Exploring The Potential Of Synthetic Fuels From CO2 And H2

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Exploring The Potential Of Synthetic Fuels From CO2 And H2

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Preface

This thesis is the final step to complete the Master's degree in Complex Systems Engineering and Management at the Delft University of Technology. I conducted my graduation research in collaboration with Royal Vopak. In the last six months, I have conducted scientific research on the potential of synthetic fuels for aviation. I want to take the opportunity to thank some people that have played a part in this process.

Firstly, I would like to thank my supervisor Rob Stikkelman, who proved to be capable of giving very professional guidance in a very approachable way. There were little jokes, personal anecdotes and some casual talking on the next steps at some times. But, when it mattered, there was also the opportunity for calm, honest and experienced feedback. My supervision felt positive, involved, and very flexible, which is quite an achievement over Zoom and Microsoft Teams. I believe this approach was, for me, the best combination to keep my head cool in the stamp that I call my room in Amsterdam. I also want to thank Daniel Scholten, for his constructive criticism in the meetings we had, and always ending the meeting with a smile and some nice words.

Fortunately, I could escape the small office next to my bed at times to work on this research at my parents in The Hague, which is something I feel very grateful for. This office away from home was a very welcome 'change of scenery' and often brought new ideas. I want to say thank you to my parents for your support and motivation, and letting me transform the house to my own little library, not only during this research but generally every time I needed it. The days studying with the really strong study group of Martha, Tim and Kato were definitely better than having to do it alone and we always felt very taken care of.

Also, I want to thank my supervisor from Vopak, Merijn Janssen and my other helping hand, Emma Zomer. When first talking to each other about the opportunity to do my thesis at Vopak, we all thought that I would be at the office and we could work together a lot more. But when this turned out not to be the case, you both made time very frequently, were super flexible and I felt supported throughout the process. You both added valuable insights to the research by questioning what I did or just pitching ideas yourself. But also, I want to stress that I really enjoyed our contact in general. You both were great, open and fun colleagues and it was always nice to talk, which is not a given since I could only go to the office once in the first 4 months of the process. Thanks to you, I still feel that I had a great time at Vopak, and I love what the new energy team is doing.

Finally, I want to thank all my friends and family for their love and support. I can look back at my time as a student with a lot of enjoyment. I am also really looking forward to the next chapter.

S.M.J. van de Graaff
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Executive Summary

The world needs to decarbonize, and that includes the transport sector, which accounts for almost a quarter of the GHG emissions. Electrification and hydrogen-powered transport are increasing significantly. But, a new category of hydrogen-based fuels (synthetic fuels) could be part of the solution as well. Synthetic fuels are fuels that are made from CO2 and low-carbon hydrogen. Their use would reduce GHG emissions and mitigate the negative effects we have on climate change. Also, they are compatible with existing infrastructure, which increases the possibility of becoming part of the energy mix in the short term. Despite the increasing attention, there is a lack of literature that combines qualitative research with quantitative insights and a lack of research on the macro-environment of the synthetic fuel system.

This study aims to provide an extensive overview of the critical internal and external uncertainties that influence the synthetic fuel supply chain. Additionally, the study wants to look at the impact of the identified factors by using scenarios to model future developments. Scholars are highlighting the potential of synthetic fuels, and the International Energy Agency expects them to play a role in the future energy mix. However, high costs and regulatory uncertainty might prove to be significant barriers to their development. The synthetic fuel system is complex, and their are a lot of factors with that impact each other and a lot of uncertainty in terms of how key factors will develop in the future. The research question focuses on the potential of synthetic fuels in the future. This research uses an integrated approach to look at the system, as the important factors are highly dependent of each other.

A PESTEL-analysis was done to highlight the different categories of factors influencing the synthetic fuel supply chain. The Political, Economic, Social, Technological, Environmental and Legal factors together form the driving forces and uncertainties surrounding synthetic fuels. After an extensive literature study to create thorough understanding of the synthetic fuel system, relevant literature was reviewed and discussed to identify the most important factors and uncertainties. These factors are elaborately discussed and then summarized and categorized. The factors with high impact were done reviewed and discussed further with quantitative experiments. The critical uncertainties were quantified by analyzing scenarios in a Mixed-Integer Linear Programming (MILP) model using the program Linny-R. The mix of qualitative and quantitative research makes it possible to understand the synthetic fuel system better. Using Linny-R, the system was modelled in a simplified way by linking the relevant feedstocks, processes and products. The advantage of Linny-R is that it is very suited for looking at integrated systems. The identified factors have a lot of interdependencies and that makes it interesting to look at the impact of uncertainties on multiple factors at the same time.

The results showed the major impact the energy price and the electrolyzer Capex have on the hydrogen and subsequent synthetic fuel prices, as they are at least twice as expensive as fossil fuels on the short term. The high current prices for renewable energy weigh heavily on the hydrogen costs, which in turn has a major impact on the costs for synthetic fuels. The results also show the importance of renewable energy availability, as the average price increases significantly due to the intermittency of renewable energy sources. This intermittency leads to lower capacity factors for the electrolyzer, which increases the electrolysis costs per tonne hydrogen. These two factors are the main cost drivers of hydrogen and finding the right balance between the capacity factor and cheap energy is key for reaching an optimal synthetic fuel price. Technological developments and efficiency gains will decrease the price significantly in the future. However, it will definitely remain challenging to become competitive in the short term. In the longer term, there is potential if adequate regulatory support is provided and hydrogen prices continue to decrease due to innovation and scalability. Hydrogen production, and even more so, synthetic fuel production in countries with favourable conditions for renewable energy could lead to lower prices than local production. A potential disadvantage is more competition and geopolitical tensions making the supply chain riskier, requiring a higher rate of return. Because the model also incorporated the fossil fuel production and the carbon emissions, the impact of policy could also be taken into account. While the results show that the impact of policy measures

like carbon pricing is definitely lower than the impact of significant hydrogen cost reductions, it is clear that this policy does make synthetic fuel production more attractive. The integrated approach of the system shows that multiple developments are needed for the ambition of cost-parity for synthetic and fossil fuels. While this cost-parity may never be reached, under the right circumstances the synthetic fuel price can become very close. Additional policy measures like blend-in quota and higher subsidies could further increase the demand.

The results highlight the challenges but also the potential of synthetic fuels. In order to make them part of the inevitable transition to sustainable alternatives for the transport sector, governments, policymakers, international organisations and customers need to align their efforts to collectively (partly) shift towards synthetic fuels. This is a big opportunity to reduce GHG emissions and reach the climate targets from the Paris Agreement.

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The challenges for synthetic fuels

1.1 Introduction

The world is finally shifting to renewable energy on a large scale. With 196 countries signing the Paris Agreement, the world shows the ambition to battle climate change before it is too late [1]. But, with the current techniques, it is highly unlikely that the Paris agreement will meet its desired environmental targets. The countries involved want to limit the temperature rise compared to 1990 to 2 degrees in 2050, but with the current developments in the sustainable energy sector, this target will not be met [2]. One of the sectors that still needs more and better solutions to decarbonize is the transport sector. The global energy sector still depends mainly on fossil fuels and that includes the transport sector. In order for a successful transition, a significant developments as well as behavioral changes are needed. Looking at the global CO2 emissions, the transport sector accounts for 23% of all CO2 emissions [3]. Today, the sector is almost totally reliant on petroleum-derived fuels, as crude oil accounts for about 92% of the energy demand for transport sector [4] [5]. Additionally, *Figure 1* shows that reducing transport emissions has been especially difficult. All other sectors have managed to reduce their GHG emissions in comparison to 1990, while the transport sector is the only sector where the emissions are still higher than in 1990.

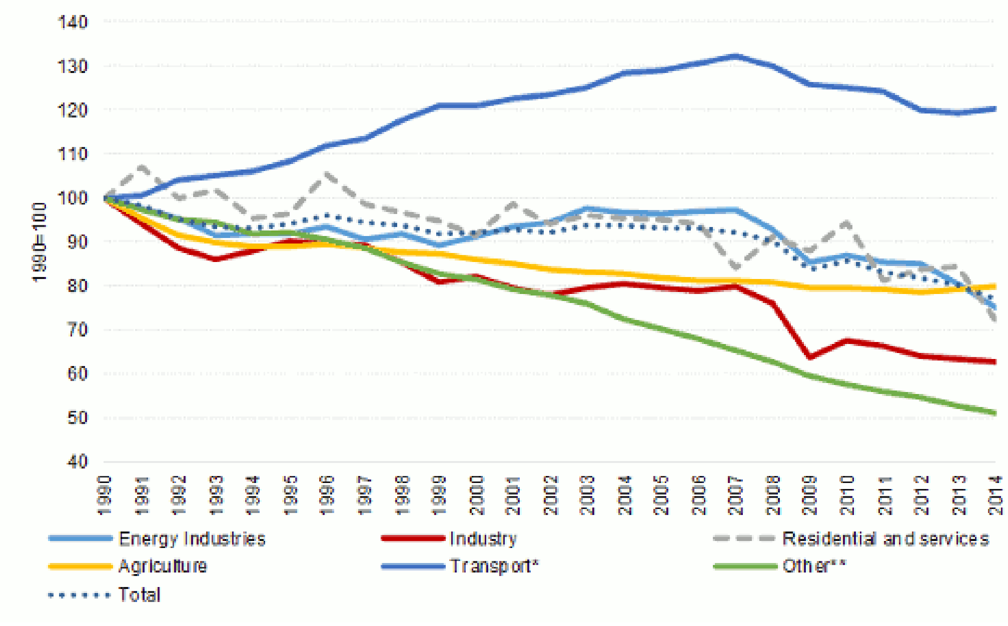


Figure 1: European GHG emissions per sector. Adapted from EU (2014)

This means that to realize the targets of the Paris Climate Agreement, drastically greener modes of transport are needed [3]. In this light, governments and international organizations cooperate with industrial companies and the transport sector to find solutions for more sustainable mobility options. This is a major challenge, as the institutional environment, technology and economic aspects all need to align to form a structure that can facilitate a transition towards more sustainable fuels. In this process, the transport sector will encounter significant challenges.

Nevertheless, companies and governments are working to drive the shift towards technologies that will produce alternatives to the current modes of transport and alternatives to the current fuels used. From a financial perspective, significant investments in R&D and subsidies are made available for clean energy technologies. From a regulatory perspective, next to international treaties like the Paris Agreement, systems like the European Trading System (ETS) and carbon pricing measures contribute to the transition. It is evident that both government and the industrial sector support the shift towards more sustainable mobility. Emissions related to transport can be reduced in two ways. The first is to reduce the total energy demand; the second is to decrease the emissions intensity of that energy [4]. People will probably have to do both. But, as the transport sector is expected to only grow due to further increasing globalization, decreasing the emission intensity should be a high priority.

A promising option is to use alternative fuels instead of conventional fuels. Under the right conditions, this could lead to a significant decrease in GHG emissions for the transport sector. The development of synthetic fuels is surrounded by high costs and many uncertainties. These two factors make accelerating their production difficult and investing in the technology risky. Institutional, economic and technological factors need to be synchronized and analyzed for synthetic fuels to have a better chance to become a player in the transport sector as soon as possible.

To summarize, decreasing the emission intensity of the transport sector is a very important part of the energy transition. Low-carbon alternatives to high-carbon fossil fuels are expensive and surrounded by regulatory, technological and economic uncertainties. For synthetic fuels, understanding the impact of these uncertainties and the dynamics of the synthetic fuel system is essential to be able to compete with fossil fuels in the future.

This research will review the potential of synthetic fuels in general and zoom in on the synthetic fuels that are most likely to be produced on a large scale in the foreseeable future by 2030 or 2050. All synthetic fuels will help reduce GHG emissions, and some are the base for many additional products. However, some have more potential than others. After careful review, the author argues that synthetic kerosene is the most promising and most irreplaceable synthetic fuel. Because of this, synthetic kerosene is the fuel that will be used for the modelling experiments and in-depth analysis.

To understand the forces and uncertainties that will influence the synthetic fuels system, a PESTEL (political, economic, social, technological, environmental and legal) analysis will be done for the production of synthetic fuels in the future. From this list of factors, the most important factors will be used to construct scenarios. The scenarios will be used in the linear model in Linny-R to see which uncertainties have the biggest impact. The combination of the model experiments and the PESTEL analysis will provide an extensive overview and relevant insights into the challenges and opportunities of the production of synthetic fuels.

1.2 Problem Definition

The introduction highlighted the challenges that surround the energy transition and the transport sector in particular. Low-carbon fuel alternatives like synthetic fuels could play a major role in decarbonizing a sector that is expected to grow and is heavily reliant on fossil fuels. In the following section, some background information on CCU and synthetic fuels will be given, after which the problem definition will be formulated.

1.3 Background

Because of the established fossil fuel production and technologies, short-term reduction of CO2 emissions has proved difficult on a scale large enough to meet the environmental targets. This has led to the emergence of Carbon Capture & Storage (CCS) and Carbon Capture & Utilization (CCU) as potentially interesting technologies in addition to the rise of renewable energy sources [6]. CCS and CCU are important concepts in achieving a reduction of GHG emissions and moving towards a circular economy. With CCS, CO2 as a result of energy production or from the air is captured and then stored in, for example, empty gas fields. This is the case with the PORTHOS project in the Port of Rotterdam, where captured CO2 of multiple companies is transported through pipes to empty gas fields in the North Sea. Shell, ExxonMobil, Air Products and Air Liquide have committed to function as the first customers of the project and function as point sources of CO2. These four companies capture part of their emissions, after which the CO2 is transported and stored in empty gas fields in the North sea. This way, their emissions are mitigated and the Port of Rotterdam has begun with a CO2 infrastructure that could be very valuable in the future.

Rotterdam owns a dubious title concerning conventional fossil fuels. It is the absolute leader in the storage and throughput of crude oil in northwest Europe, with almost 100 million tonnes of crude oil entering Rotterdam every year [7]. The crude oil is destined for refineries, both in Rotterdam itself as the rest of Europe. The facilitation of the import, storage and exploitation of these fossil fuels result in a huge environmental footprint. However, the Port of Rotterdam is ambitious in reducing its carbon footprint and setting a modern example for all ports globally, targeting a climate-neutral port by 2050 to align with the Paris Agreement [8]. This ambition has major consequences for the activities and feedstocks that the Port of Rotterdam focuses on. An increasing interest in CCS and CCU initiatives fits into this vision. In addition to capturing CO2 and thus reducing the volume of CO2 emissions, CCU seeks to create additional benefits from the use of captured CO2 [9].

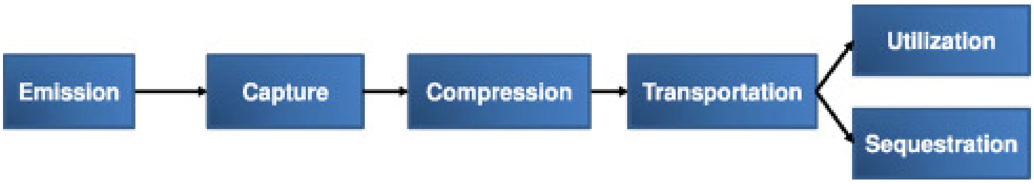


Figure 2: Simplified CCUS supply chain [10]

1.3.1 Applications of CCU

This section will provide a short overview of multiple possible CCU applications, as the list of options is comprehensive. The carbon in CO2 can be used as raw material to manufacture synthetic fuels, carbonates, polymers and chemicals. It can also be used as a recovery agent in techniques such as enhanced oil recovery [11]. The CCU technologies can be divided into three major components: mineral carbonation, enhanced oil recovery (EOR) and chemicals and fuels from CO2. Mineral carbonation can be an interesting option because of the formation of stable carbonates capable of storing CO2 for long periods. They can also provide an alternative for natural carbonates that are location-dependent. However, the energy costs and energy use are still high and scalability is low. This mitigates the positive environmental impact. Enhanced Oil Recovery is focused on using CO2 to increase recovery factors in oil reservoirs [12]. The results of EOR techniques are promising, but its contribution to reducing the environmental impact of CO2 is debatable at least as the function of the captured CO2 is to recover more fossil fuel. This research focuses on the sustainability of the transport sector, so this research will focus on the third option: the fabrication of synthetic fuels.

CCS and CCU are often compared in the literature, and they both have their advantages. Some scholars have compared CCU with CCS and find that CCU is the preferable option, as it has a higher potential to reduce emissions. However, it must be noted here that the preferred option is also dependent on external factors like the carbon price and the specific CCU application [13]. Overall, CCS will play a larger role in the short term because the technology is relatively proven, and it is a quick way to reduce emissions significantly. In the longer term, CCU could provide more economic incentives as the CO2 is used as a building stone for new, valuable products. Additionally, CCU could prove to be a solution for parts of the mobility sector that are difficult to decarbonize. CCU in the shape of synthetic fuel production could significantly contribute to making mobility more sustainable.

1.3.2 Power-to-X

Synthetic fuels are part of the bigger concept of 'Power-to-X'. Power-to-X refers to technologies that use (surplus) electricity from renewable sources. The electricity is then converted into an alternative energy source that can be stored, utilized or transported [14].

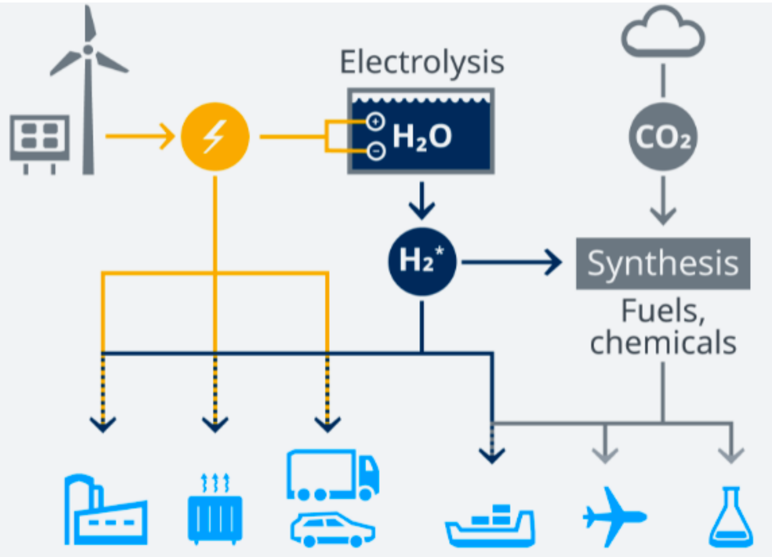


Figure 3: Power-to-X technology [15]

The basic process can be seen in *Figure 3.* Globally, energy generation from renewable sources like wind and solar is increasing substantially. The technology has improved a lot over the years, which causes better scalability and a decrease in costs. This electricity is then used for heating and industrial processes, or used to produce alternative energy sources to be able to transport the energy. Most of these energy sources are either fuels or chemicals, such as methane, formic acid and synthetic fuels. The electrolysis of water into hydrogen and oxygen plays a major part in this process. As the research focuses on a more sustainable transport sector, the focus will be on the fabrication of synthetic fuels, including e-diesel, e-gasoline, e-methanol and e-kerosene. Successful pilots have already started, and if those pilots can be commercialized, they could become an important approach to reducing CO2 emissions.

1.4 Research Gap

Large CCUS projects like PORTHOS in the Port of Rotterdam and other projects abroad show that relevant actors look at CCUS as part of the solution to reducing GHG emissions in order to meet climate targets. Recently, KLM and Shell collaborated to fly a commercial aeroplane with synthetic kerosene successfully. Professor Joris Melkert from the TU Delft calls synthetic kerosene 'the only solution for sustainable aviation'. He also stresses the importance of increasing efficiencies and decreasing growth of the aviation sector, which are equally important [16]. Academic literature on CCU in general has increased significantly in the last couple of years. Additionally, these developments have incurred an uptake in the already increasing research interest towards synthetic fuels and the utilization of CO2. Multiple scholars address the known CCU applications [9] [11] [17] [10] [18]. However, these articles do not focus specifically on synthetic fuels and look at potential CCU applications from a broader perspective, often in a qualitative way. In general, scholars agree that CCU technology will likely become part of the solution to mitigate the effect that the transport sector has on our climate. There are multiple studies that focus on how to optimize CCS and CCU networks, in order to be viable options for accelerating the energy transition [13] [10] [19]. All conclude that CCU and the production of fuels has a high potential to reduce GHG emissions, provided it is produced in the right conditions and the costs of specific parts of the supply chain can be reduced. As discussed, the development of synthetic fuels is impacted by many factors. Recently, there has been an increase in literature on synthetic fuels and the dynamics that surround the synthetic fuel supply chain. In this literature on synthetic fuels, some patterns stand out.

The first aspect that stands out is that most studies focus on specific technical aspects of the fabrication of synthetic fuels. This includes the chemical process, the process-specific challenges, or the CO2-reduction that can be achieved given certain conditions. For example, Brynolf (2018) looks at the different production pathways towards synthetic fuels [4]. She brings up important considerations, such as the compatibility with existing energy services and other factors that influence the technical choice for a certain synthesis path, but gives less attention to macro-economic factors like the development of the crude oil price, growing demand and policy. Parigi (2019) focuses mostly on the technical differences between two specific fuels, methanol and methane [20]. Parigi does make some economic comparison, but that is mostly focused in the internal economics of the process, like specific costs of the fabrication process. He does not look at the macroeconomic uncertainties like the price and potential origins of green hydrogen or CO2. This focus on internal costs as part of the economic part of the comparison is observed more often [21][22] [23]. While this knowledge on the internal costs of these processes is very valuable information, it does not capture the complete picture when one wants to look at the potential of synthetic fuels in the future. In conclusion, there is a strong emphasis on very specific technical parts of the supply chain, where there is a shortage of research that takes into account the bigger system. This trend is also observed by Ramirez (2020), who urges that much more research and focus needs to be brought to the macroeconomics of the field of synthetic fuels for them to become a practical and pragmatic part of the solution to emissions in the mobility sector [24].

The second aspect that stands out is that the majority of the studies that were found are qualitative of nature. On the one hand, this is logical, as the fabrication of synthetic fuels is still an emerging technology, and quantitative analysis would have to depend on making a considerable amount of assumptions. On the other hand, quantitative studies should accompany the literature and qualitative view on synthetic fuel potential. One of the aspects that are holding back more rapid innovations and larger investments is the uncertainty about the competitiveness of the end products of CCU. The quantitative studies that are available are mostly LCA (life cycle analyses) [6][19][25][26][27]. These studies look at the environmental impact of the entire supply chain. However, they do not analyse the supply chain by looking at other technical, economic and institutional factors that could play a part in the final price and competitiveness of the fuels. Naims (2016) gives an overview of the economics and potential scenarios of synthetic fuels without linking her ideas to a quantitative model or other optimization techniques. According to the authors' insights, combining qualitative and quantitative analysis could be very valuable.

