that it is only possible to reach a 10% IRR if the hydrogen price is set at 5.88 €/kg H2 and with an electricity price of 56 €/MWh (low price scenario). For the price scenario at 80 €/MWh, a hydrogen price of 7.32 €/kg H2 is needed to reach an IRR of 10%. Using a CAPEX grant of 25% we could reduce the hydrogen price to 7.03 €/kg H2. A 50% CAPEX grant could result in a 10% IRR with a hydrogen price of 6.74 €/kg H2. For the high-price scenario of 115 €/MWh, a 10% IRR can be reached with a hydrogen price of 9.42 €/kg H2. A 25% CAPEX grant reduces the hydrogen price to 9.13 €/kg H2 and still returns the desired 10% IRR.

5.3 Sensitivity analysis

The results of each scenario already showed that the project is very susceptible to changes in electricity prices and hydrogen prices. This section will show the sensitivity to other factors like changes in the CAPEX, OPEX, or an increase or decrease in available wind power. For the sensitivity analysis, scenario 2 is used as the baseline scenario since this scenario uses both wind and grid energy.

5.3.1 Change in hydrogen price

The desired IRR of 10% is obtained for the mid-price scenario at an LCOH of 7,49 €/kg H2. In figure 5.20 the IRR is plotted against the increase in hydrogen price per kilogram. This figure shows that 1% change in price results in a 1,43% change in IRR. Therefore it can be concluded that the hydrogen price is of key importance for the feasibility of this project.

Figure 5.20: Sensitivity to change in H2 price with respect to the basecase

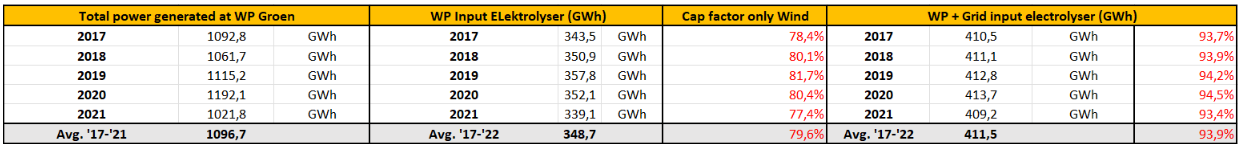
5.3.2 Change in CAPEX

Changes in CAPEX are simulated with the increasing CAPEX grant for each scenario. The sensitivity shows a decrease in Levelized cost of hydrogen for the project. The largest decrease in LCOH price found was a 14,73% decrease when a 75% CAPEX grant is used in scenario 1. It could be helpful to use a CAPEX grant to push the business case from a ”good” level to a ”great” level. However, the OPEX factors are significantly more important.

5.3.3 Change in capacity factor

An increase or decrease in capacity factor could influence the profitability of the project. Change in capacity factor is achievable in two ways for scenario 2. By increasing the availability of wind power or by increasing the power taken from the electricity grid. To increase the available wind power, the simulation assumes that there is 300 MW of wind power available instead of the 200

MW assumed in earlier calculations. This implicates that the first priority of the entire windplan Groen Turbine park, is to power the electrolyser. The capacity factors are shown in figure 5.21.



Total power generated at WP Groen			WP Input ELektrolyser (GWh)			Cap factor only Wind	WP + Grid input electrolyser (GWh)			
2017	1092,8	GWh	**2017**	343,5	GWh	78,4%	**2017**	410,5	GWh	93,7%
2018	1061,7	GWh	**2018**	350,9	GWh	80,1%	**2018**	411,1	GWh	93,9%
2019	1115,2	GWh	**2019**	357,8	GWh	81,7%	**2019**	412,8	GWh	94,2%
2020	1192,1	GWh	**2020**	352,1	GWh	80,4%	**2020**	413,7	GWh	94,5%
2021	1021,8	GWh	**2021**	339,1	GWh	77,4%	**2021**	409,2	GWh	93,4%
Avg. '17-'21	**1096,7**		**Avg. '17-'22**	**348,7**		79,6%	**Avg. '17-'22**	**411,5**		93,9%

Figure 5.21: Change in capacity factors if available windpower is increased

By increasing the available wind power with 50% (200 MW to 300 MW), the capacity factor using only wind power as the input increases from 73.8% to 79,6%. The IRR increases from 10% to 10,71%. Increasing the available wind power and therefore increasing the capacity factor shows minimal sensitivity.

5.4 Incentives to improve the business case

The deployment of hydrogen electrolysers has resulted from the rising demand for renewable energy sources and interest in decarbonising the energy industry. However, the economic viability of these technologies remains a considerable obstacle, as the electrolysis-based production of hydrogen is energy-intensive and requires substantial capital investments. In this section, different incentives to improve the business case for hydrogen electrolysis and increase their market acceptance, are discussed.

