Factors for the success of upcoming more sustainable hydrogen production technologies for use in refineries in the Netherlands

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Executive summary

The incumbent dominant design for hydrogen production used in refineries in the Netherlands is producing grey hydrogen using steam methane reforming with CO2 as byproduct. Therefore, the current incumbent hydrogen production technology used in refineries in the Netherlands is unsustainable. However, it is still unclear which hydrogen production technology will become the new dominant design during the transition to a sustainable hydrogen feedstock for refineries in the Netherlands. The research objective of this study is to assess which factors influence the success of the competing hydrogen production technologies during the transition to more a sustainable hydrogen feedstock for refineries in the Netherlands and find out which technology is most likely to become the new dominant design. The hydrogen production technologies within the scope of the research are steam methane reforming (SMR) of natural gas (grey hydrogen), SMR with carbon capture and storage (CCS) (blue hydrogen) and electrolysis of water using renewable electricity (green hydrogen).

After the introduction some background information is given about the hydrogen production technologies and the use of hydrogen in refineries. Thereafter, the theoretical framework for the research is presented using literature about technology battles, technology selection and dominant designs. Next, a list of relevant factors from the literature study are constructed and used during the first round of expert interviews. The findings from the first round of expert interviews are used to develop a final list of relevant factors for the success of the competing hydrogen production technologies for use in refineries in the Netherlands.

Next, the methodology used for the research is introduced and explained. For the study data is collected through a literature study and two rounds of expert interviews. The literature study is performed by searching scientific databases online and searching for specific publications relevant for the study on websites of reputable organizations. The first round of expert interviews is focused on exploring new relevant factors and making sure the relevant factors found in the literature are actually relevant for the success of the competing hydrogen production technologies for use in refineries in the Netherlands. During the second round of expert interviews, experts are asked to determine which categories and factors are the most important and least important for the success of the competing hydrogen production technologies for use in refineries in the Netherlands. In addition, the experts are asked to make pairwise comparisons between the factors and categories. To determine the relevance of the factors and categories for the success of each competing hydrogen production technologies for use in refineries in the Netherlands another set of questions is asked. The pairwise comparisons made by the experts are analyzed using a multi-criteria decision-making (MCDM) method for which the best-worst method (BWM) has been selected.

In the next chapter the findings from the interviews are presented together with the findings from the model of the operational cost price. The findings from the interviews are used to calculate the weights for the factors and categories using a linear model for the best-worst method developed by Rezaei (2016). These results are then used in a new excel sheet to calculate average weights, consistency ratios and technology scores. The results from the interview show that the regulator, the price of natural gas, price of hydrogen as well as supply side incentives and demand side incentives are the most important factors for the success of the hydrogen production technologies during the transition to a more sustainable feedstock for use in refineries in the Netherlands. Moreover, the findings from the model of the operational cost price of hydrogen provide valuable insight into the sensitivity and importance of the price of hydrogen to the price of natural gas, price of electricity and

carbon price for the competing hydrogen production technologies. One of the main findings from the model of the operational cost price are the average ratio between the price of electricity and price of natural gas of 238% during the 12 months of 2021. In addition, the model also illustrates that the economic competitiveness of green hydrogen with respect to blue and grey hydrogen depends to a large extent on the ratio between the electricity price and the price of natural gas. The model shows that a breakeven point of the price of green hydrogen with blue and grey hydrogen occurs around a ratio of 1 between the price of electricity and the price of natural gas. On the other hand, the model of the operational cost price of hydrogen indicates that the breakeven point of the price of blue hydrogen with respect to grey hydrogen occurs at a carbon price of €70 to €80 per ton CO2 when the price of natural gas is €146,44 MWh. A lower price of natural gas would require a lower carbon price for blue hydrogen to become more affordable and cross the breakeven price with grey hydrogen as blue hydrogen consumes more energy to capture and store the CO2 emissions.

The main contributions of the research are the novel list of relevant factors for the success of upcoming more sustainable hydrogen production technologies challenging an incumbent dominant design, grey hydrogen production. In addition, the model of the operational cost price of hydrogen provides novel insight in the interdependencies of the price of hydrogen, the price of natural gas, the price of electricity and carbon prices for the competing hydrogen production technologies within the scope of this research.

A limitation of the research is that the positive or negative influence a factor has on the success of a hydrogen production technology for use in refineries in the Netherlands has not been studied in detail. As a result, some experts might have rated a factor as not relevant during the interviews for the success of one of the competing hydrogen production technologies because it had a negative influence on the success of that technology for use in refineries in the Netherlands. A limitation of the model of the operational cost price of hydrogen is that the fixed investment costs are excluded from the calculations as well as the operational and maintenance costs. Nevertheless, the feedstock costs are the largest cost component of the overall cost price of green, blue and grey hydrogen, making the other costs less relevant.

Moreover, the model of the operational cost price of hydrogen implies that a decreasing electricity price compared to the price of natural gas would increase the competitiveness of green hydrogen for refineries in the Netherlands. The current dominant design for power generation in the Netherlands, gas fired power plants, require natural gas to produce electricity resulting in significant marginal costs and energy conversion losses. However, by increasing the installed capacity of renewable energy sources the price of electricity can be lowered because they have marginal cost close to zero since they do not require a feedstock to produce electricity. Thus, the installed capacity of renewable energy sources is an important factor for the success of green hydrogen because it can increase the frequency of oversupply of electricity while also lowering the price of electricity compared to natural gas.

In the end, the success of the hydrogen production technologies during the transition to a more sustainable feedstock for use in refineries in the Netherlands depends mainly on the development of regulations, especially RED 3, as well as the natural gas, electricity and carbon markets. As the market is currently characterized by high electricity prices blue hydrogen is currently more affordable than green hydrogen. However, increasing the installed capacity of renewable energy sources in the coming years could result in a market characterized by an oversupply of electricity and low electricity prices compared to the price of natural gas. As a result, green hydrogen could become the most affordable source of hydrogen in the Netherlands in the long term.

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1. Introduction

Hydrogen has the potential to become a vital energy carrier in a low carbon energy society in the future. However, the pathway to a low-energy future is uncertain and so is the role of alternative fuels such as hydrogen (Hanley, Deane & Gallachóir, 2018). Currently, natural gas and coal are the primary energy sources to produce hydrogen worldwide. Steam methane reforming (SMR) using natural gas is the most widely used technology and thus the dominant design for hydrogen production. Almost 75% of all hydrogen supplied worldwide is produced using natural gas, in contrast only 0.1% of the world's hydrogen supply is produced using electrolysis (IEA, 2019). There are several production processes for hydrogen: grey hydrogen is produced using fossil fuels without capturing CO2, blue (low CO2) hydrogen is produced using fossil fuels while capturing and storing the CO2 and green hydrogen is produced from water using electricity through electrolysis also known as power-to-gas or power-to-hydrogen (TNO, n.d.). Moreover, CertifHy has proposed a guarantees of origins (GO) scheme for hydrogen and presented more detailed definitions of green hydrogen and blue (low CO2) hydrogen with respect to grey hydrogen produced using steam methane reforming of natural gas as a benchmark process (CertifHy, n.d.). The definition of green hydrogen by CertifHy is hydrogen produced using electrolysis and renewable electricity while also having CO2 emissions 60% below the grey hydrogen benchmark (CertifHy, n.d.). On the other hand, blue (low CO2) hydrogen is defined as hydrogen produced from non-renewable sources with CO2 emissions 60% below the grey hydrogen benchmark (CertifHy, n.d.).

One of the main barriers to the adoption of hydrogen produced using electrolysis (green hydrogen) is the high price of green hydrogen compared to hydrogen produced using fossil fuels (Hosseini & Wahid, 2016; Blanco et al., 2018; Rambhujun et al., 2020). Therefore, using blue (low CO2) hydrogen is often proposed as an intermediate step to transition to a more sustainable hydrogen economy. In the port of Rotterdam, a storage facility in an empty gas field underneath the Nordsea is being developed to store CO2 captured from, for example, the production of hydrogen using fossil fuels (TNO, n.d.). Nevertheless, it is key to understand how the price of green hydrogen can be lowered to remove this barrier. One opportunity to do so presents itself in lowering the price of electricity since one of the key components that is determining the price of green hydrogen is the price of the electricity used in power-to-gas technologies to produce green hydrogen (Hosseini & Wahid, 2016). Another study argues a clear regulatory framework that promotes the use of hydrogen in various industries to create a market pull is still lacking (Blanco et al., 2018). A subsidy scheme could improve the business case in an early stage to stimulate the initial infrastructure investments and develop the technologies that are not yet economically competitive (Blanco et al., 2018).

Currently hydrogen is mainly used in the chemical industry to produce ammonia, for the processing of crude oil into gasoline and diesel as well as to produce methanol. According to Hydrogen Europe about 55% of the hydrogen produced around the world is used to produce ammonia, 25% for the refining of oil products and about 10% to produce methanol (Hydrogen Europe, n.d.). Thus, to enable the transition to a hydrogen economy it is valuable to have a good understanding how green hydrogen can compete in these heavy industries. During this study the focus will be on the use of hydrogen in refineries in the Netherlands. One of the key decision criteria for businesses to transition to the use and production of green hydrogen, instead of blue or grey hydrogen will be the price. The reason that the price will be important stems from the fact that hydrogen is a commodity which has the same utility regardless of the technology that is used to produce it.

During a previous group assignment expert interviews have been conducted to identify the most important factors in the battle for a dominant design between SMR and power-to-gas for hydrogen production and found that regulations, price and technological superiority are the most important factors in the technology battle. The research used the integrative framework of Suarez (2004) and the more complete framework by van de Kaa (2011) to analyse the technological dominance process and investigate which hydrogen production technology is most likely to become the dominant design in the future. Suarez (2004) explains that the battle for technological dominance is influenced by the installed base of technologies and that a bias towards the technology with the largest installed base exists. In addition, Suarez (2004) explains that consumer expectations and firm strategies such as pricing and licensing policies play an important role in the dominance process as well. Furthermore, Rambhujun et al. (2020) presents several barriers to the adoption of renewable hydrogen in the chemical industry and argues that advancements in technological processes, costs and policies need to be jointly progressed before renewable hydrogen can become mainstream. Scientific research into factors influencing technology development, competition and the emergence of dominant designs has been a topic of intense study for a significant time already (Schilling, 1998; Schilling, 2002; Suarez, 2004; Utterback & Abbernaty, 1975; Utterback & Suarez, 1993; Van de Kaa et al., 2011). In addition, several case studies have already been conducted to analyze technology battles using frameworks of factors to get more insight into which technology is most likely to become the dominant design during a technology battle (Van de Kaa et al. , 2017a; Van de Kaa et al., 2017b).

In the case of the transition to a more sustainable alternative hydrogen production technology from the current dominant design of grey hydrogen production using SMR in the Netherlands, it is also critical to have a thorough understanding on how a technology can become a dominant design for technology managers and policy makers to make more informed decisions. Promising more sustainable technologies to produce hydrogen are SMR in combination with carbon capture and storage (CCS) to produce blue hydrogen as well as electrolysers using renewable energy sources to produce green hydrogen. For hydrogen to play a key role in decarbonizing major sectors of the economy and transition to a more sustainable economy, hydrogen must be produced while avoiding negative greenhouse gas emissions such as CO_2. However, it is still unclear which technology is most likely to become the dominant design during the transition to more sustainable hydrogen feedstocks to decarbonize major sectors in the economy. Oil refining is an example of such a major sector in the Netherlands and will be the focus of this study. In addition, it is unclear which factors are relevant in determining the outcome of the technology battle during the transition to more sustainable alternative technologies for hydrogen production in the Netherlands and which of these factors will be the most important in determining the outcome.

1.1. Problem statement

The incumbent dominant design for hydrogen production used in refineries in the Netherlands is producing grey hydrogen using steam methane reforming with CO_2 as byproduct. Greenhouse gas emissions such as CO_2 have a negative environmental impact by increasing global warming and resulting climate change are a major problem facing the world today (IPCC, 2021). Thus, the dominant design for hydrogen production used in refineries in the Netherlands is unsustainable. These problems are widely acknowledged around the world and recently reaffirmed by the sixth assessment report by IPCC (2021). In addition, the support and commitment around the world for addressing this problem can be derived from the adoption by 196 parties of the Paris Agreement, including the Netherlands (UNFCCC, n.d.). However, it is still unclear which hydrogen production technology will become the new dominant design during the transition to sustainable hydrogen feedstocks for refineries in the Netherlands.

1.2. Research objective

The research objective of this study is to assess which factors influence the success of the competing hydrogen production technologies during the transition to a more sustainable hydrogen feedstock for refineries in the Netherlands. In addition, the objective is to find out which hydrogen production technology is most likely to become the dominant design during the transition to a sustainable hydrogen feedstock for refineries in the Netherlands.

1.3. Main research question

To achieve the research objective the following research question will be pursued during the study: Which factors influence the success of the competing hydrogen production technologies during the transition to a sustainable hydrogen feedstock for refineries in the Netherlands?

Sub research questions

1. Which factors are relevant in determining the outcome of the technology battle between the competing hydrogen production technologies during the transition to a sustainable hydrogen feedstock for refineries in the Netherlands according to the literature?
2. Which factors are important in determining the outcome of the technology battle between the competing hydrogen production technologies during the transition to a sustainable hydrogen feedstock for refineries in the Netherlands according to experts?
3. Which hydrogen production technology is most likely to become the dominant design during the transition to a sustainable hydrogen feedstock for refineries in the Netherlands?

1.4. Scope of research

The research will be focused on the production and use of hydrogen in refineries in the Netherlands. The study will use scientific literature, interviews with experts familiar with the hydrogen production technologies and knowledge about hydrogen use in refineries in the Netherlands. The technologies that will be assessed are hydrogen production using electrolysis and renewable energy, steam methane reforming of natural gas with and without using carbon capture and storage. To answer the research questions and assess which of these technologies is most likely to become the dominant design, findings from scientific literature, expert interviews and the model of the operational cost price of hydrogen will be used.

1.5. Research approach

To start off, findings from the literature and a first round of expert interviews will be conducted to determine relevant factors for the outcome of the technology battle. These findings will be used to develop a theoretical framework and answer the first sub research question.

After having developed the theoretical framework a second round of expert interviews can be conducted to evaluate which factors are the most important and least important for the outcome of the technology battle. To evaluate the importance of the relevant factors the multi-criteria decision-making (MCDM) best-worst method (BWM) will be used (Rezaei, 2015; Rezaei, 2016). The importance of the relevant factors will be determined by making pairwise comparisons resulting in weights for each factor using this method. The competing technologies will also be assessed similarly with respect to each relevant factor, resulting in a performance score for each technology with respect to the relevant factors. To compare the competing technologies with respect to each criteria an overall score can be determined by multiplying the weights for each relevant factor with the performance score of each alternative technology. The overall score can then be used to determine a final score by summing the overall scores of all the factors for each technology separately and dividing the sum of overall scores by the number of relevant factors to find a final score for each competing technology. The final scores can then be used to compare the competing technologies directly with each other and determine which technology is most likely to become the dominant design. As a result, the main research question as well as the second and third sub research question can be answered.

1.6. Structure of the report

The report is split up into seven chapters: introduction, background, theory, methodology, results, discussion and conclusion. The background chapter will introduce the technologies that are evaluated during the study as well as the use of hydrogen within refineries. The theory chapter will integrate findings from the literature as well as the first round of interviews to develop a theoretical framework, define the relevant factors and explain important relationships between factors. The methodology chapter will describe how the best-worst methodology will be used, how the experts for the interviews will be selected, which questions will be asked during the interviews and how the data from the interviews will be managed. The results chapter will present, explain, and analyze the findings from the first and second round of interviews as well as the findings from the model of the operational cost price of hydrogen. In the discussion chapter the interpretation of the results will be presented as well as an evaluation of the research to highlight the scientific contributions of the research, areas of improvement, the implications of the findings and the limitations of the study. Finally, the conclusion will summarize the key findings and implications of the research and present the answers to the research questions.

2. Background on the hydrogen production technologies and hydrogen use in refineries

2.1. Hydrogen production technologies

Several hydrogen production technologies exist today with varying degrees of direct and indirect CO2 emissions. Established production methods used for producing hydrogen from fossil fuels are steam methane reforming (SMR), autothermal reforming (ATR) and partial oxidation (POX) (van Dam, Cioli & Schure, 2021). About 50% of the hydrogen used in refineries is produced as by-product from catalytic reforming of naphtha and the other half is produced primarily using steam methane reforming in the Netherlands (Schure & Oliveira, 2020). The exception seems to be the Shell Pernis refinery in the Netherlands which uses partial oxidation to convert heavy refinery residues into hydrogen for as a large share of their hydrogen supply (Schure & Oliveira, 2020; Shell Global Solutions, 2018). Hydrogen production technologies using fossil fuels as feedstock produce CO2 as a by-product making them less environmentally friendly. However, the CO2 produced as by-product from these production processes can be capture and utilized in other processes or stored in reservoirs to avoid their emissions into the atmosphere. On the other hand, hydrogen production technologies exist that use electricity as feedstock to produce hydrogen from water through electrolysis. As a result, no CO2 is produced during the production of hydrogen directly. However, sufficient renewable electricity needs to be available to avoid indirect CO2 emissions that are otherwise produced during the electricity production.

2.1.1. Steam methane reforming

Steam methane reforming is the most dominant production method for producing hydrogen for refineries in the Netherlands today (van Dam, Cioli & Schure, 2021). Steam methane reforming utilizes the steam reforming process to convert hydrocarbons using steam and catalysts to form hydrogen and carbon monoxide (U.S. Department of Energy, n.d.). Natural gas is the most frequently used feedstock, but other hydrocarbons feedstock can be used as well for the steam reforming process to produce hydrogen (van Dam, Cioli & Schure, 2021). The hydrogen produced using this process is called grey hydrogen.

The steam methane reforming hydrogen production process has four main steps: pre-treatment of the feedstock, steam methane reforming, water gas shift reaction and purification. The pre-treatment of the feedstock removes impurities such as sulfur from the natural gas to prevent contaminating the catalysts during the reforming process. The steam reforming process converts the hydrocarbons, primarily methane, into hydrogen and carbon monoxide. Next, the water gas shift reaction converts the carbon monoxide into carbon dioxide and hydrogen using water. Finally, the gas mixture is purified by separating the hydrogen from the other gases using pressure swing adsorption.

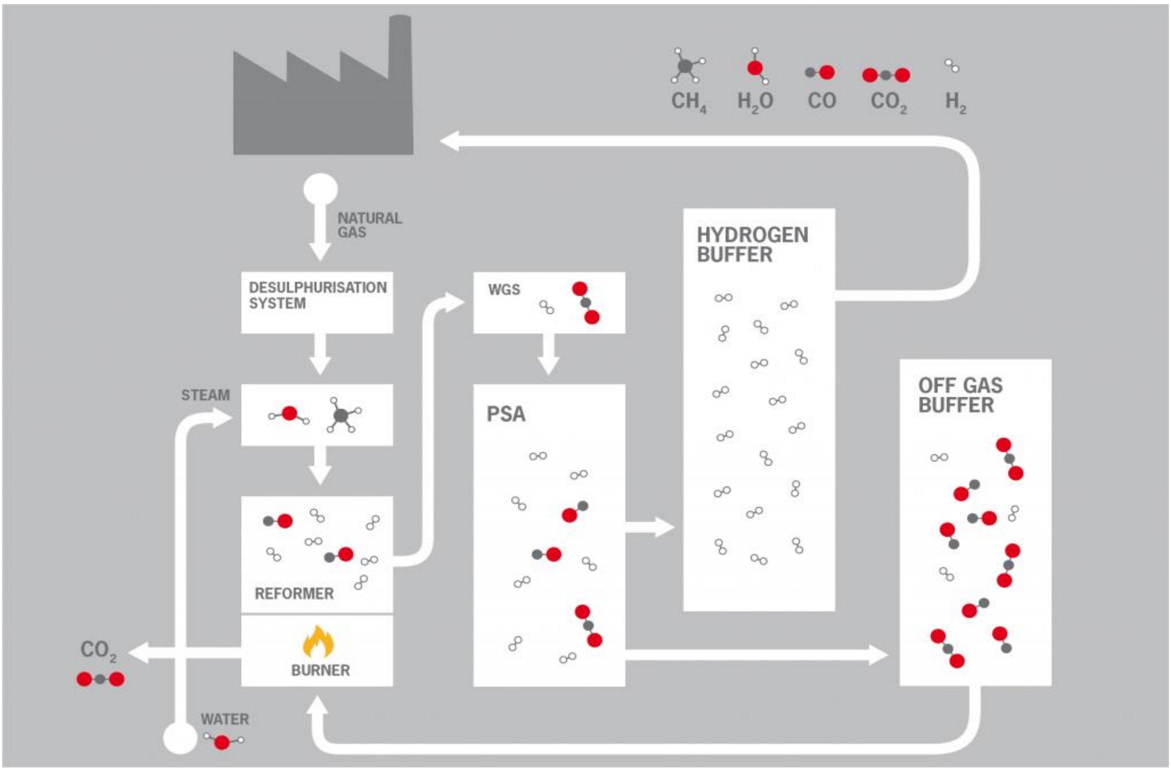

Fig 1. Steam methane reforming process and molecule flow schematic (HyGear, 2021)

2.1.2. Steam methane reforming with carbon capture and storage

Steam methane reforming with carbon capture and storage is to a large extend the same as the conventional steam methane reforming process except for the removing and storing of carbon dioxide. The hydrogen produced using steam methane reforming with carbon capture and storage is called blue hydrogen. Carbon dioxide is produced by two sources during the steam methane reforming process, one being the combustion of fossil fuels to provide heat for the process and the second being the carbon dioxide produced during the conversion process. These two sources each require different processes to capture the carbon dioxide because they are not produced in the same place. The capture of carbon dioxide from the conversion process has established solutions such as using MDEA, MEA, TEA or potassium carbonate chemical solvents to absorb and capture carbon dioxide (van Dam, Cioli & Schure, 2021). The absorption process is typically placed in between the water gas shift reaction and pressure swing adsorption of the reforming process. Capturing carbon from the combustion of fossil fuels can be achieved in a similar manner as well. However, after having captured the carbon dioxide from the process it has to be stored somewhere or utilized somehow. As a result, transport infrastructure is required to a storage location or a customer.