To summarize, the identified research gap is twofold. Firstly, there is little literature that discusses the macroeconomics of the system, taking all factors into account. Literature is often focused on specific technical parts of the process, environmental impact or economics, but not on all of those factors. Because of this, a complete analysis and a comprehensive overview of internal and external factors impacting the synthetic fuel system could add to the extant literature. Secondly, the emphasis is still on qualitative research. The available quantitative research mostly focuses on the technical aspects of the production process, and less on the impact of macroeconomic uncertainties like policy and import.

1.5 Problem Formulation

Multiple scholars have focused on different aspects of the potential and development of CCU and synthetic fuels. But even though there is some overlap and the amount of literature is increasing, the research is incomplete for two reasons. The first one is that most studies are only qualitative, which leads to a deficiency in research that matches their findings with concrete numbers. The second reason is that there is a notable emphasis on particular technical parts of the process. There is a lack of focus on macroeconomics and other important factors. In general, researchers have not yet focused on looking at the impact of the critical uncertainties that surround synthetic fuels at the moment, which are a big threshold for investment and policy. The research aims to take into account macro-economic dynamics, look at the system from a multi-actor perspective, and consider institutional and social aspects, as well as economic and technical factors. Doing so will add to insights to the extant literature on the challenges and opportunities for large-scale use of synthetic fuels.

The observed challenges are translated and summarized into the following problem formulation:

The potential of synthetic fuels is highly dependent on uncertainties represented by internal and external factors. A comprehensive overview of these factors, taking into account the macroeconomics of the synthetic fuel supply chain, is absent. The uncertainties lead to a high level of complexity, and it is essential to create additional insights into the impact of those uncertainties on synthetic fuels in the future.

1.6 Research Question

Based on the identified research gap and the problem definition, the research question for the present study can be constructed. For all relevant actors, public and private, it is essential to create additional insights into the impact of those uncertainties on the development of synthetic fuels in the future. Also, there is a need for quantitative insights that look beyond the technical parts of the supply chain.

Therefore, the research question is formulated as follows:

What is the potential of synthetic fuels and what is the impact of the most important internal and external uncertainties in the synthetic fuel system?

The research will approach the question by answering the following sub-questions:

(i) What does the synthetic fuel production process look like and what are the potential fuel end-products?

(ii) What are the internal and external uncertainties that impact the synthetic fuel system and which of them are critical for the development of synthetic fuels?

(iii) How can the research add quantitative insights to the identified critical factors?

(iv) What are potential scenarios for synthetic fuel production and what do the results mean for the development of synthetic fuels in the future?

1.7 Research Outline

Chapter 2 will elaborate on the research methodology that is used to fulfill the research question and sub-questions. Then the literature review begins, answering the first two sub-questions. Chapter 3 discusses the variety of available synthetic fuels, highlighting their specific characteristics and scoping down to a preferred fuel for the experiments. After this, Chapter 4 discusses the critical uncertainties that will influence the emergence of synthetic fuels. The second part of this paper starts in Chapter 5. In Chapter 5, the model that is made to perform quantitative analysis will be discussed and verified. In Chapter 6, the results of the experiments will be visualized and reviewed. From Chapter 7, the results and the research methods will be discussed, as well as the societal and scientific relevance. Lastly, Chapter 8 will present the conclusions and make recommendations for future research.

2

Research Methodology

In this chapter, the methodology of the research will be discussed. The goal of the methodology is to break down the research and construct separate tasks. Each task has a priority, a deadline, and there is a plan for fulfilling the task. Before any modelling or quantitative additions, it is essential to gain knowledge of the existing system and analyse literature on synthetic fuels. To do this, a desk study is conducted. This study aims to explore the synthetic fuel supply chain using scientific literature and provide an overview of the system that will function as the starting point for the model and provide context for the next phases of the research. Then, the research will continue by doing a PESTEL-analysis to analyze the driving forces of the synthetic fuel system. After this study, the quantitative phase begins, which focuses on analyzing the uncertainties and constructing experiments to review the dynamics of the synthetic fuel system. The main goal is to identify critical uncertainties and their impact on the future of the synthetic fuels system. A linear optimization model with Linny-R is constructed to run the experiments and conclude the impact of internal and external developments on the synthetic fuel system. To structure the research, the research activities and the choices made concerning the research methods are briefly described below.

2.1 System Exploration

To explore the possibilities for a synthetic fuel system, it is necessary to examine the current infrastructure and take a closer look at the process of synthetic fuel production from hydrogen and CO2 feedstock. This part is focused on understanding what fuels can be produced via CCU technology and their differences. The research will start with a desk study to answer the first sub-questions:

1. What does the synthetic fuel production process look like, and what are the potential fuel end-products?

A desk study is an efficient way to gain extra information on the context of the system. Using both non-scientific and scientific literature, a selection of promising synthetic fuels will be discussed. Also, the feedstock will be analyzed, as there are multiple options when it comes to which hydrogen and carbon source is used for the production. The results will be summarized in a table, giving a description of each fuel and showing its advantages and potential disadvantages. This system overview will act as a start of the research and provide much-needed context for the following chapters. The information on feedstocks, processes and end-product will be used as the base for the model. After this exploration of the system, a PESTEL-analysis will be done to select factors that will be used to construct scenarios for the model. This way, their impact under different circumstances will be measured in the model.

2.2 PESTEL-analysis

In the second part, the research aims to answer the second sub-question. Using the information from the first sub-question, the second question will look at the driving forces that impact the process:

2. What are the internal and external uncertainties that impact the synthetic fuel system, and which of them are critical for the development of synthetic fuels?

The uncertainties from the sub-question refer to the future developments of certain factors. How will certain prices evolve? Will the scientific community come up with alternative or improved solutions? To look at this problem, some form of scenario technique has to be used, to work with that future uncertainty. In the extant literature, there are three main schools of scenario techniques. These schools are the Intuitive-Logistics Model, La prospective Model and the Probabilistic Trend Models (PMT). Both La Prospective and PMT are theoretically applicable to a range of purposes. However, the objective of these techniques is often to determine the *most likely* development of a certain phenomenon or system.

The Intuitive-Logistics methodology is much more flexible and lends itself to a wide range of scenario purposes. The PESTEL-analysis is part of the intuitive logics approach, which is a qualitative research method often used in combination with scenarios. The intuitive logic approach embraces and integrates consideration of a broad range of factors that will shape the future, by taking into account 'PESTEL' factors [28]. The possibilities include the 'making sense' of a system up to developing strategy and impact analysis [29]. This is what the research tries to do for the synthetic fuel system and what makes a PESTEL-analysis very suited for answering the second sub-question.

These PESTEL factors represent the Political, Economic, Social, Technological, Ecological and Legal factors that impact the future of the system. All internal and external uncertainties related to these factors that surround the synthetic fuel system will be reviewed and discussed. Multiple relevant studies are reviewed to identify the factors, after which each factor will be discussed more extensively. After categorizing the PESTEL-factors, a SWOT analysis is done to categorize the factors as Strengths, Weaknesses, Opportunities and Threats. This way, the possibilities and challenges become more clear. This phase is part of exploring the synthetic fuel system and will provide a comprehensive overview of the driving forces for the development of synthetic fuels. These uncertainties are then used as input for the second part of the research, as they will be used to construct scenarios to show the impact of the most important factors. Multiple researchers have identified and highlighted the added value of combining qualitative and quantitative research [30]. This research will therefore try to convert the qualitative nature of the PESTEL-analysis into quantitative insights.

2.3 Linear Optimization

The combination of quantitative and qualitative research will provide the reader with a more complete overview. The quantitative insights will create value because it shows the effects of looking at the system with an integrated approach. The results show how the factors are related to each other and show the absolute impact of potential future scenarios. Before the identified uncertainties are translated to scenarios to measure their impact, a model needs to be constructed to run the scenario experiments. This is the base of the third sub-question:

3. How can the research add quantitative insights to the identified critical factors?

The model had to be able to visualize the simplified system and include the possibility for making scenarios. Because the modelled system includes the technical process of synthetic fuel production, Aspen Plus was considered. However, Aspen Plus is process simulation software that focuses on specific chemical and technical parts of the process. This research aims to look at the system from a more broad perspective and not look at the specific technical details of the process. Alternatively, the research will use the Mixed Integer Linear Programming (MILP) Optimization tool Linny-R. Linny-R is a visually appealing program with a clear distinction between processes, product flows and stocks. The design of this modelling program provides a better representation of the system to be modelled compared to other modelling programs such as MATLAB and Python [31]. In previous research, Linny-R is used to model the industrial complex of the Port of Rotterdam, which strengthens the conclusion to use the tool to model the complexity of the electric fuel system. Multiple other scholars use MILP as well for modelling energy systems [32]. It is a tool that allows the user to make more detailed analyses of processes than previously possible [33]. It will be used to add quantitative insights to the qualitative nature of the PESTEL analysis.

Pieter Bots, professor of the TU Delft, develops the Linny-R modelling program as an alternative to the more complex Aspen Plus and, by definition, uses financial optimization as a starting point. The tool will be used to build a simplified but representative model of the synthetic fuel system. Even without any experiments, this schematic model will provide additional insights into the system dynamics, actors involved and streams of products.

The selected critical uncertainties will be translated to scenarios to run experiments in the Linny-R model. Henriques (2019) uses Linny-R to measure the impact of external factors like tank size, ramp rate, and interrelations between parameters [34]. A larger variety of factors will be incorporated into the model in this research, such as emissions quota, policy instruments, and feedstock price variations. The research aims to incorporate all relevant factors as good as possible. The scenarios are built by varying the values of the critical uncertainties within a predetermined range. The Linny-R model will only be used as a case study to show how much the external factors will influence the development of synthetic fuels.

2.3.1 Integrated approach

Complementing a PESTEL-analysis with a quantitative research part is not observed often in the literature. This is highlighted by Yüksel (2012), stating that the problem of PESTEL-analysis is that it does not adopt a quantitative approach to measurement. PESTEL-analysis only evaluates the factors qualitatively, which does not fully allow an objective and rational analysis of the factors [35]. Quantifying the most important factors will be a valuable addition to quantify the impact of the observed factors. Linny-R also enables the research to look at an integrated system. The system is very complex and the internal and external factors, as well as the uncertainties, have a lot of interdependencies. It is essential to look at the whole system as the impact on the emissions could be just as important as the impact on the price. After this study is finished, the author will reflect on this combination of methods and make recommendations for future research.

2.4 Scenario Analysis

Scenario analysis is a method for developing future scenarios to guide relevant actors towards strategic decision making [36]. For this research, the scenarios are used to provide insights into how uncertain factors could develop in the future and how this will influence the synthetic fuel system. The approach looks at the critical uncertainties, important predetermined trends and the behaviour of actors who have a stake in the particular future. This approach and scope match really well with the identified knowledge gap and research question. The aim of this part is to fulfil sub-question 4:

4. What are potential scenarios for synthetic fuel production, and what do the results mean for the development of synthetic fuels in the future?

The scenario analysis will follow a sequence of steps in line with the intuitive logistics model to stay consistent with research paradigms. In the literature review of Frith and Tapinos (2020), it is clear that there is consensus on four distinct phases of scenario analysis [37]. These phases are project preparation, scenario exploration, scenario development and scenario utilisation. This research will follow a similar sequence. The project preparation and the exploration phase are covered by the literature study and the PESTEL-analysis in Chapter 4 and Chapter 5. The scenario development and utilization are covered in Chapter 7: Results. Below, a short general description is given of each phase.

2.4.1 Project Preparation

This section marks the starting point for developing scenarios. This phase comes down to setting the scope and defining the intended use of the scenario experiments. Some parts of the scope are already determined for this research, as the Port of Rotterdam as the geographical location. Other parts need further examination. For emerging technologies, the scenario analysis should be broader than the technology itself to get a complete overview of the system [38].

2.4.2 Scenario Exploration

This phase refers to looking at the broader system by identifying the PESTEL-factors. The phase is characterized by explorative research and will give context to the research. This includes identifying major stakeholders, recognizing trends and uncertainties in the system and determining the key forces of the environment [36]. In this research, the scenario exploration is done in Chapter 5.

2.4.3 Scenario Development

In this phase, the internal and external factors are selected, and the critical uncertainties are identified. Then, various values within a predetermined range will be assigned to these critical uncertainties to build the scenarios to show the impact of a changing environment on the synthetic fuel system. Wright (2013) states that application of the approach enables 3 things: [28]:

- Identification of the driving forces of the future that are present in the broad business environment and will impact an “issue of concern”— often the viability of a focal organization and its offering into the marketplace;
- Consideration of the range of possible and plausible outcomes of each of these forces;
- Understanding of how the forces interact with each other in terms of cause and effect, and chronological order

In this research, the scenarios are developed in Chapter 7. The scenarios are based on the information from Chapter 4 and the identified critical uncertainties from Chapter 5. The impact of the scenarios is discussed using a linear optimization model, which is elaborated on in Chapter 6.

2.4.4 Scenario Utilization

In the fourth phase, scenario utilization, the developed scenarios are used to run experiments, make recommendations and define potential strategies [37]. The scenarios will be used as input for a linear optimization model in Chapter 7. By running the scenarios, the research aims to identify the most critical driving forces in the synthetic fuel system and how they interact with each other.

2.4.5 Scenarios

In the literature, there is little consensus on what defines a scenario. Some scholars argue that a 'scenario' is an image of the world that leads to certain values for a number of factors. In this research, the definition 'scenario' will be used in a less overarching context. The aim of the scenarios is to provide information, ideas and stimuli in order to be able to plan strategically and make better decisions [28]. Therefore, the definition 'scenario' is used in this research to vary important identified factors by describing specific situations in which they have low or high values to show the impact of these situations. Additionally, the scenario experiments will be complemented with sensitivity analysis on some of the identified factors, as this also gives a good idea about their impact.

2.5 Research Scope

In this section, the context of the research is scoped. Choices to scope the research were made mainly in three categories: location, emissions and timeline.

What is included?

Location

The model and the conditions aim to represent the conditions and the supply chain in the Port of Rotterdam. The industrial complex is an interesting location to produce synthetic fuels due to the presence of essential infrastructure for the production of synthetic fuels, their ambition to decarbonize, and the strategic position for importing and exporting goods. Furthermore, Rotterdam is already busy with transforming and accommodating the transition to renewable alternatives and are planning on becoming the hydrogen hub for North-West Europe [39]. The model will look at the impact of the identified uncertainties. Subsequently, the research aims to add a chapter on a foreign location to model a situation with (close to) ideal conditions for synthetic fuel production.

Emissions

Regarding emissions, the study focuses on CO2. CO2 is the greenhouse gas with the largest negative impact on global warming. Also, as CO2 is used as feedstock for synthetic fuels, it is at the centre of the product and the critical component of why synthetic fuels could possible be an addition to or substitute fossil fuels. Therefore, reducing CO2 is the most effective way to mitigate the effects we have on global warming. Although other GHG like NOx and SOx are getting increasingly more attention for their negative impact on the environment, this research will focus on CO2. This is because the combustion of synthetic fuels will not necessarily decrease these emissions. However, it will reduce CO2 by capturing it during industrial processes and thus preventing it from entering the atmosphere.

Timeline

The most available research is relatively recent and investigates alternative fuels. Therefore, the base year for the scenarios is 2020. Furthermore, most research focuses on the years 2030 and 2050 as reference points for technological developments, R&D improvements and future conditions and market dynamics. Therefore, 2030 will function as the year for the medium-term scenarios and 2050 for the long-term scenarios. These years also correspond to targets from the Paris Agreement and the European Union.

2.6 Overview

To sum up, the research will focus on synthetic fuel production in the Port of Rotterdam, because of their potential to reduce emissions in the transport sector. The research consists of three distinct phases. Firstly, the synthetic fuel system will be explored by examining the production process and potential end-products using literature. The information on the process and end-products will be used as context and serve as the base for the model. Then, a PESTEL-analysis will be done to identify the critical uncertainties of the synthetic fuel system. Lastly, the critical uncertainties will be quantified and analyzed by doing experiments in a Linny-R model. After this, the results will be discussed. The research ends with a conclusion and recommendations.

3

Exploring the synthetic fuel system

Chapter 3 marks the beginning of the analysis. In the following chapter, a desk study will be conducted to explore and discuss multiple synthetic fuels that can be produced via a CCU pathway, as well as the required feedstock and processes. The findings in this Chapter are the result of careful analysis of a multitude of literature sources. Analyzing the feedstock and the potential end-products is an essential part of understanding the larger synthetic fuel system. The results are essential for scoping the research and will be used as the base for the MILP-model in Chapter 5 and Chapter 6. This section aims to answer the first sub-question:

1. *Analyse the synthetic fuel production process and identify the potential fuel end-products.*

In section 3.1, the main feedstocks of the fuels will be discussed, hydrogen and carbon dioxide. In section 3.2, the available synthetic fuels are discussed. Lastly, an overview of the discussed synthetic fuels is presented in section 3.3. In 3.4, a preliminary conclusion will be given, which also includes the choice for one fuel as the base for the model experiments.

3.1 Feedstock

All synthetic fuels have one thing in common: they are made from CO2 and hydrogen. The prices and production processes of these two feedstocks are very important for the production of the fuels. The following sections will discuss how these two feedstocks are produced and what possibilities and limitations there are.

3.1.1 Hydrogen

Hydrogen is the lightest and most abundant element in the periodic table. However, in order to use it for applications like synthetic fuels, hydrogen needs to produced from water and energy using electrolysis. Under normal circumstances, it is gaseous and called hydrogen gas. Pressurized hydrogen has a very high energy density of about 120 MJ per kilogram, which is three times as high as natural gas [40]. Hydrogen (H2) is at the core of many Power-to-X applications, and this is also the case in the production of synthetic fuels. Together with carbon dioxide, it is one of the two feedstocks for synthetic fuel. Hydrogen can be made via multiple production pathways, which will be discussed in the chapters below. Hydrogen production is increasing significantly across the globe, and this could prove to be a vital development for synthetic fuel production [41].

Grey Hydrogen
Grey hydrogen refers to hydrogen made from fossil fuels and is at the moment by far the form that is globally the most common. The production takes place via a process that is called Steam Methane Reforming (SMR). The reaction consists of steam under high pressure reacting with natural gas (CH4), producing hydrogen and CO2. Unfortunately, almost all of the hydrogen (over 95%) globally produced is grey hydrogen. This way of producing hydrogen results in relatively high CO2 emissions throughout

the supply chain of hydrogen. Because of the emission of CO2, grey hydrogen is not considered a viable feedstock for a sustainable production pathway; therefore, it is not considered for the production of synthetic fuels. However, it is worth noting that the processes to produce fuels from hydrogen and carbon dioxide are already successfully being performed with grey hydrogen. This way, grey hydrogen could play a part as bridging feedstock to test and develop the infrastructure in the short term. In this research, grey hydrogen is considered out of scope for the model experiments, as blue hydrogen will function as the bridging fuel.

Blue Hydrogen

Blue Hydrogen refers to hydrogen that is produced with a combination of natural gas combustion and CCS. Essentially, it is grey hydrogen where the CO2 is captured and stored underground. It is one of few CO2-reduction strategies in hydrogen production and offers an economically feasible and proven technique to implement low-carbon hydrogen in the industry [42]. It is mostly viewed as a production pathway that functions as a temporary measure towards green hydrogen production. It is very suitable for industrial areas like the Port of Rotterdam. Blue hydrogen is still in the development phase, but there are quite some large scale projects. One of them is in the Port of Rotterdam, called the Port of Rotterdam CO2 Transport Hub and Offshore Storage (PORTHOS). The CO2 is captured by multiple companies in the industrial sector of Rotterdam and transported by PORTHOS in underground pipelines through empty gas fields in the North Sea [43].

It is not possible to capture 100% of the carbon. However, blue hydrogen is low-carbon and therefore considered a viable alternative for the production of synthetic fuels. Blue hydrogen is characterized by relatively low costs in the short term, and that is easily scalable. When the transport infrastructure from, for example, the Port of Rotterdam to the gas fields in the North Sea is in place, it is relatively accessible for other companies to join in the PORTHOS project as there is enough space for CO2 in the gas fields.

Green Hydrogen

In the last decade, the climate targets became substantially more ambitious. This creates a major role for hydrogen, especially in sectors where decarbonizing is difficult, as the transport sector. However, the GHG emissions related to the supply chain of grey hydrogen make large scale hydrogen production difficult. The alternative is green hydrogen. After grey hydrogen, green hydrogen is the most well-known option to produce hydrogen. Green hydrogen is also called 'renewable hydrogen' as the process is fueled with renewable energy.

The most common way to produce green hydrogen is via water electrolysis, where water is split into hydrogen and oxygen. The electrolysis uses electricity from renewable energy sources such as solar photovoltaic, offshore and onshore wind power [44]. The potential for green energy is much higher than the demand for electricity that is needed for electrolysis, so in theory, there is more than enough energy [45]. Due to its dependency on renewable energy, the location where the hydrogen is produced is very important as every location has different access to renewable energy sources. Countries in the MENA region (Middle-East and North Africa) have very high access to solar and wind sources, making it a region with a lot of potential to produce affordable green hydrogen.

The main advantage of using green hydrogen as a feedstock for synthetic fuels is that it serves as a zero-emission feedstock, which greatly reduces the overall GHG emissions of synthetic fuels. Hydrogen experts differ on whether to focus on blue or green hydrogen. In the short term, it is evident that green hydrogen is more expensive. That's why blue hydrogen is suggested as an ideal short-term solution. It can be ramped up to a commercial scale more easily than green hydrogen and could function as transition feedstock. The main cost drivers of green hydrogen are the energy costs and the electrolysers' investment (capital) costs. When the electrolyzer runs on a low capacity factor, the costs of green hydrogen significantly increase. This means that next to the price, the (constant) availability of renewable energy is important. Scaling up green hydrogen production will also decrease costs per unit and will be a significant challenge in the coming years.

Turquoise hydrogen

Turquoise hydrogen is a novel alternative production way that sits between blue and grey hydrogen. It uses natural gas as feedstock, but the production is driven by heat rather than by the combustion of fossil fuels in methane pyrolysis. The heat is produced by electricity [46]. Similar to grey hydrogen and steam methane reforming, the products are hydrogen and carbon. However, with methane pyrolysis, the carbon is in solid form rather than CO2. This eliminates the need for CCS, and it is even possible to use the solid carbon in other applications like the production of tyres and soil improver. When the electricity that is generating the heat is renewable, the process is carbon neutral. However, because turquoise hydrogen is at a very early stage of development and that there are no known large-scale pilots, it will not be considered feedstock for synthetic fuels. For the model, turquoise hydrogen will be considered out of scope due to the low technology readiness level and blue hydrogen being a more suitable alternative to green hydrogen. Another form of hydrogen is 'pink hydrogen', that uses nuclear power for the electrolysis of water. This is also considered to be out of scope. Not all countries have nuclear power and the Netherlands never have 'excess' renewable energy that has no other use than hydrogen production. On the short-term, no extra nuclear plants are expected to be built.