5.4.1 Frequency control and grid balance

Participation in the frequency control market is one strategy to encourage the deployment of hydrogen electrolysers. Frequency control refers to the regulation of the frequency of the electricity system, which is essential for preserving the grid's stability and dependability. As explained in section 3.5, Grid balance and frequency control are methods to generate extra income for projects like a hydrogen electrolyser. By incorporating hydrogen electrolysers into the market for frequency management, they can provide grid-balancing services by altering their hydrogen production in response to variations in grid frequency. This not only creates more income for the system operator, but also enhances the economic viability of hydrogen electrolysers by raising their utilisation rates and generating an additional revenue stream.

5.4.2 Grid congesiton

Another strategy to promote the deployment of hydrogen electrolysers is to profit from solving grid congestion problems. Grid congestion refers to situations in which the transmission and distribution network has insufficient capacity to accommodate the flow of power. This can lead to the deactivation of renewable energy sources, such as wind and solar, that are frequently located in remote places with limited grid connection. By situating hydrogen electrolysers in places with significant grid congestion, they can absorb excess renewable energy production that would otherwise be limited. This provides a significant service to the grid operator and can produce additional income for the electrolyser operator via payments for curtailment avoidance or congestion management. Since grid congestion is a relatively new problem, absolute numbers to profit from solving these problems are not been broadly published yet. a recommendation for further research could be to investigate the possibilities for a PEM electrolyser to profit from this.

5.4.3 Flexible energy contracts

Using variable energy prices to power the electrolyser is a third technique to promote the deployment of hydrogen electrolysers. The cost of energy can change significantly over time, depending on factors such as demand, weather conditions, and availability of supply. By designing hydrogen electrolysers to operate on changing energy costs, they can take advantage of low-cost power during periods of excess supply and limit their usage during periods of high-cost electricity. This can increase the electrolyser's economic viability by lowering its running expenses and boosting its profitability.

5.5 Conclusion

The business model calculations show the parameters where the demanded 10% IRR is obtained for a 50 MW PEM electrolyser system located at or near windplan Groen. The parameters for each of the three scenarios are show differences but these differences are not extreme. The key findings from the sensitivity analysis show is that the business case shows high sensitivity to changes is in electricity price and hydrogen price. Lower sensitivities are shown to the factors in the system like CAPEX factors and the change in capacity factor.

An interesting result from the calculations is the sensitivity to changing transport costs, which is lower than presumed. While the scenario 3, with a minimal grid connection, shows the lowest LCOH, the difference between scenarios 1 and 3 in electricity transport costs is approximately €4 million, the difference in LCOH is €0,17 per kg H2 (at 0% CAPEX grant). This difference is less extreme that presumed before the research. This reduces the sensitivity to location and creates new possibilities to place electrolysers near locations with high grid congestion and therefore create a new revenue stream for the project, possibly increasing profitability.

Incentives such as involvement in the frequency control market, taking advantage of grid congestion, and utilising variable energy prices can improve the business case for hydrogen electrolysers and encourage their market adoption. These tactics not only offer extra revenue streams for the electrolyser operator but also provide valuable services to the grid operator, including as balancing services, curtailment avoidance, and congestion management. Policymakers and industry stakeholders may accelerate the deployment of hydrogen electrolysers and promote the transition to a more sustainable and decarbonised energy system by implementing these incentives.

6 CONCLUSION, DISCUSSION AND RECOMMENDATIONS

6.1 Conclusion

In conclusion, investing in hydrogen could be a feasible option for Pure Energie for several reasons. Firstly, the global demand for clean energy is rapidly increasing, and hydrogen is considered to be a key player in the transition to a low-carbon economy. This presents a significant market opportunity for Pure Energie, which is already an established player in the renewable energy industry. However, to reach a viable business case, several parameters have to be in check in order for the project to succeed.

Pure Energie has a broad portfolio of renewable energy-producing assets in the Netherlands. To combine hydrogen optimally with these assets, the choice was made to use a PEM electrolyser of 50 MW. Based on the portfolio of Pure Energie, windplan Groen is selected as the most suitable for hydrogen expansion. This location has a total output of 300 MW of which 25 of the 90 turbines are (partially) owned or operated by Pure Energie. During the business case calculations, three scenarios for different system setups have been analysed. The scenarios: powering the electrolyser directly from the grid, using power from both the grid and directly the wind turbines as input, or using only the wind turbines as input and having an auxiliary connection to the grid as a safety measure. The results of all three scenarios are relatively close to each other. More interesting is the sensitivity to the electricity price and the hydrogen price, as well as the insensitivity to the transport of electricity cost. This factors implicate that the price of the input energy and the price per kilogram of hydrogen is more important than the geographical position of the project. Another location could also improve the business case by placing it near locations with high grid congestion. This should create additional income streams for the project.

In order for the hydrogen project to be successful, a Power Purchase Agreement (PPA) or a fixed energy contract is important. A variable contract could result in a feasible project as well. However, this is unlikely due to the risk of extreme losses.