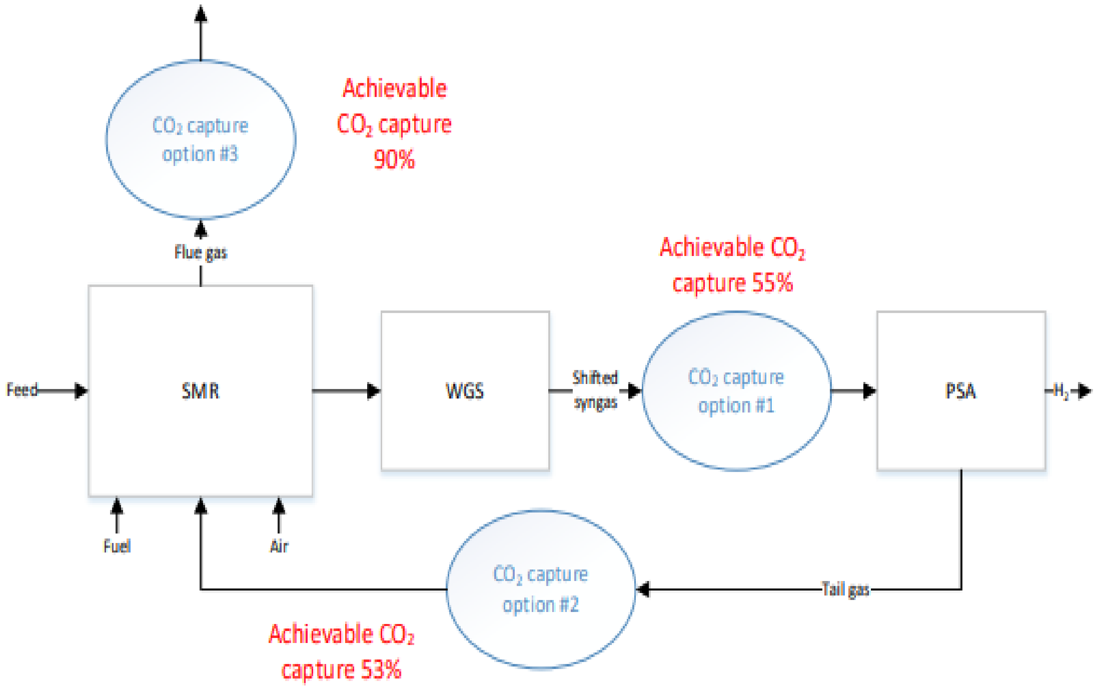

Fig 2. Steam methane reforming carbon capture process schematic including achievable CO2 capture rates at various process steps (Van dam et al., 2021).

2.1.3. Electrolysis

Electrolysis is the process of producing hydrogen using electricity to split water into hydrogen and oxygen. Green hydrogen is the hydrogen called which is produced using renewable electricity combined with electrolysis. There are several different types of electrolysers that use electricity to produce hydrogen, the most mature are alkaline and proton membrane exchange (PEM) electrolysers (Kumar & Himabindu, 2019).

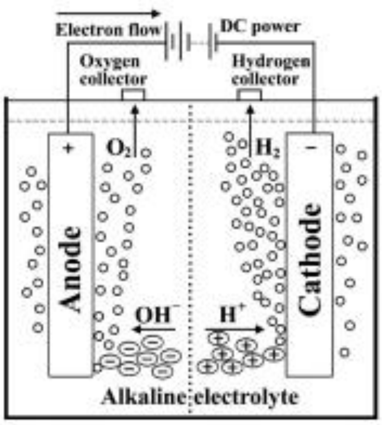

Fig 3. Alkaline water electrolysis process diagram (Ziazi et al., 2017).

2.2. Hydrogen use in refineries

Hydrotreating processes such as desulphurization and hydrocracking are the main processes in petrochemical refineries that use hydrogen. Desulphurization is primarily used to remove sulfur from oil crude oil or intermediate oil products as sulfur is an undesirable contaminant (McKinsey, n.d.-c). Sulfur is an undesirable contaminant because oil products containing sulfur produce sulfur oxides when they are burned. In addition, sulfur can also harm some catalysts used in the refining process by contaminating them (McKinsey, n.d.-c). Sulfur can be removed from oil products using a hydrotreating process to form hydrogen sulfide (H2S) by mixing the oil products with hydrogen and heating them (McKinsey, n.d.-b). Other contaminants can be removed from oil products in a similar fashion using a hydrotreating process often in combination with a solid metal catalyst such as cobalt-molybdenum or nickel-molybdenum (McKinsey, n.d.-b). Another contaminant in oil products is nitrogen which can be removed using a hydrotreating process, adding hydrogen and heating the oil mixture to form ammonia (McKinsey, n.d.-b). Hydrogen is also used in refineries to crack hydrocarbons, which is a process to breakdown large hydrocarbon molecules into smaller ones (McKinsey, n.d.-a). The hydrocracking process is used in refineries by adding hydrogen to an oil mixture to produce lighter oils, such as gasoline, diesel and kerosine, from heavier oils (McKinsey, n.d.-a).

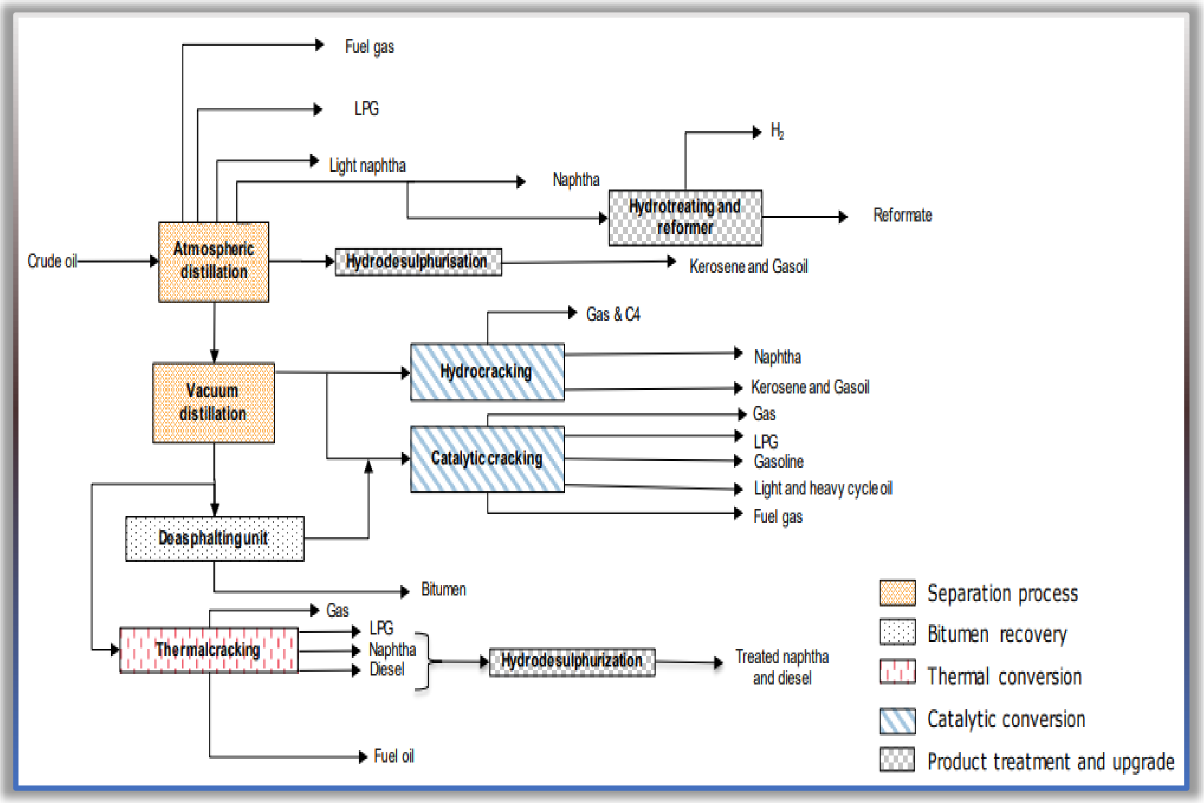

Fig 4. Process flow diagram of a refinery (Schure & Oliveira, 2020). The hydrocracking and desulphurization (hydrotreating) processes consume hydrogen in the refinery.

3. Theory

This chapter will introduce the theoretical foundation of the research project. The focus will be on explaining how the study fits into the existing scientific literature on technology battles, technology selection and dominant designs. Furthermore, factors that influence the technology selection process according to the literature will be introduced as well as factors mentioned by experts during a first round of interviews. These factors will be used to develop a list of relevant factors for the success of the competing hydrogen production technologies, within the scope of this study, for use in refineries in the Netherlands. The list of relevant factors will provide the foundation of the rest of the study. Therefore, the selection process of the relevant factors will be explained clearly in a manner to ensure rigor, objectivity, replicability, and testability of the study.

Technology battles occur in various sectors and industries such as the telecommunication sector, disk drive industry and energy sector. During a technology battle competing technologies solving the same problem compete for dominance in a specific market to become the dominant design. A dominant design can be defined as a product architecture which is persistently chosen by most users within a market, thus fulfilling the needs of most users within that market without having to revisit basic design choices of a product (Gallagher, 2007; Suarez, 2004; Henderson & Clark, 1990). An important measure in this context is the market share of a particular product architecture. This measure is important because the product architecture which persistently has the largest market share within a market is the dominant design within that market using the definition of a dominant design given above. During this study the product architecture under study are the competing hydrogen production technologies: electrolysis using renewable energy (green hydrogen), steam methane reforming with carbon capture and storage (blue hydrogen) and steam methane reforming without carbon capture and storage (grey hydrogen). Moreover, the market where these technologies will compete during this study is the market for use in refineries in the Netherlands.

Certain industries, markets and technologies are more prone to settle on one dominant design instead of reaching a semi equilibrium state in which several competing technologies maintain a relatively large market share in the same market (Schilling, 1998). Markets that are characterized by having strong network externalities and reliance on complementary goods are more prone to settle on one dominant design (Schilling, 1998). In addition, dominant designs can also be determined through forces outside the market such as regulations by government authorities (Schilling, 1998). Dominant designs can be determined through market forces, resulting in a de facto dominant design (Gallagher, 2007). However, dominant designs can also be determined through regulations composed by a committee or government authority, resulting in a de jure dominant design (Gallagher, 2007).

An example of a market with strong network externalities are social media platforms because the value to users of a social media platform increases directly with number of other users, in other words the value increases directly with the installed base of the social media platform. Markets with similar market conditions as the disk drive industry or gaming console market are also likely to settle on one dominant design as they are characterized by having a strong reliance on compatible complementary goods such as compatible DVDs and compatible video games. These kinds of markets are characterized by indirect network externalities because an increase in the installed base of a technology within a market characterized by a strong reliance on complementary goods will increase the value of the complementary goods of that technology. Similarly, in a market characterized by a strong reliance on complementary goods, the value of the technology required to use complementary goods will increase with an increase in complementary goods for that technology. The hydrogen market for use in refineries in the Netherlands can be characterized as a market with a reliance on complementary goods as the value of hydrogen for refineries increases with the number of complementary sources of hydrogen available to them. For hydrogen producers the value of their technology also increases with the demand for hydrogen by refineries in the Netherlands. Thus, the hydrogen market for use in refineries in the Netherlands can be characterized by indirect network externalities.

The competing hydrogen production technologies for use in refineries in the Netherlands currently have a dominant design which is grey hydrogen produced using steam methane reformers. Steam methane reformers have persistently been the preferred choice as a hydrogen production technology for use in refineries in the Netherlands. The changing pressure on firms to reduce their environmental impact and CO_2 emissions since the Paris agreement was signed in 2015 is changing the competitive landscape for hydrogen production technologies in the Netherlands. Therefore, this study aims to determine which factors are relevant for the success of the competing hydrogen production technologies within the scope of this research. Furthermore, the study aims to find out whether the upcoming more sustainable hydrogen production technologies are likely to overcome the incumbent technology and become the new dominant design.

3.1. Technology battles and dominant designs

Technology battles are an area of interest within business and management studies that has been researched extensively and resulted in several theories, frameworks and case studies analyzing phenomena that have been published in the scientific literature. Technology battles have been analyzed from multiple perspectives such as technology management, evolutionary economics, institutional economics and network economics (van de Kaa et al., 2011). Technology management researchers were one of the first to study the emergence of dominant designs systematically according to Suarez (2004). Utterback and Abernathy were the first to introduce the emergence of a dominant technology and gave rise to the literature on dominant designs according to Utterback and Suarez (1993) and Gallagher (2007). Utterback and Abernathy (1975) argue that a firm's environment affects the most appropriate strategy for innovation which in turn varies systematically depending on environmental factors and technology development. Moreover, Utterback and Abernathy (1975) introduced an integrative theory of the innovation process and a conceptual model describing the pattern of relationships between the rate of innovation and the stage of technology development.

In the evolutionary discipline an evolutionary model has been proposed for technological discontinuities and dominant designs by Anderson and Tushman (1990). The importance of installed base, compatibility and network externalities for the standard setting process is highlighted in the research by Farrell and Saloner (1986) as well as by Katz and Shapiro (1985). Furthermore, Suarez (2004) has proposed an integrative framework for understanding how a technology achieves dominance when competing with alternative technologies, by arguing which criteria are important during different phases of the dominance process. In addition, more recently van de Kaa et al. (2011) has proposed a more complete framework using 29 factors to understand how a technology achieves dominance when competing with alternative technologies.

Moreover, Schilling (1998) has also proposed a model for technological success and failure based on economic and technological factors. Schilling (1998) argues that the emergence of a dominant design exhibits clear characteristics of path dependency while also emphasizing that firms can influence the technology selection process through strategic management. The likelihood of technological lockout is explained using the installed base of the technology, available complementary goods, timing of entry and firm capabilities which can all be explained as functions of strategic actions (Schilling, 1998). Schilling (2002) continued upon her work by arguing that a firm's learning orientation and timing of entry also play an important role in technology success within industries characterized by network externalities. Industries characterized by network externalities affect the likelihood of a dominant design emerging because network externalities cause increasing returns to adoption, leading to winner-take-all markets (Schilling, 2002).

3.2. The role of hydrogen in decarbonizing the energy sector

Fonseca et al. (2019) have performed a systematic literature review to identify the trends in the design of distributed energy systems using hydrogen as an energy vector. Their research has focused on identifying the main energy sources that are used to produce hydrogen, the main technologies that are used to produce it including their advantages, disadvantages and challenges, as well as the end-use of hydrogen and objectives (e.g. technical, economic, environmental) for using hydrogen (Fonseca et al., 2019). Their systematic literature review suggests that predominantly research has focused on techno-economic analysis of hydrogen use in energy systems (Fonseca et al., 2019). In addition, it also suggests that research has been predominantly about electrolysers and fuel cells as hydrogen production technologies and less so on steam methane reforming or gasification (Fonseca et al., 2019). Moreover, the literature has addressed several end-use cases of hydrogen but has been mainly focused on hydrogen as a medium to mute fluctuations of renewable energy production. Furthermore, Fonseca et al. (2019) suggest that there is an opportunity for future research on social aspects, context specific conditions and uncertainty to improve the decision making for planning this type of energy system. Da Silva Veras et al. (2017) have performed a similar study by analyzing trends of the hydrogen production processes around the world and also characterized the main technologies that are being used. In addition, da Silva Veras et al. (2017) argues that the uncertainties of hydrogen produced using renewable energy appear to be the lack of technologies that give it a competitive edge over other energy competitors. Therefore, da Silva Veras et al. (2017) argues for the need of future economic research and especially focused on the competitiveness of hydrogen produced using renewable energies.

Schiebahn et al. (2015) have performed a study where they presented a technological overview of the power-to-gas technology, performed a system analysis and an economic assessment during a case study in Germany. Their findings suggest that the production costs of renewable hydrogen or methane are several times higher than those of conventional natural gas, making large scale production of renewable alternatives uneconomical. On the other hand, Shiebahn et al. (2015) argue that the utilization of renewable hydrogen in the transportation sector has more potential because of the efficiency gains hydrogen fuel cell vehicles can achieve over internal combustion engine vehicles allowing for an economically sound business case because hydrogen can be cost competitive with gasoline.

Another study by van de Graaf et al. (2020) argues that the transition to hydrogen is about more than technical and economic factors, it is also about geopolitics of the energy transformation. Van de Graaf et al. (2020) argue that hydrogen has been a blind spot in the emerging literature on the energy transformation and opens up a broader set of social science research questions. Moreover, van de Graaf et al. (2020) argue that the technologies and infrastructures underpinning a hydrogen economy can be shaped with clear differences resulting in different winners and losers depending on the source, handling, shipping and end use of hydrogen. Therefore, the geopolitical struggles and conflicts between stakeholders will shape the hydrogen value chain, global market and pace of the energy transition (van de Graaf et al., 2020). Furthermore, it is suggested that hydrogen could become the new oil in the transition to sustainable energy. However, it is not expected that a similar cartel such as OPEC will emerge in hydrogen geopolitics as several technologies allow hydrogen to be produced almost anywhere (van de Graaf et al., 2020). Thus, it is almost impossible for a small number of suppliers to weaponize the export of hydrogen (van de Graaf et al., 2020).

Parra et al. (2019) argue that hydrogen can play a key role in the deep decarbonisation of energy systems as electricity from renewable energy can be used with power-to-gas technologies to produce low carbon gas that can be used to decarbonize the transport and heat sector. Currently, the use of renewable energy is much lower in heat (9%) and transport (3%) than in electricity (23%) (Parra et al., 2019).

The study by Schure and Oliveira (2020) describes the dutch refinery sector, the refinery process, products, applications and markets and options for decarbonization. The decarbonization of the dutch refinery sector according to Schure and Oliveira (2020) can be achieved through carbon capture and storage (CCS), an alternative energy supply, an alternative feedstock, alternative processes as well as using waste heat. The use of green hydrogen for decarbonization would be through using hydrogen produced using renewable energy sources and power-to-gas as an alternative feedstock. For refineries to pivot to an alternative feedstock to decarbonize large scale low CO2 hydrogen production facilities have to be build (Schure & Oliveira, 2020).

Sadeghi, Ghandehariun and Rosen (2020) performed a comparative economic and life cycle assessment of hydrogen production using natural gas reforming, coal gasification and electrolysis using electricity by solar panels and solar radiation. Their results indicate that hydrogen produced using electrolysis and solar panels is more than 3 times as expensive but also has more than 3 times less CO2 emissions than hydrogen produced using fossil fuels (Sadeghi, Ghandehariun and Rosen, 2020). Hydrogen produced using electrolysis and solar radiation is more than 5 times as expensive but also emits more than 5 times less CO2 emissions than hydrogen produced using fossil fuels (Sadeghi, Ghandehariun and Rosen, 2020). Thus, carbon taxes could have a significant impact in the competitiveness of these hydrogen production technologies. Therefore, raising carbon taxes could increase the sustainability of the hydrogen supply chains of refineries and make hydrogen produced using renewable energy a more attractive substitute for hydrogen produced using fossil fuels.

3.3. Theoretical considerations for developing a model of the operational cost price of hydrogen

The model of the operational cost price of hydrogen is developed to get more insight into the interdependencies and sensitivity of the price of hydrogen to the price of electricity, price of natural gas and carbon prices. The decision has been made to only focus on the feedstock cost and carbon cost to produce hydrogen to calculate the price of hydrogen for the competing hydrogen production technologies. This decision has been made because the feedstock cost represents the largest cost component of hydrogen for green, blue and grey hydrogen production. The price of carbon is also included as a variable in the model because without it blue hydrogen would never become more affordable than grey hydrogen as energy is consumed to capture CO2. In addition, a transportation and storage system also needs to be built to store the capture CO2 eventually, resulting in additional capital costs. Nevertheless, the capital costs have been excluded from the model for simplicity and because of their relatively small share of the hydrogen production costs compared to the feedstock costs.