3.1.2 CO2

Next to hydrogen, the other main component of synthetic fuels is carbon dioxide (CO2). The use of CO2 as feedstock for fuels and chemicals could play a large role in mitigating climate change and is a promising pathway to reducing the dependency on fossil fuels in the mobility sector [22]. Instead of emitting the CO2, after capture, it can be either stored (CCS) or used as feedstock for another product (CCU). CCU, therefore, has two components of value. The first one is the reduction of CO2 emissions. Additionally, the captured CO2 creates value by serving as feedstock for additional products. It is interesting and important to look at the ownership of the CO2 after it is captured because when it is used as the feedstock of valuable products, the CO2 has value itself.

Rotterdam is an industrial cluster that wants to combine economic growth with sustainable development and ambitious climate targets. Storing and reusing the CO2 that is emitted by the Port industry is essential to reach those targets [17]. This ambition to store CO2 is translated into the PORTHOS project, where industrial companies capture their CO2 and pay to store the CO2 in empty gas fields in the North Sea [43]. The CO2 is first transported via an onshore structure of pipelines until it arrives at a hub before it goes into an offshore pipeline. At this hub, CO2 from other locations can arrive with ships to be stored as well. CO2 could also be transported and decentrally stored for CCU purposes like the production of synthetic fuels from this hub.

Currently, there is not yet a market on which CO2 as feedstock is traded. This also means that there is not yet a market price for CO2 as feedstock. The CO2 that is traded for CCU purposes comes from a bilateral contract between industrial companies. However, IEA expects that the annual trade in CO2 will increase dramatically and therefore expects the emergence of a CO2 market. For simulation, the model will follow assumptions from available literature and assume CO2 to be available for 35€/tonne [5].

An important thing to realise here is how synthetic fuels will reduce emissions. During the combustion of synthetic fuels, CO2 is still emitted into the atmosphere, unlike with electric or hydrogen-powered cars. The emission reduction is realized by capturing the CO2 and putting it into the fuel as feedstock, preventing it from entering the atmosphere. Technically, the process is only carbon-neutral if biogenic CO2 is used.

Biogenic CO2
There is some debate about the use of CO2 as feedstock for synthetic fuels as the technical climate change mitigation potential of CCU is affected by the CO2 source [18]. The production of synthetic fuels prevents CO2 from being emitted from the air. But unlike battery electric vehicles or hydrogen cars, the combustion of synthetic fuels still leads to CO2 being emitted into the air. Also, the demand for CO2 does create incentives for burning fossil fuels. There are multiple possible carbon sources, including fossil and biogenic point sources [25]. To maximize the climate change mitigation potential, the CO2 used should be biogenic or extracted from the air via Direct Air Capture (DAC) [27]. Biogenic CO2 is CO2 that is emitted during the combustion of biomass or waste. This biomass has a CO2-neutral life cycle, which would lead to a carbon-neutral combustion process. The emissions would be net-zero with synthetic fuels as the captured CO2 is released again during the fuel combustion. In the Port of Rotterdam, biogenic CO2 is already captured, transferred and used in greenhouses nearby through a company that is called OCAP (Organic CO2 for Assimilation and growth in Plants). To maximise the climate mitigating potential and to ensure the lowest carbon payments for the production, synthetic fuels could focus on this kind of carbon. As CCU is not recognized yet as carbon-reducing technology, the use of biogenic CO2 will most likely be essential for synthetic fuels to be able to profit from subsidies and high CO2 emissions prices for fossil fuels.

Direct Air Capture
Where CO2 and biogenic CO2 are the results of combustion, new technologies to capture CO2 also arise. An example of this is Direct Air Capture (DAC). This is a technology to capture directly from the atmosphere. When used in combination with CCS, DAC could potentially lead to negative CO2 emissions. With CCU, DAC leads to net-zero, as combustion of the fuels does release the CO2 back into the air. Unfortunately, the technique is still in the early development stages and very expensive. Even in the most positive assumptions, DAC is at least 3 times more expensive than CO2 from point sources. As the high costs are the main challenge for synthetic fuels to compete, DAC does not look like a preferable short-term addition. Regardless of the high price and relatively low TRL, the first large project using direct air capture has already started in Chile and plans to produce 550 million litres of synthetic gasoline per year by 2026 [47]. To put this in perspective, that is enough for a million people to drive their car for a year. Additionally, 10 years ago, other technologies like energy from solar PV was not expected no reach the relatively low cost it is now. While there are some evident challenges for the technique, such as the large amount of energy needed for the capture due to the low concentration of CO2 in the air, it could be a promising addition to the synthetic fuel supply chain if the technique continues to develop. The IEA also expects DAC to account for 10% of the carbon reduction by 2050, showing the potential and expectations for the technology [48].

3.2 Available Fuels

From the information and developments discussed in previous sections, it is evident that regulations on CO2 emissions are tightening and that low-CO2 alternatives are essential to reach local and international climate goals like the Paris treaty. It is clear that minor adjustments are insufficient to mitigate the effects on our climate. In the following section, a collection of synthetic fuels will be discussed. They could play an important role in partly substituting the current use of fossil fuels in the mobility sector. This section will provide the synthetic fuel system context and discuss potential production routes and end products to consider for the model. Firstly, each fuel will be discussed individually. Lastly, the results will be summarized in a table, showing each fuels specific characteristic.

3.2.1 Methanol

Methanol is a versatile chemical for storing renewable energy and CO2, mostly produced via chemical processes [49]. Methanol production via methanol synthesis by using captured CO2 and hydrogen already exists on scales larger than pilots [50]. The methanol is synthesized from CO and hydrogen via CO hydrogenation:

$$CO + 2H_2 = CH_3OH$$

An advantage is that it is a liquid that allows for relatively easy transportation, storage and distribution. In this respect, it is similar to, for example, gasoline and diesel fuels. By-products are produced in quantities that are so significantly small that they can be neglected. Methanol has the potential to reduce GHG emissions strongly. The European Parliament, for example, states that synthetic methanol could reduce GHG emissions by 91-94% in comparison with the conventional methanol production pathway [51]. While methanol is toxic to humans, the current large-scale production ensures that methanol has a relatively high acceptance [21].

Another advantage is the high number of possible applications. Methanol can be further processed and upgraded to a large number of other fuels, of which some will be discussed in the next chapters. Methanol itself is also named as a potential fuel, mostly for marine transport. However, the low energy density of methanol would require significantly larger tanks or more frequent refuelling [52]. The multitude of applications forms the base of the already large methanol economy [53]. It is considered a 'commodity chemical'. Methanol can be transformed into propylene and ethylene. These chemicals are produced on a large scale by the petrochemical industry. Another option is to use methanol as feedstock to produce DME (dimethyl ethers) and OME (polyoxy dimethyl ethers). DME and OME are fuels that are called second-generation e-fuels and could potentially play a part in reducing emissions in the transport and mobility sector [53].

3.2.2 DME

DME (dimethyl ether) is a gaseous processed fuel that can be produced in multiple ways. One of those production pathways is through DME synthesis from methanol [23]. It is also possible to produce DME from syngas, and it can serve as an interesting intermediary product to produce gasoline [54]. DME is gaseous at ambient temperature but relatively easy to liquefy because the temperature and pressure needed to change DME to a liquid state are modest. Therefore, DME is easy to transport and store. DME is clean and colourless and has the potential to be used in multiple sectors and applications. It can be used as fuel in the mobility sector, as well as for power generation and domestic and industrial heating. It is increasingly used as a clean alternative fuel and as an energy carrier [55]. DME emissions contain very low levels of particulate matter, including CO2 and NOx. Therefore, DME has a high potential to reduce GHG emissions. Depending on the DME production process's feedstock and internal energy consumption, the GHG reduction potential can be as high as 94% [51].

3.2.3 OME

OME represent polyoxymethylene dimethyl ethers, and OME, like DME, is synthesized from methanol. $OME_{3\text{-}5}$ contains three to five CH_2O units and is an interesting fuel to use in diesel engines without significant fuel system modifications. Furthermore, when blended with diesel, OME can reduce the formation of soot particles, unburned hydrocarbons and carbon monoxide emissions during combustion [53]. This potential to reduce GHG emissions and its compatibility with existing infrastructures make OME an interesting alternative fuel.

The fabrication of OME is relatively easy and consists of catalytic steps from methanol or DME. According to Schemme, the different production routes of OME already have a technology readiness level of 5 or more, which means the development phase is where the technological concept works and fabrication of the product is close [23]. However, the current production routes do have some issues as they are quite expensive. Also, the production routes perform low in terms of energetic efficiency, which further increases costs and potentially GHG emissions, depending on the energy source [53]. For production on a larger scale, the costs and energy use of the process will have to decrease.

3.2.4 Fischer-Tropsch Fuels

Fischer-Tropsch fuels are made via Fischer-Tropsch synthesis. To do this, syngas is formed from CO2 and hydrogen. The syngas is a mixture of CO and hydrogen, so the required CO must be formed from CO2 and hydrogen in a Reverse Water Gas Shift (RWGS) [56]. In some cases, direct supply of CO is possible with, for example, steel production. This syngas is then turned into long-chain hydrocarbon waxes called syncrude during the FT-synthesis. Finally, the waxes are upgraded by standard refinery processes to produce FT-fuels like gasoline, diesel en kerosene (*Figure 4*). Fischer-Tropsch synthesis is a proven concept and is already commercialized in processes that run on fossil fuels [57] [56]. All Fischer-Tropsch fuels are especially interesting because of their resemblance to fossil fuels. This means that they can be used in the existing infrastructure [54]. Unlike hydrogen, synthetic fuels are easily stored and transported [58].

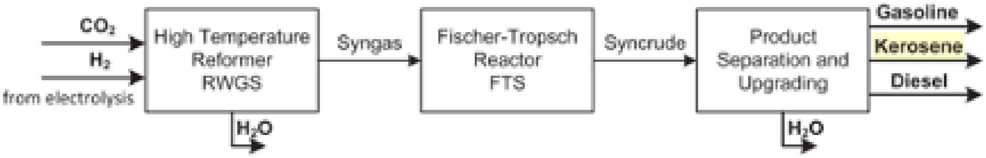


Figure 4: Fischer-Tropsch Synthesis to produce gasoline, diesel and kerosene [5]

Gasoline
Gasoline is the first of three fuels that can be made via Fischer-Tropsch synthesis. Gasoline is a transparent flammable liquid, and it is primarily used as a fuel in the internal combustion engines (ICE) of cars and other road vehicles. Gasoline is a hydrocarbon fuel, which provides the majority of all transportation energy [57]. Petroleum oil is the dominant feedstock to produce gasoline, but synthetic gasoline from CO2 and hydrogen could be a viable and more sustainable alternative. In *Figure 5*, CO2 from a fossil point source is used as the feedstock for the fuel synthesis. At the industrial plant, the CO2 is captured. Then, the CO2 is conversed to carbon monoxide (CO) with a Reverse Water Gas Shift (RWGS). In the subsequent process, gasoline is synthesized with Fischer-Tropsch synthesis.

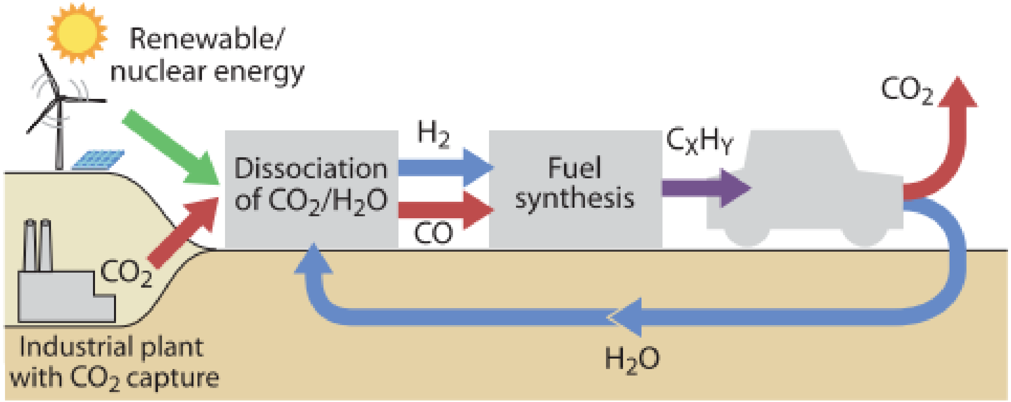


Figure 5: Fuel synthesis using a local point source [57]

As previously discussed, the process could have a bigger impact on emissions when the CO2 from the local point source would be substituted with biogenic CO2 or CO2 from the air via Direct Air Capture. The latter would ensure a closed-loop hydrocarbon fuel cycle. This difference can be seen in *Figure 5* and *Figure 6*. Direct Air Capture or at least biogenic CO2 is the preferable option as the positive environmental impact would be maximized that way.

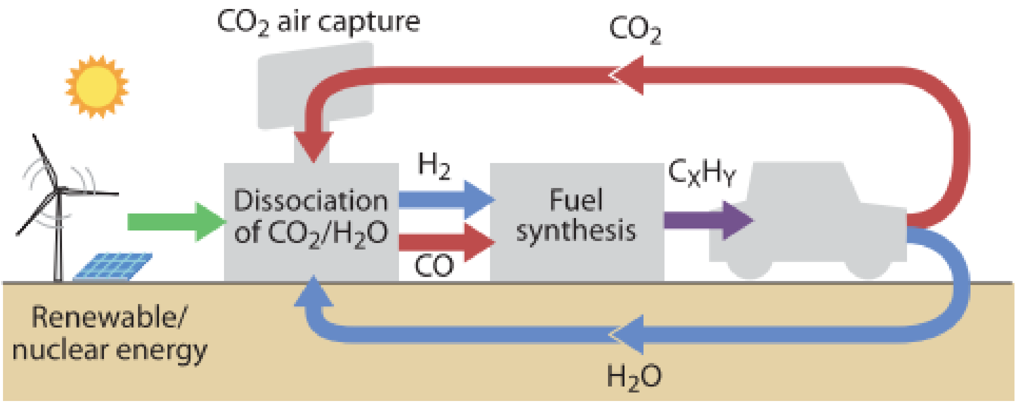


Figure 6: Fuel synthesis with a closed carbon loop [57]

Another pathway to fabricate synthetic gasoline separate from Fischer-Tropsch synthesis is through a Methanol-to-Gasoline process (MtG). Both production pathways are considered to have the potential to become competitive with conventional gasoline fuel. In the MtG process, methanol is first synthesized, and then it is converted into hydrocarbons using zeolite catalysts [59]. The byproduct is water. Since the first MtG plant was opened in the early 1990s, the technology has seen improvements that significantly lowered capital and operational costs.

Diesel

The second Fischer-Tropsch fuel is diesel. FT-diesel is a processed diesel product compatible with the existing diesel infrastructure and can be used in internal combustion engines that run on diesel without further adjustments. It is an alternative for road transport as well as marine transport. Multiple studies have looked at the costs of the production process[25] [57] [56]. Electricity comprises a major part of the production costs. This means that the assumptions on electricity prices are central in the cost estimates [60]. The conversion efficiency from syngas to diesel, as well as the electricity and hydrogen prices, depend on process assumptions and has significant uncertainties. Diesel could be interesting for the maritime sector, although it has some strong competition from methanol and ammonia.

Kerosene

The third and last Fischer-Tropsch fuel that will be discussed is synthetic kerosene. Kerosene is especially interesting because of the lack of low-emission alternatives for aviation. Road transport can be and already is partly electrified. Marine transport can potentially use bio-methanol, LNG, ammonia and other alternatives. For the aviation industry, the lack of viable alternative fuels will most likely lead to a continuation of fossil-fuel dependency. The aviation sector is expected to continue to grow as well, and potential transitions are made even more complex by the sunk costs and the long use cycles of existing airplanes.

A pilot with synthetic kerosene in a commercial aircraft was already successful recently, although the initiators have big concerns about scalability [16]. Drünert (2020) also expresses his concerns as the potential of synthetic kerosene is highly dependent on the availability of CO2 point sources and sufficient renewable energy generation [61]. However, most studies do emphasize the potential of synthetic kerosene as an option to make the aviation sector more sustainable, especially under the right conditions [56] [62] [3]. The fact that synthetic kerosene can be used in the existing infrastructure and also as a blend-in fuel in a sector where there are the least alternatives makes synthetic kerosene arguably the most interesting synthetic fuel.

3.3 An overview of electric fuels

In *Table 1*, an overview is presented of the potential feedstock for synthetic fuels and the potential fuel end-products that are discussed in sections 3.1 and 3.2. For each feedstock and fuel technology, the most notable characteristics have been summarized.

Category	*Fuel Technology*	*Characteristics*	*Source*
Hydrogen Feedstock	Grey Hydrogen	Low cost; high CO2 emissions; very common; SMR; proven technique	[41]
	Blue Hydrogen	Relatively low cost; low CO2 emissions; Carbon Capture & Storage; proven technique	[42] [43]
	Green Hydrogen	High cost; potentially low cost; zero CO2 emissions; electrolysis; proven technique	[44] [45]
	Turquoise Hydrogen	Zero CO2 emissions; gas feedstock; heat-driven; methane pyrolysis; low TRL; solid carbon product	[46]
CO2 Feedstock	CO2	GHG gas; potential to capture, store and use; result of fuel combustion; easily transported	[22] [17] [43] [5]
	Biogenic CO2	GHG gas; potential to capture, store and use; result of waste or biomass combustion; easily transported	[18] [25] [27]
	DAC	GHG gas; high costs; potential to capture, store and use; result of extraction from atmosphere; easily transported; potential for negative emissions; low TRL	[47][48]
Synthetic Fuels	Methanol	Easy transportation, storage, distribution; very common; methanol synthesis; proven technique; high GHG-reduction potential; potential to process and upgrade further	[49] [50] [51] [21] [52] [53]
	DME	gaseous fuel; low GHG emissions; DME synthesis; from methanol or syngas; potential intermediary product; easily liquefied, transported, stored	[23] [54] [55] [51]
	OME	low GHG emissions; DME synthesis; from methanol; potential intermediary product; easily transported, stored; medium-high TRL; high costs; low efficiency	[53] [23]
Fischer-Tropsch	FT-gasoline	FT-synthesis; low-carbon alternative; mainly for ICE (road transport); proven concept	[57] [59]
	FT-diesel	FT-synthesis; low-carbon alternative; mainly for ICE (road transport); potential for maritime industry; proven concept	[25] [57] [56] [60] [59]
	FT-kerosene	FT-synthesis; low-carbon alternative; jet-fuel for aviation sector; proven concept; no promising sustainable alternatives	[16] [61] [56] [62] [3]

Table 1: An overview of possible synthetic fuel end-products and their main characteristics. Own composition

3.4 The inevitability of synthetic kerosene

There is a wide variety of potential CCU applications and a wide variety of synthetic fuels as well. All of the fuels mentioned in this section can potentially play a part in reducing emissions and substituting fossil fuels. This is the case for reducing CO2 emissions, as well as other GHG like NOx, SOx and soot particles. The majority of the fuels that are discussed in the previous chapters have a high TRL and are compatible with existing infrastructure. This compatibility is something that stands out for synthetic fuels and greatly increases their chance of playing an important part in the energy transition. However, most synthetic fuels have quite some 'sustainable competition'. Diesel could prove to be a viable alternative for shipping, but the maritime sector has high hopes for ammonia as well. Gasoline and other fuels mentioned could be interesting for cars and road transport, but the road sector is already starting to electrify at a rapid pace, and hydrogen-powered vehicles are also developing fast. These alternatives have the major benefit that there are no emissions during the use of the vehicle, where synthetic fuels still emit CO2. This is the reason that one fuel arguably stands out, which is kerosene. Synthetic kerosene would function as an alternative in an industry that is very difficult to decarbonize in other ways. Aviation is hard to electrify due to the range and capacity restrictions, and the same is the case for hydrogen planes. Also, replacing the existing airplanes fleet and airport infrastructure is costly and a huge risk. Synthetic kerosene does not have any of these disadvantages and can be used in the existing planes and infrastructure. This is also the reason that for synthetic fuels, the IEA sees the most potential in the aviation sector. This becomes very clear from *Figure 7*:

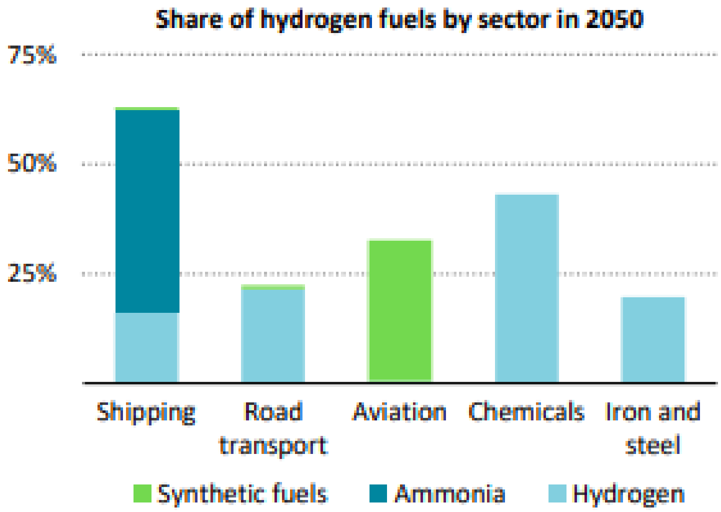


Figure 7: The aviation sector has the highest potential for synthetic fuels [48]

In conclusion, while all synthetic fuels could definitely play a part in the energy transition, kerosene is arguably the most promising synthetic fuel. All fuels that deviate significantly from fossil kerosene are simply unacceptable due to a too high loss of load capacity, passengers and range [3]. Additionally, large investments would be needed for completely new airplanes and engine designs. Synthetic kerosene is made through Fischer-Tropsch synthesis just like gasoline and diesel, so their supply chains are almost identical. This means that scaling up FT-gasoline and FT-diesel will be much easier once the production of FT-kerosene is increasing as well. Ideally, the three Fischer-Tropsch fuels are produced together, to introduce scale and location benefits. Because of all this, the model experiments will focus on comparing synthetic kerosene with the conventional fossil alternative. The comparison of the synthetic and fossil kerosene prices will represent the chance of all synthetic fuels to become competitive, while focusing on the fuel that will most likely become indispensable for decarbonizing aviation.