Hydrogen gas could be used as a replacement for natural gas or other types of fossil fuels. To compare hydrogen to dutch natural gas, 1 kg of hydrogen contains approximately 4 times as much energy as 1 cubic meter of natural gas. The Levelized Cost of Hydrogen (LCOH) for the scenarios is calculated to be between €5,58 and €9,59 per kg of hydrogen, depending on the amount of CAPEX subsidy and the cost of electricity. This could be comparable to natural gas prices of €1,40 to €2,40 per cubic meter of gas. Using additional subsidies to reduce the cost of hydrogen for the customer, could result in a competitive price point.

Current prices of hydrogen are above €10 per kg of H2 [Staalkaart groene waterstof, 2023] and prices of natural gas are on average in 2023 €1.12 per m3 gas [Zicht op Energie, 2023]. This shows that the calculated prices of hydrogen are below the current market price but above the price of natural gas. So hydrogen is not competitive with natural gas based on price. Taking into account the unique selling point of hydrogen for it being completely renewable and green, it could be competitive for companies looking to decrease their environmental footprint and which are willing to pay for this premium.

The electrolyser could also be used to hedge risk for new wind turbines. Since SDE subsidies are reducing [RVO - Rijksdienst voor Ondernemend Nederland, 2022], a long term fixed energy contract between a wind turbine and a hydrogen electrolyser could be a interesting construction to hedge the risk of market prices for energy. The electrolyser is calculated to be profitable at an electricity price of €80,- per MWh and hydrogen price of € 7,02 per kg. E.g. If a wind turbine is calculated to be profitable from an electricity price of €60,- per MWh, the two assets could both be profitable and are secured of a fixed price for a long period. This results in a reduced portfolio risk of Pure Energie.

6.2 Discussion

The discussion of this research will focus on the acquired information, the findings, the methods of acquiring the information, as well as the limitations of this study. First, a reflection on the research setup and methodology is made and the shortcomings are reported. secondly, we reflect on the assumptions used to create the scenarios and the business model. at last, we reflect on the findings and consider the limitations of the model and how these shape the outcome.

6.2.1 Research setup and methodology

The goal of this research was to investigate the commercial investment possibilities of renewable hydrogen production, and especially for Pure Energie as a company. Since Pure Energie is a company, the investment should have significant economical returns, as well as have a good fit to the vision and already existing portfolio of the company. Therefore the main research question was formulated as follows:
To support the research question, literature research has been conducted at the beginning of this research. This gave an overview of the already available hydrogen systems and also the specifics of green hydrogen production as well as the European and Dutch road map for hydrogen project development. To enforce the findings of the literature review, interviews with several key players in the hydrogen systems market have been conducted. Given the scope of the thesis and the time frame, the literature review should be sufficient. However, given more time and capacity, it could be extended more in terms of the energy market and price movements. The interviews that have been conducted are comprehensive and to the point, but could also be extended in terms of the number of interviews as well as going more in-depth into complete system layouts that are available in the market. What could be interesting is to investigate the upcoming techniques and systems that are promising instead of focusing on the already available systems.

Guidelines, road maps, and subsidies available for hydrogen investments are still described very little in the literature. From a theoretical perspective, there is a reasonable amount of information (see Chapter 3.6) on subsidies already available. However, since hydrogen investments are not common practice yet, practical cases have not been thoroughly described yet. Given more time and resources, this could also be an interesting topic for further research.

Considering the cost of a hydrogen system, the research has gone into depth on multiple aspects of the hydrogen plant as well as confirming this information with the manufacturers of these systems. Given the wake of multiple geopolitical uncertainties and abnormalities, the prices of these systems could deviate in the future [UN Environment Programme, 2023]. Therefore the pre-pandemic as well as the pre-Russo-Ukrainian war price levels [IRENA, 2020] were assumed for the system costs (CAPEX) and also for some of the operational costs (OPEX) factors. For future research, it is recommended to look into the changes in both the energy market as well as the component/materials market to construct a hydrogen plant. Currently, the prices are not seen as representative of long-term future expectations [SIEMENS ENERGY, 2022].

Considering the quantitative data, the main data that is used to research to calculate the business opportunities, is the historic wind data at the Windplan Groen site. The historic data covers the wind speeds from 2017 to 2021 at 15-minute intervals. This data is considered to truthfully represent the future expectations of the wind characteristics at that location. The wind data is extrapolated against the power curve of the newly installed wind turbines and is used to create a visualisation of the expected power generated by these new wind turbines. The average is taken and used as input for the business model. Given the scope of the research, this data should be sufficient. However, the data is collected from different types of wind turbines, slightly shorter ones. This could have a marginal effect on the registered wind speeds. Future research could investigate this discrepancy but it is assumed that the difference is not substantial.