According to Chardonnet et al. (2017) the capex for a 20 MW electrolyser operating at atmospheric pressure costs 750 €/kW. Thus, the capex for an entire 20 MW plant would be €15 million. A 20 MW electrolyser will be able to produce around 4000 Nm^3 of hydrogen per hour (Chardonnet et al., 2017). In addition, Chardonnet et al. (2017) states that the operational and maintenance cost for such an electrolyser would be 2% of the capex, equal to €0.3 million, and the system would have a lifetime of 20 years. Using a cost of capital of 5%, the annual capex costs would be equal to €39,80 million/20 or €1,99 million assuming linear depreciation of the plant to zero. Now if we assume the plant would operate with a 50% capacity factor meaning it would operate for 50% of the year at full capacity, then the feedstock cost of electricity at a price of €150/MWh would result in an additional annual cost of €12,61 million. The numbers presented above indicate that the share of electricity with respect to the overall cost of hydrogen is even higher than the 60-70% indicate by the Hydrogen Council (2021b), with electricity having a share of 84,6% of the total hydrogen production cost. Thus, the price of electricity is crucial for the economic competitiveness of green hydrogen.

Similarly, the feedstock cost is the main cost driver of blue and grey hydrogen as well. According to Collodi et al. (2017) the capex cost of a steam methane reforming plant without carbon capture and storage is €170,95 million with a lifetime of 25 years and a production capacity of 100000 Nm^3 hydrogen per hour. Thus, this plant has a production capacity about 25 times larger than a 20 MW electrolyser. Nevertheless, the annual feedstock costs for this plant are €70,96 million compared to the €8,06 million annual operational and maintenance costs (collodi et al., 2017). Using a cost of capital of 5%, the annual capex costs would be equal to €578,90 million/25 or €23,16 million assuming linear depreciation of the plant to zero. Therefore, the share of natural gas in the cost of grey hydrogen production is around 69,4% of the total cost of grey hydrogen production. As a result, the price of natural gas is key for the economic competitiveness of grey hydrogen. It is important to note that the price of natural gas used to calculate the feedstock costs here is €21,60 MWh and therefore is significantly lower than the price of natural gas used for the calculations in the model because a price of natural gas of €146,44 MWh has been used for most calculations based on the market price of natural gas on 20/12/2021. Nevertheless, a higher price of natural gas would only increase the share of natural gas in the total cost of hydrogen production for a steam methane reforming plant.

The blue hydrogen production cost calculations are based on the plant design called case 3 by collodi et al. (2017) because this plant has the highest carbon capture rate which avoids 89% of the CO2 emissions compared to the base case, described above for grey hydrogen production. According to collodi et al. (2017) the capex of this plant would amount to €305,33 million with a lifetime of 25 years and a production capacity of 100000 Nm^3 hydrogen per hour. The annual feedstock cost for this plant would amount to €77,97 million and the annual operational and maintenance cost would be €12,03 million (collodi et al., 2017). Using a cost of capital of 5%, the annual capex costs would be equal to €1033,96 million/25 or €41,36 million assuming linear depreciation of the plant to zero. As a result, the share of natural gas in the cost of blue hydrogen production is around 59,4% of the total cost of blue hydrogen production. Thus, the share of natural gas still constitutes most of the hydrogen production costs for blue hydrogen albeit to a lesser degree than for grey hydrogen production and green hydrogen production.

Another important consideration to compare the price of green, blue and grey hydrogen is the interdependency of the price of electricity and price of natural gas. The price of electricity depends to a large degree on the price of natural gas because of the dominant share of gas fire powered plants used for power generation in the Netherlands. According to the 2020 energy policy review of the Netherlands by the IEA natural gas was the dominant fuel used for electricity generation in 2018 with a share of 51%, followed by coal with a share of 26% and thereafter wind energy with 9% (IEA, 2020). However, increasing the share of renewable energy sources in the energy mix of the Netherlands could reduce the dependency of the electricity price on the price of natural gas. In addition, increasing the installed capacity of renewable energy sources could also lower the market price of electricity in the Netherlands as renewable energy sources have a marginal cost near zero. In contrast, gas fired power plants requires natural gas as feedstock to produce electricity thus the marginal costs of gas fired power plants are substantial and dependent on the price of natural gas.

4. Methodology
4.1. Research approach

The approach of the research project is to collect data to determine which factors determine the success of the competing hydrogen production technologies for refineries in the Netherlands. Primary and secondary data sources will be used to find relevant factors for the success of the competing hydrogen production technologies for refineries in the Netherlands. The primary data sources for this study will experts from whom data will be collected through open and semi structured interviews. In addition, secondary data sources will be used such as academic papers, government publications and publications from research institutes. The theoretical foundation of the study will be based primarily on secondary data sources to make sure the study fits into the existing scientific literature on technology battles, technology selection and dominant design. The novelty of the study is primarily the specific focus on the transition to sustainable feedstocks of hydrogen for use in refineries in the Netherlands. This case study has specific relevant factors that will be important for the success of the competing hydrogen production technologies. To determine which factors are relevant specifically to this case study expert interviews will be used combined with data from studies focused specifically on these hydrogen production technologies and the use of hydrogen in refineries. After determining a list of relevant factors for the success of the competing hydrogen production technologies the importance of the factors will be evaluated using a multi-criteria decision-making (MCDM) method during a second round of expert interviews. The MCDM method that will be used during the study is the best-worst method (BWM) which will be explained in detail in this chapter. During the second round of expert interviews the performance of the technologies with respect to each relevant factor will also be determined. As a result, the overall performance of the competing technologies can be compared using the performance of the technologies with respect to each factor and the importance of each factor. Last but not least, during the second round of interviews experts will be asked whether or not the relevant factors can be influenced by stakeholders and if it can be influenced, who could influence it. This will give insight in the ability of stakeholders to influence the outcome of the technology battle and which factor stakeholders could best focus on to have a significant impact on the outcome of the technology battle.

4.2. Data collection

Data collection is an important part of any research project, and this study is no exception. The data for this project is collected using a literature study and expert interviews. The methodological approach of the literature study and interviews will be explained in this section.

4.2.1. Literature review

The literature review is the first step of data collection for this research project to discover knowledge gaps in the scientific literature and form a theoretical foundation for the rest of the study. The first step of the literature study is to search for scientific literature related to technology battles, technology selection and dominant designs by searching on scientific databases using relevant keywords. The scientific databases used during this study are Scopus and ScienceDirect. In addition, google is used as well to search for certain articles and publications by reputable organizations such as TNO, IEA, PBL and McKinsey. Articles and publications by these organizations are used more after reading the more foundational scientific articles on technology battles, technology selection and dominant designs. The second step of the literature review is focused on determining which factors are relevant for the success of the hydrogen production technologies within the scope of the research project. In addition, the use of hydrogen in refineries in the Netherlands is also considered at this point to include relevant factors related to this specific use case as well. To find relevant factors for the success of hydrogen production technologies and their use in refineries in the Netherlands scientific literature is relevant but more detailed studies have also been found which are conducted by policy and company advising organizations such as PBL, McKinsey and IRENA. These data sources are more prone to present biased information then scientific literature because of the demands of their clients which can be governments or companies they are working with. For this study these data sources have been used while keeping in mind that these sources could present some data in a biased manner. As a result, valuable insights from these studies are not excluded from this research project.

The relevant factors which are selected during this study must be explicitly or implicitly mentioned by at least by two literature sources; one literature source and one expert during an interview or two experts during an interview. When a factor is relevant according to the literature, but most of the interviewed experts consider the factor to be irrelevant for the success of the competing hydrogen production technologies it is excluded from the final list of relevant factors. From the literature review an initial list of relevant factors will be constructed which will be used during the first round of interviews to check whether the factors on the list are relevant according to experts. The findings from the literature study and first round of interviews will be used to construct the final list of relevant factors for the success of the competing hydrogen production technologies for refineries in Netherlands. The list of relevant factors will then be subdivided into categories of factors to group similar factors together. By grouping factors together pairwise comparisons between the categories can be made and it will be easier to distinguish the similarities and differences between the relevant factors for experts.

4.2.2. Interviews

For the study primary data is also collected through expert interviews to gather more detailed insights specifically relevant to the case study. During the study two rounds of expert interviews are conducted.

The first round of interviews is conducted to find relevant factors for the success of the hydrogen production technologies for refineries in the Netherlands. These interviews will be semi-structured with some predetermined open questions to start exploring which factors could be relevant for the success of the competing technologies. During the first round of interviews the focus will be on asking questions to search for new relevant factors which were not yet found during the literature study. In addition, the experts will be asked whether they consider a factor as relevant for the success of the competing hydrogen production technologies for use in refineries in the Netherlands using the list of relevant factors that is constructed during the literature study. In the appendix the open questions used for the first round of interviews can be found.

The second round of interviews is conducted to determine the importance of the categories and factors for the success of the hydrogen production technologies for refineries in the Netherlands. In addition, the performance of each of the competing hydrogen production technologies will also be rated with respect to each relevant factor. Moreover, the experts will be asked whether the relevant factors can be influenced by stakeholders and if so, who could influence the factor. The second round of interviews will be semi-structured interviews using a list of predetermined questions to conduct the interview. In the appendix the questions used for the second round of interviews can be found.

For the expert interviews experts must be found, approached and willing to collaborate in the research project. The first step of finding experts for the interviews is determining selection criteria for the interviewees. Expert are selected for the interviewees based on their knowledge about the hydrogen production technologies, their knowledge about the use of hydrogen in refineries and knowledge about the regulatory environment regarding hydrogen and sustainable energy. Experts which are knowledgeable about the topic are found by asking my mentor at Vattenfall for recommendations, using Google to lookup refineries, energy companies and industrial clusters in the Netherlands. The contact details of the experts are received through recommendations or by searching for contact details on the website of their organization. Next, the expert will be approached by sending an email asking if they are willing to participate in an interview for the research project. The interviews are then planned using team's meetings and the experts are asked for their informed consent to participate in the research project. The experts are asked to sign a standardized informed consent form that is used as proof of the experts voluntarily participation in the research project and that they accept that the audio and video are recorded during the interview. The recorded audio and video of the interview are confidential, but they are useful to transcribe the interview afterwards. Anonymized transcripts of the interviews will be produced, and such non-personal data will be made publicly available for further research. The informed consent form used for the study can also be found in the appendix.

4.3. Data analysis

To analyse which factors are the most and least important for the success of the competing hydrogen production for use in refineries in the Netherlands a multi-criteria decision-making (MCDM) method is used. A multi-criteria decision-making method can be used to make pairwise comparisons between multiple criteria to determine the most and least important criteria for a given problem. During this study the problem the decision maker faces is figuring out which factors are the most important for the success of the competing hydrogen production technologies to be used in refineries in the Netherlands. Therefore, a multi-criteria decision-making method can be used to make pairwise comparisons between relevant factors for the success of hydrogen production technologies for use in refineries in the Netherlands. Several MCDM methods exist such as AHP, TOPSIS, DEA and BWM. The best-worst method (BWM) has been selected as the MCDM to be used during this study because of its simplicity, advantages over the AHP and availability of a linear model in Excel to easily solve the MCDM problem.

Now the steps of the best-worst method will be explained to determine the weights for the relevant factors during the expert interviews using the methodology as developed by Rezaei (2015; 2016).

Step 1: Determine a set of decision criteria. In this step a set of relevant criteria or factors for the success of the competing hydrogen production technologies to be used in refineries in the Netherlands will be determined.

Step 2: Determine the best, i.e. the most important factor, and the worst, i.e. the least important factor. The best factor will be the most important factor for the success of the competing hydrogen production technologies to be used in refineries in the Netherlands during this study. In addition, the worst factor will be the least important factor for the success of the competing hydrogen production technologies to be used in refineries in the Netherlands during this study. In this step, an expert will be asked to identify the best and worst factor during the second round of expert interviews.

The resulting best-to-others vector will be:

$A_B = (A_{B1}, A_{B2,} \ldots, A_{Bn})$

In this case A_{Bj} indicates the preference of the best (most) important factor B over the other factor(s) j.

Step 3: Determine the preference of the most important factor over all other factors using a number between 1 and 9. In this case, the rating 1 means that other factor is equally as important as most important factor and 9 means that other factor is not important at all compared to the most important factor. Thus, the most important factor with respect to itself is rated with 1 and the least important factor with respect to the most important factor is rated with a 9. The factor(s) in between the most important factor and least important factor will be rated with an integer number between 1 and 9 with respect to the most important factor.

The resulting other-to-worst vector will be:

$A_W = (A_{W1}, A_{W2,} \ldots, A_{Wn})^T$

In this case A_{Wj} indicates the preference of the other factor(s) j over the worst (least) important factor W.

Step 4: This step will be similar to step 3 however, the other factors will be compared to the least important factor in this case. This will enable us to check the consistency of the comparisons between factors made by an expert during the interview.

Determine the preference of the least important factor over all other factors using a number between 1 and 9. In this case, the rating 1 means that the other factor is equally as important as the least important factor and 9 means that the other factor is far more important compared to the least important factor. Thus, the least important factor with respect to itself is rated with 1 and the most important factor with respect to the least important factor is rated with a 9. The factor(s) in between the most important factor and least important factor will be rated with an integer number between 1 and 9 with respect to the least important factor.

Step 5: Determine the optimal weights for the relevant factors. The optimal weight for the factors is the weight where for the pairwise comparison between the most important factor and another factor, and the pairwise comparison between another factor and the least important factor, the maximum absolute differences is minimized. In other words, when w_B is the weight of the best (most) important factor, w_j is the weight of the other factor for all other factors j, and w_W is the weight of worst (least) important factor. Then, the optimal weight for the factor is the one where, for each pair w_B/ w_j and w_j/w_W, the following is true $w_B/w_J = a_{Bj}$ and $w_j/w_W = a_{jW}$. To satisfy these conditions for all j, a solution should be find where the maximum absolute differences $\left|\frac{w_B}{w_j} - a_{Bj}\right| and \left|\frac{w_j}{w_W} - a_{jW}\right|$ for all j is minimized. The sum of all the weights should be 1 and the weights should be non-negative. The following problem can then be solved to determine the optimal weights and a consistency index.

$$\left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \xi, \text{for all j}$$

$$\left|\frac{w_j}{w_W} - a_{jW}\right| \leq \xi, \text{for all j}$$

$$\sum_j w_j = 1$$

$$w_j \geq 0, \text{for all j} \qquad (1)$$

For this study a linear model in excel will be used to solve this problem. The linear model used during the study is developed by Rezaei (2016). The input data for this model will be the findings from the expert interviews about the most important factor and category and the least important factor and category. In addition, the findings of the comparisons of the other factors with respect to the most important factor and least important factor with respect to the other factors will also be used as input data for the model. The results derived from this model will be the weights of the factors and categories as well as the Ksi* which can be used to calculate the consistency ratio. Next, these results are used in another excel sheet to calculate the overall weights by summing the weights given by the experts to factors and categories. In addition, the overall relevance of the factors and categories for the success of each hydrogen production technology for use in refineries in the Netherlands will be calculated in the excel sheet as well. These overall relevance scores for the factors and categories will also be multiplied by their respective overall category and factor weights to determine a category weighted relevance score and within category weighted relevance scores for each factor and category for the three hydrogen production technologies separately. In addition, an overall weighted relevant score will also be calculated by multiplying the overall factor relevance with the overall factor weights. The overall weighted relevant score will enable the direct comparisons of factors between different categories because the category and factor weight are both included. Finally, three technology scores will be determined the first using the relevance of the categories, the second using the relevance of the factors and a third score using the overall weighted relevance derived from the scores given by the experts during the second round of interviews.

5. Results

5.1. Findings from first round of interviews

This section will present the findings from the first round of interviews. A short description of the experts that have been interviewed will be presented in table 1. Thereafter, the factors which are relevant for the success of the competing hydrogen production technologies during the transition to a sustainable feedstock for refineries in the Netherlands according to the literature are presented in table 2. The list of relevant factors is constructed using factors mentioned explicitly or implicitly to be relevant for the success of the hydrogen production technologies for refineries in the Netherlands in scientific literature or relevant articles published by respectable organizations. Furthermore, experts have been interviewed and are asked open questions to discover new relevant factors for the success of the technologies. In addition, the interviewees have been asked whether the factors found during the literature study are relevant or not according to them, these results can also be found in table 2. The findings from the literature study and first round of interviews are used to construct the final list of relevant factors and can be found in table 3. The definitions of the categories and factors on the final list are also described in this section.

Table 1. Description of the experts interviewed during the first round of interviews.

Expert	Background	Expertise
1	Industry	Business development oil and gas transport in the Netherlands (15 years)
2	Industry	Energy regulations advisor (17 years)
3	Industry	Business development green hydrogen and renewable energy (11 Years)

The findings from the literature study and the first round of expert interviews are presented in the table 2. During the second round of interviews the experts are asked to judge whether a factor on the list of relevant factors found during the literature study is relevant for the success of the hydrogen production technologies to be used in refineries in the Netherlands. These results can be found in the last column of the table below.

Table 2. The relevant factors found during the literature study are presented here, including citations from the literature and expert judgements with regards to the relevance of the factor for the success of the competing hydrogen production technologies for use in refineries in the Netherlands.

Factor	Literature citation	Literature source	Judged as relevant by expert
Price of hydrogen	“We find that hydrogen can unlock approximately 8 per cent of global energy demand with a hydrogen production cost of USD 2.50 per kg, while a cost of USD 1.80 per kg would unlock as much as roughly 15 per cent of global energy demand by 2030.” (Hydrogen Council, 2020, p. 23) “To realise investments in the use of green hydrogen, green hydrogen must be cheaper or no more expensive than blue or grey hydrogen.” (HyWay 27, 2021, p. 88)	Hydrogen Council (2020, p. 23), HyWay 27 (2021, p. 88)	Expert 1,2,3

Factor	Literature citation	Literature source	Judged as relevant by expert
Price of natural gas	"The cost of hydrogen varies significantly across regions, as it depends heavily on the prices and availability of energy inputs. To produce low-carbon hydrogen from reforming plus CCS, companies require access to low-cost natural gas" (Hydrogen Council, 2020, p. 28)	Hydrogen Council (2020, p. 28)	Expert 1,2,3
Price of electricity	"In addition to capital costs, the costs of electrolysis are also driven by operational costs, of which the price of electricity is a large part." (HyWay 27, 2021, p. 89)	HyWay 27 (2021, p. 89)	Expert 1,2,3
Security of supply	"One of the key differences with trade in crude oil or natural gas is that hydrogen trade will be less asymmetric. It is technically possible to produce hydrogen almost everywhere in the world." (Van de Graaf et al., 2020, p. 4) "Two main challenges that lie ahead for the power sector are ensuring the availability of enough renewable electricity to cover the increased demand caused by end-use decarbonization (i.e., direct and indirect electrification of end uses), and ensuring that power systems are capable of handling increasingly higher shares of variable renewables." (IRENA, 2020b, p. 177)	Van de Graaf et al. (2020, p. 4) IRENA (2020b, p. 177)	Expert 1,2,3
Supply side incentives	"Investing in electrolysis is currently not profitable because the alternatives are cheaper, meaning that private parties will invest less in upscaling electrolysis capacity than is socially desirable. Financial support is needed to get investments off the ground and, by means of these investments, achieve the desired increase in scale and reduction in costs." (HyWay 27, 2021, p.89) "Implement financial policies and incentives to accelerate early-stage innovation and deployment of green hydrogen technologies." (IRENA, 2021a, p. 18)	HyWay 27 (2021, p.89), IRENA (2021a, p. 18)	Expert 1,2,3
Demand side incentives	"Putting a price on carbon emissions and other supporting policies regarding matters like standards or blending obligations are important for the relative business cases of the different colours of hydrogen." (HyWay 27, 2021, p. 90) "Stimulate demand for green hydrogen through carbon pricing and other regulatory measures." (IRENA, 2021a, p. 18)	HyWay 27 (2021, p. 90), IRENA (2021a, p. 18)	Expert 1,2,3
Regulator	"Promoting hydrogen uptake across the various end use sectors requires an integrated policy approach. The main pillars of this are: national hydrogen strategies that bring all the elements together, set a long-term vision shared with industry and guide efforts from multiple stakeholders; setting policy priorities for sectors where hydrogen could add the most value according to national conditions; governance systems and enabling policies that remove barriers and facilitate growth; guarantees of origin systems to track production emissions and be able to value the lower GHG emissions" (IRENA, 2020a, p. 19)	IRENA (2020a, p. 19)	Expert 1,2,3