4

PESTEL-Analysis

To understand the potential of synthetic fuels in the energy mix of the mobility sector, it is important to comprehend the challenges and bottlenecks in developing these fuels. While there is no question whether the production of synthetic fuels is possible, there are many uncertainties regarding scalability, the supply, origin and price of feedstock and the environmental impact. In this chapter, the uncertainties surrounding the fabrication of electric fuels will be discussed, and the critical uncertainties will be identified. By doing so, it will answer the second sub-question:

2. Analyze the internal and external uncertainties that impact the synthetic fuel system and identify the critical factors.

This study aims to consider the full set of factors that will influence the future, according to the intuitive logics approach. It will incorporate the Political, Economic, Social, Technological, Ecological and Legal (PESTEL) factors that will influence and shape the future of synthetic fuels [28]. The PESTEL factors interact with each other, are wide in range, and together they will provide a comprehensive overview of the challenges and opportunities of synthetic fuel fabrication in the future. In the sections below, the most important factors in each category will be discussed. Some factors provide context regarding the wider system and global trends. Other, more concrete factors will be used as critical uncertainties to run experiments in the model. This study aims to show the dynamics of changing them and get a better, more sophisticated understanding of their impact. After the PESTEL-analysis, the factors will be visualized in a SWOT analysis, showing the Strengths, Weaknesses, Opportunities and Threats.

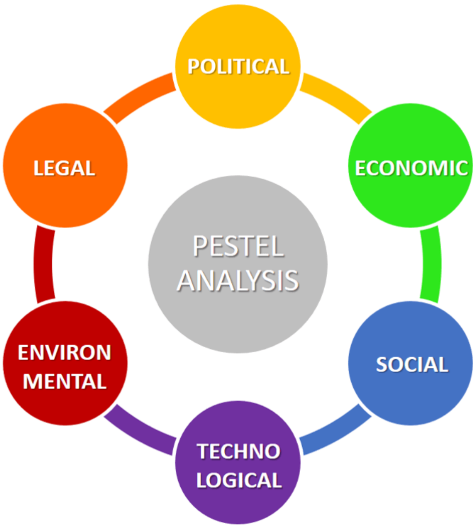


Figure 8: PESTEL-analysis to provide the macro-environmental context [63]

4.1 Literature on critical uncertainties

After discussing the wide range of potential synthetic fuels and scoping down the research to synthetic kerosene in order to conduct the experiments, the wider context of the system will be discussed. To do this, multiple literature sources were used, of which the findings of the most important ones are visualized in *Table 2* below. Because most of the literature focused on Political, Economic and Technical factors, these factors are visualized in separate columns. The Social, Environmental and Legal factors are grouped together. Additionally, in order to make a well-considered selection, the goal and perspective of each cited paper are important. Therefore, the cited literature is reviewed in short paragraphs after *Table 2*.

Source	PESTEL-factors			
	Political	*Economic*	*Technical*	*Other(S,E,L)*
Van Kranenburg et al. [3]	CO2 tax EU-ETS	CO2 costs Energy costs Electrolyzer Capex	Technological innovation	Promotion of Synfuels (S) Blending Quota (L) Climate Change (E) Social Acceptance (S)
Parigi et al.[20]		CO2 costs Energy costs Electrolyzer Capex	Operating Hours	Climate Change (E)
Schemme et al. [23]		Hydrogen Costs Energy costs Electrolyzer Capex	Technological maturity Efficiency	Climate Change (E)
Tremel et al. [21]	R&D investments Subsidy	Crude Oil Price Gas Price Energy costs Electrolyzer Capex	Compatibility Efficiency	Growing Demand (S) Public Acceptance (S)
Schmidt et al. [49]	RE investments	CO2 costs Energy costs Electrolyzer Capex	New Tech (DAC) Efficiency Scalability	Growing Demand (S) Blending Quota (L)
Ausfelder & Wageman [64]	Subsidy	CO2 costs Energy costs Electrolyzer Capex	Efficiency	Growing Demand (S) Scarcity of materials (E)
Brynolf et al.[4]		CO2 costs Energy costs Electrolyzer Capex Hydrogen Price Heat Price	Efficiency Depreciation Compatibility	Climate Impact (E)
Dimitrou et al. [59]	Carbon tax Subsidy	Crude Oil Price CO2 costs Synthesis costs Opex & maintenance costs Energy costs Electrolyzer Capex	Efficiency	Global social stability (S)
Van der Giesen et al. [27]		CO2 costs Energy costs Electrolyzer Capex CCS costs	New Tech (DAC)	Climate Impact (E)

Table 2: Literature study on critical factors of the synthetic fuel system. Own composition

Van Kranenburg
This research is done by TNO and aims to give insights into the whole range of synthetic fuels in the future. It is one of the most complete studies that were found. The study provides recommendations for relevant actors, such as fuel providers, fuel producers, logistics, energy suppliers, governments, and ports. The study also sketches a timeline for implementation and provides an explanation of which fuel is suited for which industry. The study provides an extensive overview of the forces at play in the synthetic fuel system and also highlights the benefits of choosing the Port of Rotterdam as a synthetic fuel production location for the Netherlands. However, measuring the specific impact of the relevant drivers is of less importance to this research.

Schemme
Schemme performs a techno-economic analysis of multiple synthetic fuels. The study aims not to compare synthetic fuels to fossil fuels, but only to each other. Schemme highlights the lacking compatibility between studies about synthetic fuels, because of the importance of varying conditions. Subsequently, Schemme offers a comparison of multiple fuels using flow models in Aspen Plus. The study focuses on specific technical elements like the technical maturity (and related costs) of parts of the supply chain and the electrolyzer and process efficiencies. Schemme does not compare synthetic fuels to fossil fuels. He also does not address the role of policy and carbon pricing instruments.

Tremel
Tremel also performs a techno-economical analysis of multiple gaseous and liquid fuels. Tremel focused on the different possible production pathways to produce fuels instead of already choosing one. This focus creates an emphasis on a specific technical part of the supply chain throughout the paper. However, Tremel does highlight the importance of considering compatibility with the existing infrastructure and public acceptance to identify appropriate technologies that could play a role in our future infrastructure and energy systems. He even suggests that the production costs of synthetic fuels are higher in almost every scenario, which means other factors like the environmental impact have to be made more important. Subsequently, he does not consider policies like carbon pricing, but he suggests that governments should do more to accelerate production by, for example, subsidies and R&D investments.

Schmidt
The study of Schmidt focuses specifically on synthetic fuels as a solution for decarbonizing the aviation sector. He emphasizes the challenge of introducing renewable energy into aviation and compares the performance of synthetic kerosene as an alternative. He also compares the costs of using CO2 from a concentrated source and from Direct Air Capture. He argues that most processes (like Fischer-Tropsch synthesis) currently used in the supply chain are proven technologies and should have no problem scaling up to a more industrial level. The comparison with fossil kerosene is present but brief, and the impact of policy is not addressed.

Ausfelder & Wageman
Ausfelder and Wageman start their essay by highlighting the ambitious climate targets and then argue that synthetic fuels could play a role in reaching them. The aim of the study is to identify challenges and boundary conditions for substituting fossil fuels with a 'Power-to-Liquid' alternative. They highlight the importance of efficiency, low-cost renewable energy and the availability of renewable energy. They also provide an overview of available CO2 point sources, showing there is a considerable amount of CO2 present in the Rotterdam industrial complex. Similar to multiple other scholars that are already discussed, they don't mention anything about the development of the fossil fuel price and the potential impact of policy instruments.

Brynolf

Brynolfs study is focused solely on reviewing the production costs, stating carbon tax is out of scope for the study. This means that the study, which includes a quite extensive literature review, is really focused on the technical part of the supply chain. This gives valuable insights into the technical developments and processes, but it does not place fuel production within the wider system by comparing it to fossil fuel.

Dimitrou

Dimitrou examines the technical and economic feasibility of a biomass-to-liquid process. This means that the CO2 used for the Fischer-Tropsch synthesis is biogenic. The work of Dimitrou is one of the more complete studies that were reviewed. Although the effects of an increase in the crude oil price and subsidies are not quantified, their impact is recognized as a potentially decisive factor for synthetic fuels to become competitive. Dimitrou does also mention some form of a carbon tax but chooses not to further explore the effects of the EU-ETS and nation carbon pricing instruments.

Van der Giesen

Van der Giesen focuses less on the economic part of producing synthetic fuels (although he does mention the main cost drivers), and more on the energy and climate impact. Van der Giesen identifies multiple challenges, of which the most important one is the amount of energy that is needed throughout the synthetic fuel supply chain. He also looks into Direct Air Capture as an alternative technology, highlighting the extra impact that would have while acknowledging the costs and even higher demand for renewable energy.

4.1.1 Trends in literature

As discussed in the research gap, there is no shortage of literature about synthetic fuels in the last years. The scholars above each have their own focus points and assumptions, and all make valuable contributions to the scientific literature on synthetic fuels. However, according to the authors' insights, they do not cover the complete picture. Van Kranenburg comes close, providing an extensive overview and making recommendations for almost all relevant actors. But as observed more often, the qualitative part is not followed up by quantitative insights. Other scholars choose not to incorporate the comparison with fossil fuels or the impact of policy. By performing a PESTEL-analysis and combining it with the linear optimization model, the research aims to show the complete picture.

4.2 Political Factors

After reviewing literature, the research will continue by further elaborating on the context of the synthetic fuel system by highlighting the PESTEL-factors. This first section covers all the political and governmental factors that influence the industrial system within the scope. In the transition to more sustainable energy production, government intervention is inevitable and can be the difference between success and failure. The ways and the degrees of political intervention can impact the speed of progress and the direction of developments. Political factors can include multiple factors such as the political environment, government policies, government awareness programs, government policies, international agreements, international cooperation, import duties, foreign trade policies, special tariffs, taxes [63].

4.2.1 Tax and subsidies

Economic measures are one of the most common instruments used by politicians to influence and direct processes in a certain direction. With the energy transition, this is not different as there are already measures in place and used on a large scale. A political factor with substantial impact is imposing a tax on unwanted processes like emitting CO2 and grant subsidies to processes that accelerate the energy transition like CCS and CCU. These measures to increase the price of emitting carbon are called ’carbon pricing’.

The European Union Emissions Trading System
The first way to do this is through the EU-ETS [42]. Because of this system, a limited number of certificates allow the industry to emit carbon, which leads to scarcity. The scarcity creates a price for the certificates and thus incentives to reduce emissions. The system is an instrument to reduce the overall volume of CO2 emissions. By introducing supply and demand, the system introduces a market price for CO2 emissions. By reducing the volume of available certificates over time, the ETS can ’artificially’ increase the market price of CO2. This market price has to be incorporated into the price of high-carbon conventional fuels, which makes their production and use more expensive. Currently, CCU is not yet incorporated the same way as CCS. Over the last years, an increasing amount of scholars have strongly argued that regulatory changes here are needed and that synthetic fuels should be treated equally to hydrogen and e-mobility [65]. This way, a higher ETS price leads to a decreasing cost gap between fossil fuels and synthetic fuels. In the experiments, the impact of the ETS price on the fossil kerosene price will be visualized using policy scenarios.

Carbon Tax
Another possibility is a carbon tax, which can be imposed nationally as well [66]. Which measure or combination of measures is taken depends on the national and economic circumstances. The difference between the two instruments is that the carbon tax is a price measure, where the ETS is focused on a maximum volume. In Europe, the carbon tax is supplementary to the EU-ETS and can be significant. For example, Sweden, which has the highest carbon tax globally, charges more than 100€ per ton of carbon emissions, which is more than twice the current price of the ETS, which is already high. But carbon taxing initiatives are also becoming more common worldwide, as can be seen in *Figure 9.* 61 initiatives cover almost 25 percent of the global annual greenhouse gas emissions. Combining the two instruments will lead to serious costs for emitting carbon and thus create options for low-carbon alternatives. In the Netherlands, the carbon tax functions as an addition to the EU-ETS to guarantee a minimum carbon price per tonne. When the ETS price is lower than the price set by the Dutch government, an additional tax makes up for this difference. This decreases uncertainty about the CO2 price, which decreases investments risks for sustainable alternatives.

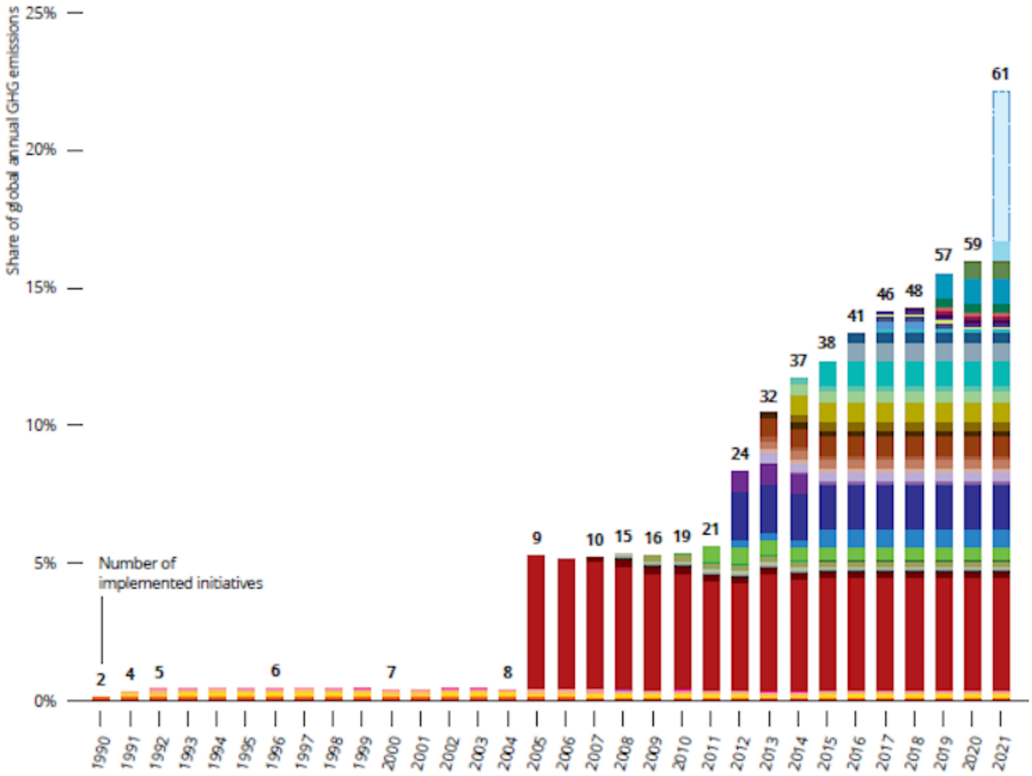


Figure 9: Global Carbon Tax initiatives [67]

Subsidies

The third important political measure governments can use to accelerate desired developments are subsidies. If synthetic fuels remain more expensive than conventional fuels, subsidies can be a political measure to fill that gap. Subsidy decreases the business risks for companies and plays a vital role in investment decisions regarding new energy technologies. There are many subsidies possible. For example, subsidy to invest in wind parks or CO2 capture facilities like the government did for Shell, ExxonMobil, Air Liquide and Air Products in the PORTHOS project. Other possible subsidies could be given to green energy or green hydrogen per kWh energy or per kilogram or tonne of green hydrogen. A subsidy per litre or gallon of synthetic fuel could also be an option.

All policy measures have the best effect if they are guaranteed long-term, to provide a stable investments climate to incentivize key players. Until now, there has been some criticism on the lack of long-term incentives and research from Brussels [62]. Long-term policy measures provide a stable investment climate for the private sector, which is a big advantage because many projects are long-term as well. The disadvantage of a subsidy per unit of hydrogen or fuel is that there is a risk that the subsidy becomes really expensive if the production increases faster than expected.

4.2.2 Import and Export

A way for politics to influence the energy sector is by facilitating and promoting trade between countries and continents. The Dutch government can actively look for trade and import opportunities for green hydrogen and promote Rotterdam as the main location for hydrogen import for North-West Europe. This section focuses more on the impact of a specific geographical location than on the political forces that influence and dictate (intercontinental) trade of resources like hydrogen. However, it is interesting to research if another location than Rotterdam could provide conditions that are so good that they might have a better chance at producing competitive fuels in the short-term future.

The import of foreign hydrogen will most likely play a large role for the Port of Rotterdam to become the hydrogen hub for North-West Europe. Countries with the most resources, like oil from the Middle East, have dominated the energy sector. With hydrogen, other countries could become dominant due to their geographical advantages, like the availability of renewable electricity to produce green hydrogen. For example, Australia has the potential to become a large-scale exporter of hydrogen for countries like Korea and Japan [18]. North-West Europe, North-Africa, Southern-Europe and the Middle-East have a lot of potential because of the availability of a lot of solar and wind energy. These connections can play a role in the import of sufficient green hydrogen. The main take-out from this factor is that the fuels' competitiveness is largely dependent on the particular environment of where they are produced. Whether it is the best option to import hydrogen and produce fuels in the Port of Rotterdam or produce the fuels next to the hydrogen and import the fuels is a big difference. This research aims to add insights into the geographical advantages of specific locations.

4.3 Economic Factors

Economic factors represent the macro-economic forces that influence the industry and the business environment. Economic factors influence supply and demand and, therefore, the price of products and services. Economic factors refer to the direction of the economy in which an organization competes [63]. Economic factors can be price fluctuations, economic growth, inflation, interest [68].

4.3.1 Capital Expenditures

The Capital Expenditures (Capex) is a typical economic factor that needs to be taken into account. That is especially interesting when looking at developing new technologies, as they often require significant investments. In the case of CCU in the Rotterdam port area, the investments don't start from scratch. The existing infrastructure provides a solid base. Additionally, refineries already present in Rotterdam have a large number of chemical systems needed to produce synthetic fuels such as heat exchangers, reactor vessels, mixing tanks, centrifugal machines, and more [69]. However, significant investments remain necessary, most notably for electrolyzers. The electrolyzers are needed to produce large quantities of green hydrogen for many applications, including synthetic fuels.

In any case, the Rotterdam port area is very suited to facilitate the production of synthetic fuels on a commercial scale. Vital parts of the infrastructure are already in place; there is a CO2 infrastructure and availability with PORTHOS, technical knowledge, and people with the required knowledge to run and operate refineries producing synthetic fuels. Additionally, the North Sea is an excellent location for offshore wind energy, which needs to be used by the electrolyzers to produce green hydrogen.

Within this research, the Capex refer to the significant investments needed for the electrolyzers to produce green hydrogen [4]. To produce sufficient green hydrogen for future applications, there is a very great demand for electrolyzer capacity. However, the capital costs are quite high, which greatly increases the costs of green hydrogen and thus synthetic fuels. Using scenarios in the model, this research will try to show how significant the impact really is. In *Figure 10*, a breakdown of the electrolyzer Capex is shown:

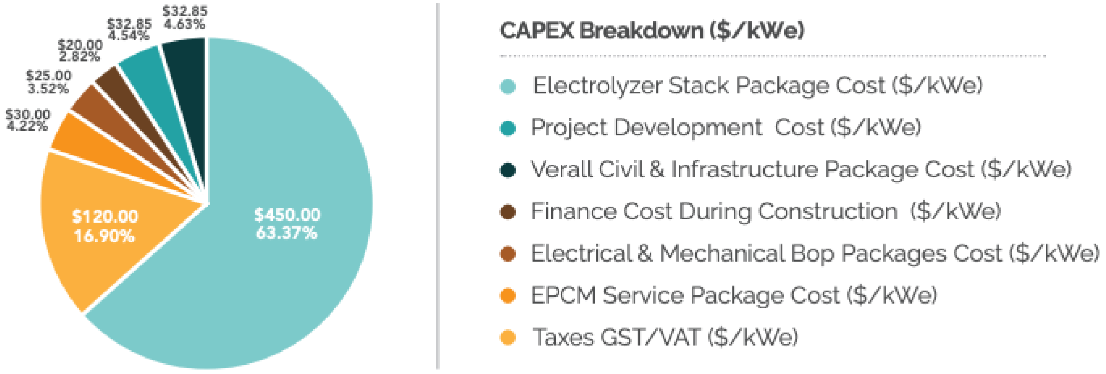


Figure 10: Breakdown of the electrolyzer Capex [70]

4.3.2 Energy price

The price of (renewable) energy is a vital part of the production of electric fuels. Synthetic fuels are a Power-to-X product, meaning that products of value are made from electricity. Especially when the fuels are produced with green hydrogen, the price of renewable electricity is a significant factor as the majority of the costs of green hydrogen are the result of energy prices. Multiple studies have already pointed out that the electricity costs and the capital costs of the electrolyzer are significant parameters affecting the costs of synthetic fuels [57] [4]. The energy price depends on multiple factors, like the energy source and the installation of renewable energy sources (RES). The energy price from the grid will differ from the price of a separate offshore wind park or only the use of excess energy due to intermittency. Every option has pro's and cons, and it is worth investigating those. The model experiments will show the impact of the energy price and the capacity factor on the green hydrogen price, using multiple policy scenarios. The experiments will also show under which conditions green hydrogen will have the lowest production costs and if those costs are low enough to produce cost-competitive synthetic fuels.

4.3.3 Crude Oil Price

The price of a barrel of crude oil makes up a very significant part of the fossil kerosene price. This means that with a high oil price, fossil kerosene becomes significantly more expensive and easier for bio- and synthetic fuels to compete [59]. High oil prices are often the result of high demand, low supply, OPEC quota, or decreasing dollar value [71]. Especially the OPEC quota stands out, as other products are affected by the other factors as well. The ability to produce oil is focused on just very few countries, causing them to control the oil price. Geopolitical tensions between, for example, the OPEC and the US or Russia could directly or indirectly cause the oil price to surge. For example, in 2013, the United States announced it would use airstrikes as retaliation against Assad for the use of chemical weapons. Anticipating disruptions in the region, the demand surged and caused the oil price to increase to over 100€ per barrel of crude oil.

4.3.4 Hydrogen Price

As part of the energy transition, the demand for (green) hydrogen will grow significantly. Firstly, in 2020, the hydrogen use of the European Union was a little less than 10 Mt of hydrogen per year, which is mostly grey hydrogen [45]. Secondly, the 2019 hydrogen roadmap expects the hydrogen demand to increase to almost 17 Mt of hydrogen per year for various applications [72]. As visible in *Figure 11*, synfuels for aviation as well as heavy shipping are described as long-term no-regret moves. This segment is described as alternatives where hydrogen-based solutions are the only option for decarbonization.