Based on the quantitative data, the literature, and the interviews, the business model calculator is created. The model considers a standard business model with a 15-year investment horizon and is corrected for inflation as well as the risk-free rate. Given the knowledge acquired in the earlier phases of the research, the business calculator has been filled in accordingly. Several assumptions have been made to support these calculations. these assumptions are described in the following section. OPEX and CAPEX are the main drivers for a business model calculator as used in this research. Therefore, the assumptions in these categories are directly correlated with the outcome of the model. For future research, I would suggest focusing investigation on potential revenue streams such as grid congestion and net balancing. These methods of creating revenue are possible with PEM elektrolysers. Given the time frame and scope of this research, these revenue mechanisms are not directly used, due to the lack of concrete information and prices for these operations. Grid congestion is a new mechanism in the energy market and prices have not yet been published at the time of research.

6.2.2 Assumptions

Given the scope and time frame of this research, several assumptions have been made. These assumptions are primarily used during the business model calculations and are mainly a generalisation of the information found during the literature review and interviews. The following assumptions were made:

- Energy Price - Due to highly fluctuating energy prices as a results of the CoVid-19 Pandemic as well as the Russo-Ukrainian war, energy prices have been generalised into three scenarios. A high, middle, and low price scenario. Future research could investigate the characteristics and expectations of future energy prices more in-depth. This could result in more accurate business model calculations and outcomes.

- Wind Analysis - The wind data used during the research consists of historic wind speed measurements at the Windplan Groen site. This data is assumed to be representative but could be improved. Improving the wind data could result in more accurate business model calculations, but it is not expected to have a significant influence.

- OPEX and CAPEX costs - Based on the information provides by the manufacturers during the interviews, as well as the literature review, OPEX and CAPEX costs are based on the IRENA2020 report [IRENA, 2020]. This report dates from 2020, which is considered recent. However, it was released before the Russo-Ukrainian war and during the CoVid-19 pandemic. This could implicate that the prices and numbers are no longer representative for new hydrogen plants. Future research could investigate the influence of these geopolitical occurrences on energy and resource prices. This is necessary for accurate business model calculations and results.

- Expected Internal Rate of Return - The IRR is used to evaluate an investment's profitability. It stands for the discount rate at which the project's net present value (NPV) is equal to zero. An IRR of 10% indicates that Pure Energie anticipates a return greater than the project's cost of capital. However, it is critical to consider if this rate is consistent with industry norms, the project's risk profile, and the strategic objectives of the business. It should also be noted that it is a minimum threshold for Pure Energie. A higher IRR is desirable.
- Operating efficiency of the electrolyser - The amount of energy needed to generate a specific output is referred to as operating efficiency. It reflects the amount of energy needed to create one kilogram of hydrogen in the case of a hydrogen electrolyser (60 kWh in this case). This efficiency indicator is essential for determining the electrolysis process's overall performance and economic sustainability. In [IRENA, 2020], full plant operating efficiencies have been described to be between 51-80 kWh/kg H2. The decision of 60 kWh is slightly higher than average since compression of the hydrogen gas is not adopted in this business model. Compression is one of the plant processes that has a high energy consumption.

6.2.3 Results

The results of the business case calculations are important for the significance of this thesis. Therefore, the results have to be discussed thoroughly and the strengths but also weaknesses of the report have to be indicated for future research.

The conclusion emphasizes that the characteristics required to achieve the desired 10% internal rate of return (IRR) for a 50 MW PEM electrolyser system positioned at or near windplan Groen have been discovered by the business model calculations. The discrepancies between the three scenarios that have been seen are not very extreme, indicating that the project's feasibility is generally constant. This result gives rise to trust in the accuracy of the calculations used in the business case.

The business case's sensitivity analysis reveals the variables that have a big impact on the results. Changes in the price of hydrogen and power are seen to have a significant impact on the business case, indicating that these variables need to be closely watched and handled. On the other hand, the analysis shows that system-related elements, like capital expenditures (CAPEX) and variations in the capacity factor, have lower sensitivity. For decision-makers, this information is useful since it enables them to concentrate on important factors while maximizing the project's financial success.

The computations' less sensitive-than-expected response to shifting transport costs is an intriguing outcome. While scenario 3 has the smallest levelized cost of hydrogen (LCOH), scenario 1's power transport costs are around €4 million higher than scenario 3, which has a limited grid link. Although, assuming a 0% CAPEX grant, the comparable difference in LCOH is only €0.17 per kg H2. This result contradicts the presumption and suggests that the project's location is less important than anticipated. The project may be able to add a new source of income and boost overall profitability by locating electrolysers close to locations with heavy grid congestion.

The conclusion also emphasizes how incentives may affect the viability of the hydrogen electrolysis business case. Additional revenue streams can be created while offering the grid operator useful services by integrating the electrolyser operator in the frequency control market, capitalizing on grid congestion, and using variable energy prices. These include curtailment avoidance, congestion management, and balancing services. The addition of such incentives improves the electrolysis project's financial performance while also advancing the creation of a carbon-free, more sustainable energy system.

6.3 Recommendations

According to the analysis of the hydrogen electrolyser project, additional research is required in a number of areas to improve its efficiency and financial viability. These territories consist of:

1. Considering energy prices play a major part in evaluating the economic sustainability of the hydrogen electrolyser project, it is advised that additional study be conducted to acquire a more accurate forecast of future energy prices. This can be accomplished by evaluating past trends, market dynamics, and future regulations in order to generate more precise price estimates.