Factor	Literature citation	Literature source	Judged as relevant by expert
Technological superiority	“Water electrolysis is a commercial technology and the policies described above can kick-start and maintain a national hydrogen sector. But continued effort is needed in research and innovation to make green hydrogen competitive with grey hydrogen and fossil fuels.” (IRENA, 2021b, p. 47) “While key hydrogen technologies are ready to start scaling up, continuous innovation is critical to drive down costs and increase competitiveness.” (IEA, 2021, p. 211)	IRENA (2021b, p. 47), IEA (2021, p. 211)	Expert 1,2,3
Complementary goods	“If, for a given technology, there is a necessary set of complementary goods required for the technology to be useful or desirable to customers and a firm is unable or poorly suited to produce its own complementary goods, that firm is at the mercy of other complementary goods providers. If complementary goods providers do not support the technology, or the complementary goods produced are not of competitive price or quality, the firm may find its technology locked out of the market.” (Schilling, 1998, p. 11)	Schilling (1998, p. 11)	
Learning rate	“At a learning rate of 20%, the capital costs of electrolysis could be as much as 80% cheaper by 2030. In comparison, solar panels have a learning rate of more than 20% (IRENA, 2020a) and offshore wind 6 to 8% (TKI Wind op Zee, 2021).” (HyWay 27, 2021, p. 89) “Current learning curve expectations for electrolyzer scale-ups range from 11-12% between 2020 and 2030 for polymer electrolyte membrane (PEM) and alkaline technologies. However, these learning curves appear conservative compared with the early development of other low-carbon technologies like batteries, solar PV or onshore wind, which saw learning rates of approximately 20-40% between 2010 and 2020.” (Hydrogen Council, 2021a, p. 24)	HyWay 27 (2021, p. 89), Hydrogen Council (2021a, p. 24)	Expert 1,2,3 (somewhat convincing)

The findings from the literature study and first round of expert interviews are used to construct the final list of relevant factors. The final list of relevant factors for the success of the competing hydrogen production technologies for use in refineries in the Netherlands is presented in table 3. Only one of the factors from the initial literature review is excluded from this list which is the factor complementary goods. The factor complementary goods is excluded from the final list of relevant factors for the success of the competing hydrogen production technologies for use in refineries in the Netherlands because all the experts interviewed during the first round of interviews judged the factor as not relevant for the success of the technologies. Moreover, the expert 1 and 2 emphasized the importance of price for the success of the hydrogen production technologies to be used in refineries in the Netherlands. They said that the choice between the hydrogen production technologies comes down to the price of the hydrogen one way. However, they also emphasized that regulations and subsidies are instrumental to develop the hydrogen supply chain for the more sustainable alternative hydrogen production technologies. Thus, the outlook for the green and blue hydrogen production technologies depends to a significant degree on policies developed and implemented by policy makers from the EU and the Netherlands. Specifically, the current renewable energy directive 2 (RED 2) and the upcoming renewable energy directive 3 (RED 3) European regulations were mentioned as relevant for the success of the hydrogen production technologies by expert 1 and 2. In addition, expert 3 emphasized the importance of the European RED 2 for the success of the hydrogen production technologies as well. Moreover, expert 3 noted that currently refineries reduce their CO_2 footprint by adding biofuels to their fossil fuel products. This approach to reducing CO_2 emissions by refineries is especially interesting considering the RED 2 because green hydrogen will become a substitute for biofuels as a Renewable Fuel of Non-Biological Origin (RFNBO) while blue hydrogen will not qualify as a RFNBO because it is produced from fossil fuels. Nevertheless, expert 2 noted that there is uncertainty about the future developments and requirements for the use of green hydrogen by refineries because refineries are partly included in targets for the mobility sector and partly included in the targets for the industry sector within the upcoming RED 3. The first round of interviews with the three experts did unfortunately not result in finding new relevant factors but the interviews were instrumental in determining the relevance of the criteria found during the literature study.

In the table below the relevant factors are also subdivided into 3 categories: price, technological characteristics and government. The categorization of the factors has been done to make similarities and differences between the factors more apparent. The categorization will also make it easier for experts to compare the factors among each other during the second round of interviews because the differences between the factors in one category are more comparable.

Table 3. Final list of relevant factors and categories.

Category	Factor
Price	Price of hydrogen
	Price of natural gas
	Price of electricity
Technological characteristics	Security of supply
	Technological superiority
	Learning rate
Government	Supply side incentives
	Demand side incentives
	Regulator

The definitions of the categories and factors as used during the second round of interviews are now presented. The definitions primarily serve the purpose of clarifying the meaning of the categories and factors to experts who are asked to compare the categories and factors among each other. It is important to clearly define these factors to avoid ambiguity and ensure the replicability, rigor and testability of the study. Therefore, a comprehensive list of definitions of the relevant factors will follow now.

Categories

There are three different categories of factors, these are price, technological characteristics and government.

- The category price is about the price of the inputs of the hydrogen production technologies and the input price of hydrogen for use in refineries.

- The category technological characteristics are about technology specific attributes of the competing hydrogen production technologies.
- The category government is about the effect of government authorities on the success of the competing hydrogen production technologies for the use in refineries in the Netherlands.

Factors

The price category has 3 relevant factors:

- The price of hydrogen is the input price of hydrogen for use in refineries
- The price of natural gas is the input price of natural gas for use in steam methane reformers
- The price of electricity is the input price of electricity for use in electrolysers

The technological characteristic category has 3 relevant factors

- Security of supply is about the reliability of hydrogen supply from each hydrogen production technology
- Technological superiority is about the technological performance of the hydrogen production technology such as efficiency and environmental impact
- Learning rate is the rate of improvement of the technology and can be expressed in the reductions of capital investment costs overtime
- Complementary goods are goods that increase the value of a technology for their users, a increase in the number of complementary goods thus increases the value of a technology with complementary goods. An example of complementary goods for the competing hydrogen production technologies are the number of electricity or natural gas sources.

The government category has 3 relevant factors:

- Supply side incentives are incentives such as subsidies to develop more sustainable hydrogen production facilities
- Demand side incentives are incentives such as carbon taxes to reduce CO2 emissions and search for more sustainable hydrogen feedstocks by refineries
- Regulator determines what is allowed, what is required and what is not allowed, for example by requiring the use of green hydrogen as percentage of the overall use of hydrogen in refineries or banning the use of grey hydrogen

5.2. Findings from second round of interviews

Description of the experts interviewed including the organization they are working for and with which technologies they have been directly involved.

Table 4. Description of the experts interviewed during the second round of interviews.

Expert	Organization	Description of role	Directly involved with
1	Industry	Business developer energy transition paths within industrial cluster Zeeland, West-Brabant and East Flanders	Green, blue and grey hydrogen production and use in refineries
2	Industry	Business development manager hydrogen	Project development of green hydrogen production and collaborating with customers, partners and regulators in the Netherlands and Germany. Projects: CurtHyl
3	Industry	Portfolio manager green hydrogen Netherlands and Germany	Green hydrogen production and customers purchasing hydrogen in the Netherlands and Germany. Projects: CurtHyl
4	Industry	Technical lead NorthH2	Technical knowledge about green hydrogen production. Projects: NorthH2
5	Academia	Innovation manager focused on gas in the energy transition and developing public/private partnerships	Green, blue and grey hydrogen production and application of hydrogen within the industry. Projects: North sea energy (PosHYdon), H-vision
6	Academia	Professor at a technical university, promoted on petroleum distillation and worked as a chemical engineer at Shell	Technological and organizational aspects of green, blue and grey hydrogen production
7	Academia	Manager of roadmap CO2 neutral industry	Researching carbon capture, green and blue hydrogen production, synthetic fuels, biofuels, industrial transformation with regards to energy and energy infrastructure. Projects: H-vision
8	Industry	CO2 reduction advisor	Reducing CO2 emissions of a refinery in the Netherlands
9	Industry	Manager electrification and hydrogen	Grey, blue and green hydrogen producers and hydrogen users in the Port of Rotterdam
10	Industry	Business manager oil and refining	Gas markets Russia
11	Industry	Refinery process engineer	Use of hydrogen in refineries
12	Industry	Government affairs manager	Green hydrogen regulations for refineries

5.2.1. The importance of the relevant categories and factors for the success of the hydrogen production technologies for use in refineries in the Netherlands

The findings from the pairwise comparison of the categories and factors by the experts will now presented. The results are derived from the interviews and the linear model for the best-worst method developed by Rezaei (2016). The results presented in the table are the weights for the relevant categories and factors as well as the Ksi* found using the linear model. The weights are a measure of importance for the relevant categories and factors for the success of the hydrogen production technologies for use in refineries in the Netherlands. In addition, an overall weight is calculated for each relevant category and factor by summing the weights of all the experts and dividing them by the number of experts interviewed. The calculations have all been performed in excel, the excel sheets used to derive the results presented below will be included in the appendix.

Table 5. The findings from the comparisons between the categories: price, technological characteristics and government are presented below

Category weights	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6
Price	0,74	0,67	0,67	0,13	0,68	0,67
Technological characteristics	0,18	0,06	0,06	0,13	0,07	0,27
Government	0,08	0,27	0,28	0,73	0,25	0,06
Calculations consistency ratio	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6
Ksi*	0,01	0,14	0,17	0,47	0,08	0,14
Consistency index	5,23	5,23	5,23	5,23	5,23	5,23
Consistency ratio	0,00	0,03	0,03	0,09	0,02	0,03

Category weights	Expert 7	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12	**Overall category weight**
Price	0,60	0,06	0,07	0,07	0,24	0,24	0,40
Technological characteristics	0,06	0,60	0,25	0,18	0,11	0,11	0,17
Government	0,35	0,34	0,68	0,75	0,64	0,64	0,42
Calculations consistency ratio	Expert 7	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12	
Ksi*	0,10	0,07	0,08	0,15	0,09	0,09	
Consistency index	5,23	5,23	5,23	5,23	2,30	2,30	
Consistency ratio	0,02	0,01	0,02	0,03	0,04	0,04	

Table 6. Findings from the comparisons between the factors within the category price

Factor weights	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7
Price of hydrogen	0,77	0,63	0,81	0,15	0,67	0,06	0,33
Price of natural gas	0,16	0,07	0,12	0,76	0,06	0,60	0,33
Price of electricity	0,06	0,30	0,07	0,08	0,27	0,35	0,33
Calculations consistency ratio	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7
Ksi*	0,21	0,02	0,16	0,61	0,14	0,10	0,00
Consistency index	5,23	5,23	5,23	5,23	5,23	5,23	0,00
Consistency ratio	0,04	0,00	0,03	0,12	0,03	0,02	0,00

Factor weights	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12	**Overall weight in the category**	**Overall weight**
Price of hydrogen	0,72	0,05	0,06	0,07	0,07	0,37	0,15
Price of natural gas	0,22	0,47	0,68	0,62	0,62	0,39	0,16
Price of electricity	0,06	0,47	0,26	0,32	0,32	0,24	0,10
Calculations consistency ratio	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12		
Ksi*	0,16	0,00	0,11	0,02	0,02		
Consistency index	5,23	5,23	5,23	5,23	5,23		
Consistency ratio	0,03	0,00	0,02	0,00	0,00		

Table 7. Findings from the comparisons between the factors within the category technological characteristics

Factor weights	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7
Security of supply	0,69	0,68	0,75	0,72	0,73	0,27	0,80
Technological superiority	0,23	0,06	0,07	0,06	0,07	0,06	0,08
Learning rate	0,08	0,26	0,18	0,22	0,20	0,67	0,12
Calculations consistency ratio	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7
Ksi*	0,00	0,11	0,15	0,16	0,08	0,14	0,05
Consistency index	5,23	5,23	5,23	5,23	5,23	5,23	5,23
Consistency ratio	0,00	0,02	0,03	0,03	0,02	0,03	0,01

Factor weights	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12	**Overall weight in the category**	**Overall weight**
Security of supply	0,68	0,75	0,72	0,06	0,06	0,57	0,10
Technological superiority	0,26	0,06	0,06	0,23	0,23	0,12	0,02
Learning rate	0,06	0,19	0,22	0,72	0,72	0,30	0,05
Calculations consistency ratio	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12		
Ksi*	0,11	0,19	0,16	0,23	0,23		
Consistency index	5,23	5,23	5,23	5,23	5,23		
Consistency ratio	0,02	0,04	0,03	0,04	0,04		

Table 8. Findings from the comparisons between the factors within the category government

Factor weights	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7
Supply side incentives	0,07	0,16	0,06	0,14	0,06	0,67	0,78
Demand side incentives	0,68	0,08	0,67	0,08	0,60	0,06	0,15
Regulator	0,25	0,76	0,27	0,78	0,34	0,27	0,07
Calculations consistency ratio	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7
Ksi*	0,08	0,07	0,14	0,03	0,07	0,14	0,13
Consistency index	5,23	5,23	5,23	5,23	5,23	5,23	5,23
Consistency ratio	0,02	0,01	0,03	0,01	0,01	0,03	0,03

Factor weights	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12	Overall weight in the category	Overall weight
Supply side incentives	0,29	0,17	0,07	0,54	0,54	0,30	0,13
Demand side incentives	0,29	0,07	0,25	0,29	0,29	0,29	0,12
Regulator	0,43	0,76	0,68	0,17	0,17	0,41	0,17
Calculations consistency ratio	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12		
Ksi*	0,43	0,11	0,08	0,04	0,04		
Consistency index	5,23	5,23	5,23	1,00	1,00		
Consistency ratio	0,08	0,02	0,02	0,04	0,04		

The consistency index can be found in table 1 in the paper by Rezaei (2015). The consistency index for most of the pairwise comparison during this study is 5.23 according to Rezaei (2015) as the pairwise comparisons between the best and worst factor or category are rated with a 9 for almost all comparisons. The only exceptions in the consistency index are for the pairwise comparison made by expert 7 for the price factors, the categories for expert 11 and 12 as well as the government factors for expert 11 and 12. These sets of pairwise comparisons have a consistency index of 0; 2,3 and 1 respectively as can be derived from table 1 in the paper by Rezaei (2015). Expert 7 judged the price of hydrogen, price of natural gas and price of electricity to be equally important, thus the difference between the best and worst factor in this case was 1. As a result, the consistency index for these comparisons made by expert 7 is 0,00 according to Rezaei (2015). In this case, the consistency ratio can be approximated using a consistency index very close to 0 since the consistency ratio is calculated by dividing Ksi* by the consistency index (Rezaei, 2015). Therefore, the consistency ratio for the pairwise comparisons by expert 7 for the price factors is approximately 0. The consistency ratios for the other pairwise comparisons are calculated in the same manner in the excel sheet and can be found in tables just presented as well.

5.2.2. Relevance of the categories and factors for the success of green, blue and grey hydrogen production for use in refineries in the Netherlands

Now the findings from the questions about the relevance of the categories and factors for the success of the three different hydrogen production technologies for use in refineries in the Netherlands will be presented. The performance of each competing hydrogen production technology for use in refineries can also differ for each of the relevant factors. Therefore, to determine the performance of the competing hydrogen production technologies with respect to each factor the experts have been asked to rate the relevance of the categories and factors for each competing hydrogen production technology. To compare the relevance of the factors and categories for each of the competing technologies the experts are asked to rate each factor or category with respect to each competing hydrogen production technology with a relevance score of 0 (not relevant), 3 (less relevant), 5 (relevant) or 7 (highly relevant).

The findings about the relevance of the categories and factors with respect to each technology can thereafter be used in combination with the factor and category weights to determine the technology scores as described in the methodology. As a result, the success of the competing technologies can be compared because the technologies with high relevance for the most important factors and categories will be most likely to succeed if the factor or category has a positive influence on the success of the technology. When the factor or category which is important and highly relevant for the success of green, blue or grey hydrogen to be used in refineries in the Netherlands has a negative influence on the success, then the technology is unlikely to succeed. So, it is important to distinguish whether a factor or category has a positive or negative influence on the success of a technology. The results will be discussed in more detail in the discussion.

The relevance scores of the categories and factors for the success of green hydrogen production using electrolysers and renewable electricity for use in refineries in the Netherlands will be presented below in tables. In addition, the relevance scores given by the experts and the average overall relevance of the categories and factors will be presented as well.

Table 9. The relevance scores of the categories and factors as well as the technology scores for the success of green hydrogen production for use in refineries in the Netherlands.

Relevance for green hydrogen	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12	**Overall Relevance**	**Category Weighted Relevance**	**Overall Weighted Relevance**
Category price	7	5	5	7	5	7	7	5	5	5	5	5	5,67	2,28	
Price of hydrogen	7	5	5	5	7	7	7	5	0	3	5	5	5,08	1,86	0,75
Price of natural gas	5	3	7	5	3	5	0	3	5	7	0	0	3,58	1,41	0,57
Price of Electricity	7	7	7	7	7	7	7	7	7	5	7	7	6,83	1,65	0,67
Category Score	6,33	5,00	6,33	5,67	5,67	6,33	4,67	5,00	4,00	5,00	4,00	4,00	5,17	4,92	
Category technological characteristics	7	3	5	7	7	7	7	5	7	7	7	7	6,33	1,10	
Security of supply	7	3	5	7	7	7	7	7	7	7	7	7	6,50	3,73	0,65
Technological superiority	7	3	5	7	7	5	7	5	5	5	7	7	5,83	0,72	0,12
Learning rate	7	7	7	7	7	7	7	7	7	7	7	7	7,00	2,12	0,37
Category Score	7,00	4,33	5,67	7,00	7,00	6,33	7,00	6,33	6,33	6,33	7,00	7,00	6,44	6,57	
Category government	7	7	7	7	7	5	7	7	7	7	7	7	6,83	2,89	
Supply side incentives	5	7	5	7	5	5	5	7	5	5	7	7	5,83	1,72	0,73
Demand side incentives	7	5	7	7	5	3	7	7	5	7	5	5	5,83	1,71	0,72
Regulator	7	7	7	7	7	5	7	7	7	7	7	7	6,83	2,81	1,19
Category Score	6,33	6,33	6,33	7,00	5,67	4,33	6,33	7,00	5,67	6,33	6,33	6,33	6,17	6,25	
Technology score 1	7,00	5,00	5,67	7,00	6,33	6,33	7,00	5,67	6,33	6,33	6,33	6,33	6,28	6,28	
Technology score 2	6,56	5,22	6,11	6,56	6,11	5,67	6,00	6,11	5,33	5,89	5,78	5,78	5,93	5,91	
Technology score 3															5,77

The table below will present the relevance scores of the categories and factors for the success of blue hydrogen production using steam methane reformers and carbon capture and storage for use in refineries in the Netherlands. The relevance scores given by the experts and the average overall relevance of the categories and factors can be found in the table.

Table 10. The relevance scores of the categories and factors as well as the technology scores for the success of blue hydrogen production for use in refineries in the Netherlands.

Relevance for blue hydrogen	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12	**Overall Relevance**	**Category Weighted Relevance**	**Overall Weighted Relevance**
Category price	7	7	5	7	5	3	7	5	3	5	5	5	5,33	2,15	
Price of hydrogen	7	7	5	5	5	5	7	5	0	3	5	5	4,92	1,80	0,72
Price of natural gas	7	5	7	5	5	3	5	3	5	5	7	7	5,33	2,09	0,84
Price of Electricity	3	5	0	3	3	3	3	3	5	3	3	3	3,08	0,75	0,30
Category Score	5,67	5,67	4,00	4,33	4,33	3,67	5,00	3,67	3,33	3,67	5,00	5,00	4,44	4,64	
Category technological characteristics	5	5	5	5	3	5	7	5	3	3	7	7	5,00	0,87	
Security of supply	3	5	5	7	5	5	5	7	7	7	7	7	5,83	3,35	0,58
Technological superiority	5	5	5	5	5	5	5	5	5	3	7	7	5,17	0,63	0,11
Learning rate	3	5	5	3	5	5	0	5	3	3	5	5	3,92	1,19	0,21
Category Score	3,67	5,00	5,00	5,00	5,00	5,00	3,33	5,67	5,00	4,33	6,33	6,33	4,97	5,17	
Category government	5	5	7	7	5	5	7	7	7	5	7	7	6,17	2,61	
Supply side incentives	5	5	5	5	3	3	3	5	5	3	7	7	4,67	1,38	0,58
Demand side incentives	5	3	5	5	7	5	5	5	5	5	5	5	5,00	1,47	0,62
Regulator	3	7	7	7	7	5	5	5	7	5	7	7	6,00	2,47	1,05
Category Score	4,33	5,00	5,67	5,67	5,67	4,33	4,33	5,00	5,67	4,33	6,33	6,33	5,22	5,31	
Technology score 1	5,67	5,67	5,67	6,33	4,33	4,33	7,00	5,67	4,33	4,33	6,33	6,33	5,50	5,63	
Technology score 2	4,56	5,22	4,89	5,00	5,00	4,33	4,22	4,78	4,67	4,11	5,89	5,89	4,88	5,04	
Technology score 3															5,02

The table below will present the relevance scores of the categories and factors for the success of grey hydrogen production using steam methane reformers without carbon capture and storage for use in refineries in the Netherlands. The relevance scores given by the experts and the average overall relevance of the categories and factors can be found in the table.

Table 11. The relevance scores of the categories and factors as well as the technology scores for the success of grey hydrogen production for use in refineries in the Netherlands.