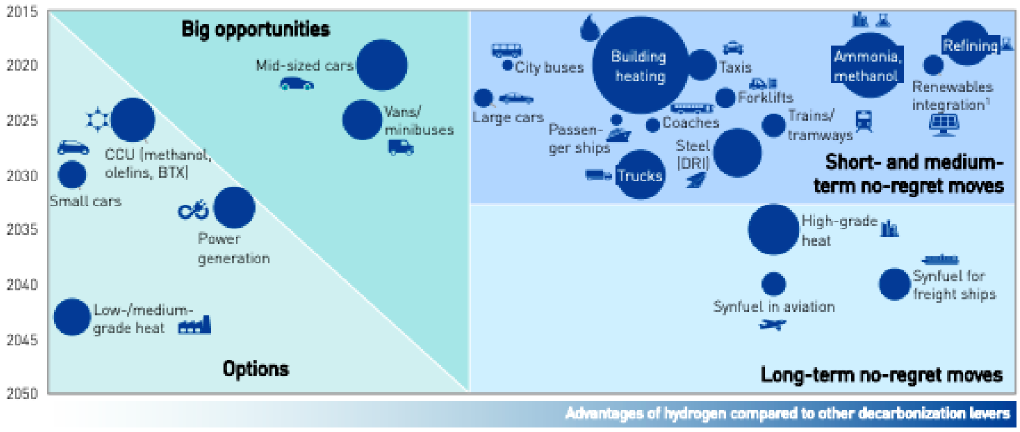


Figure 11: Hydrogen Applications Short and Long Term [72]

This increase in demand will increase the production and import of hydrogen, but not necessarily the availability of hydrogen synthetic fuels as it is also needed for other applications. However, the price of green hydrogen, either imported or produced domestically, is expected to drop significantly due to economies of scale and technological innovation [72]. This price drop will inevitably have a huge positive impact on the costs of synthetic fuels. The Hydrogen Council even states that under the right conditions, hydrogen in synthetic fuels for aviation will become cost-competitive with high-carbon alternatives from as early as 2035 [41]. In the model, blue hydrogen will be considered a possible feedstock for the production of synthetic fuels. One of the goals of the experiments is to show under which conditions green hydrogen will become the preferred option, as blue hydrogen is expected to be cheaper in current conditions.

4.3.5 Price of CO2

The price of CO2 has multiple meanings when looking at the production of synthetic fuels. Firstly, CO2 is needed as feedstock for the fuels, as it is one of the two building blocks for all selected synthetic fuels. Secondly, there are costs related to the emission of CO2 in industrial processes. As these costs are expected to increase, the capture of CO2 and the subsequent use of synthetic fuels will become more attractive. In the following paragraphs, both costs will be discussed.

CO2 feedstock price

Using CO2 as a feedstock for chemicals and fuels could help mitigate climate change and the dependency on fossil fuels [22]. In the short term, the CO2 used will be captured CO2 from local points sources in the industrial cluster. In the long term, other sources could become viable alternatives. There is already room and ambition for an international hub to import CO2 for storage in the Rotterdam PORTHOS project. This CO2 can potentially also be used for CCU. The price will be dependent on both the amount of CO2 captured and CO2 imported. It is most likely that concentrated 'point-sources' in the Rotterdam industrial cluster will provide sufficient CO2 in the coming years [69]. Shell, Exxon Mobil, Air Liquide and Air Products together have already committed to being the first customers PORTHOS project, which will ensure a significant flow of captured CO2 through the PORTHOS infrastructure in Rotterdam [43]. However, their contribution to the project is partly based on government subsidies which require that the CO2 is for CCS specifically and not CCU. For the production of synthetic fuels, it is important that the additional value of CCU is recognized and that CO2 from the PORTHOS infrastructure becomes available for CCU. At the moment, there is not yet a market for CO2. The CO2 used as feedstock in, for example, greenhouses and synthetic fuel pilots all comes from bilateral contracts between emitting and using parties. The expected increase in demand will likely lead to a CO2 market in the future.

In the longer term, technology like Direct Air Capture can prove to be a better alternative. It is available everywhere, and the technology is getting more and more attention. Currently, the price is still around 300 €/t CO2 and a factor 3 to 10 times as expensive as CO2 that is captured from point-sources. The technology readiness level is still too low and in an early stage of development. However, it is expected that the costs will drop significantly due to reduced maintenance costs and reduced capital expenditures due to mass production. Technical advances in the future could also reduce energy costs. According to Fasihi (2019), the costs could be below 50 €/t CO2 by 2040 [73]. In 2020 already, a tri-lateral consortium of German, Chilean and Italian technology companies had received funding to implement a synthetic methanol plant in Chile, which will benefit from the good conditions for wind energy and only use carbon from direct air capture [47].

CO2 emission price

Another important driver of the transition towards synthetic fuels will be the price of emitted CO2. A possible approach to reducing the emission of CO2 could be to use the EU Emissions Trading System (ETS) to increase the price of emitted carbon, which was already introduced at the political factors [74]. Just recently, the price in Europe has increased to more than 50€ for one tonne of CO2 (*Figure 12*). Furthermore, the EU-ETS has the ambition to create an even higher carbon price in the future, where now there is also still a significant allocation of free allowances to the aviation sector and other CO2-intensive industries.

Figure 12: The carbon price of the EU-ETS is significantly increasing [75]

This carbon pricing will have a significant impact on two factors. Firstly, the prices of conventional fuels like diesel, gasoline, and kerosene will rise because the higher carbon price has to be incorporated into the fuel price. With a decrease in free allowances and an increasing carbon price, kerosene and flying will become more and more expensive. This increases the chance that synthetic fuels will become economically competitive with conventional fuels. Another effect is that techniques with zero percent carbon emission like green hydrogen could become more competitive with, for example, blue hydrogen, where there is still a 10% loss of carbon in the process of carbon capture. This could increase the investments in green hydrogen and the availability of green hydrogen for synthetic fuels.

A crucial notion here is that CCU is not yet exempted from the ETS. This means that producers still have to pay emissions rights for the carbon they use to produce synthetic fuels, where there are no payments required for storing the carbon underground with CCS. While the European Union and individual nations are working on laws to change this, it is still not the case. The research aims to look at the potential impact of incorporating CCU under the ETS, potentially adding a carbon tax.

4.4 Social Factors

The social factors cover the part of the system that is influenced by, for example, cultural trends, population growth, environmental concerns of the public, education and more. They basically represent a combination of the demographics of the system in which the industry operates and the norms and values that influence the sector. Social factors can be particularly important when companies want to brand their new products or persuade governments to give them financial or institutional support.

4.4.1 Environmental concerns

Many scholars who have looked at the driving forces of green hydrogen and synthetic fuels have also cited environmental concerns [59] [62] [76] Globally, humanity's impact on the climate and global warming is becoming more and more evident. And more and more countries and companies are taking responsibility in working towards more environmentally friendly solutions. This shift in attitude does not directly impact the fabrication and development of synthetic fuels in the Port of Rotterdam. However, by voting for greener parties in politics and changing the way people think about conventional fuels like coal and gas, the growing environmental awareness is a huge driving force behind concrete measures like taxes and subsidies. Companies are doing more as well, realizing that it is not an option to keep doing what they're doing. The environmental concerns of the public will accelerate government intervention and sustainable innovation.

4.4.2 Growing demand

Another important social factor is the growing demand for fuels in general. The world population is growing, but not only the total number of people. Rapid economic growth in, for example, Asian countries is leading to an increase in fuel demand, and globalisation makes it easier for people and goods to travel around the world. The aviation sector is expected to grow significantly, the maritime sector as well. The growth of demand will lead to an increased dependency on oil-rich countries and create risks for energy security and global social stability [59]. Additionally, the increase in demand will go hand in hand with a further increase in GHG emissions, which makes the search for low-emission alternatives even more important.

4.5 Technological Factors

Technological factors refer to the technology that is related to the product and the sector. This includes the technology readiness level (TRL) of a product or process, but in a wider scope, they represent the influence of R&D, the potential of technology, the rate of innovation and the current sources of energy. All these technological factors affect the operations of the industry and the speed of technological improvements. They may influence decisions on whether to invest in a product or sector or not.

4.5.1 Technological Innovation

Because of the novelty of the technology, there are, of course, some technological uncertainties. For example, how will certain technical parts of the synthetic fuel supply chain develop in the coming years? Technological developments often lead to significant cost reductions per unit. Another example is the efficiency of certain processes like the CO2 capture rate, electrolysis and Fischer-Tropsch synthesis. Higher efficiencies mean lower energy use and costs and a higher chance of being used and developed on a large scale.

4.5.2 New Technologies

As discussed in previous sections, new technologies like Direct Air Capture could greatly increase the positive environmental impact of synthetic fuels, as when the two technologies are combined, the fuels are essentially carbon-neutral. While this specific technology might prove to be too energy-inefficient, it is a good example of potential innovations that could contribute to a more competitive end product with higher emission reductions. New electrolysis technologies like Solid Oxide Electrolyzer Cells (SOEC) have also increased efficiency by allowing lower operating temperatures [77].

4.6 Environmental Factors

Environmental issues should be considered as any other important factor, and the assessment of those issues should be incorporated in all relevant actors and the industry as a whole [78]. The environmental segment refers to the trends and changes of the physical environment in which the sector operates. Environmental factors are becoming more important over the years due to rising emissions, scarcity of materials, and the earth's warming. This leads to pressure from NGO's and environmental policies from governments.

4.6.1 Climate change

This factor represents the number one reason for the energy transition. The planet is getting warmer because of the increasing amount of greenhouse gasses in the atmosphere. A large part of these emissions are the direct results of humans, and their amount and indirect effect on the environment is amplified by globalisation and a growing population. This is why politics and the public have sustainable energy technologies so high up the agenda. The increasing amount of GHG emissions in the atmosphere and the rising temperatures worldwide create an unprecedented feeling of urgency to come up with renewable alternatives. These environmental concerns have become the biggest drivers of sustainable policy and innovation.

4.6.2 Scarcity of materials

Another environmental factor is the scarcity of materials. While there is still enough at the moment, conventional fuels like oil and gas will deplete in the coming decades. With humans having become very dependent on travel and energy security, it is essential that viable alternatives are being developed. The scarcity of materials could also lead to increasing oil prices in the future, making synthetic fuels more attractive [29]. However, green hydrogen production could also suffer from the scarcity of materials as essential materials as iridium, scandium and yttrium are also marked as having a high supply risk. [79]

4.7 Legal Factors

These factors have some overlap with political factors. They include specific laws like the health laws, safety laws and employment laws, and national legislation, sector-specific policies and laws regarding technology and the environment. Overall, they concern the legal issues regarding the operations of the different actors in the system.

4.7.1 Fuel Combustion Laws

This factor refers to laws that would directly increase the use of synthetic fuels, like a mandatory blending quota in jet fuel. Because the synthetic fuels look so much like their fossil counterparts, it is possible to 'blend in' synthetic fuels in conventional fuels and thus fly on a combination of fossil en synthetic fuels. A compulsory blending quota would directly increase the demand for synthetic fuels, making investing more interesting, which would increase the opportunity for more rapid development en efficiency wins due to scale advantages [74]. The blending quota could go hand in hand with green certificates, another legal option to incentivize the use of synthetic fuels. This would entail the possibility of buying certificates of using synthetic fuels without requiring the holder of the certificate to use the synthetic fuels himself. This would decrease the logistic challenges of transporting the fuels to end-users and potentially decrease costs.

4.8 SWOT-analysis

PESTEL and SWOT analyses are tools that are extensively used to analyze the context of a system. Firstly, PESTEL-analysis helps to consider all internal and external factors in the macro-economic environment that could influence the system within the scope of the research. Consequently, the SWOT analysis interprets the factor from the PESTEL analysis and categorizes them. SWOT makes a distinction between internal and external factors with a positive or negative impact. This way, SWOT analysis divides the factors into 4 categories, Strengths, Weaknesses, Opportunities and Threats. The combination of SWOT/PESTEL analysis is often used to identify factors that can be set as criteria in further analysis [80].

	Positive	Negative
Internal	**Strengths** Proven technology Low emissions	**Weakness** High Capex High energy use & costs
External	**Opportunities** Pricing instruments Fuel combustion laws New technologies Technological innovation Increasing environmental concerns	**Threats** Scarcity of materials Oil price volatility Growing demand for fuels Regulatory uncertainty

Table 3: SWOT-analysis of the synthetic fuel system context

The SWOT analysis is a compact way of interpreting the PESTEL-factors. As expected, *Table 3* shows that the majority of the factors is external, which creates a high level of uncertainty. Visualizing the PESTEL-factors like this helps to construct scenarios for the future.

4.9 Conclusions: an overview of the critical uncertainties

In *Figure 13*, the discussed PESTEL-factors are visualized in a PESTEL-impact map. All discussed factors are classified as low, medium or high impact. When looking at the factors with the highest impact, there are two categories. Firstly, climate change and the environmental concerns about it. These environmental and social factors drive increasing awareness and international cooperation like the Paris Agreement. The other high factors are related to the feedstock prices of synthetic fuels, the feedstock prices of fossil fuels and the carbon price. As low cost-competitiveness is the main argument against starting large scale synthetic production right now, these factors are really important. The uncertainty of these prices and their development in the future is of critical importance for the chances of success and the time frame in which production and distribution are possible. The classification is based on the observed literature and is discussed in the previous subsections. The high impact factors were consistently considered essential by scholars. The low impact factors were less frequently named and considered important but not vital.

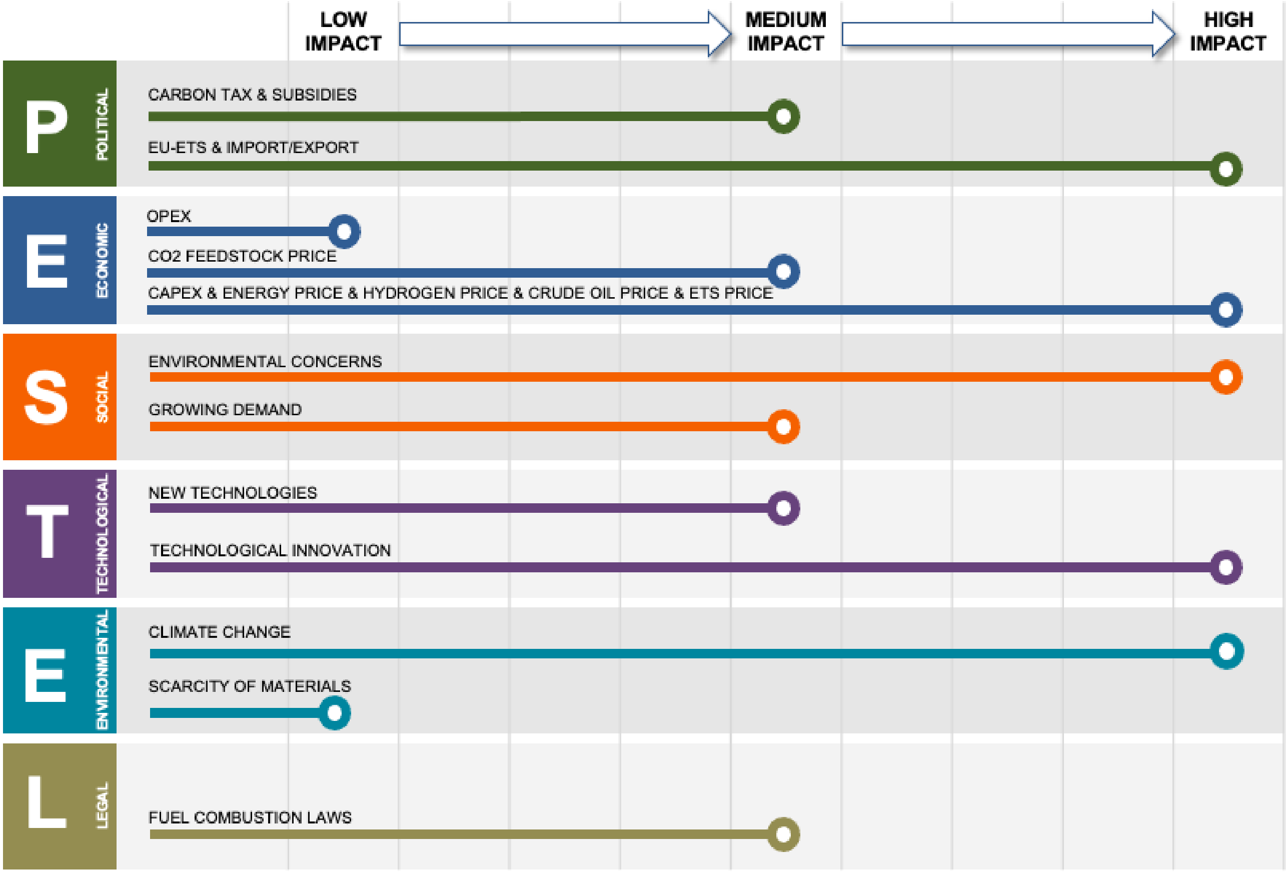


Figure 13: PESTEL Impact Map. Own composition based on literature by Van Kranenburg [3], Schemme [23], Tremel [21], Schmidt [49], Ausfelder & Wageman [64], Brynolf [4], Dimitrou [22] and the IEA [48].

In the next phase of the research, the model set-up and the experiments will focus as much as possible on measuring the factors with the highest impact. Climate change and environmental awareness are considered to have a more indirect impact. They are the reason why the possibility of producing expensive synthetic fuels is seen as a possibility in the first place. Similarly, other factors interact with each other as well. A growing demand could lead to an increase in the oil price, and environmental concerns could lead to stricter political sanctions. The experiments aim to show how the prices of fossil fuels and synthetic fuels could develop in the future.

5

Modelling

This section presents the linear optimization model that was constructed in Linny-R. The model is built to assess the impact of PESTEL-factors on the fabrication of synthetic fuels and create valuable insights into the overall dynamics of the system. This chapter aims to provide the reader with an understanding of how the model was built, which assumptions were made in the process and how the results are produced. The model is constructed to fulfil the following sub-answer:

3. Devise a model to add quantitative insights to the synthetic fuel system analysis.

In section 5.1, a general explanation will be given on Linny-R and the definitions of the different 'building blocks' used in the model. Section 5.2 provides the reader with an elaborate description of the model in three parts: synthetic fuel production, synthetic fuels versus fossil fuels and an example of a cluster, where the model zooms in on a specific process. Section 5.3 contains an overview of the data that was used for the model and what sources were used to find the data. Section 5.4 includes a verification of the model.

5.1 Linny-R

Linny-R is an executable graphical specification language for (mixed integer) linear programming [81]. In this research, Linny-R is used to make a model of the simplified supply chain system of synthetic kerosene production via Fischer-Tropsch synthesis. The oval shapes represent products, where the rectangles represent processes. By linking the processes and products with each other, a supply chain is created. The links represent the rate between a product and a process. For example, the production of 1 ton of hydrogen needs 1.17 MWh of electricity [42]. The double-edged squares represent clusters. These clusters represent a subsystem of products and processes and are essential for the overview to remain clear. In later sections, they will be further discussed. The ovals with a dotted line represent data products. These are used only by the author to read out information on the values and prices of important products.

Linny-R is a cost optimization model. This means that when the model is run, Linny-R will automatically choose the pathway with the highest accumulated cash flow. For example, Linny-R will always 'use' or choose blue hydrogen if that is cheaper than green hydrogen, provided there are no limitations on the amount of blue hydrogen that can be produced. The linear model will obviously lead to some simplification of the real, often non-linear, relations between processes and products in the cluster. But it is still expected that the model represents the real dynamics of the system and will serve as a valuable tool for exploring the synthetic fuel supply chain and the impact of the most important factors.

5.2 Model Description

This section aims to describe the system that is designed with the linear optimization model and the functionalities of the model. The designed model is a simplified representation of the synthetic fuel supply chain in the Port of Rotterdam. To give a clear description of the model, the model will be explained in three steps. The first step represents the production of synthetic kerosene, from the feedstock to the Fischer-Tropsch synthesis. This part is visible in *Figure 14*. Then, the description zooms in on a part of the process. Thirdly, the description will zoom in on a cluster to show how the model uses these deeper layers. Lastly, the right part of the model will be shown as this shows the comparison of synthetic and fossil kerosene. The main goal of the description is to elaborate on how the model is designed. However, Linny-R is a visually appealing program, and the description also provides the reader with a systematic overview of the synthetic fuel supply chain.

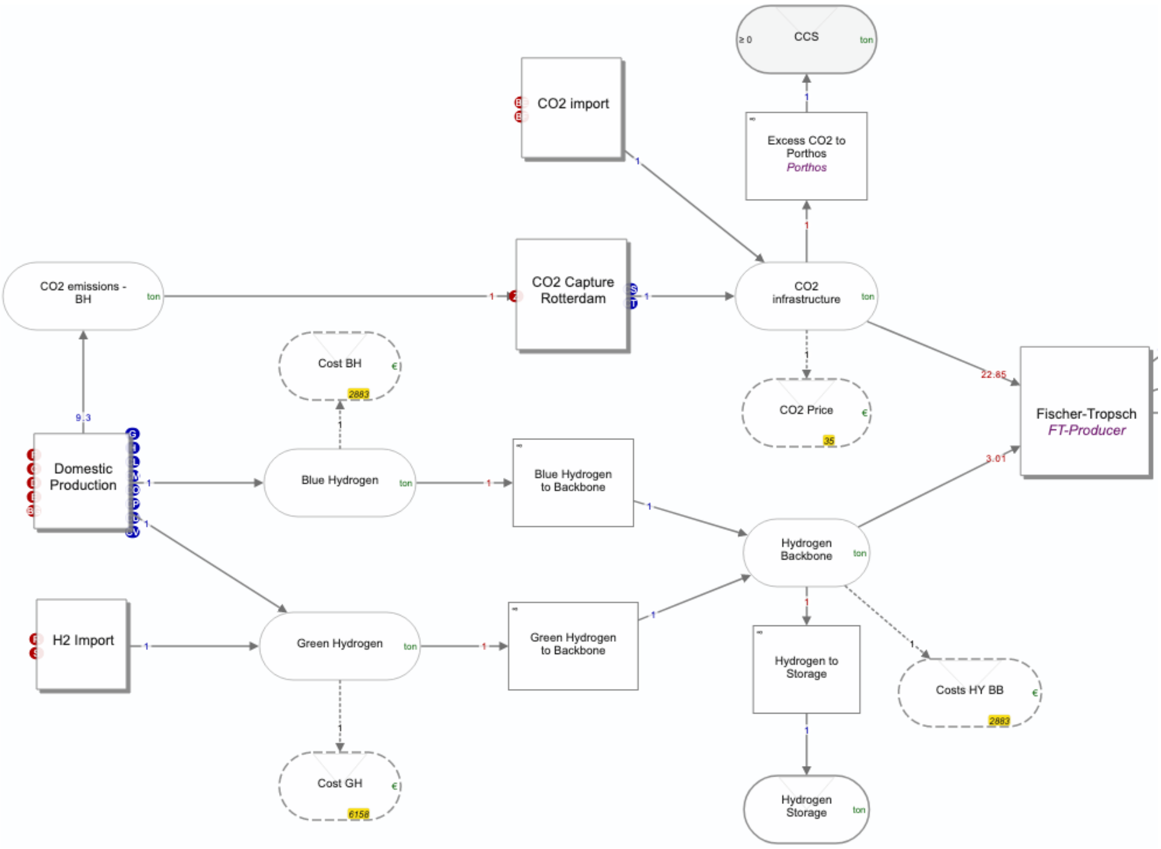


Figure 14: Linny-R model: Synfuel Production

Figure 14 represents the 'left side' of the model. The most important products that are needed for the Fischer-Tropsch synthesis are hydrogen en CO2. These two feedstocks are represented in the CO2 infrastructure and the hydrogen infrastructure. As grey hydrogen was left out of scope due to environmental reasons, the hydrogen used for synthetic fuel production is either blue or green. As can be seen in the model, both types of hydrogen are locally produced (Cluster Domestic Production), while importing green hydrogen is also possible. Hydrogen that is not used by the Fischer-Tropsch synthesis is stored in the hydrogen storage. This hydrogen storage represents all other hydrogen demand for the Port of Rotterdam, which is out of the scope of this research but could include hydrogen for hydrogen cars, hydrogen to be transported for use in Germany, hydrogen for heating and hydrogen for other chemical applications.