2. Forecasting the price of green hydrogen is essential for establishing the financial viability of the project. Consequently, additional research is required to more definitely anticipate the price of green hydrogen. This can be accomplished by assessing the production cost of green hydrogen and the price of hydrogen derived from fossil fuels.

3. Revenue production via net congestion and grid balancing: More research is required to investigate the potential for earning additional income via net congestion and grid balancing. This may involve examining the current market conditions, the future demand for these services, and the regulatory structure governing them.

4. Increasing the efficiency of the cell stack in the short term is essential for enhancing the performance of the electrolyser. To improve efficiency in the short term, it is recommended to conduct an additional study into the most recent breakthroughs in cell stack technology, such as novel materials and production procedures.

5. The availability and amount of subsidies for green hydrogen electrolysis projects vary between areas and nations. Thus, it is vital to undertake additional research on the availability and scope of hydrogen electrolysis project subsidies. This research could include an examination of current subsidy policies, their efficacy, and possible future changes.

To improve the efficiency and financial viability of the hydrogen electrolyser project, additional research is required. By investigating these areas in greater detail, it will be feasible to optimise the project's performance, improve its profitability, and promote the widespread acceptance of green hydrogen as a clean and sustainable energy source.

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A : SCENARIO 1 COST BREAKDOWN

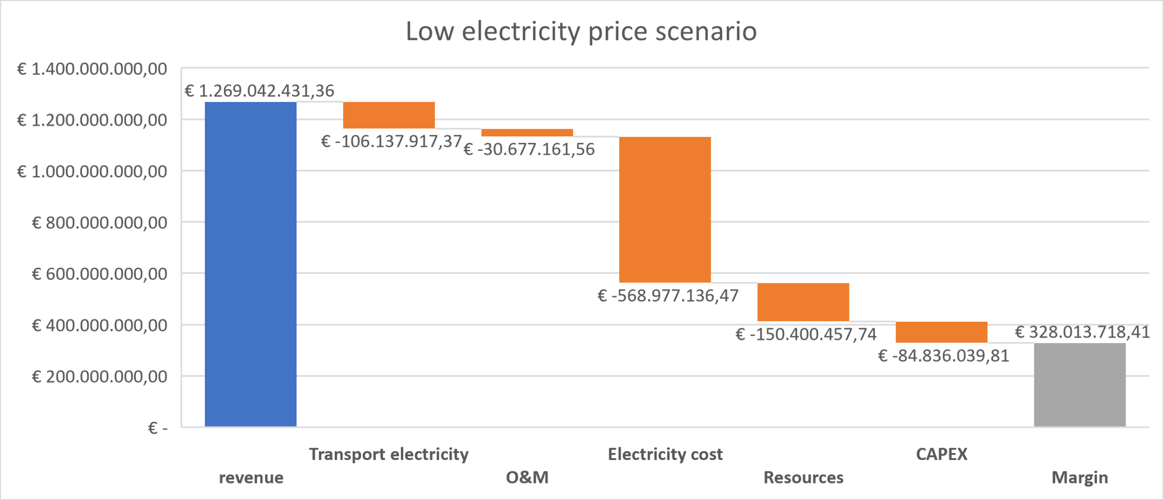

Figure A.1: Cost breakdown low energy price scenario: scenario 1

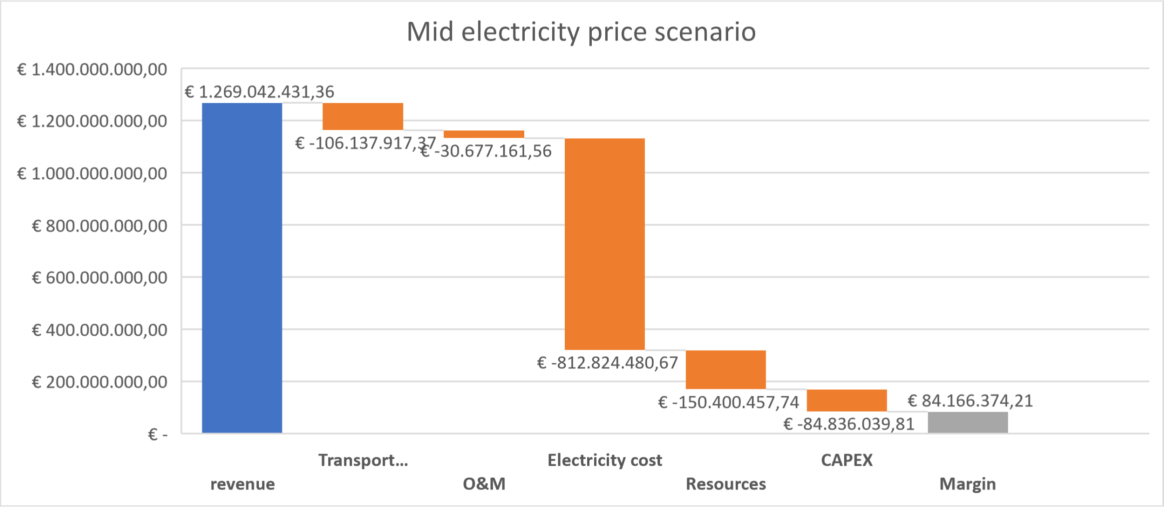

Figure A.2: Cost breakdown mid energy price scenario: scenario 1

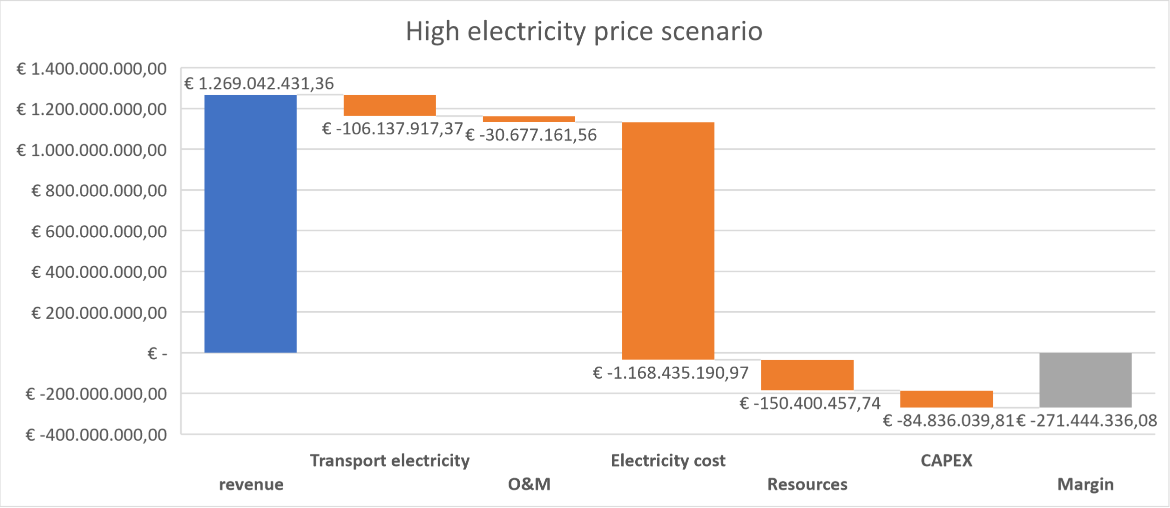

Figure A.3: Cost breakdown high energy price scenario: scenario 1