Relevance for grey hydrogen	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10	Expert 11	Expert 12	**Overall Relevance**	**Category Weighted Relevance**	**Overall Weighted Relevance**
Category price	7	3	5	7	5	7	5	5	0	3	5	5	4,75	1,91	
Price of hydrogen	7	3	5	5	3	7	7	3	0	0	3	3	3,83	1,40	0,56
Price of natural gas	7	7	7	5	7	7	5	3	3	5	3	3	5,17	2,03	0,82
Price of Electricity	3	3	0	3	3	0	3	3	0	3	0	0	1,75	0,42	0,17
Category Score	5,67	4,33	4,00	4,33	4,33	4,67	5,00	3,00	1,00	2,67	2,00	2,00	3,58	3,85	
Category technological characteristics	3	5	0	5	3	3	5	5	0	0	3	3	2,92	0,51	
Security of supply	3	7	5	7	3	5	5	7	7	7	3	3	5,17	2,97	0,51
Technological superiority	3	3	5	3	3	5	5	5	0	3	3	3	3,42	0,42	0,07
Learning rate	3	0	0	3	0	3	0	0	0	0	0	0	0,75	0,23	0,04
Category Score	3,00	3,33	3,33	4,33	2,00	4,33	3,33	4,00	2,33	3,33	2,00	2,00	3,11	3,61	
Category government	5	7	7	7	5	3	7	3	3	3	7	7	5,33	2,26	
Supply side incentives	0	3	5	3	0	3	0	0	3	0	7	7	2,58	0,76	0,32
Demand side incentives	5	3	7	7	5	5	0	5	0	0	5	5	3,92	1,15	0,49
Regulator	3	5	7	7	3	3	0	5	0	0	7	7	3,92	1,61	0,68
Category Score	2,67	3,67	6,33	5,67	2,67	3,67	0,00	3,33	1,00	0,00	6,33	6,33	3,47	3,52	
Technology score 1	5,00	5,00	4,00	6,33	4,33	4,33	5,67	4,33	1,00	2,00	5,00	5,00	4,33	4,68	
Technology score 2	3,78	3,78	4,56	4,78	3,00	4,22	2,78	3,44	1,44	2,00	3,44	3,44	3,39	3,66	
Technology score 3															3,67

5.3. Model of the operational cost price of hydrogen

A model of the operational cost price of hydrogen for the competing hydrogen production technologies has been developed using the methodology described in the previous chapter. The model provides some valuable insights in the relationship between the hydrogen price, natural gas price and carbon price which were not immediately apparent after the two rounds of interviews with experts. Moreover, several experts noted during the second round of interviews that they had a difficult time comparing the price of hydrogen, price of natural gas and electricity among each other because they were interdependent. The model of the operational cost price of hydrogen provides some insight in these interdependencies.

The operational cost price of hydrogen for the competing hydrogen production technologies is compared given one snapshot of the dutch natural gas price, electricity price and carbon price. This has been done using real world values found of these prices on 20/12/2021 in the Netherlands (fig 5). In addition, ten alternative scenarios with varying natural gas prices, electricity prices and carbon prices have been developed and visualized to make comparisons between the hydrogen production technologies during different market conditions. These alternative scenarios highlight the sensitivity of the hydrogen cost price to the natural gas price, electricity price and carbon price. These ten alternative scenarios can be found in the appendix.

Table 12. The parameters for the model of the operational cost price of hydrogen for the current scenario using market data on 20/12/2021.

Parameter	**Value**	**Source**
Price of natural gas (eur/MWh)	146,44	ICE (n.d.)
Price of electricity (eur/MWh)	360,78	EPEX SPOT (n.d.)
Price of carbon (eur/ton CO2)	79,38	EEX (n.d.)
MWh natural gas required per kg hydrogen produced grey (MWh/kg)	0,0439	Collodi et al. (2017, p. 16), Keen Compressed Gas Co (2020)
MWh natural gas required per kg hydrogen produced blue (MWh/kg)	0,0483	Collodi et al. (2017, p. 16), Keen Compressed Gas Co (2020)
Unit of electricity required per unit hydrogen produced (MWh/kg)	0,051	Chardonnet et al. (2017, p. 9)
CO2 emissions (ton) per (kg) hydrogen produced using SMR	0,00989	Collodi et al. (2017, p. 16), Keen Compressed Gas Co (2020)
CCS capture rate in %	89%	Collodi et al. (2017, p. 16)

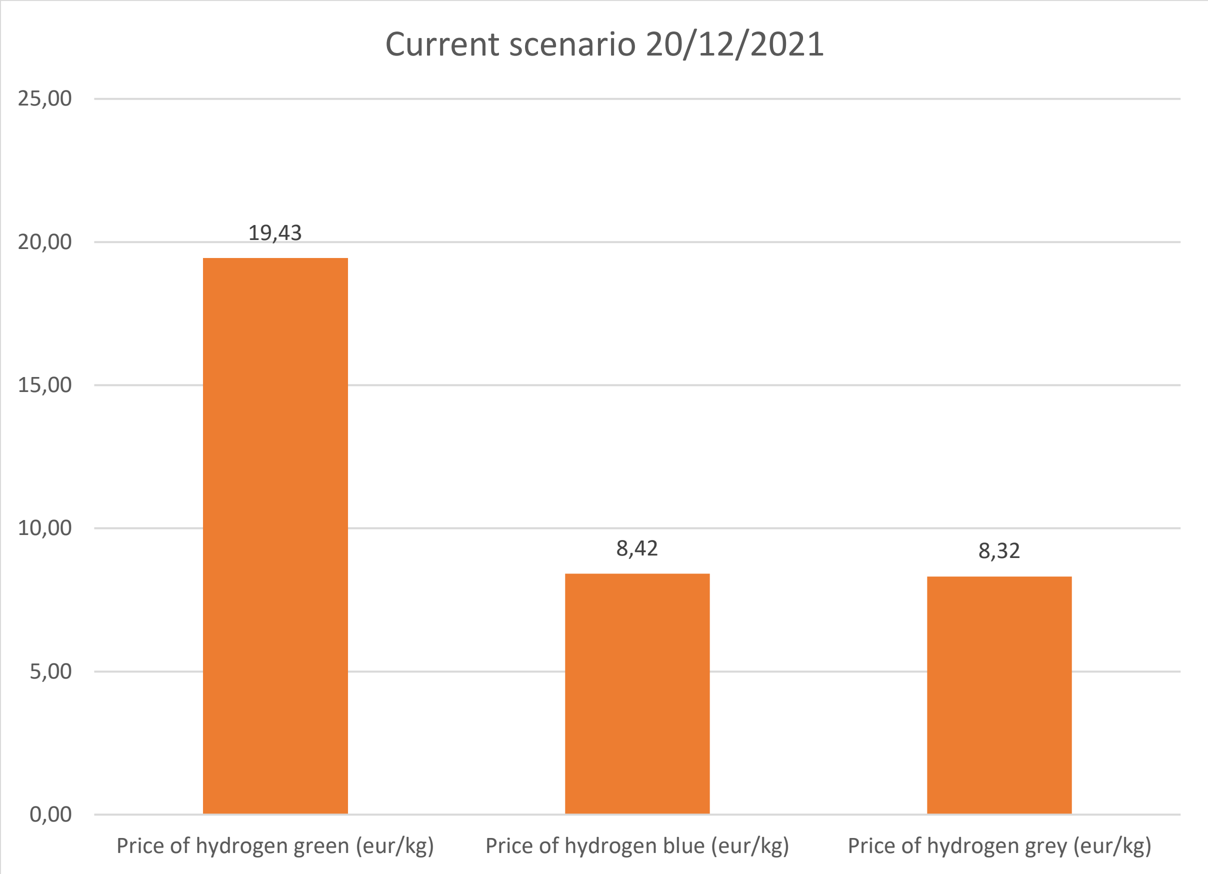

Fig 5. The price of operational cost price of green, blue and grey hydrogen in eur/kg calculated using market data on 20/12/2021.

The operational cost price of hydrogen has also been modelled using changing natural gas and electricity prices as well as with changing carbon prices. The price of green hydrogen, blue hydrogen and grey hydrogen is calculated with the price of natural gas being equal to the price of natural gas in eur/MWh. Furthermore, the price of green hydrogen is also calculated using an average ratio between price of electricity with respect to the price of natural gas as well as for a hypothetical scenario were the price of electricity would be equal to 75% of the price of natural gas. The average ratio between the electricity price and natural gas is determined using the power base load price of the first trading day of each month during the 12 months of 2021 and dividing that by the closing price of the dutch ttf natural gas future (EPEX SPOT, n.d.; ICE, n.d.). The ratio between the electricity price and natural gas price for the 12 months of 2021 can be found in the table 13 below. The price of blue hydrogen is also compared with grey hydrogen using the natural gas price from 20/12/2021 and a changing carbon price (fig 7).

Table 13. The ratio between the price of electricity and the price of natural gas calculated using market data for the first trading day of each month during 12 months in 2021.

Date in 2021	Ratio of electricity price vs gas price
5 January	2,80
1 February	3,17
1 March	3,05
1 April	2,66
3 May	2,65
1 June	2,63
1 July	2,46
2 Aug	2,07
1 Sep	2,30
1 Oct	1,24
1 Nov	1,49
1 Dec	1,99
Average	**2,38**

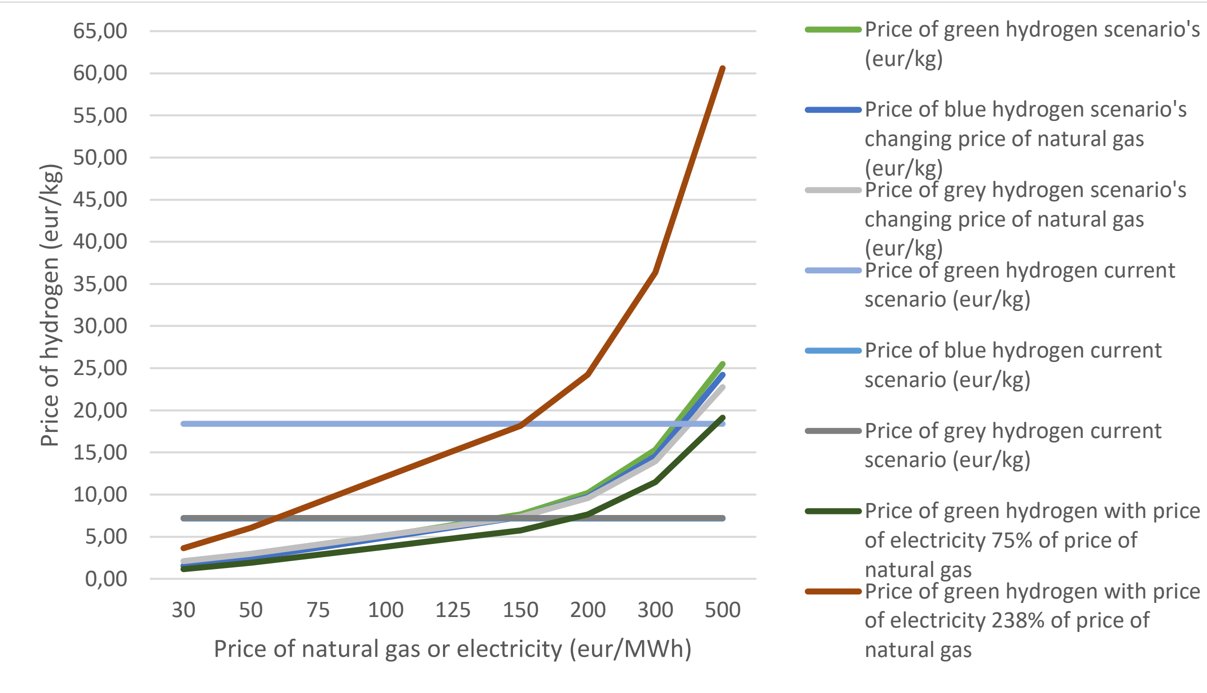

Fig 6. The price of green, blue and grey hydrogen in eur/kg when the price of natural gas and price of electricity changes from 30 eur/MWh to 500 eur/MWh while having a carbon price of 79,38 eur/ton CO2.

Figure 6 illustrates the changing price of green, blue and grey hydrogen when the price of natural gas and price of electricity changes from 30 eur/MWh to 500 eur/MWh while having a carbon price of 79,38 eur/ton CO2. Therefore, this figure provides insight in the sensitivity of the price of green, blue and grey hydrogen to the price of natural gas and the price of electricity. The horizontal lines are the prices of green, blue and grey hydrogen using the prices on 20/12/2021 as described earlier. First, the price of green, blue and grey hydrogen is calculated using a price of electricity equal to the price of natural gas, these price curves are the three curves closest together in figure 6. On top of that, two additional scenarios for the price of green hydrogen have been calculated to compare the differences between the price of green, blue and grey hydrogen depending on the ratio between the electricity price and natural gas price. One scenario is calculated for the price of electricity being equal to 75% the price of natural gas with the price of natural gas changing from 30 eur/MWh to 500 eur/MWh and the price of electricity changing from 22,5 eur/MWh to 375 eur/MWh. Similarly, the price of green hydrogen is also calculated with the price of electricity being equal to 238% of the price of natural gas. An average ratio between the electricity price and natural gas price in the Netherlands has been calculated earlier resulting in the price of electricity being 2.38 times higher than the price of natural gas. Therefore, a price of electricity equal to 238% of the price of natural gas can be considered as a reasonable assumption of the actual price of green hydrogen compared to blue and grey hydrogen when the price of natural gas changes.

The figure below illustrates the price of hydrogen using the price of natural gas on 20/12/2021 (146,44 eur/MWh) and changing the carbon price between 50 eur/ton CO2 and 200 eur/ton CO2. As a result, the figure provides insight in the sensitivity of the price of blue and grey hydrogen to carbon prices. Green hydrogen is excluded from this figure as no CO2 is directly emitted during the production of green hydrogen.

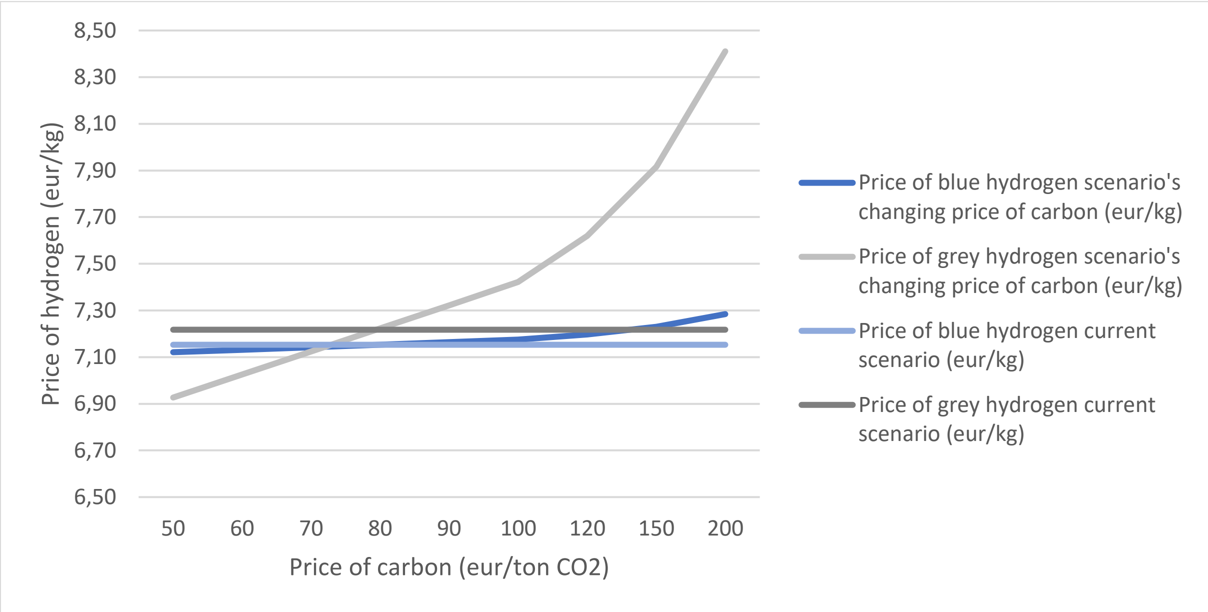

Fig 7. The price of blue and grey hydrogen in eur/kg when the price of carbon is changing from 50 eur/ton CO2 to 200 eur/ton CO2.

6. Discussion

In this chapter the findings from the research study will be discussed. The chapter will recap the research problem, research objective and summary of the main findings from the study. Next, an interpretation of the results found during the literature study, first round of interviews and second round of interviews will be presented. Thereafter, the limitations of the study will be discussed such as theoretical and methodological limitations. Finally, some practical implications of the research will be presented and recommendations for future research will be given.

6.1. Summary of the problem, purpose and findings

The incumbent dominant design for hydrogen production used in refineries in the Netherlands is producing grey hydrogen using steam methane reforming with CO2 as byproduct. Therefore, the current dominant design for hydrogen production used in refineries in the Netherlands is unsustainable. However, it is still unclear which hydrogen production technology will become the new dominant design during the transition to sustainable hydrogen feedstocks for refineries in the Netherlands.

The purpose of this study is to research which factors influence the success of hydrogen production technologies for use in refineries within the scope of the study. Gaining insight into the factors for success of the hydrogen production technologies for use in refineries will contribute to the scientific literature and have practical relevance for producers of hydrogen, refineries as well as policy makers.

One of the main findings from this study is the list of relevant factors and categories for the success of the hydrogen production technologies for use in refineries in the Netherlands. The list of relevant factors and categories has been developed using a literature study and a first round of expert interviews. In addition, the second round of interviews have resulted in finding weights for all the relevant factors and categories based on the importance as judged by experts. Furthermore, relevance scores have also been determined by the experts for each of the factors and categories with respect to each competing hydrogen production technology. Thus, relevance scores have been determined for the green hydrogen production technology (electrolysis using renewable energy), blue hydrogen production (steam methane reforming in combination with carbon capture and storage) and the current dominant design grey hydrogen production (steam methane reforming). Finally, three technology scores are determined for the success of each of the competing hydrogen production technologies for use in refineries in the Netherlands by weighting the relevance scores for each of the factors and categories. One technology score is determined by summing the weighted relevance score of the categories and dividing it by the number of categories. The second technology score is determined by summing the weighted relevance score of the factors and dividing it by the number of factors. The third technology score is determined by summing the overall weighted relevance score for the factors, this score uses the combined category and factor weight to weigh the relevance of each factor. The details about these findings can be found in the results chapter and the calculations can be found in the appendix excel sheets.

Furthermore, a model of the operational cost price of hydrogen has been developed to provide insight in the interdependency between the price of electricity, price of natural gas, carbon prices and how they affect the price of hydrogen. Several experts noted during the second round of interviews that they had a difficult time comparing the price of hydrogen, price of natural gas and price of electricity because they deemed them to be interdependent. In addition, some experts also noted during the second round of interviews that carbon prices were a relevant factor affecting the cost price of hydrogen. Therefore, the model of the operational cost price of hydrogen was developed after conducting most of the second round of interviews with experts, to gain insight in the interdependencies between the price of hydrogen, price of natural gas, price of electricity and carbon prices. Moreover, the model also provides insight in the sensitivity of the price of hydrogen to the price of electricity, price of natural gas and carbon prices. However, a more rigorous sensitivity analysis could add more detailed insights in the sensitivity of the price of hydrogen to these variables. The main findings from the model are that currently using market data of the price of natural gas, price of electricity and carbon prices on 20/12/2021 the price of blue hydrogen has the lowest operational cost based on the feedstock with 7,15 eur/kg hydrogen. Thereafter, the price of grey hydrogen is not much more expensive with 7,22 eur/kg hydrogen followed by green hydrogen with a more than two times higher operational cost price for hydrogen of 18,40 eur/kg. In addition, the model shows that the operational cost price of green hydrogen based on the feedstock becomes almost competitive with blue and grey hydrogen when the price of electricity is equal to the price of natural gas. When the price of electricity is equal to 75% of the price of natural gas green hydrogen would currently have the lowest cost price based on the operational costs of the feedstock. However, as calculated using market data from 2021 the average electricity price in the Netherlands is 2.38 times the price of natural gas. Finally, the model shows that the breakeven price of blue hydrogen and grey hydrogen is somewhere between 70 and 80 eur/ton CO2 when the price of natural gas is equal to 146,44 eur/MWh making the operational costs of blue hydrogen based on the feedstock less expensive than grey hydrogen at carbon prices of 80 eur/ton CO2 or higher.

6.2. Interpretation of the results

In this section interpretations of the results will be discussed. The focus will be on what the findings from the literature study and expert interviews imply as well as how they can be interpreted. In addition, some comments will be made about the relation between the findings and the scientific literature. Moreover, the contributions of the research will also be discussed to clearly explain how the study has contributed to the scientific literature.