As can be seen in the model, there is some emission of CO2 in domestic production, which is a result of the fact that only 90% of CO2 can be captured during the production of blue hydrogen. In the cluster 'CO2 Capture Rotterdam', other CO2 point sources can deliver CO2 to the CO2 infrastructure. CO2 import is not yet common practice. However, this could become common practice, especially in combination with storage (PORTHOS). The import of CO2 could, in the long-term, also lead to the essential availability of CO2 for synthetic fuel production. It will be interesting to see if the import of CO2 can positively impact the business case for synthetic fuels. The cluster 'CO2 Capture Rotterdam' also includes payments due to carbon pricing instruments like the EU-ETS and the carbon tax that has to be paid for emissions. These payments add up to the price of blue hydrogen, although the capture rate of 90% prevents it from having a really high impact. Similar to hydrogen storage, the CCS represents all other demands for CO2. This means that the model assumes that the CO2 that is not needed for the production of synthetic fuels will be processed by PORTHOS and stored underground. This also means that other options for CO2 use are not included in the model but could include CO2 for greenhouses or CO2 for other CCU applications discussed in section 1.2, like enhanced oil recovery or chemicals.

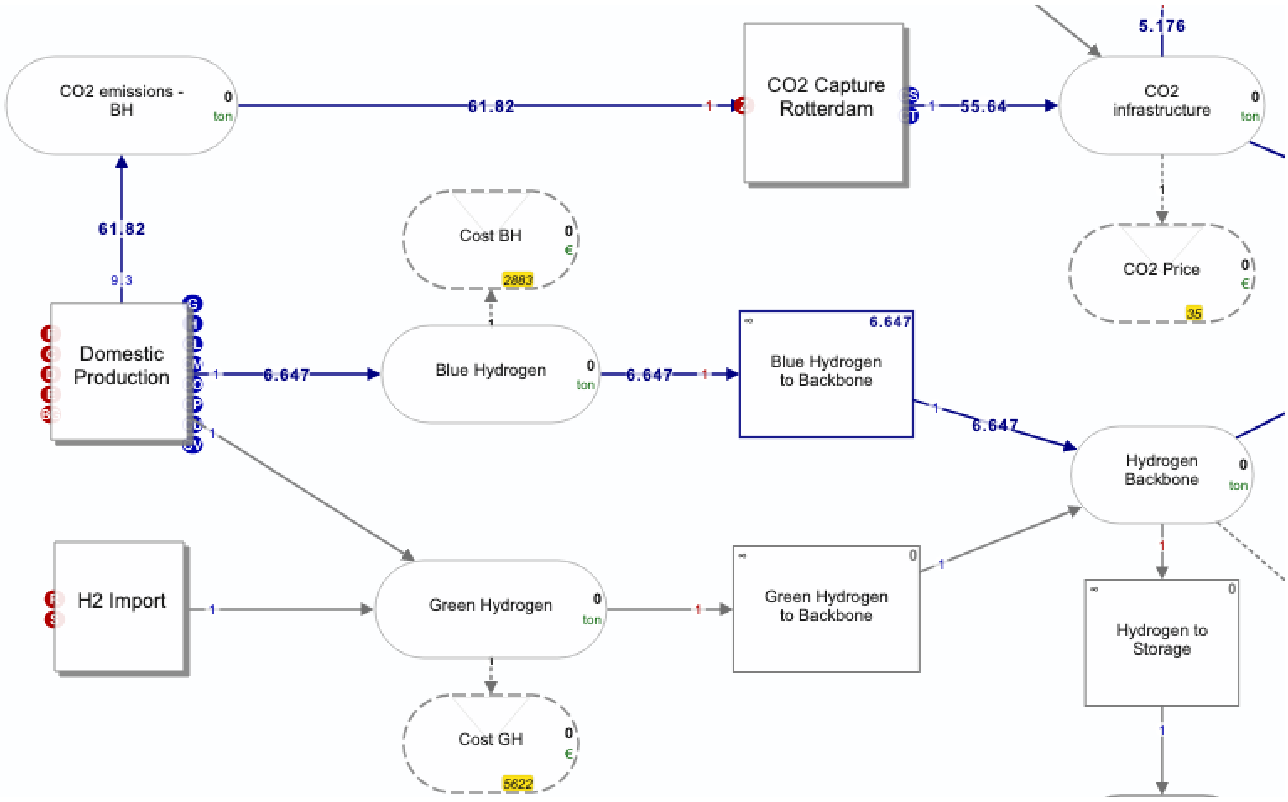


Figure 15: Linny-R model: Blue Hydrogen Production Vs Green Hydrogen Production

Figure 15 is meant to give the reader an idea about what happens when the model is run. In this specific case, the model chooses to use blue hydrogen, as its price is almost twice as low as the price of green hydrogen. The prices of both feedstocks can be seen in the data-products 'Cost BH' and 'Cost GH'. By varying the set-up variables identified through PESTEL-analysis, the conditions change, allowing the user to experiment and look under which conditions green hydrogen could become the preferable option. These set-up variables include the electricity price, the gas price for blue hydrogen, and the processes' Capex. When green hydrogen is cheaper, the model will automatically stop using blue hydrogen, and switch to green hydrogen as the preferred feedstock.

5.2.1 Clusters

Figure 16 is an example of a cluster in the model, in this case representing the domestic production of green and blue hydrogen. The cluster entails the SMR and electrolysis processes to produce the different colours of hydrogen. Somewhat simplified, the main inputs are visible on the left. As explained, the inputs all have a price and an input rate. These are represented by the yellow numbers in the product (price) and the red numbers on the link (rate). Next to energy and gas costs, the processes have specific Capex and Opex, represented by the negative black prices. A detailed explanation of how these costs have been calculated will be given in section 7.2. On the right side, the products and by-products are visualized. For example, there are 8 tons of oxygen as a by-product for every ton of hydrogen produced. For every ton of blue hydrogen produced, there would be 9.3 tonnes of CO2 emitted without capture. After capture, only 10% of the emissions remain, making blue hydrogen a low-carbon alternative. Representing the domestic production and other processes in clusters allows the main model to stay visually appealing and clear. The model also uses clusters for fossil fuel production, the CO2 capture in Rotterdam and more processes.

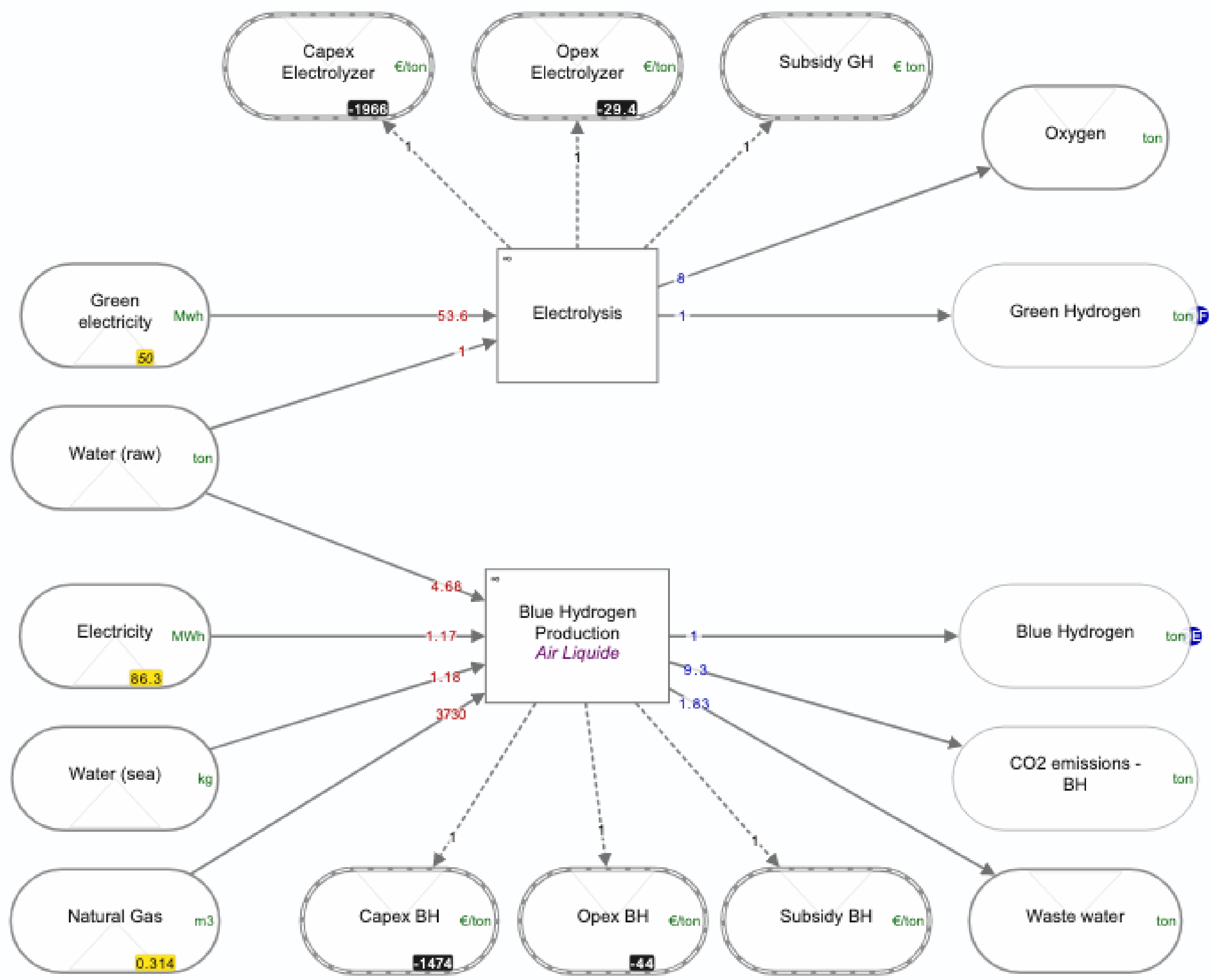


Figure 16: Linny-R model: Cluster of the domestic production of green hydrogen and blue hydrogen

5.2.2 Fossil vs Synthetic Kerosene

Figure 17 represents the 'right side' of the model. In this section, the model shows the inputs, production levels and prices of synthetic kerosene and fossil kerosene. This is the part with the cluster for fossil fuel production, as the price development of fossil fuels is very important in the comparison between synthetic fuels and fossil fuels. It was insufficient to only model the synthetic fuel production, because the model had to be able to take into account carbon pricing instruments like the EU-ETS and the Carbon Tax. Also, based on the PESTEL-analysis, the crude oil price is expected to impact the fossil fuel price significantly. If the model would run without any constraints, except for a certain 'Total Demand Kerosene', the model would choose between the fossil or the synthetic fuel pathway, that way showing which is the cheapest option. At default (current) conditions this is, of course, the fossil fuel pathway.

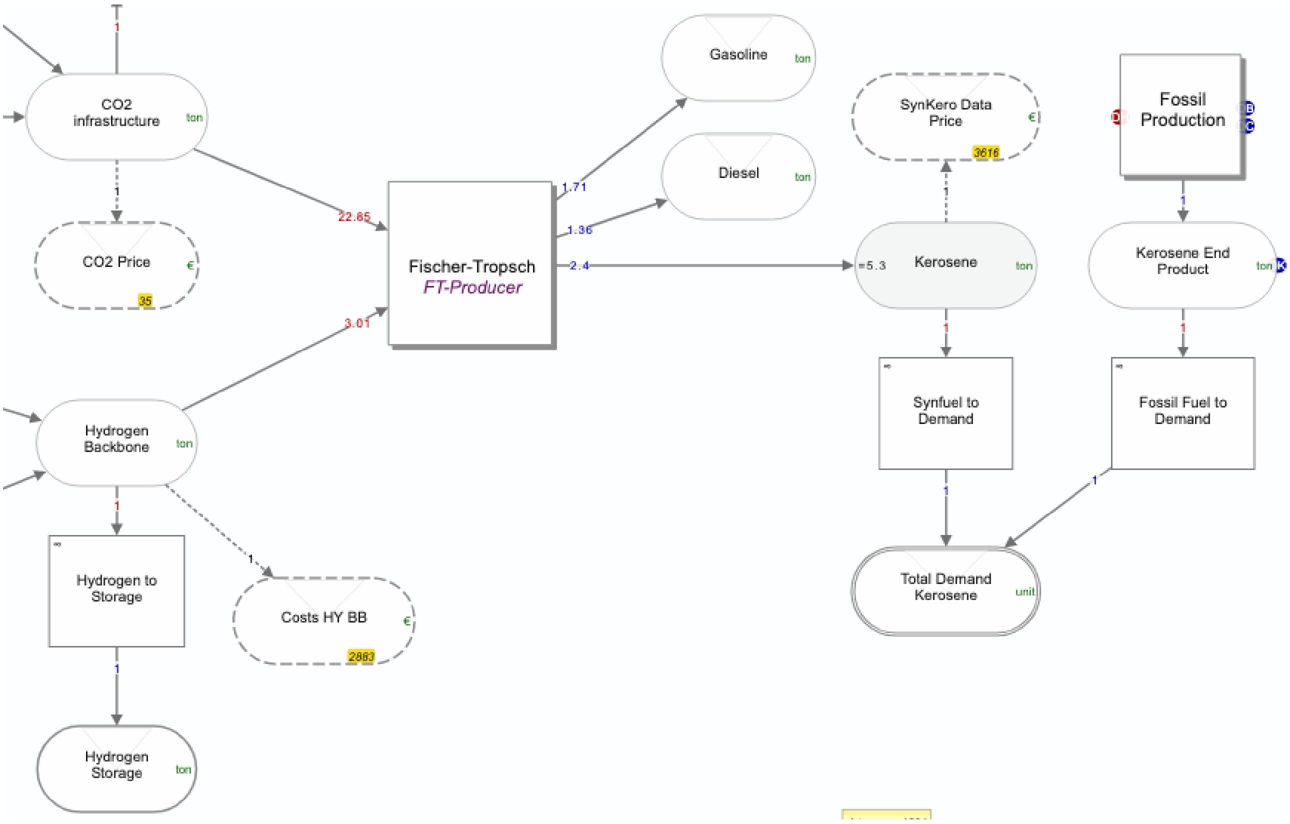


Figure 17: Linny-R model: Synthetic kerosene and fossil kerosene to demand

5.2.3 Integrated approach

The system is modelled using an integrated approach. As can be seen in the model screen shots and the clusters, the model looks at multiple outputs. For example, the effect of using green hydrogen over blue hydrogen has multiple effects. Firstly, the price of hydrogen for synthetic fuel production will change, depending on the price and availability of renewable energy. But this also has an impact on the CO2 emissions, which will be lower with green hydrogen. On a more macro-economic level, this would also mean that the demand for CO2 storage will decrease and the demand for renewable energy will further increase. Linny-R is very useful to present the interdependencies of the system as a whole.

5.3 Model Set-up

In this section, a short overview will be given on the input parameters and their default value. Only the inputs with a price have been included. For that reason is seawater, for example, that is used for the cooling part of the blue hydrogen production process excluded from the table. In the additional columns, the process that is affected by the input variable, the default value of the variable and the source are shown. The overview is given by *Table 4*:

Input Variable	*Process*	*Default Value*	*Source*
Green Electricity	Electrolysis	50 €/MWh	[4]
Capex Electrolysis	Electrolysis	1966 €/ton	Own calculations (Section 7.2.2)
Opex Electrolysis	Electrolysis	29.4 €/ton	Own calculations (Section 7.2.2)
Capex Blue Hydrogen Production	Blue Hydrogen Production	1474 €/ton	Own calculations (Section 7.2.2)
Opex Blue Hydrogen Production	Blue Hydrogen Production	44 €/ton	Own calculations (Section 7.2.2)
Natural Gas	Blue Hydrogen Production	0.314 €/m3	[82]
Grid Electricity	Blue Hydrogen Production	86.30 €/MWh	[83]
Captured CO2	CCS ⇒ CO2 infrastructure	35 €/ton	[84] [4]
ETS Payments	CO2 Payments BH	50 €/ton	[75]
Carbon Tax	CO2 Payments BH	0 €/ton	[85]
Crude Oil	Refinery	72 €/barrel	[86]
ETS Payments	CO2 Payments Kerosene	50 €/ton	[75]
Carbon Tax	CO2 Payments Kerosene	0 €/ton	[85]

Table 4: Model Set-Up: An Overview

The set-up variables also represent the most important factors that were identified from the PESTEL-analysis. By incorporating them into the model as input, the model can be used to see the dynamics of changing them individually or together. When looking at the impact of these variables, the author looked at their impact on the decision variables. These were the CO2 emissions, the price of hydrogen and most importantly, the price of synthetic fuels and the price of fossil fuels.

5.4 Model Verification

Section 6.2 and 6.3 have presented a description of the model and the model set-up values. In designing and constructing the model, a considerable amount of steps are taken, which allows for the possibility of errors. To mitigate this risk of error, it is important to verify the model to ensure the model works as expected. Since the model can't be compared to a benchmark model (there are very few Linny-R models available online, and zero that with the same subject or scope), the model verification will be done in multiple steps. By doing the verification in steps, the separate model components with a known relation between input and output are tested individually. To do this, multiple verification methods were applied [87].

Balance Checks
Balance checks are done by performing simple or isolated calculations of variables and then checking them against model values.

Structured walk-throughs
The model is methodically inspected by following all input variables through the processes and calculation steps to the end-products by doing structured walk-throughs.

Extreme conditions
The model is tested by creating extreme conditions and evaluating the models' behaviour and performance.

Balance Checks
By doing balance checks, simple calculations are done with isolated parts of the model and benchmarked against the model values. While there could be small rounding errors, a significant difference between the values indicates model inaccuracies.

Balance Check	Description	Verified
Green Hydrogen	Green Hydrogen Price is within current industry standards	✓
Blue Hydrogen	Blue Hydrogen Price is within current industry standards	✓
Fossil Kerosene	Fossil Kerosene Price is within current industry standards	✓
Green Hydrogen	Green Hydrogen Price matches the sum of the feedstock prices times their respective rate	✓
Blue Hydrogen	Blue Hydrogen Price matches the sum of the feedstock prices times their respective rate	✓
Fossil Kerosene	Fossil Kerosene Hydrogen Price matches the sum of the feedstock prices times their respective rate	✓
Emission Costs	Price Difference for fossil fuels matches the set emission costs	✓

Table 5: Model Verification: Balance checks

During the balance checks, no unexpected values were found by testing the main feedstock products of the model. The carbon pricing policy measures also have the expected effect on carbon-emitting products.

Structured walk-throughs
During the structured walk-throughs, each pathway in the model is inspected by following the production streams from the input to the end-product. For example, attention was given to the choice the model made whether to use blue or green hydrogen, dependent on the price. Similarly, the impact of import was reviewed and the models' choice between synthetic and fossil fuels. The data products that show the prices, but don't have any other function for the model, helped a lot for the model verification.

Extreme conditions

By setting extreme conditions in the model, the robustness of the model is reviewed. *Table 5* shows the lower and higher bounds that were chosen set for the model parameters. Feedstock prices were decreased and increased by 80%, and the capital costs were set to zero and doubled. The carbon pricing instruments were set to their negative default value, so the fossil fuels actually would become cheaper and doubled. For all extreme conditions, the model behaved as expected.

Input Variable	Lower Bound	Upper Bound	Verified
Green Electricity, Grid Electricity, Crude Oil, Natural Gas	-80%	+80%	✓
Capex & Opex	0€	Double Default Value	✓
Pricing instruments	Negative Default Value	Double Default Value	✓

Table 6: Model Verification: Extreme Conditions

Logical interpretation of results

Lastly, the flows and results of the model were tested against the logic of the author. By doing so, unclear results can potentially be noted. Testing against the logic of the author allows for significant bias, But it is an uncomplicated opportunity to challenge the results of the model. None of the results that were found deviated from logic, and in combination with the before-mentioned verification methods, the model verification is considered to be successfully completed.

6

Experiments

In this section, the results of the Linny-R experiments will be presented with a short description. Subsequently, the results will be discussed more in-depth in Chapter 7: Discussion. The objective of the experiments and their results is to give the reader relevant insights into the dynamics of the synthetic fuel system of the Port of Rotterdam by focusing on the fourth sub-question:

> *4. Translate the critical uncertainties into scenarios and analyze the model results.*

In other words, variation of which important factors will have the most impact, which 'buttons' can and need to be pressed to increase the competitiveness of synthetic fuels and is this possible within realistic scenarios? The goal is to identify the future driving forces in the broad business environment.

Firstly, the research will explore the range of future fossil kerosene prices to know what price synthetic fuels have to compete with. Then, the research will focus on adding quantitative insights to the PESTEL-analysis by looking at the impact of the identified factors and visualizing the results based on different scenarios. Other factors will be measured with a sensitivity analysis. The scenarios will give multiple possible synthetic fuel prices, which will be compared to the fossil fuels prices to conclude their potential competitiveness. Subsequently, the research will do two more experiments. Firstly, the impact of large-scale hydrogen import will be included. Secondly, the production of synthetic fuels in a different country, with more favourable conditions, will be reviewed and compared to domestic production.

6.1 Fossil Kerosene Price

In this section, the future price of fossil kerosene will be explored in order to examine the prices that synthetic fuels might have to compete with. At the moment, modern airplanes use kerosene and emit CO2 as they burn the kerosene for flying. The predictions are that in 2050, the kerosene used for aviation will be doubled compared to 2017. As electric planes are expected to deliver insufficient range and capacity, other alternatives for fossil kerosene have to be found. The main challenge is that those alternatives are not yet priced competitive. The cost drivers of synthetic fuels production are essential to understand for synthetic fuels to compete with fossil fuels. But equally important for the competitiveness of synthetic fuels is the price of fossil fuels and other alternatives.