B : SCENARIO 2 COST BREAKDOWN

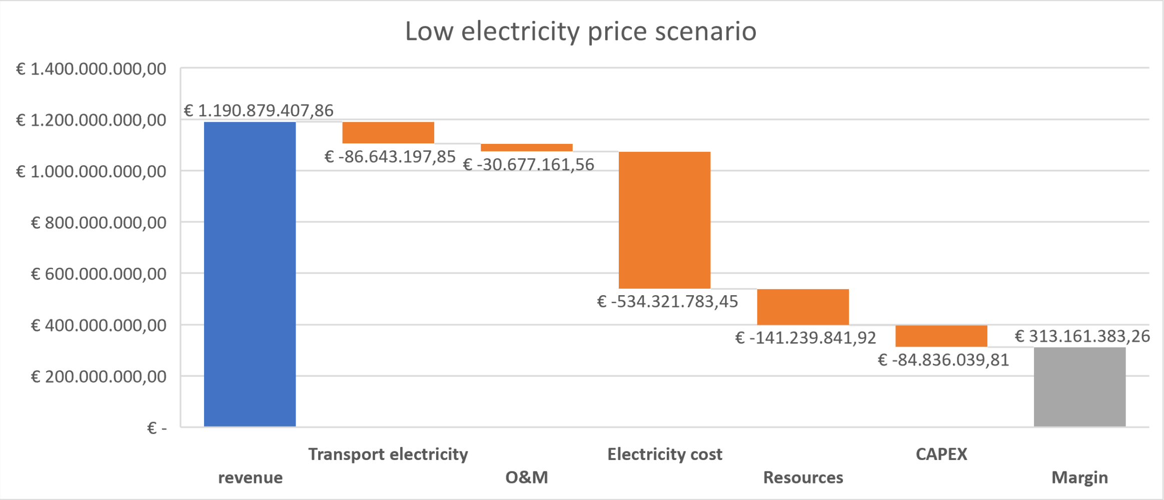

Figure B.1: Cost breakdown low energy price scenario: scenario 2

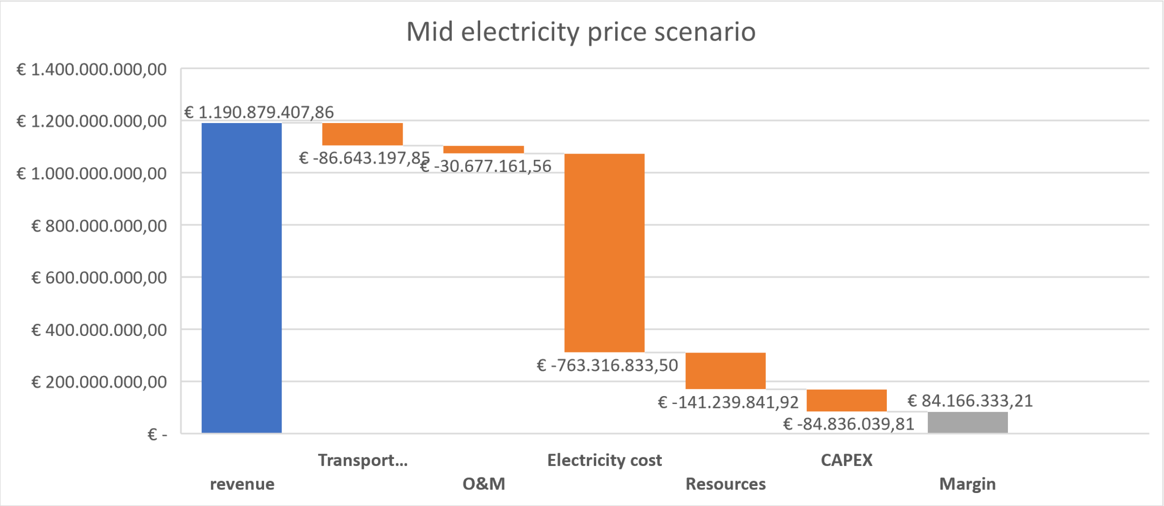

Figure B.2: Cost breakdown low energy price scenario: scenario 2

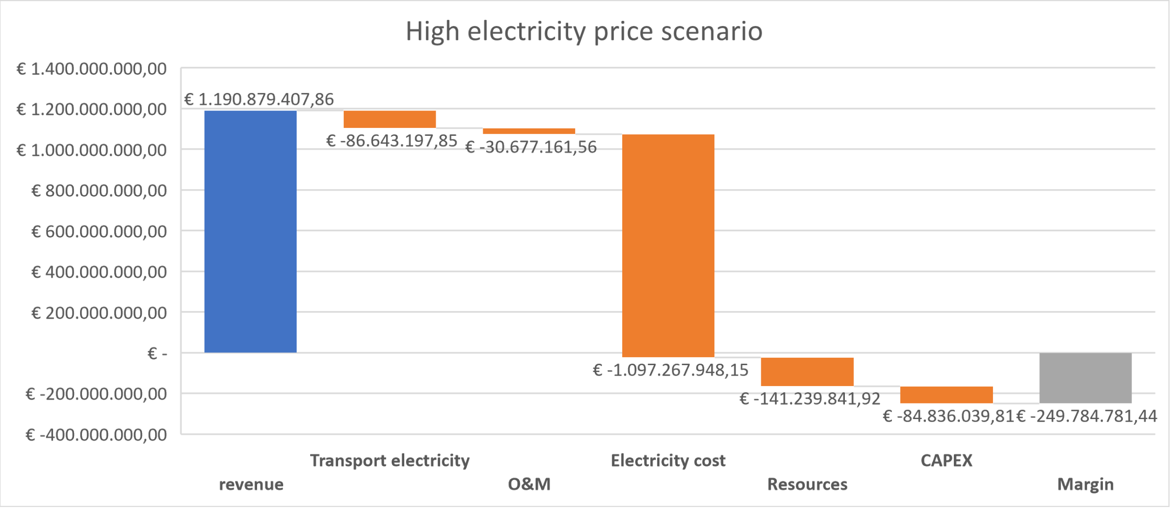

Figure B.3: Cost breakdown low energy price scenario: scenario 2

C : SCENARIO 3 COST BREAKDOWN

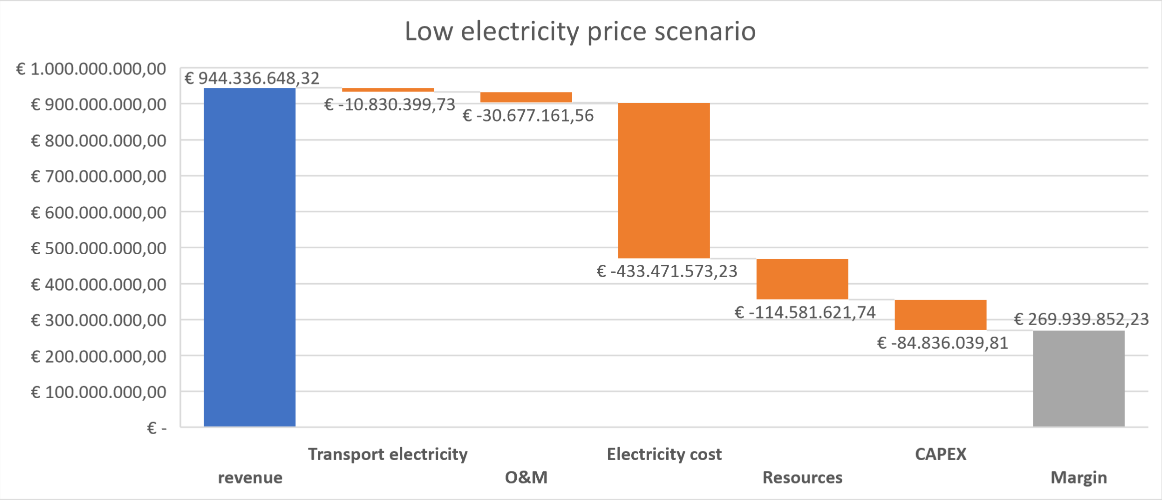

Figure C.1: Cost breakdown low energy price scenario: scenario 2

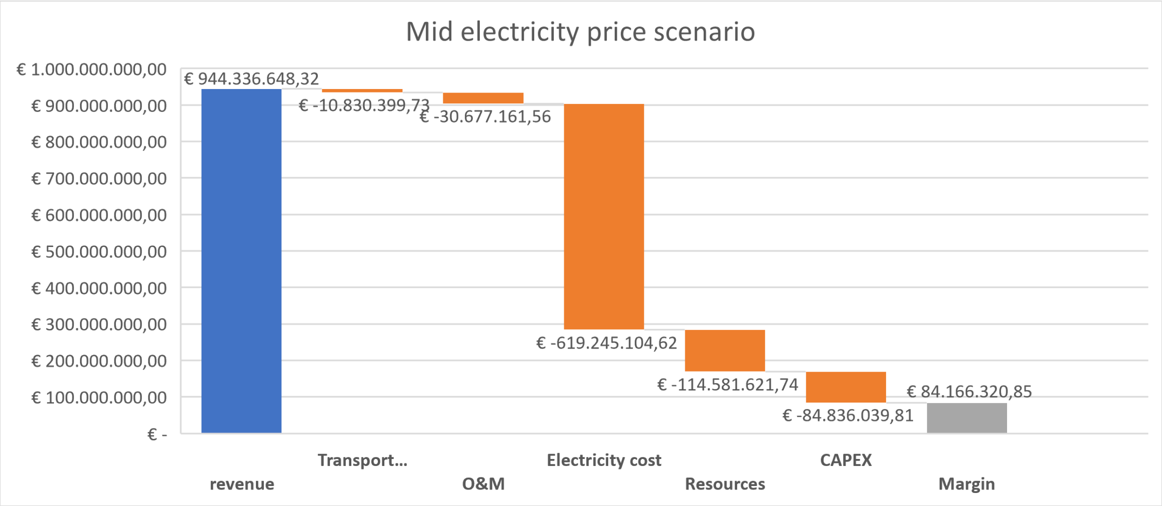

Figure C.2: Cost breakdown mid energy price scenario: scenario 2

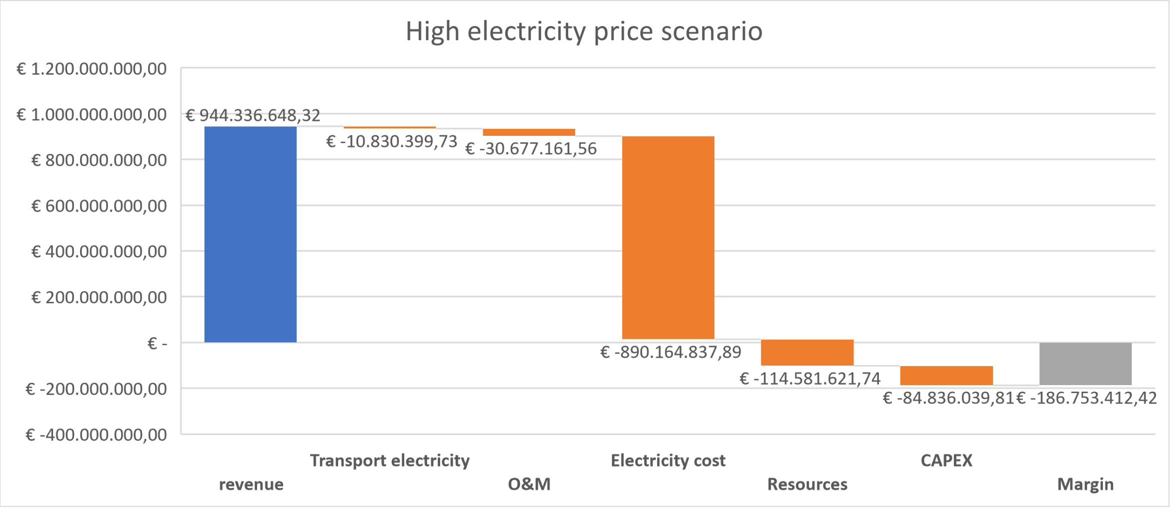

Figure C.3: Cost breakdown high energy price scenario: scenario 2