6.2.1 Interpretation of the findings from the literature study

The findings from the literature study resulted in a list of relevant factors for the success of hydrogen production for use in refineries in the Netherlands. In addition, the literature study contributed to the study by providing a theoretical foundation with regards to technology battles, technology selection and dominant designs. The technology management literature stream of the scientific literature about technology battles provided a valuable theoretical foundation for the rest of the research. The technology management literature emphasizes that technology selection can be influenced by firm level factors as well as environmental factors and is not entirely path dependent (Schilling, 1998, 2002, Suarez 2004, van de Kaa et al., 2011). Within the scientific literature about technology battles several streams exists besides technology management such as network economists, evolutionary economists and institutional economists (van de Kaa et al., 2011). Moreover, by researching the relevant factors for success of the hydrogen production technologies for use in refineries in the Netherlands the research implicitly assumes that relevant factors for success exist. Within the scientific literature about technology battles several case studies have already been performed to find factors which influence the success of competing technologies within the energy sector (Van de Kaa et al., 2017a; Van de Kaa et al., 2017b; Van de Kaa et al., 2019; Van de Kaa et al., 2020). The findings from the literature study and first round of interviews with experts during this study again confirm the existence of relevant factors for success of competing technologies in the energy sector.

The findings from the literature study also imply that the hydrogen production technologies for use in refineries do not have strong network externalities because the value of the hydrogen production technologies does not directly increase with the number of users or in this case refineries using one technology. Hydrogen production technologies do have indirect network externalities because the value of the technologies does increase with adoption because of learning and economies of scale. However, the first round of expert interviews resulted in the finding that complementary goods are not relevant for the success of hydrogen production technologies for use in refineries. This finding was somewhat unexpected as complementary goods are found to be a relevant factor in the scientific literature about technology battles. Schilling said the following about the relevance of complementary goods for technology success:

> "If, for a given technology, there is a necessary set of complementary goods required for the technology to be useful or desirable to customers and a firm is unable or poorly suited to produce its own complementary goods, that firm is at the mercy of other complementary goods providers. If complementary goods providers do not support the technology, or the complementary goods produced are not of competitive price or quality, the firm may find its technology locked out of the market." (Schilling, 1998, p. 11)

6.2.2. Interpretation of the findings from the first round of interviews

That complementary goods were judged to be irrelevant by experts can be interpreted in several ways. One interpretation is that there are no relevant complementary goods for competing hydrogen production technologies. However, it can be argued that renewable electricity is a complementary good for green hydrogen production using electrolysers. In addition, it can be argued that natural gas is a complementary good for blue and grey hydrogen production using steam methane reformers. Another interpretation is that firms have proper access to necessary complementary goods such as electricity and natural and these complementary goods are of a competitive price and quality. As a result, hydrogen producers will not be locked out of the market for use in refineries because of a lack of necessary complementary goods. Therefore, complementary goods are irrelevant for the success of the hydrogen production technologies for use in refineries in the Netherlands.

6.2.3 Interpretation of the weights of the relevant factors and categories

The findings from the second round of interviews have resulted in the weights for the relevant factors and categories based on their importance as judged by experts interviewed. In addition, the second round of interviews resulted in the relevance scores of the factors for each of the competing hydrogen production technologies. The weights for the relevant factors and categories can be interpreted as the importance of a relevant factor or category for the success of the competing hydrogen production technologies for use in refineries in the Netherlands. Thus, the factor with the largest weight is the most important factor the success of the hydrogen production technologies in this case the factor that is the regulator with an overall weight of 0,17. The second, third and fourth most important factor according to experts interviewed are the price of natural gas with an overall weight of 0,16, followed by the price of hydrogen with an overall weight of 0,15 and thereafter the supply side incentives with an overall weight of 0,13. The two least important factors are clearly the technological superiority with an overall weight of 0,02 and the learning rate with an overall weight of 0,05. The categories are given an overall weight of 0,40 for the category price, 0,17 for the category technological characteristics and 0,42 for the category government.

It is interesting that not all experts agree that the regulator is the most important factor within the category government as only 5 of the 12 experts interviewed rated it as the most important factor within the category. However, there seems to be consensus that it is somewhat more important than the other factors within the category, supply side incentives and demand side incentives which are judged as similar in importance. In addition, the category weight of the government is only slightly higher than the price category weight. As a result, the weights for the most important factor, the regulator, is almost as important as the second and third most important factor the price of natural gas and the price of hydrogen. Therefore, the answers of one or two experts could easily change the order of these three most important factors. Thus, the order of importance of the relevant factors should in this case not be considered as that distinctive.

Moreover, it is interesting that expert 7 rated the price of hydrogen, price of natural gas and price of electricity as equally important indicating the difficulty of the expert to distinguish the importance of these factor between each other. In addition, expert 9 rated the price of natural gas and the price of electricity as equally important indicating a similar problem in distinguishing the importance of these factors by this expert. Several experts noted during the second round of interviews that they had a difficult time comparing the price of hydrogen, price of natural gas and price of electricity with each other because of their interdependencies and not being applicable to each of the competing technologies in the same manner. This makes sense because the price of hydrogen (the input price of hydrogen for refineries) depends on the price of natural gas (the input price of natural gas for steam methane reformers) or price of electricity (the input price of electricity for electrolysers) depending on the hydrogen production technology used. As a result, the answers by the experts for the price factors might be somewhat distort because of different interpretations of the factors for the success of the hydrogen production technologies. Therefore, making sure that factors are not interdependent and being equally applicable to competing technologies is an area of improvement for this study.

The results also show that the experts that did not judge the price of natural gas to be the most important factor within the category price, judged the price of hydrogen to be the most important factor. Experts 1, 2, 3, 5 and 8 not all judged the price of hydrogen to be the most important factor instead of the price of natural gas. An explanation of the differences in the answers by these experts could be explained by the interdependencies of the price factors. Since the price of hydrogen (the input price of hydrogen for refineries) depends on the price of natural gas (the input price of natural gas for steam methane reformers) or price of electricity (the input price of electricity for electrolysers) depending on the hydrogen production technology used. Therefore, these experts could have interpreted the price of hydrogen as being dependent on the price of natural gas and the price of electricity.

With regards to the security of supply it is interesting that all experts interviewed agree that it is the most important factor within the category technological characteristics except for expert 6, 11 and 12. Expert 6, 11 and 12 judged the learning rate to be the most important factor within the category technological characteristics instead. The selection and definition of the relevant factors within category technological characteristics could also be improved because steam methane reformers are already widely used and a mature technology while at the same time there is still significant room for improvement of the electrolyser design, manufacturing, and operation. As a result, the security of supply for grey and blue hydrogen production is currently well established while it is not yet established for green hydrogen production. In addition, the room for improvement of the electrolyser technology makes the learning rate a more important factor for the success of this technology while at the same time having a negligible impact on the success of steam methane reformers.

6.2.4. Interpretation of the consistency ratio

The consistency ratio is calculated for each of the set of comparisons made by the experts interviewed. The consistency ratio measures the reliability of the output of the best-worst method which is derived from the input given by the experts during the second round of interviews when they are asked to make pairwise comparisons between the categories and factors (Rezaei, 2015). The consistency ratio can range between 0 and 1 with results closer to 0 being more consistent (Rezaei, 2016). The results show that the consistency ratio for the pairwise comparisons made by the experts are all close to 0 with the highest consistency ratio being 0,12. Most of the pairwise comparisons made by the experts have consistency ratios below 0,05 and are therefore reliable. A consistency ratio of 0,12 is not even that high and therefore it can be argued that the pairwise comparisons made by expert 4 for the factors within the category price are also reliable.

6.2.5. Interpretation of the relevance scores and technology scores for each hydrogen production technology

The findings from the relevance scores given by the experts during the second round of interviews will now be discussed and interpretations of the technology scores will be given for each hydrogen production technology.

Relevance of factors and categories for the success of green hydrogen production for use in refineries in the Netherlands

The relevance scores for green hydrogen production for use in refineries in the Netherlands show that the categories are all relevant for the success of green hydrogen production but that the category government is especially relevant for the success of green hydrogen production. According to the results of the overall weighted relevance score the regulator is clearly the most relevant factor for the success of green hydrogen which is partly determined by the weight of the factor regulator and the weight of the category government. The price of hydrogen is the second most important factor for the success of green hydrogen production according to the overall weighted relevance score which is largely the result of the weight of the price of hydrogen. In contrast, the price of electricity is rated to be more relevant than the price of hydrogen by the experts interviewed for the success of green hydrogen but the weight of the price of electricity is somewhat lower resulting in a slightly lower overall weighted relevance score for the price of electricity. The third and fourth most relevant factor for the success of green hydrogen according to the experts interviewed are the supply side incentives and demand side incentives. Interestingly, security of supply is also rated as a highly relevant factor for the success of green hydrogen production. This could probably be because of the dependence on volatile renewable energy sources making it more difficult to achieve security of supply for green hydrogen. The only factor that appears to be less relevant for the success of green hydrogen is the price of natural gas. This is not completely unexpected as the natural gas is not required to produce green hydrogen, however as most electricity is currently still generated using natural gas in the Netherlands it is interesting that the price of natural gas is rated as less important for the success of green hydrogen which is highly dependent on the price of electricity.

The first technology score for the green hydrogen production technology indicates that the categories are very relevant for the success of green hydrogen production for use in refineries in the Netherlands. The second technology score indicates that the factors included in this study are relevant for the success of green hydrogen for use in refineries in the Netherlands. The third technology score indicates that when the factor weights and category weights are combined to determine the overall weighted relevance of the factors that the factors are relevant for the success of green hydrogen for use in refineries in the Netherlands. There are some variants in the technology scores for the success of the green hydrogen production technology, but it appears to be just noise because of variations in the relevance scores given to the categories and the factors as well as the category and factor weights.

Relevance of factors and categories for the success of blue hydrogen production for use in refineries in the Netherlands

The relevance scores for blue hydrogen production for use in refineries in the Netherlands show that the categories are all relevant for the success of blue hydrogen production but that the category government is the most important category. At the same time, it appears that the category price and technological characteristics are both almost equally as important for the success of blue hydrogen production. According to the results of the overall weighted relevance score the regulator is the most relevant factor for the success of blue hydrogen production followed by the price of natural gas and price of hydrogen.

The first technology score for the blue hydrogen production technology indicates that the categories are relevant for the success of blue hydrogen production for use in refineries in the Netherlands. The second technology score indicates that the factors included in this study are relevant for the success of blue hydrogen for use in refineries in the Netherlands. The third technology score indicates that when the factor weights and category weights are combined to determine the overall weighted relevance of the factors that the factors are relevant for the success of blue hydrogen for use in refineries in the Netherlands. It is interesting that the first technology score based on the relevance and weight of the categories is somewhat higher than second and third technology score. It is particularly interesting because the second and third technology score are very close together while only the third technology score also includes category weights in the calculation. This difference can be explained as a difference between the category relevance and weights given by the experts in comparison with the relevance and weights given to the factors. Nevertheless, the differences are not that large and could also be caused by noise in the data.

Relevance of factors and categories for the success of grey hydrogen production for use in refineries in the Netherlands

The relevance scores for grey hydrogen production for use in refineries in the Netherlands show that the categories government and price are relevant for the success of grey hydrogen production but that the category technological characteristics is less relevant for the success of grey hydrogen production. According to the results of the overall weighted relevance score the price of natural gas is the most relevant factor for the success of grey hydrogen production followed by the regulator and price of hydrogen. The security of supply is the fourth overall weighted most relevant factor despite experts' judgement that the security of supply is equally relevant as the price of natural gas for the success of grey hydrogen production. The overall weight for the factor security of supply compared to the regulator is the primary cause of this difference in results. Therefore, it can be argued that the security of supply is more important than the regulator for the success of grey hydrogen production for use in refineries in the Netherlands. In addition, there appears to be a lack of consensus about the relevance of the price of hydrogen for the success of grey hydrogen production for use in refineries in the Netherlands among the experts interviewed.

The first technology score for the grey hydrogen production technology indicates that the categories are relevant for the success of grey hydrogen production for use in refineries in the Netherlands. The second technology score indicates that the factors included in this study are somewhat less relevant for the success of grey hydrogen for use in refineries in the Netherlands. The third technology score indicates similarly that when the factor weights and category weights are combined to determine the overall weighted relevance of the factors that the factors are somewhat less relevant for the success of grey hydrogen for use in refineries in the Netherlands.

It is interesting to compare the technology scores between the competing hydrogen production technologies for use in refineries in the Netherlands. Green hydrogen production has the highest technology scores, followed by blue hydrogen production and grey hydrogen. This difference can be interpreted as a difference in relevancy of the categories and factors selected during for the competing hydrogen production technologies with the categories and factors being the most relevant for the success of green hydrogen production for use in refineries. For the success of blue hydrogen production, the categories and factors are also still relevant but to a lesser degree. With regards to grey hydrogen production the categories and factors used during the study are the least relevant for the success of grey hydrogen for use in refineries in the Netherlands.

6.2.6. Contributions of research

The contributions of this study will now be discussed. One of the main contributions of the research is the developing a new list of relevant factors and categories for the success of hydrogen production technologies for use in refineries in the Netherlands. Within the existing scientific literature about technology battles, technology selection and dominant designs, several frameworks exist with factors relevant for the success of competing technologies to become the dominant design in their market (Suarez, 2004; van de Kaa et al., 2011). In addition, several studies have already been performed to determine factors for the success of competing technologies in various sectors including the energy sector. However, a study into the factors for success of green hydrogen production (using electrolysis and renewable energy), blue hydrogen production (steam methane reforming in combination with carbon capture and storage) and grey hydrogen production (steam methane reforming without carbon capture and storage) for use in refineries in the Netherlands has not yet been performed. Thus, this study contributes to the literature on technology battles by studying this specific case. By applying the scientific literature about technology battles to develop a theoretical framework for this study, the research contributes to the literature about technology battles by applying the findings from previous studies in a new context. Moreover, the research contributes to existing literature on technology battles and specifically on how it can be applied in the energy sector. The findings from the study are relevant factor and categories for the success of upcoming more sustainable hydrogen production technologies for use in refineries in the Netherlands. Therefore, the research contributes to the literature by studying which factors and categories are relevant for the success of more sustainable energy technologies. In addition, the study focuses on factors for success of upcoming more sustainable hydrogen production technologies to overtake an incumbent unsustainable dominant design. The research also contributes to the scientific literature by developing a novel list of relevant factors for the success of green, blue and grey hydrogen production technologies for use in refineries in the Netherlands. This list of relevant factors can be used as a starting point to develop a framework to study technology battles between other sustainable energy technologies where an incumbent unsustainable technology is the dominant design but is expected to be challenged by upcoming sustainable alternatives.

Last but not least, the model of the operational cost price of hydrogen is another novel contribution to the literature of hydrogen production technologies and their competitiveness from an economic perspective. The model adds to the scientific literature of hydrogen production technologies from an economic perspective by providing insight in the main cost drivers, the electricity feedstock for electrolysers and the natural gas feedstock for steam methane reformers. The model also provides insight in the breakeven price of the production technologies during different market environments. Moreover, the model provides insight into the sensitivity of the price of hydrogen of the hydrogen production technologies to their respective feedstocks and the carbon price for blue hydrogen and grey hydrogen.

The findings together provide evidence to conclude which factors will be the most important for the success of the competing hydrogen production technologies to be used in refineries in the Netherlands. These findings provide valuable input for policy makers to develop more appropriate regulations to facilitate a desirable transition to more sustainable hydrogen feedstocks for refineries in the Netherlands. In addition, the findings provide insight in the most important factors for the success of the hydrogen production technologies for use in refineries in the Netherlands which can help technology managers better focus their efforts on improving the most important factors to develop a more profitable business case.

6.3. Limitations of research

The limitations of the research will now be discussed. One of the limitations of the study is that the list of relevant factors for success of the hydrogen production technologies for use in refineries is not exhaustive. In theory an infinite list of relevant factors for the success of hydrogen production technologies for use in refineries in the Netherlands can be developed. Nevertheless, the findings from the literature study including the first round of interviews have most likely resulted in including the most relevant factors for the success of the competing hydrogen production technologies for use in refineries in the Netherlands. However, a repeat study or additional interviews asking experts which factors affect the success of the hydrogen production technologies could increase the confidence and reliability of the findings during the first round of interviews. Another limitation of the research is that the positive or negative influence a factor has on the success of a hydrogen production technology for use in refineries in the Netherlands has not been studied in detail. As a result, some experts might have rated a factor as not relevant during the second round of interviews for the success of one of the competing hydrogen production technologies because it had a negative influence on the success of that technology for use in refineries in the Netherlands. Furthermore, there exist some interdependencies between the price of hydrogen, price of natural gas and price of electricity that might have resulted in different interpretations by the experts interviewed during the second round of interviews which might have caused some distortion in their relative weights. The effect of interdependencies between factors as well as the effect of overlap between factors such as the price of hydrogen and demand side incentives (including CO2 taxes) or the price of hydrogen and price of natural gas is an area of improvement of this study. However, the model of the operational cost price of hydrogen does provide some insight in these interdependencies among the price of hydrogen, price of natural gas, price of electricity and carbon prices.

Another limitation of the study is the implicit assumption that the factors and categories are all equally important, as expressed in the factor and category weights, for the competing hydrogen production technologies. For example, very little electricity is used in steam methane reformers while it is the primary feedstock for electrolysers, making the price of electricity not as important for the success of blue or grey hydrogen production but very important for the success of green hydrogen production. The findings about the relevance of the factors and categories with respect to each hydrogen production technology do compensate for these discrepancies to some extent but might not capture all subtle differences. As the factors and categories have varying importance for each hydrogen production technology, experts might have had a hard time to give a general weight for each category and factor representative for all the competing hydrogen technologies combined. With regards to the methodology there are limitations to the generalizability of the findings as the study focuses on one specific case and the number of experts is limited. In addition, the experts interviewed might have a biased view on the factors for success of the hydrogen production technologies depending on their job function and the organization they are working. Another limitation of the study is that some of the experts have been interviewed at the same time which might have influenced their answer because of groupthink. Finally, during two second round interviews the time ran out before having asked all questions as a result the questionnaire was send to the interviewees to answer the questions themselves as a survey. Therefore, these results might have been influenced because of the different data collection method compared with the other expert interviews.

A limitation of the model of the cost price of hydrogen is that the fixed investment costs are excluded from the calculations as well as the operational and maintenance costs. The fixed investment costs will become significant when the capacity factor of a hydrogen production plant is low. This is important to keep in mind when considering an investment in an electrolyser that would only operate during periods with excessive electricity supply resulting in significantly lower electricity prices because if these periods only occur infrequently the electrolyser might only be operating for around 10% of the year at full load. As a result, the fixed investment cost would be a significantly higher share of the overall costs compared to a situation where the electrolyser could operate around 70% of the year at full load. Another limitation of the model could be the accuracy of the MWh required to produce one kg hydrogen for green, blue and grey hydrogen as they are based on secondary data sources.

6.4. Implications of research

The most important factors for success can be used as KPIs by managers developing hydrogen production facilities. In addition, the relevance of the factors for success for each of the competing hydrogen production technologies can also be used to determine which factor is specifically relevant for one of the competing hydrogen production technologies. As a result, the highly relevant factors can be focused on primarily to improve the technology in the future. The findings can also be used by refineries in the Netherlands to determine which hydrogen production technology they can best select based on their expectation of positive or negative developments going forward with respect to the most important and relevant factors for the hydrogen production technologies.

The model of the operational cost price of hydrogen has also provided valuable insights in the interdependency between the price of hydrogen, the price of natural gas, the price of electricity and carbon prices. The model implies that the price of grey hydrogen is the most affordable when carbon prices stay below around 70 eur/ton CO2, above around 80 eur/ton CO2 blue hydrogen will become the most affordable with a price of natural gas of 146,44 eur/MWh. When the price of natural gas is lower, the price of carbon in eur/ton CO2 where blue hydrogen will become cheaper than the price of grey hydrogen will be lower. The price of green, blue and grey hydrogen has also been calculated and illustrated using changing natural gas prices and electricity prices. Moreover, an electricity price to natural gas price ratio of 238% and 75% is also used to compare the price of green hydrogen with blue and grey hydrogen during different market environments. The electricity price to natural gas price ratio of 238% is the average ratio of the price of electricity with respect to natural gas during 2021, calculated using market data of one trading day during every month in 2021. Thus, the price of green hydrogen calculated using a price ratio of 238% is representative of actual market dynamics assuming the ratio of the price of electricity compared to natural gas does not change significantly. However, hourly electricity prices can fluctuate significantly especially during times of excess solar energy or wind energy because of favorable weather conditions. Therefore, the ratio of the electricity price with respect to the price of natural gas could fluctuate significantly on an hourly basis.