The two main cost drivers of fossil kerosene in the future are the price of crude oil and the price of emitting carbon. It will be assumed that these drivers make up the fossil kerosene price together. Scenarios for both factors will be combined to generate 9 configurations, which will give 9 different fossil kerosene prices. As the scenarios represent extreme situations, the prices will represent the complete possible range for fossil kerosene. The current fossil kerosene price is around 900 €/tonne.

6.1.1 Oil Price

The most important cost driver of the kerosene price is the price of crude oil. This is a factor with high uncertainty and a big impact, and the price is very volatile. In the last 10 years, the price has been as low as 17€ per barrel and as high as 110€ per barrel. To show the impact of this volatility, three scenarios were constructed, including extreme values for the crude oil price.

Scenario 1: Oil Price Crash
The historical prices are not necessarily representative of future oil prices. Especially because the lower bound value is a result of the Covid-19 pandemic. However, fuel prices do fluctuate a lot and prices as low as 30€ are not very uncommon. The OPEC countries, for example, created an artificially low oil price to compete with US shale oil producers. They increased supply to increase their market share and cause problems for shale oil production. In the lower bound scenario, an oil price of 30€ per barrel will be assumed.

Scenario 2: Oil Price Medium
This scenario will function as a base scenario for the oil price to see what effect the carbon pricing instruments will have on the fossil kerosene price under standard conditions. At the moment, the price sits somewhere between the lower and upper bounds at 72€ per barrel. This base scenario will use the current price.

Scenario 3: Oil Price Surge
In this scenario, it will be assumed that either geopolitical tensions between OPEC and other countries or a high demand increase are causing the oil price to increase substantially. As discussed in the PESTEL-analysis, the uncertainty and volatility of the oil price are high. Considering the wide range of crude oil prices over the last 10 years, this scenario will assume an oil price surge to a price of 100€ per barrel.

High oil prices are often the result of high demand, low supply, OPEC quota, or decreasing dollar value [71]. Especially the OPEC quote stands out, as other products are affected by the other factors as well. The ability to produce oil is focused on just very few countries, causing them to control the oil price. Geopolitical tensions between, for example, the OPEC and the US or Russia could directly or indirectly cause the oil price to surge. For example, in 2013, the United States announced it would use airstrikes as retaliation against Assad for the use of chemical weapons. Anticipating disruptions in the region, the demand surged and caused the oil price to increase to as much as 100€ per barrel. In this upper bound scenario, a crude oil price of 100€ per barrel will be assumed.

6.1.2 Carbon Pricing Instruments

From the PESTEL-analysis, it is clear that there are possibilities to stimulate synthetic fuel production using pricing instruments like subsidy, the ETS and an additional carbon tax. From the model, it becomes clear that such policy instruments are essential for bringing the price of synthetic and fossil fuels closer together. When the price difference decreases, the purchasing of synthetic fuels will become much more appealing. Subsequently, scaling up production and investments will become more appealing as well. The following sections aim to provide insights into the effect of these policy measures. This experiment aims to show the effect of incorporating CCU in the ETS and looks at the efficiency of an additional carbon tax.

Scenario 1 & 2: CCU is recognized in the EU-ETS
Right now, the combustion of synthetic fuels costs the same amount of carbon tax as normal kerosene because CCU is not yet part of the European Union Emission Trading System. This is a significant threshold for synthetic fuels to become competitive with fossil fuels, as their potential to mitigate

negative climate effects is not rewarded. Over the last two years, the price has roughly varied between 20 and 50 €/tonne, with the latter being the recent price [75]. While this shows the price is increasing, it also shows the volatility of the carbon price and how dependent the price is on the proper issuing of certificates. According to scenarios of the European Commission, six potential pathways would lead to a price for EU-ETS allowances of 32-65 €/tonne. This research will use these prices for scenarios 1 and 2, which will present a low and a high ETS price to show the impact of synthetic fuels.

Scenario 3: High EU-ETS prices
The current price of 50€ was reached earlier than anticipated when the EU-ETS started. In 2014, the expectation was that the carbon price would need until 2030 to reach 50€ en would fluctuate around 10-20 in 2020. This shows that the prices are hard to predict. Also, more ambitious environmental targets could press the EU to reduce the number of allowances to increase the price. Scenario 3 will assume a very high ETS allowance price of 200€.

6.1.3 Future Fossil Fuel Prices

Combining a high oil price with more expensive carbon taxing will inevitably lead to higher fossil fuel prices. It will be interesting to see how high the price will become because it will give an idea about the potential fossil fuel price range. The oil price scenarios and the Carbon Pricing scenarios are combined to see the full range of potential oil prices in the future. In the experiment manager of the model, the scenarios can be easily combined to give the synthetic fuel price of all possible combinations:

	Low ETS Price (32€/ton CO2)	High ETS Price (65€/ ton CO2)	Extreme ETS Price (200€/ ton CO2)
Oil Price Crash 30€/barrel	406	510	932
Oil Price Medium 72€/barrel	836	939	1362
Oil Price Surge 100€/barrel	1122	1226	1648

Table 7: Fossil Kerosene Prices for multiple scenario combinations

The table clearly shows how big the differences can be, as the difference is a factor 4 between the highest (406 €/ton) and lowest (1648 €/ton) fossil kerosene price. It is expected that when the oil price is low, the ETS price is low, or both are low, synthetic fuel will not be able to compete under any conditions. But when the conditions for fossil fuels are less favourable, and the EU-ETS can increase the prices of carbon emissions, synthetic fuels could become competitive in the future, under the right conditions.

6.1.4 Introduction of Carbon Tax

As shown in the PESTEL-analysis, a carbon tax that supplements the EU trading system is becoming more common, which leads to higher costs for emitters. There are different variations of a carbon tax. Sweden, for example, has the highest carbon tax in the world but exempts the parts of their industry that already part of the EU-ETS. In this scenario, the proposed carbon tax of the Dutch government will be leading. The idea of this carbon tax is to ensure a minimal carbon price in addition to the ETS. If the ETS price is higher than the carbon tax, no payments are required. When the ETS price is lower, the emitters are taxed the difference between the EU-ETS price and the national carbon tax.

The Dutch carbon tax is showed in *Figure 18*.

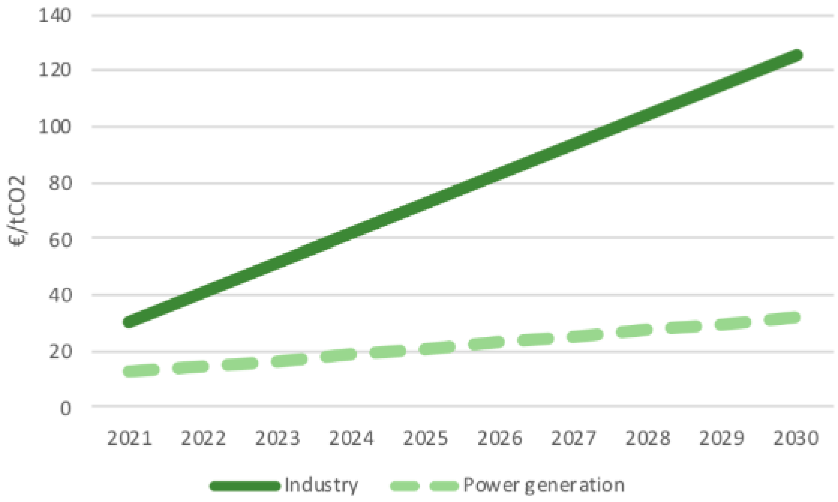


Figure 18: Development of Dutch Carbon Tax [85]

As can be seen in *Figure 18*, the minimal price for emitting carbon is gradually increased to 125€/ton CO2. This way, the Dutch government takes away uncertainty and hopes to stimulate investments in climate mitigating processes and products. To show the impact of this carbon tax, the fossil fuel price development is showed in *Figure 19*. For the carbon tax price, the 2030 price is assumed, just as in the other scenarios. This gives a price of 125€/ton CO2. This minimum price will decrease the uncertainty surrounding carbon payments, which will lead to a more stable investment climate.

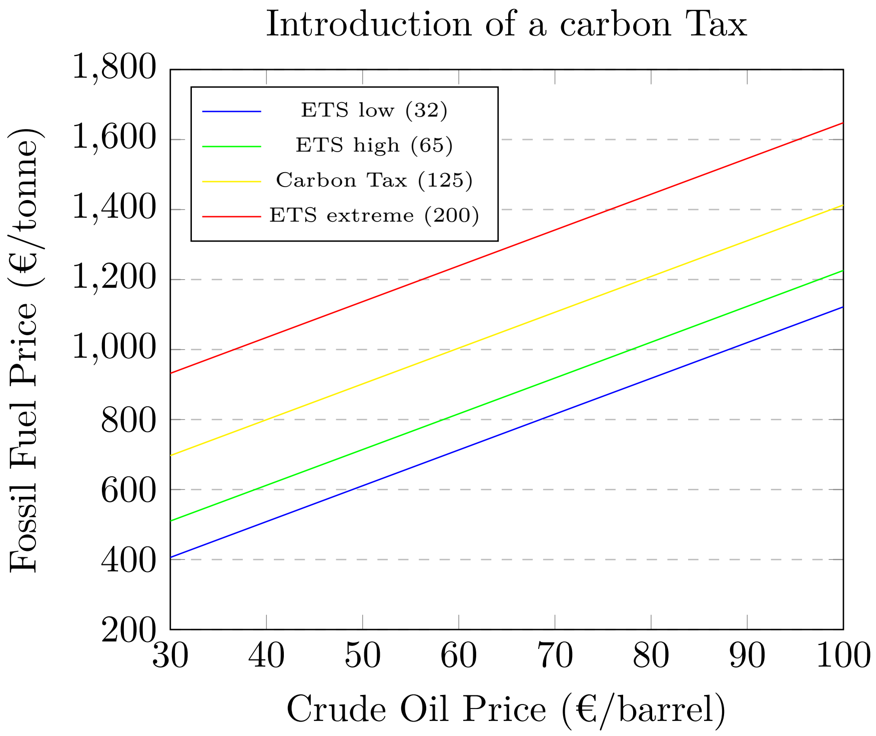


Figure 19: Introduction of a Carbon Tax

The main takeaway of this figure is that the price uncertainty without the carbon tax is between the blue en the red line. With the tax, the uncertainty is reduced to the price between the yellow and the red line. Policy measures like this would stimulate investments in synthetic fuels and accelerate production. Also, as mentioned before, the government can further decrease investment risks by offering subsidies. The government can impose taxes on unwanted processes, products or emissions; it can, of course, also stimulate desired products. The market position of synthetic fuels would be strengthened by government support in the form of subsidies, as they will decrease either the feedstock price or the synthetic fuel price, depending on which part of the supply chain is subsidized. In the next section, the impacts of critical factors on the synthetic fuel price will be reviewed under multiple scenarios. This will lead to a similar matrix of potential prices, which can be compared with each other. In the next section, the research will look at the synthetic fuel price.

6.2 Synthetic Kerosene Price

In this section, the impact of important factors on the synthetic fuel price is measured. All factors are derived from the PESTEL-analysis and using sensitivity analyses and scenario experiments. The research aims to provide valuable insights on the most important costs drivers of synthetic fuels the development of the synthetic fuel price in comparison to fossil fuel. As discussed in previous chapters and by multiple scholars, the electricity price has a huge influence on the price of synthetic fuels. The first experiments will focus on the impact of the energy price on the hydrogen feedstock and renewable energy availability. Then, the experiments will focus on trends regarding technological development and efficiency and if these innovations could make synthetic fuels more competitive.

6.2.1 Blue Hydrogen or Green Hydrogen

This first part of the experiment is focused on discovering the price differences between blue and green hydrogen. Green hydrogen is considered the preferable feedstock in the long term, as it is considered a carbon-neutral feedstock. However, blue hydrogen is expected to be more cost-competitive and more easily scalable in the short term. Blue hydrogen is expected to 'pave the way' for green hydrogen to start developing essential new industries and their infrastructures in the coming years. These include the chemical and synfuel industries that use hydrogen as a feedstock [88].

The first thing that the model shows is that the electricity price has to be really low for green hydrogen to become competitive with blue hydrogen if all other factors are considered to stay the same. The production is at full capacity. It is assumed that the electricity needed for the process is purchased from the grid for blue hydrogen, which leads to the average industrial electricity price in the Netherlands of 86€/MWh [83]. In combination with the costs for natural gas and capital expenditures, this electricity price leads to a price of a little less than 2900€/ton hydrogen.

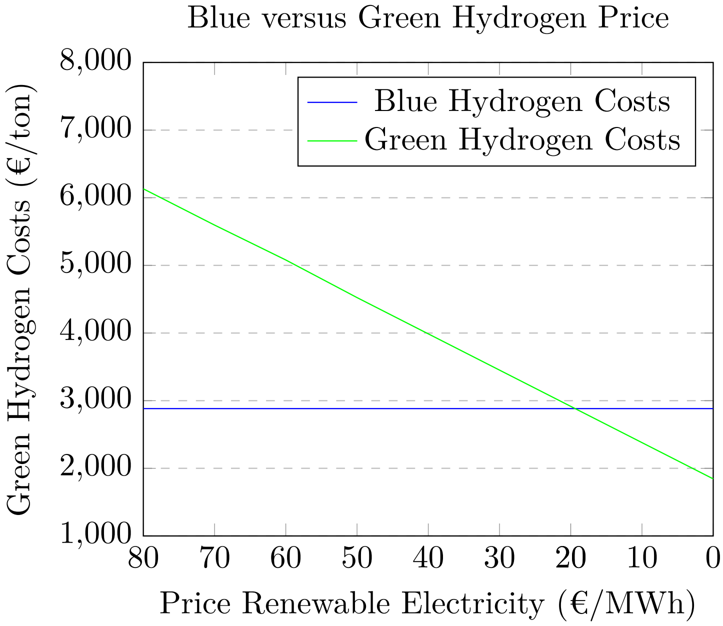


Figure 20: Blue vs Green Hydrogen Price (own composition)

The graph shows that with grid electricity prices for green hydrogen, the green hydrogen price would result in a price two to three times higher than blue hydrogen a little over 6000 €/ton hydrogen. This outcome is consistent with findings from other scholars [89]. In this experiment, the electricity price is varied between an upper bound of 80 €/MWh and a lower bound of 0 €/MWh to show the rapid decrease in costs for green hydrogen with decreasing energy costs. By varying the price of renewable energy for green hydrogen production and plotting the resulting green hydrogen price, the break-even point can be found for green and blue hydrogen. According to the model, this break-even point is at around 20 €/MWh, which is still significantly below the current industrial prices for electricity and expected prices in the future. This is consistent with the expectation that blue hydrogen will remain the cheaper option in the foreseeable future. In the next chapter, some policy scenarios are worked out to gain further insights into the policy and design options for the electricity price.

6.2.2 Energy Price

The main barrier for synthetic fuels to become the new fuel of choice is that the costs are too high. According to multiple scholars and discussed in the previous chapter, the electricity price is one of the main cost drivers for synthetic fuel. A huge part of the green hydrogen price depends on the price of renewable energy [64] [20] [26]. To look at the effect of a varying electricity price, an experiment was designed that uses multiple scenarios to develop the price for renewable energy [84]. The experiment aims to show the relation between the price and availability of renewable energy, as they result in varying capital costs and energy costs.

Scenario 1: Using electricity from the grid

In this scenario, the fuel producer uses grid electricity but has a contract with a renewable energy producer. The fuel producer can use no more electricity than the renewable energy installation produces [84]. If such contracts are absent, the hydrogen produced is not green, and the positive environmental impact of using electrolysis would be mitigated. This scenario results in a high capacity factor but also high energy prices. It is assumed that the electricity needed for the process is purchased from the grid, which leads to the average industrial electricity price in the Netherlands of 86€/MWh, equal to the electricity price for blue hydrogen [83].

Scenario 2: Using excess renewable energy
In the second scenario, it is assumed that only excess renewable energy is used for the green hydrogen production needed for synthetic fuels. One of the biggest problems of renewable energy is intermittency and the lack of good energy storage options. Power-to-X technologies can be seen as part of the solution, as they could use excess energy to produce products that contain energy, which is the case for synthetic fuels. There are multiple times every day when there is more electricity produced than what is needed. In this scenario, exactly that electricity is put to use and used for green hydrogen production, which is later used to produce synthetic fuels. It is assumed that the excess electricity is free of charge. This intermittency leads to a significant decrease of the capacity, to about 4 hours/day. This leads to a capacity factor of about 15%, which corresponds to about 1200 yearly operating hours [84].

Scenario 3: Using new renewable energy installations
The second scenario assumes that the synthetic fuel facility only uses energy from a new renewable energy source that is not connected to the grid and is built specifically to provide electricity for green hydrogen production, for example, an offshore wind park. These off-grid energy sources generate all the electricity that is used for synthetic fuel production. This will result in significantly lower electricity costs, as there are no distribution and transmission costs. In this scenario, it is assumed that the electricity costs are 50% lower than the electricity costs from the grid [84]. In this scenario, the wind energy capacity factor of the Netherlands is used, which is around 40%, corresponding with 3200 yearly operating hours [90].

Capex
To gain insights on the effects of the policy scenarios, it is essential to show the impact of the decreasing energy price and the decreasing capacity factor as a result of the policy scenarios. In the policy scenarios, the capacity factor decreases when the energy price decreases. The expectation is that the production costs are the lowest with low energy costs and a high capacity factor, which leads to low costs for the Capex per tonne hydrogen of the electrolyzer. Because of this, a trade-off will arise between lower energy costs and a higher capacity factor. To look at the direct impact of the capacity factor on the capital expenditures, calculations on the Capex have been made for the Capex per tonne of hydrogen. This way, the impact and the relation of the electricity price and the capital expenditures can be examined. Initially, the Capex per tonne hydrogen is calculated for full capacity (5000 operating hours) using data from the International Energy Agency [91]. The values in *Table 1* were used to calculate the Capex per tonne hydrogen:

Variables [91]	Value
Operational Hours	5000 [92]
Discount Rate	8%
Depreciation Time Electrolyzer	≈ 19 years [92] [91]
Current Capex (€/KWe)	900
Stack Lifetime (Operating Hours)	95000
Annual Opex (% of Capex)	1,5%
Conversion Rate (kWh / kg hydrogen)	33,6
Efficiency	64%
Discount Factor	0,463

Table 8: Input for Capex calculations

To accurately calculate the net present value (NPV) of an investment, it is necessary to determine the discount factor of the investment. To account for the value of future cash flows, the discount factor must be considered when calculating the Capex. This is the first step of being able to calculate the Capex. Using the data from the table, the discount factor can be calculated using:

$$\frac{1}{(1+DiscountRate)^{Depreciation}} \tag{1}$$

The discount factor can then be used to calculate the Capex. Other factors that increase the Capex/tonne are the Capex per kWe and the conversion rate. The conversion rate refers to the amount of electricity that is needed to produce 1 kilogram of hydrogen. A lower conversion rate means that less electricity is needed. Factors that decrease the Capex per tonne hydrogen are a high number of operational hours and a high efficiency. The operational hours are the result of the capacity factor. According to scholars, the yearly operating hours of an electrolyzer amount to about 5000 hours[92]. The efficiency refers to the ability of the electrolyzer to use electricity for hydrogen production with as low as possible losses. The Capex per tonne hydrogen is then calculated using the following formula:

$$Capex/tonne = \frac{Capex(kWe) * 1000 * DiscountFactor * ConversionRate}{OperationalHours * Efficiency} \tag{2}$$

Values from the three scenarios were used in the model using the equations, and the results are plotted in *Figure 21*. In the following sections, the relation between the electricity price, the electrolyzer Capex and the resulting synthetic fuel price will be discussed.

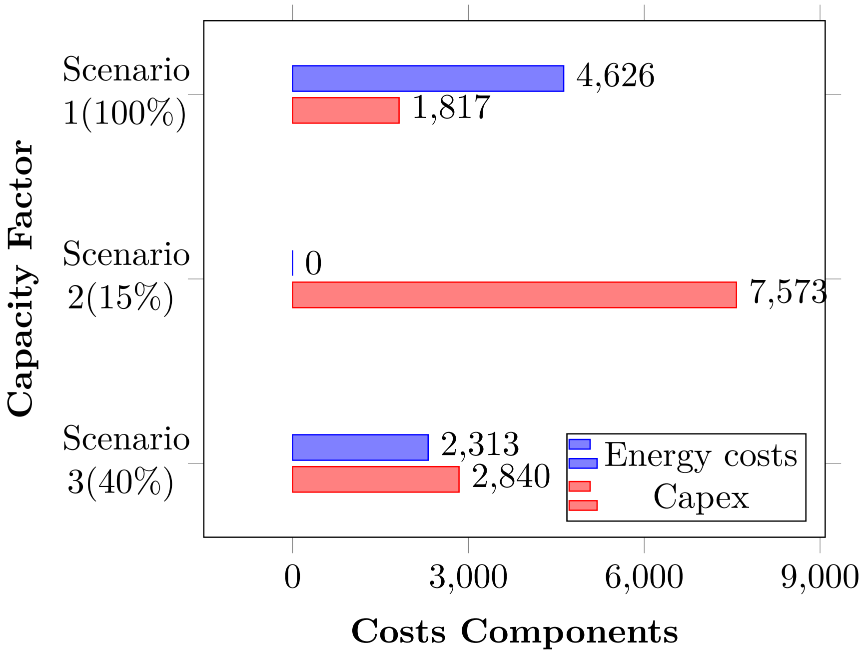


Figure 21: Trade-off between capacity and energy costs (own composition)

Figure 21 shows the Capex and electricity costs that are derived from the Linny-R model for the three policy scenarios. At full capacity of 100% (5000 operating hours), the Capex for the production amount to €1966/tonne. But, when when the capacity factor decreases, there is a very high increase in capital costs. What becomes very clear from the table is that the cost reduction from using only renewable excess energy is a trade-off that will highly increase the costs for hydrogen production. This is interesting because apparently, the production costs will increase by using only excess renewable energy. According to this experiment, the price reduction of green energy can not result in too much capacity loss. An even higher increase will counter its positive effect on the costs.

The figure shows that reducing the capacity factor to as low as 15% in scenario 2 will never be a viable option for hydrogen production. In the experiment, some cost reduction is achieved using the lower energy costs in scenario 3. If a capacity factor could be realized that is even a little higher than the assumption of 40%, it is an interesting alternative for the current situation. The main takeaway from this experiment is that it is essential to have high availability of renewable energy at a low price.