The model of the operational cost price of hydrogen also illustrates that the price of green hydrogen is a bit more expensive than blue and grey hydrogen when the price of electricity is equal to the price of natural gas. However, the price of green hydrogen becomes the most affordable when the price of electricity is around 75% of the price of natural gas. These findings can be used to determine when green hydrogen becomes competitive with blue and grey hydrogen. In addition, these results imply that a decreasing electricity price compared to the price of natural gas would increase the competitiveness of green hydrogen for refineries in the Netherlands. Continuing this train of thought, the price of electricity can be lowered by increasing the installed capacity of renewable energy sources since they have marginal cost close to zero. On the other hand, the current dominant design for power generation in the Netherlands, gas fired power plants require natural gas to produce electricity resulting in energy conversion losses and significant marginal costs. Thus, a new factor for the success of green hydrogen could be added to the list of relevant factors for the success of the hydrogen production technologies, being the (excess) installed capacity of renewable energy sources. Nonetheless, current market conditions do also provide opportunities to profit from producing green hydrogen during times of oversupply of renewable electricity, resulting in an electricity price below the price of natural gas. However, the frequency of oversupply of electricity does not occur that often currently in the Netherlands but would most likely increase in size and frequency with a growing share of installed capacity of renewable energy sources. This will be important for the success of green hydrogen production because it would increase the capacity factor at which electrolysers can operate profitably resulting in a smaller share of fixed costs in the cost price of green hydrogen.

6.5. Recommendations

Some recommendations for future research will now be made. The research initially was partly focused on investigating how stakeholders can influence the success of the hydrogen production technologies for use in refineries in the Netherlands. Some initial data has been gathered during the second round of interviews by asking the experts open questions about whether each of the relevant factors could be influenced by stakeholders and if so, who these stakeholders could be. The initial results indicate that most if not all the relevant factors can be influenced by stakeholders. In addition, several stakeholders have been described as being able to influence the factors these stakeholders include the EU/NL government, refineries, grid operators (tennet/gasunie), manufacturers of hydrogen production technologies, Russia (gazprom), Saudi Arabia (Aramco), Norway and citizens to name a few. Future research could focus on conducting a more thorough stakeholder analysis to determine which stakeholders could influence the relevant factors. In addition, a more in-depth analysis could also focus on how stakeholders could influence the relevant factors by conducting more exploratory interviews using a questionnaire to answer this question. Moreover, future research could study whether the relevant factors are relevant for the success of hydrogen production technologies for other applications such as ammonia or steel production. Future research could also study whether the are significant differences in relevant factors for the success of hydrogen production technologies for use in refineries in different regions or countries. Significant differences in the competitiveness of the hydrogen production technologies could be expected in areas with favorable renewable energy sources or very low natural gas prices. Furthermore, future research could also focus on studying whether the relevant factors are applicable to different upcoming sustainable energy technologies trying to overtake an incumbent dominant design and develop a framework for the success of upcoming sustainable alternative technologies challenging an incumbent unsustainable dominant design. In addition, future research could also focus on studying in more detail the positive and negative effects of the relevant factors on the success of the hydrogen production technologies for use in refineries in the Netherlands. The extent of the applicability of the relevant factors for each of to the competing hydrogen production technologies could also be an interesting area for further research. The findings from this study can also be used to investigate the techno-economic relationships between the relevant factors for the competing hydrogen production technologies for use in refineries in the Netherlands and develop a model to simulate the competitiveness of the technologies in multiple scenarios. The model of the operational cost price is a start of a techno-economic model which can be used to simulate the effects of changing market conditions on the economic competitiveness of the competing hydrogen production technologies. However, the model could be developed further by adding operational cost, maintenance costs, fixed investment costs and subsidies as well. Finally, a possible methodological improvement of the study could be to conduct surveys instead of interviews to reduce the amount of time needed to conduct interviews and the response rate of experts might be increased as well.

7. Conclusion

In this chapter the research questions and sub research questions will be answered. The sub research questions will be answered first and the conclusion will finish with the answer to the main research question.

Sub research questions

1. Which factors are relevant in determining the outcome of the technology battle between the competing hydrogen production technologies during the transition to a sustainable hydrogen feedstock for refineries in the Netherlands according to the literature?

According to the literature the factors which are relevant in determining the outcome of the technology battle between the competing hydrogen production technologies during the transition to a sustainable hydrogen feedstock for refineries in the Netherlands are: the price of hydrogen, the price of natural gas, the price of electricity, security of supply, technological superiority, learning rate, complementary goods, supply side incentives, demand side incentives and the regulator.

2. Which factors are important in determining the outcome of the technology battle between the competing hydrogen production technologies during the transition to a sustainable hydrogen feedstock for refineries in the Netherlands according to experts?

According to the experts interviewed during the first round of interviews the factors found in the literature are all important except for complementary goods in determining the outcome of the technology battle between the competing hydrogen production technologies during the transition to a sustainable hydrogen feedstock for refineries in the Netherlands. The findings from the second round of expert interview show that the price of hydrogen is the most important factor according to the experts, followed by the price of natural gas, security of supply and regulator.

3. Which hydrogen production technology is most likely to become the dominant design during the transition to a sustainable hydrogen feedstock for refineries in the Netherlands?

The hydrogen production technology which is most likely to become the dominant design during the transition to a sustainable hydrogen feedstock for refineries in the Netherlands will depend to a large degree on the factors that were found to be the most important during this study. These factors are the regulator, the price of natural gas, the price of hydrogen, supply side incentives and demand side incentives. The findings of this study show a varying degree in the relevance of these factors for the success of green hydrogen production using electrolysis and renewable energy compared to the other sustainable hydrogen feedstock for refineries within the scope of this research, blue hydrogen production using steam methane reforming of natural gas and carbon capture and storage. For both technologies the regulator is the most relevant factor. Providing convincing evidence why green hydrogen or blue hydrogen is most likely to become the new dominant design during the transition to a sustainable hydrogen feedstock for refineries in the Netherlands is difficult as it is still uncertain how EU policies and NL policies will be shaped in the future. Nevertheless, the EU Renewable Energy Directive 2 (RED 2) and the upcoming Renewable Energy Directive 3 (RED 3) have been mentioned by experts as important for the success of the competing hydrogen production technologies. At this point RED 2 has been implemented by the EU which does not yet include incentives to use blue or green hydrogen. However, the RED 3 which is being developed currently seems to favor green hydrogen over blue hydrogen because the directive includes a target for the use of Renewable Fuels of Non-Biological Origin (RFNBOs) for industry and mobility and blue hydrogen does not qualify as a RFNBO. The proposal states that refineries would be required to use RFNBOs equal to 2,6% of the total energy use in the mobility sector by mixing RFNBOs in their fuels or using it in the refinery processes (PBL, 2021). Thus, assuming the regulator will not change their stance with respect to green and blue hydrogen, the regulator would increase the likelihood of success of green hydrogen more than blue hydrogen. However, this is subject to change in the future as the RED 3 is still in development and it also needs to be adopted and implemented by the dutch government afterwards.

The second most important factor for the success of green hydrogen production is the price of electricity according to the overall relevance. On the other hand, the second most important factor for blue hydrogen production is the price of natural gas according to the overall relevance. These differences between the production technologies make sense because the feedstock for green hydrogen is electricity, making it an important factor for the competitiveness with respect to blue and grey hydrogen. On the other hand, natural gas is the feedstock for blue hydrogen thus it makes sense that it is an important factor for the competitiveness of blue hydrogen with respect to green and grey hydrogen. The model of the operational cost price of hydrogen has provided valuable insights in the relationship between the price of natural gas, price of electricity, carbon price and the price of green, blue and grey hydrogen. To determine the likelihood of success of green and blue hydrogen during the transition to a more sustainable alternative feedstock for refineries in the Netherlands the price of green and blue hydrogen during a given market condition can be compared. On 20/12/2021 the price of natural gas was 146,44 eur/MWh, the price of electricity was 360,78 eur/MWh and the carbon price was 79,38 eur/ton CO_2. Using these market conditions, the operational cost price of blue hydrogen is the lowest with 7,15 eur/kg followed by grey hydrogen with 7,22 eur/kg and finally green hydrogen being significantly more expensive with 18,40 eur/kg. As a result, blue hydrogen is the most affordable hydrogen production technology, increasing the likelihood of success of the technology during the transition to a sustainable alternative feedstock for refineries in the Netherlands.

However, as discussed earlier the model of the operational cost price of hydrogen does imply that green hydrogen becomes more competitive compared to blue and grey hydrogen when the price of electricity decreases compared to the price of natural gas. As a result, green hydrogen is already competitive during times of oversupply of renewable electricity resulting in electricity prices below the price of natural gas. Given the right market conditions green hydrogen can already be the most affordable source of hydrogen. The right market conditions for the success of green hydrogen depend to a large extent on the availability of (excess) renewable electricity. Therefore, increasing the installed capacity of renewable energy sources could increase the likelihood of success of green hydrogen production for use in refineries in the Netherlands because the oversupply of electricity and its frequency will most likely increase with a growing share of installed capacity of renewable energy sources. In addition, more frequent oversupply of electricity will increase the capacity factor of electrolysers and as a result reducing the dependency of hydrogen production costs on fixed investment costs making it more competitive with blue and grey hydrogen.

The third and fourth most important factor for the success of the competing hydrogen production technologies are supply side incentives and demand side incentives. The most common supply side incentives for the development of CO_2 reduction technologies in the Netherlands is the SDE++ subsidy mechanism. Both electrolysers and carbon capture and storage facilities qualify to apply for SDE++ subsidies in the Netherlands thus neither green nor blue hydrogen has a clear advantage in this regard that could increase their likelihood of success. Nonetheless, the supply side incentives do increase the likelihood of success of the more sustainable alternative green and blue hydrogen production technologies over grey hydrogen production. The demand side incentives stimulate the search by refineries for sustainable hydrogen feedstocks to avoid paying carbon taxes through the EU ETS, therefore demand side incentives do increase the likelihood of success of green and blue hydrogen production but have a negative effect on the likelihood of success of grey hydrogen.

To conclude, green hydrogen is most likely to become the new dominant design during the transition to a more sustainable alternative feedstock for refineries in the Netherlands in the long term because European regulators seem to prefer it over blue hydrogen in the development of the upcoming RED 3. However, there is some uncertainty in this regard as the RED 3 is still in development and thus subject to change. Moreover, the RED 3 also has to be adopted and implemented by the dutch government afterwards. In addition, the price of green hydrogen is currently still significantly higher than the price of blue or grey hydrogen but during the energy transition the installed capacity of renewable electricity will grow and will most likely result in electricity prices below the price of natural gas for a growing number of hours during a given year. As a result, electrolysers will be able to operate profitably with a higher capacity factor overtime, making them more competitive with blue and grey hydrogen production. Nevertheless, during the current market conditions blue hydrogen is the most affordable because of the relatively high carbon prices and high electricity prices. Thus, the market conditions in the Netherlands will first have to change to a market characterized by a relatively large share of renewable electricity generation and preferably having frequent oversupply of electricity resulting in electricity prices below the price of natural gas. Blue hydrogen production will stay the preferred choice for the foreseeable future until the market changes to a market with electricity prices which frequently are below the price of natural gas, assuming that the carbon price does not decline significantly as that could make grey hydrogen more attractive again. The supply side incentives and demand side incentives do accelerate the transition away from the use of grey hydrogen in refineries in the Netherlands towards the use of green and blue hydrogen by subsidizing these technologies and increasing the costs for polluting hydrogen production technologies such as grey hydrogen production. However, the supply side incentives and demand side incentives do not favor green over blue hydrogen or the other way around. All in all, the development of regulations, in particular RED 3, as well as the development of the electricity price with respect to the price of natural gas will be critical in determining whether green hydrogen or blue hydrogen production will become the new dominant design during the transition to a more sustainable hydrogen feedstock for refineries in the Netherlands.

Main research question

Finally, the main research questions will be answered. Which factors influence the success of the competing hydrogen production technologies during the transition to a sustainable hydrogen feedstock for refineries in the Netherlands?

The answer to the main research question is the final list of relevant factors for the success of the competing hydrogen production technologies during the transition to a sustainable hydrogen feedstock for refineries in the Netherlands developed using the findings from the literature study and first round of expert interviews. These factors are subdivided in three categories: price, technological characteristics and government. The factors which influence the success of the competing hydrogen production technologies during the transition to a sustainable hydrogen feedstock for refineries in the Netherlands are: the price of hydrogen, the price of natural gas, the price of electricity, security of supply, technological superiority, learning rate, complementary goods, supply side incentives, demand side incentives and the regulator. In addition, it can be argued that the installed capacity of renewable energy sources will also be an important factor for the success of green hydrogen production during the transition to a sustainable hydrogen feedstock for refineries in the Netherlands. The installed capacity of renewable energy sources could be an important factor for the success of green hydrogen because renewable energy sources have a marginal cost near zero, giving it a significant potential to reduce the price of electricity to below the price of natural gas. As a result, the price of green hydrogen could become more competitive than blue and grey hydrogen production for use in refineries in the Netherlands.

Reflection

The master thesis project has been a challenging project for me. The topic that I had selected was and still is very interesting to me. However, I did struggle a lot with finding and staying motivated during the research project. I think that a large part of my struggles with finding and staying motivated came from working from home and being in environment which is not as stimulating as the university or an office would have been. Nevertheless, working from home has its benefits as well but I am not sure if it is that suitable for me to keep my productivity up. With regards to the research during the master thesis itself, I had a hard time getting started with writing and I kept losing myself in endlessly reading scientific publications and articles that appeared to be relevant and interesting. As a result, it took a lot longer than I expected to put something on paper. The planning of the process was probably my biggest hurdle as I did not have a clear idea how I was going to get from start to the finish for a while. Therefore, I had a really hard time figuring out what to do when and it seemed too big to comprehend in the beginning. In the end dividing the thesis in chapters was helpful to make the steps to get from start to finish more comprehensible. However, the final struggle must have been just sitting down and starting to type, I always had an excuse to put it off but once I just started typing it was not that bad.

A reflection on the management of technology program. I learned a lot during my master management of technology, especially at the beginning. In the beginning I had a hard time figuring out how to study for the courses because I was so not used to answering open ended questions during exams coming from a bachelor mechanical engineering. However, the subjects where exactly what I was looking for. When I decided to apply for the master Management of Technology, I was looking for a business focused master which had a solid connection to engineering and technology. The courses which stood out to me and which I really enjoyed were high-tech marketing, integration moment, inter- and intra- organizational decision making, technology battles, sustainable innovations and transition and corporate entrepreneurship and start-ups.

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Appendix

Questionnaire first round of interviews

First round of interviews

First round of interviews open question to discover relevant factors for the success of the competing hydrogen production technologies during the transition to a sustainable feedstock for refineries in the Netherlands

Open questions:

1. What do you think determines the technology selection between SMR, SMR with CCS and electrolysis for use in refineries in the Netherlands?
2. Are there according to you factors which influence the technology selection?
3. Are there any specific factors that can be influenced by technology managers?
4. Are there any specific factors that can be influenced by policy makers?
5. Are there any specific factors that can be influenced by other stakeholders?
6. Are there any specific context or environmental dependent factors that influence the technology selection but cannot be influenced by stakeholders?
7. Why do you think that these factors are relevant during the technology selection?

Questions to check whether the factors on the list developed during the literature study are relevant:

8. Do you think that factors on this list are relevant during the technology selection?
9. Why do you think that these factors are relevant (or not)?

Questionnaire second round of interviews

Best-worst method questionnaire

Introduction of interview

The purpose of this interview is to determine the importance of relevant factors for the success of competing hydrogen production technologies for use in refineries in the Netherlands. The competing hydrogen production technologies within the scope of this study are hydrogen production using electrolysis and renewable energy, steam methane reforming of natural gas with and without using carbon capture and storage. In addition, a few questions will be asked to determine the relevance of the factors in comparison with the competing hydrogen production technologies. These results will provide insight into the similarities and differences among the technologies and will serve an important role in determining the likelihood of success of the competing technologies. Finally, a few questions will be asked to determine whether the factors can be influenced by stakeholders and if so, to find out who that could be.

List of relevant factors for the success of the competing hydrogen production technologies for use in refineries in the Netherlands.

Category	Factor
Price	Price of hydrogen
	Price of natural gas
	Price of electricity
Technological characteristics	Security of supply
	Technological superiority
	Learning rate
Government	Supply side incentives
	Demand side incentives
	Regulator

Categories

There are three different categories of factors, these are price, technological characteristics and government.

- The category price is about the price of the inputs of the hydrogen production technologies and the input price of hydrogen for use in refineries.
- The category technological characteristics are about technology specific attributes of the competing hydrogen production technologies.
- The category government is about the effect of government authorities on the success of the competing hydrogen production technologies for the use in refineries in the Netherlands.

Factors

The price category has 3 relevant factors:

- The price of hydrogen is the input price of hydrogen for use in refineries
- The price of natural gas is the input price of natural gas for use in steam methane reformers
- The price of electricity is the input price of electricity for use in electrolysers

The technological characteristic category has 3 relevant factors

- Security of supply is about the reliability of hydrogen supply from each hydrogen production technology
- Technological superiority is about the technological performance of the hydrogen production technology such as efficiency and environmental impact
- Learning rate is the rate of improvement of the technology and can be expressed in the reductions of capital investment costs overtime

The government category has 3 relevant factors:

- Supply side incentives are incentives such as subsidies to develop more sustainable hydrogen production facilities
- Demand side incentives are incentives such as carbon taxes to reduce CO2 emissions and search for more sustainable hydrogen feedstocks by refineries
- Regulator determines what is allowed, what is required and what is not allowed.

Questions:

1. Can I record this interview?
2. What is your name?
3. What is your function?
4. At what organization do (did) you work?

5. With which of the hydrogen production technologies have you been involved?
6. Do you know how hydrogen is used in refineries?

To assess the importance of the list of relevant factors the factors will be compared using pairwise comparisons following the best-worst method. The comparisons will be made within the categories of selected relevant factors followed by comparisons among the categories themselves.

I would like to start by asking you to compare the factor categories first

1. Which is the most important factor category for the success of the competing technologies?
    - Price
    - Technological characteristics
    - Government
2. Which is the least important factor category for the success of the competing technologies?
    - Price
    - Technological characteristics
    - Government
3. According to you category A is the most important factor for the success of the competing technologies, how would you score category B in comparison to A between 1 and 9? In this case, the rating 1 means that factor B is equally as important as A and 9 means that factor B is not important at all compared to A. (ask this question for all other categories that are not A except for the least important factor)
4. According to you category D is the least important factor for the success of the competing technologies, how would you score category E in comparison to D between 1 and 9? In this case, the rating 1 means that factor E is equally as important as A and 9 means that factor E is far more important compared to A. (ask this question for all other categories that are not D except for the most important factor)

Now I would like to ask you to compare the factors within the factor categories among each other in a similar manner.

1. In the factor category price, which is the most important factor for the success of the competing technologies?
    - Price of hydrogen
    - Price of natural gas
    - Price of electricity
2. In the factor category price, which is the least important factor for the success of the competing technologies?
    - Price of hydrogen
    - Price of natural gas
    - Price of electricity
3. According to you factor A is the most important factor for the success of the competing technologies, how would you score factor B in comparison to A between 1 and 9? In this case, the rating 1 means that factor B is equally as important as A and 9 means that factor B is not important at all compared to A. (ask this question for all other factors that are not A except for the least important factor)
4. According to you factor D is the least important factor for the success of the competing technologies, how would you score factor E in comparison to D between 1 and 9? In this case, the rating 1 means that factor E is equally as important as A and 9 means that factor E

is far more important compared to A. (ask this question for all other factors that are not D except for the most important factor)

5. In the factor category technological characteristics, which is the most important factor for the success of the competing technologies?
    - Security of supply
    - Technological superiority
    - Learning rate
6. In the factor category technological characteristics, which is the least important factor for the success of the competing technologies?
    - Security of supply
    - Technological superiority
    - Learning rate
7. According to you factor A is the most important factor for the success of the competing technologies, how would you score factor B in comparison to A between 1 and 9? In this case, the rating 1 means that factor B is equally as important as A and 9 means that factor B is not important at all compared to A. (ask this question for all other factors that are not A except for the least important factor))
8. According to you factor D is the least important factor for the success of the competing technologies, how would you score factor E in comparison to D between 1 and 9? In this case, the rating 1 means that factor E is equally as important as A and 9 means that factor E is far more important compared to A. (ask this question for all other factors that are not D except for the most important factor)

9. In the factor category government, which is the most important factor for the success of the competing technologies?
    - Supply side incentives
    - Demand side incentives
    - Regulator
10. In the factor category government, which is the least important factor for the success of the competing technologies?
    - Supply side incentives
    - Demand side incentives
    - Regulator
11. According to you factor A is the most important factor for the success of the competing technologies, how would you score factor B in comparison to A between 1 and 9? In this case, the rating 1 means that factor B is equally as important as A and 9 means that factor B is not important at all compared to A. (ask this question for all other factors that are not A except for the least important factor)
12. According to you factor D is the least important factor for the success of the competing technologies, how would you score factor E in comparison to D between 1 and 9? In this case, the rating 1 means that factor E is equally as important as A and 9 means that factor E is far more important compared to A. (ask this question for all other factors that are not D except for the most important factor)

The performance of each competing hydrogen production technology for use in refineries can also differ for each of the relevant factors. Therefore, to determine the performance of the competing hydrogen production technologies with respect to each factor I would like to ask you a couple more questions. To compare the relevance of the factors for each of the competing technologies I will ask you to give each technology a relevance score of 0 (not relevant), 3 (less relevant), 5 (relevant) or 7 (highly relevant) for each of the factors and categories.

Categories

1. How relevant is the category price for the success of green hydrogen production using electrolysis and renewable electricity for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
2. How relevant is the category price for the success of blue hydrogen production using steam methane reforming and carbon capture and storage for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
3. How relevant is the category price for the success of grey hydrogen production using steam methane reforming for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)

4. How relevant is the category technological characteristics for the success of green hydrogen production using electrolysis and renewable electricity for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
5. How relevant is the category technological characteristics for the success of blue hydrogen production using steam methane reforming and carbon capture and storage for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
6. How relevant is the category technological characteristics for the success of grey hydrogen production using steam methane reforming for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)

- 7 (highly relevant)

7. How relevant is the category government for the success of green hydrogen production using electrolysis and renewable electricity for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
8. How relevant is the category government for the success of blue hydrogen production using steam methane reforming and carbon capture and storage for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
9. How relevant is the category government for the success of grey hydrogen production using steam methane reforming for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)

Factors

10. How relevant is the price of hydrogen for the success of green hydrogen production using electrolysis and renewable electricity for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
11. How relevant is the price of hydrogen for the success of blue hydrogen production using steam methane reforming and carbon capture and storage for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
12. How relevant is the price of hydrogen for the success of grey hydrogen production using steam methane reforming for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)

13. How relevant is the price of natural gas for the success of green hydrogen production using electrolysis and renewable electricity for use in refineries in the Netherlands?

- 0 (not relevant)
- 3 (less relevant)
- 5 (relevant)
- 7 (highly relevant)

14. How relevant is the price of natural gas for the success of blue hydrogen production using steam methane reforming and carbon capture and storage for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
15. How relevant is the price of natural gas for the success of grey hydrogen production using steam methane reforming for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)

16. How relevant is the price of electricity for the success of green hydrogen production using electrolysis and renewable electricity for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
17. How relevant is the price of electricity for the success of blue hydrogen production using steam methane reforming and carbon capture and storage for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
18. How relevant is the price of electricity for the success of grey hydrogen production using steam methane reforming for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)

19. How relevant is the security of supply for the success of green hydrogen production using electrolysis and renewable electricity for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
20. How relevant is the security of supply for the success of blue hydrogen production using steam methane reforming and carbon capture and storage for use in refineries in the Netherlands?

- 0 (not relevant)
- 3 (less relevant)
- 5 (relevant)
- 7 (highly relevant)

21. How relevant is the security of supply for the success of grey hydrogen production using steam methane reforming for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)

22. How relevant is the technological superiority for the success of green hydrogen production using electrolysis and renewable electricity for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
23. How relevant is the technological superiority for the success of blue hydrogen production using steam methane reforming and carbon capture and storage for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
24. How relevant is the technological superiority for the success of grey hydrogen production using steam methane reforming for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)

25. How relevant is the learning rate for the success of green hydrogen production using electrolysis and renewable electricity for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
26. How relevant is the learning rate for the success of blue hydrogen production using steam methane reforming and carbon capture and storage for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
27. How relevant is the learning rate for the success of grey hydrogen production using steam methane reforming for use in refineries in the Netherlands?
    - 0 (not relevant)

- 3 (less relevant)
- 5 (relevant)
- 7 (highly relevant)

28. How relevant are supply side incentives for the success of green hydrogen production using electrolysis and renewable electricity for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
29. How relevant are supply side incentives for the success of blue hydrogen production using steam methane reforming and carbon capture and storage for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
30. How relevant are supply side incentives for the success of grey hydrogen production using steam methane reforming for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)

31. How relevant are demand side incentives for the success of green hydrogen production using electrolysis and renewable electricity for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
32. How relevant are demand side incentives for the success of blue hydrogen production using steam methane reforming and carbon capture and storage for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
33. How relevant are demand side incentives for the success of grey hydrogen production using steam methane reforming for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)

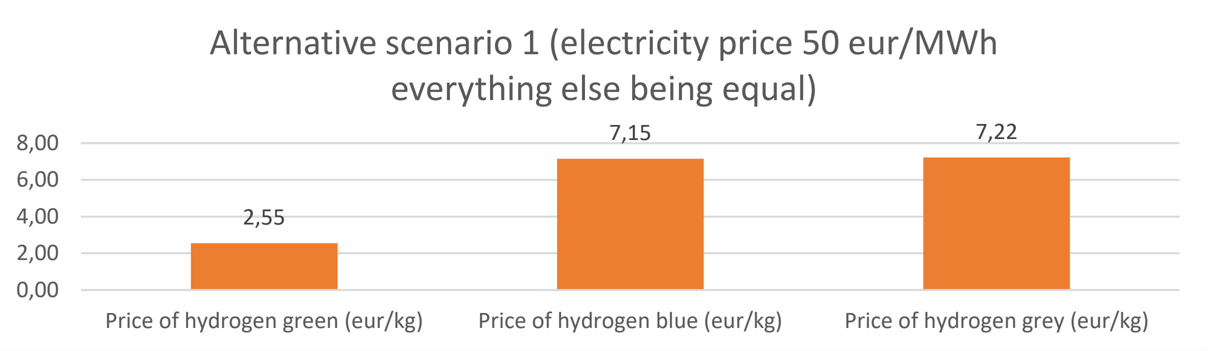
34. How relevant is the regulator for the success of green hydrogen production using electrolysis and renewable electricity for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
35. How relevant is the regulator for the success of blue hydrogen production using steam methane reforming and carbon capture and storage for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)
36. How relevant is the regulator for the success of grey hydrogen production using steam methane reforming for use in refineries in the Netherlands?
    - 0 (not relevant)
    - 3 (less relevant)
    - 5 (relevant)
    - 7 (highly relevant)

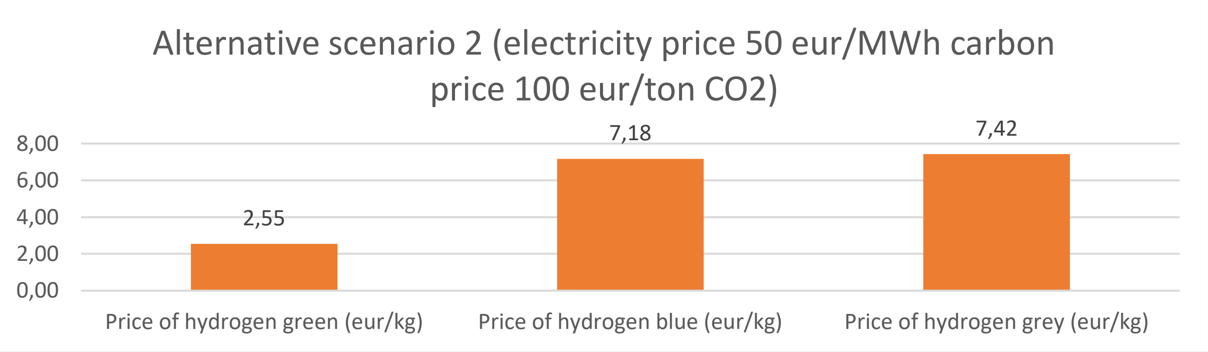
Finally, I would like to ask a few quick questions whether stakeholders can influence the relevant factors or not and if so, who could influence the factor. This will provide insight into how the success of the competing hydrogen production technologies for use in refineries in the Netherlands could be influenced and by who.

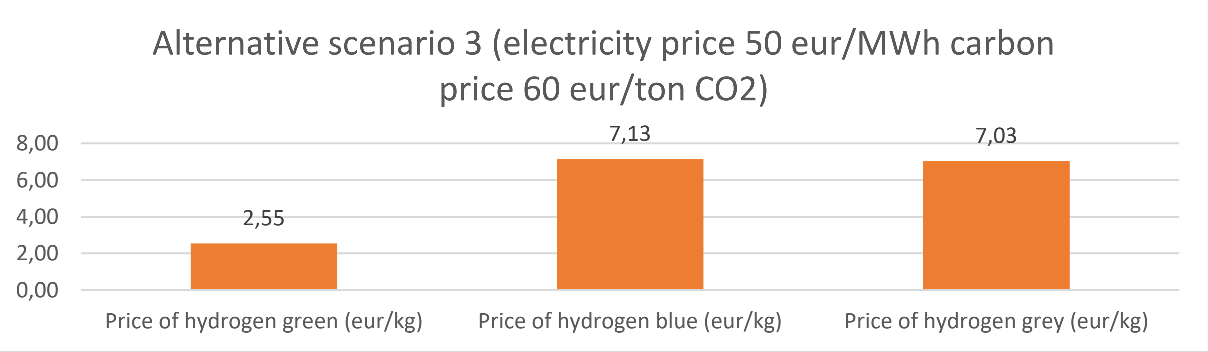
1. Can stakeholders influence the price of hydrogen, if so who comes to mind?
2. Can stakeholders influence the price of natural gas, if so who comes to mind?
3. Can stakeholders influence the price of electricity, if so who comes to mind?
4. Can stakeholders influence the security of supply, if so who comes to mind?
5. Can stakeholders influence the technological superiority, if so who comes to mind?
6. Can stakeholders influence the learning rate, if so who comes to mind?
7. Can stakeholders influence the supply side incentives, if so who comes to mind?
8. Can stakeholders influence the demand side incentives, if so who comes to mind?
9. Can stakeholders influence the regulator, if so who comes to mind?

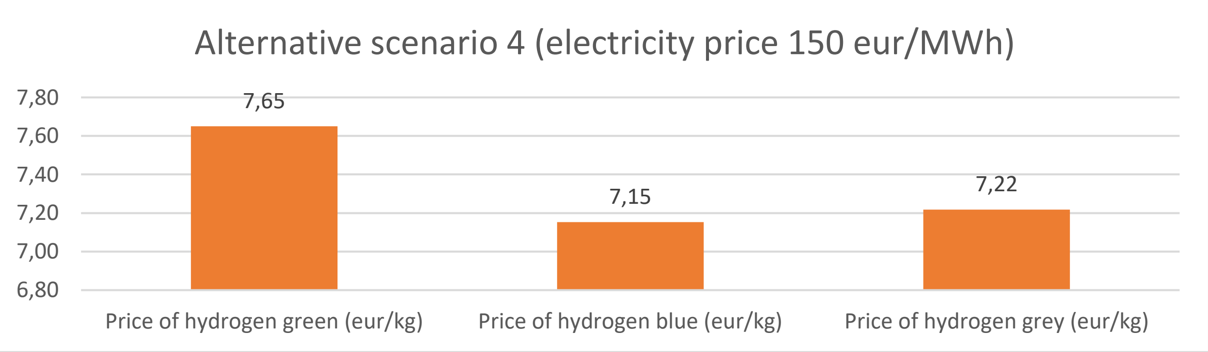
Results from the model of the operational cost price of hydrogen for alternative scenarios

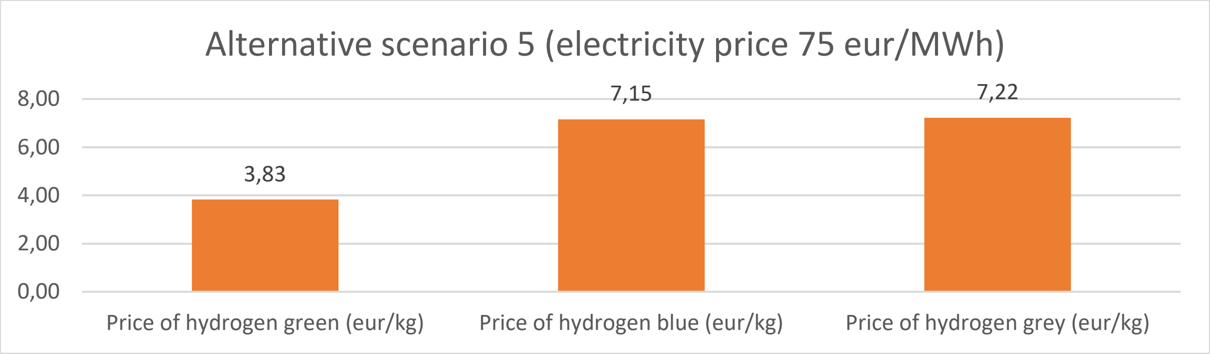
The price of green, blue and grey hydrogen has also been calculated and visualized for several alternative scenarios were the price of electricity, the price of natural gas and/or the price of carbon changes with respect to the market conditions as of 20/12/2021. The visualizations of the alternative scenarios are present below.

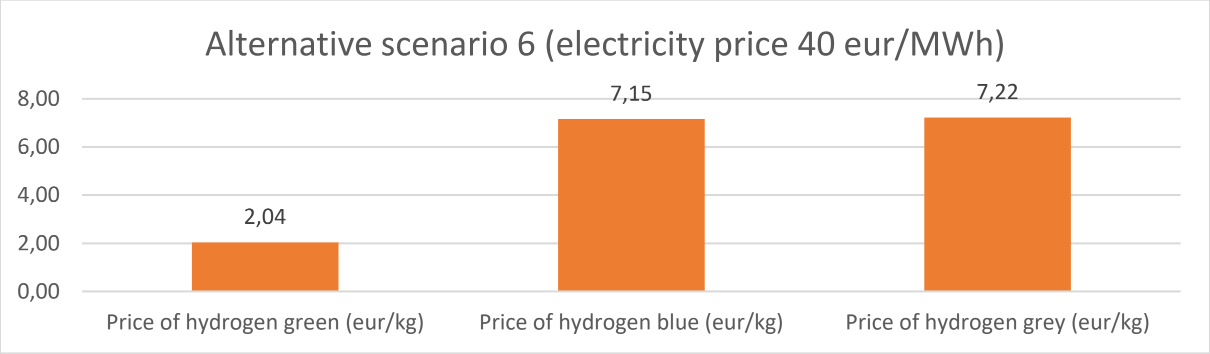


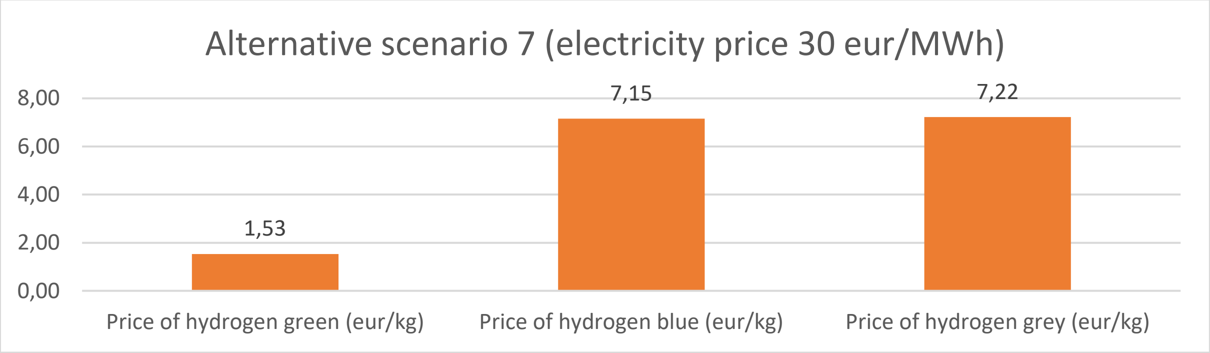


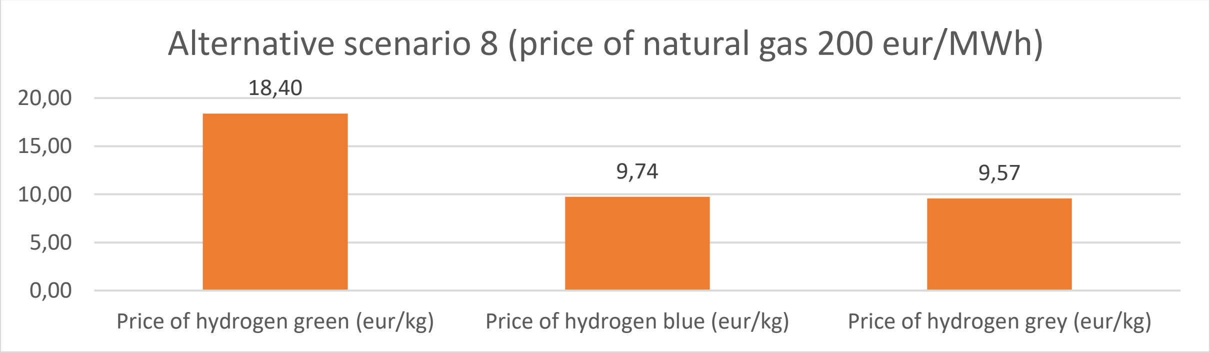


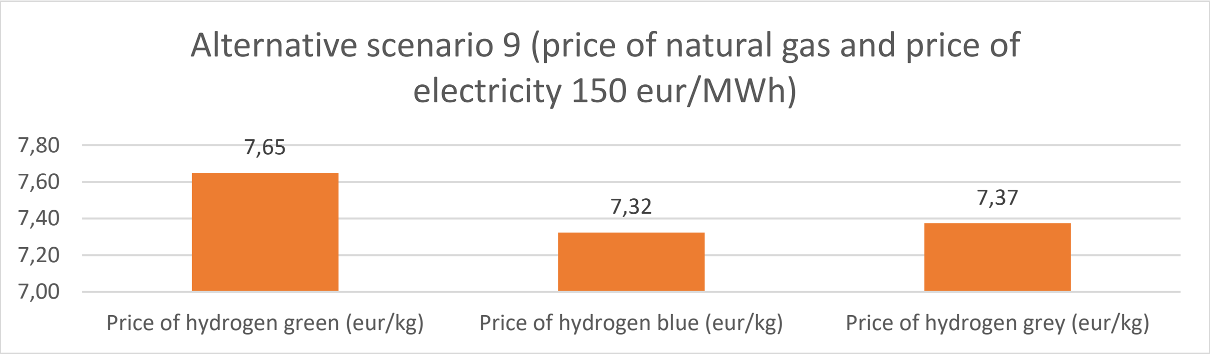


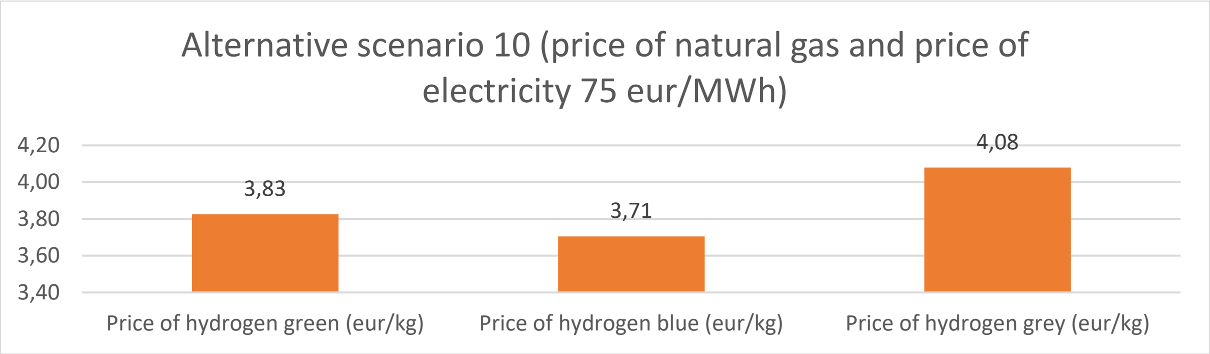

Alternative scenario 5 (electricity price 75 eur/MWh)
8,00
6,00
4,00
2,00
0,00
3,83
7,15
7,22
Price of hydrogen green (eur/kg)
Price of hydrogen blue (eur/kg)
Price of hydrogen grey (eur/kg)


Alternative scenario 6 (electricity price 40 eur/MWh)
8,00
6,00
4,00
2,00
0,00
2,04
7,15
7,22
Price of hydrogen green (eur/kg)
Price of hydrogen blue (eur/kg)
Price of hydrogen grey (eur/kg)


Alternative scenario 7 (electricity price 30 eur/MWh)
8,00
6,00
4,00
2,00
0,00
1,53
7,15
7,22
Price of hydrogen green (eur/kg)
Price of hydrogen blue (eur/kg)
Price of hydrogen grey (eur/kg)


Alternative scenario 8 (price of natural gas 200 eur/MWh)
20,00
15,00
10,00
5,00
0,00
18,40
9,74
9,57
Price of hydrogen green (eur/kg)
Price of hydrogen blue (eur/kg)
Price of hydrogen grey (eur/kg)


Alternative scenario 9 (price of natural gas and price of electricity 150 eur/MWh)
7,80
7,60
7,40
7,20
7,00
7,65
7,32
7,37
Price of hydrogen green (eur/kg)
Price of hydrogen blue (eur/kg)
Price of hydrogen grey (eur/kg)


Alternative scenario 10 (price of natural gas and price of electricity 75 eur/MWh)
4,20
4,00
3,80
3,60
3,40
3,83
3,71
4,08
Price of hydrogen green (eur/kg)
Price of hydrogen blue (eur/kg)
Price of hydrogen grey (eur/kg)