Analysis of the policy scenarios

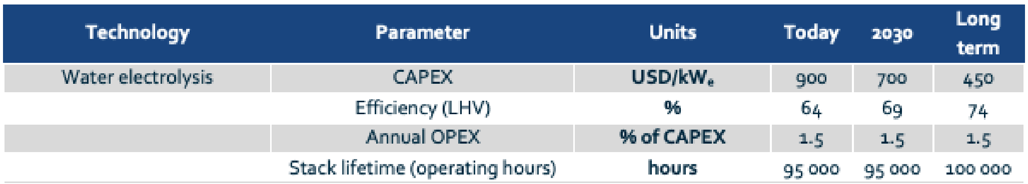
Scenario 1 could be regarded as a base scenario. The capacity factor is high due to the use of electricity from the grid for electrolysis. To ensure the hydrogen is green, renewable energy certificates have to be bought to ensure the energy used is indirectly green. This scenario, however, has the disadvantage that the costs of electricity are too high to be able to compete with blue hydrogen and eventually reach a price where synthetic fuels become more attractive.

Scenario 2 assumes that only electricity that would otherwise be unused or curtailed is used to produce synthetic fuels. This electricity is free of charge, but the disadvantage of this scenario is that the capacity factor is relatively low, increasing the electrolysis's capital costs. This scenario assumes that excess renewable energy will lead to a capacity factor of 15%, which will result in higher capital costs for the electrolyzer [84]. This becomes very clear in *Figure 21*, showing the complexity of the trade-off. An additional disadvantage of this low capacity factor could be that the hydrogen and fuel output are relatively low. This reduces the opportunities for a return on investment and reduces the opportunities for policy support, such as premiums per ton green hydrogen or litre of fuel. Potential valuable byproducts like oxygen are produced in lower quantities as well.

Scenario 3 assumes the use of off-grid renewable energy generation for the production of hydrogen. This decreases energy costs and increases the capacity factor in comparison to scenario 2. While the electrolyzer still can't operate at full capacity, the combination of a lower energy price (43€/ MWh) and a 40% capacity factor results in a lower total price for hydrogen production. The costs of building the renewable energy capacity such as the wind or solar park needed for this scenario are not considered in the results. The production costs, time and risks of this installation can not be neglected. However, a considerable amount of new renewable capacity is expected to be built for the purpose of producing hydrogen and other Power-to-X applications. Building renewable capacity specifically for hydrogen production seems to have the highest potential to result in cheap hydrogen. In the next sections, the impact of technological developments and efficiency gains will be discussed.

6.2.3 Technological Developments

The previous section shows that the current investment costs and energy costs result in prices where it is really hard to compete with fossil fuels. But from the PESTEL-analysis, it is clear that technological innovation could be a big driver to improve the future market position of synthetic fuels. In the following experiments, technological developments and related cost improvements will be incorporated into the model to gain insights into the potential of synthetic fuels to become more cost-competitive in the future. The International Energy Agency expects significant reductions for the capital costs of electrolyzers in the coming years due to technological developments and economies of scale. This will lead to significantly lower Capex in 2030 and 2050 (*Figure 22*).



Technology	Parameter	Units	Today	2030	Long term
Water electrolysis	CAPEX	USD/kW$_e$	900	700	450
	Efficiency (LHV)	%	64	69	74
	Annual OPEX	% of CAPEX	1.5	1.5	1.5
	Stack lifetime (operating hours)	hours	95 000	95 000	100 000

Figure 22: Decreasing capital costs for electrolysis, data from IEA [91]

These developments will hugely improve the potential for synthetic fuels to compete with their fossil counterparts, as they will lead to a significant reduction of costs, as can be seen in *Figure 23*. For every scenario and capacity factor, the cost reduction by 2050 will be far exceeding 50%. But it also shows the potential for 2030 if a high capacity can be combined with good renewable energy conditions that lead to cheap renewable energy prices. According to the results in *Figure 23*, the Capex costs could be reduced to as low as 1418 €/tonne by 2030. If this is combined with very low renewable energy prices, this could lead to a green hydrogen price below 3€ or even 2€, which is the order of magnitude where synthetic fuels have a chance to become competitive.

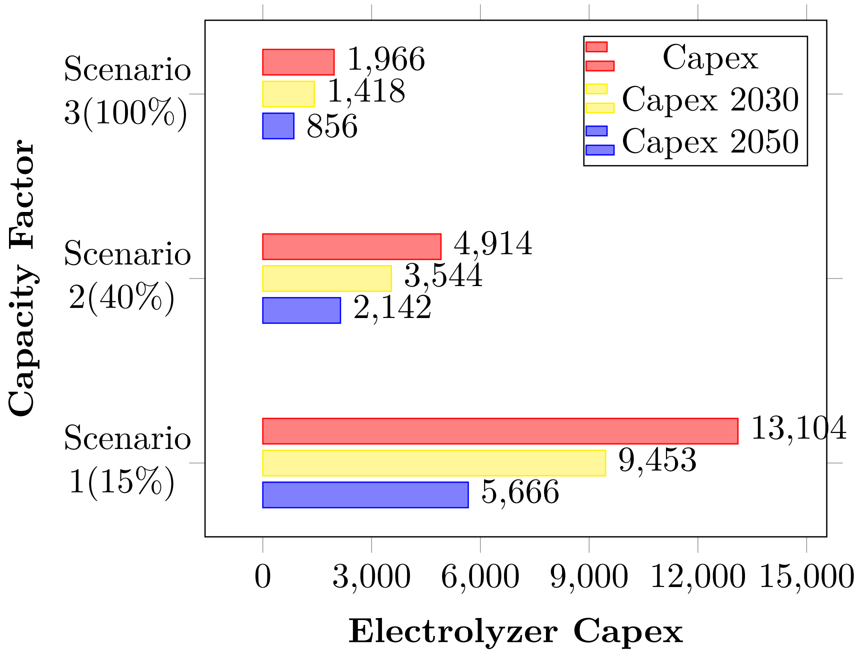


Figure 23: The impact of future decreases in Capital Costs (own composition)

Efficiency Gains

As can be seen in *Figure 22*, not only are the Capex decreasing, the electrolyzer efficiency is improving as well. It is interesting to see how big the contribution of efficiency gains is compared to the decreasing Capex/kWe, as the PESTEL-analysis showed that technological developments like increasing efficiencies could also reduce the synthetic fuel costs by reducing the costs of some technical parts of the supply chain. A sensitivity analysis was done to see the impact where the efficiency was varied between 60% and 80% as the current and future expected efficiencies fall within this range. The experiment assumes a capacity factor of 100% (Scenario 3) and will look at the cost dynamics for the current year, 2030 and 2050, with a variation in electrolyzer efficiency.

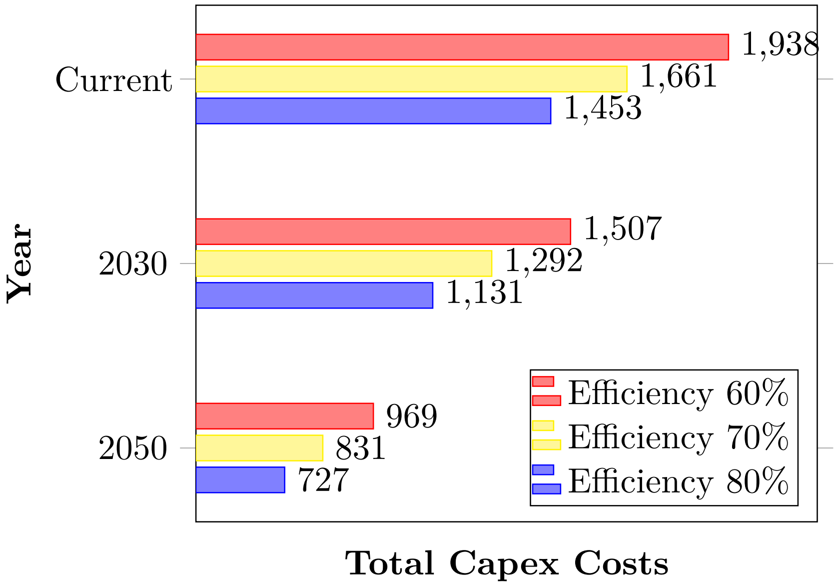


Figure 24: The impact of electrolyzer efficiency improvements (own composition)

Figure 24 shows that the differences are very significant. For 2030, the Capex reduction between efficiency of 60% and 80% is almost 25%. This is a very substantial costs reduction of over 400€ per tonne of hydrogen and could be the difference between being able to compete and needing a lot of government support to have a business case.

6.2.4 Fossil Kerosene vs Synthetic Kerosene

Using the Linny-R model, the development of the synthetic fuel price is visualized in *Figure 25* using Capex improvements and varying the renewable electricity price to see when the synthetic fuels can match their price with fossil kerosene. For reference, the current price for fossil kerosene is added as well.

As becomes clear from *Figure 25*, the costs of local production of synthetic fuel kerosene could be as low as 925€/tonne in 2050, in the most favourable conditions. This means that the expected reduction of Capex costs will indeed continue to decrease until 450 €/kWe (the costs are currently at 900 kWe), and the efficiencies will indeed improve as well. This also means that the electricity used for green hydrogen production is free and the electrolyzer can still run at full capacity. Although this sounds like a lot of improvement, other scholars even cite sources where cost reductions to 300kWe on a short-term (before 2030) could be realised [93]. Graré (2019) expects to reduce costs as low as 200 €/kWe by 2030 if the electrolyzers are built on a Gigawatt scale. This will most likely prove to be a little optimistic, but if those prices are indeed possible in the short term, the production of synthetic

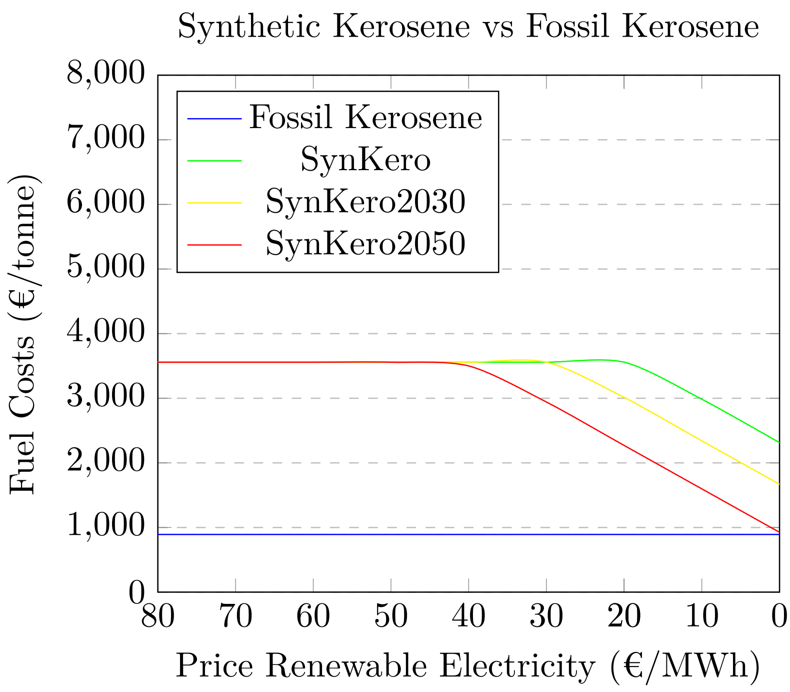


Figure 25: Synthetic Fuel Price Development (own composition)

fuels could surge sooner than expected.

Still, the results show that the price of synthetic fuels is still significantly higher than fossil fuels under the current conditions. Even with an energy price of 0 €/MWh, which is not realistic, the Capex costs are so high that synthetic fuels are significantly more expensive than their fossil equivalent. In the model, blue hydrogen is used when it is cheaper than green hydrogen, which explains the horizontal start of the price curve. With the assumptions used in the model, it seems that a combination of excellent conditions would still not lead to a synthetic fuel price that is close to their fossil fuel equivalent. The price gap looks too big to cover completely with government support like subsidies as well.

At the start of this chapter, the price range of fossil fuels was reviewed using scenarios for the oil price and the ETS price. In *Table 9*, the best scenario price for synthetic fuels will be compared to the potential synthetic fuel price in the future.

	Low ETS Price (32€/ton CO2)	High ETS Price (65€/ ton CO2)	Extreme ETS Price (200€/ ton CO2)
Oil Price Crash 30€/barrel	406	510	932
Oil Price Medium 72€/barrel	836	939	1362
Oil Price Surge 100€/barrel	1122	1226	1648

Table 9: Synthetic Kerosene vs Fossil Kerosene Price (2030)

In *Table 9*, the best-case scenario for 2030 is compared to the fossil fuel price scenario from section 6.1. When the price difference is within a 10% margin, the fossil scenario is coloured yellow. When synthetic fuels are cheaper, the scenario is coloured green, and when fossil fuel is cheaper, the scenario is coloured red. With the assumptions made in this research, in the scenario for 2030, the fossil fuel price is 1669 €/ton. As the table shows, even with no energy costs, the synthetic fuel price only comes close to the fossil fuel price in a very extreme scenario of really high ETS allowance prices and an oil price surge. The fact that there is still a price difference after all the technological improvements and pricing instruments shows the difficulty for synthetic fuels to become a major player within the aviation sector. The table shows that it is very difficult for synthetic fuels to compete with fossil fuels at a low oil price due to the minimal Capex and energy costs of green hydrogen production. With normal to high oil prices, the fossil fuel prices go towards a price of €1000 €/ton, but that is still substantially lower than the expected synthetic fuel prices, even under the best circumstances. The results show that synthetic fuels are very difficult to become competitive without higher prices for EU allowances. And even with a high EU-ETS price, the differences are small. In the best-case scenario for 2050, the optimal synthetic fuel price has dropped further to 925 €/tonne kerosene. In *Table 10*, the same comparison is made with this new price.

	Low ETS Price (32€/ton CO2)	High ETS Price (65€/ ton CO2)	Extreme ETS Price (200€/ ton CO2)
Oil Price Crash 30€/barrel	406	510	932
Oil Price Medium 72€/barrel	836	939	1362
Oil Price Surge 100€/barrel	1122	1226	1648

Table 10: Synthetic Kerosene vs Fossil Kerosene Price

In *Table 10*, the same price comparison is made as in *Table 9*, but now for 2050. Although the table looks promising, the comparison is made on the assumption of an energy price of 0€/MWh. As discussed, this is unrealistic in combination with maintaining a high capacity factor. This would most likely only be realistic for excess renewable energy like in scenario 2 and not consistently for full capacity. With more realistic energy prices, it will most likely remain very difficult for local synthetic fuel production to become competitive with fossil fuels. However, the table does visualize the major impact cost reductions have on the synthetic fuel price and the potential for synthetic fuels to become competitive in the future.

6.3 Import of green hydrogen

In the previous experiments, the impact of various factors on synthetic fuel costs were discussed and visualized. For example, high energy costs lead to high electrolysis process costs, which leads to high costs for the required hydrogen feedstock. The experiments showed that the hydrogen price could fall to the desired level in extreme scenarios. However, in realistic positive scenarios, the green hydrogen price is still around 3000 €/ton in 2030.

As was discussed in the PESTEL-analysis, the hydrogen market could be subject to change. Just as there are countries with a high volume of oil, gas or other natural resources, there are countries with very good conditions for renewable energy production, which increases the capacity factor and significantly decrease the price. This experiment looks at the impact of importing hydrogen from other parts of the world, as it is expected that hydrogen production could be much cheaper elsewhere. However, decentralized and foreign production would also mean additional transport costs, transport emissions and liquefaction costs, depending on the hydrogen carrier. This could make it equally hard to compete. In the following section, the research aims to add to the results by reviewing imported hydrogen from a location with very good conditions for renewable energy. It will be assumed that the Port of Rotterdam will import hydrogen from the Port of Sohar in Oman.

6.3.1 Port of Sohar

The choice for the Port of Sohar (PoS) in Oman was made for two reasons. Firstly, Oman has an abundance of renewable energy sources like solar and wind. This availability decreases electricity costs and provides an opportunity for installing large scale electrolyzers. Oman is part of the 'MENA' (Middle-East & North Africa) region. This region is known for very good wind and solar resources, allowing a high combined capacity factor, which is crucial to achieving very low green hydrogen prices [70]. Secondly, the Port of Rotterdam has a 50% stake in the Port of Sohar, making it a plausible hydrogen import/export relations location. The PoS even announced a 25GW hydrogen project in May 2021 [94]. Due to the favourable conditions, megaprojects like this beginning to take shape as the world is preparing for a significant increase in hydrogen demand. Due to these conditions, in combination with economies of scale, considerable hydrogen cost reductions are expected. For synthetic fuels to have a chance to become competitive, the hydrogen production must be large scale [70].

Hydrogen produced abroad has to be shipped to Rotterdam in the form of a hydrogen carrier. The most notable carriers are liquid hydrogen, LOHC (Liquid Organic Hydrogen Carriers) and ammonia. An example of such a LOHC is methyl-cyclohexane. The study of Lanphen (2019) reviewed the performance and costs from these carriers if exported to Rotterdam from countries with good renewable energy conditions [95]. The results of that study are shown in *Figure 26*:

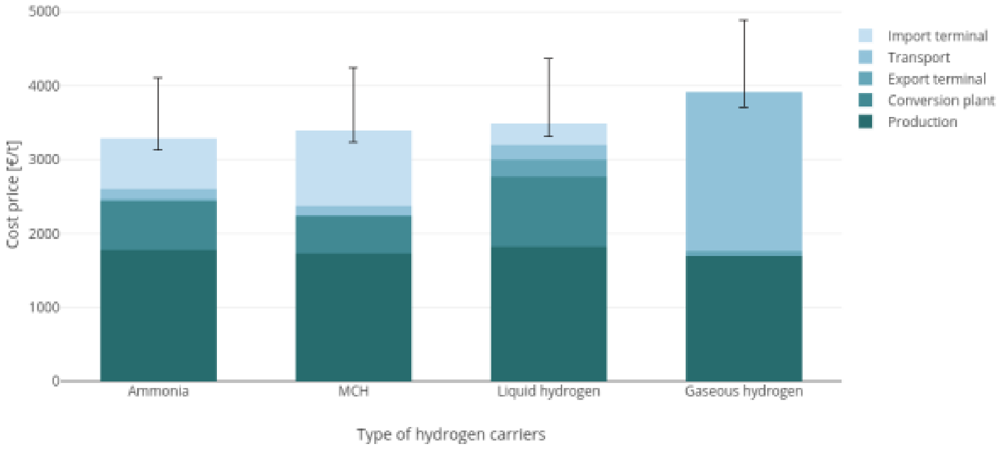


Figure 26: Costs of hydrogen import for multiple carriers [95]

All carriers have advantages and disadvantages. Without entering the discussion about which carrier will be the preferred carrier of the future, the results show that the expectation is that the production costs of the hydrogen itself will drop to less than 2000 €/tonne. However, adding transport and conversion costs shows that the price would become similar to the 3000 €/ton that the model estimated for local hydrogen production. Conversion costs are necessary because at ambient temperature and pressure, hydrogen is an explosive gas. That means it is transported either in a liquid shape, which is done by cooling or temporarily storing the hydrogen in another molecule. As countries often prefer to produce locally, which gives them some autonomy of the process and reduces shortage risks, it is not likely that this would be a preferred option.

It must be noted here that other studies show even more promising results. For example, the study of Roobeek (2020) also estimated the costs of hydrogen import, looking specifically at the costs of hydrogen transport between Oman and Rotterdam. This study found an even lower production price, combined with lower transport and conversion costs:

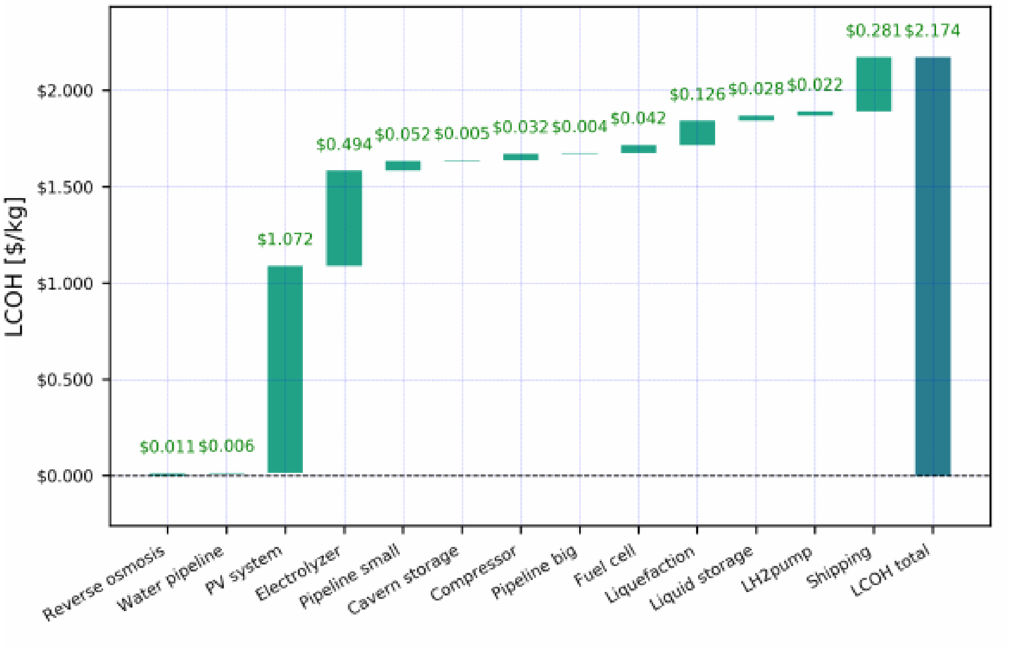


Figure 27: Levelized Cost of Hydrogen, transport from Oman to Rotterdam [96]

As *Figure 27* shows, the costs are considerably lower, at 1826 €/ton including transport and conversion (costs converted to euros). Without transport and conversion, the hydrogen production itself cost only 1315 €/tonne. These low value shows the importance of assumptions when looking the costs of importing and producing hydrogen. After reviewing the study of Roobeek, several assumptions were found that could be the basis of this lower price. For example, an electrolyzer Capex is found of 200 €/kWe, which is the lowest estimation that was found in any literature. As the impact of a low Capex has been extensively discussed in this research, this estimate greatly reduces the price. However, the costs of 200 €/kWe in 2030 are less than half of the costs projection of the International Energy Agency in 2050, which predict a cost reduction to 450 /kWe by 2050. Half the price, 20 years earlier than a renowned institution like the IEA, could be very optimistic. This example shows again how much is dependent on assumptions and how the critical cost drivers of synthetic fuels, like the Capex, will develop in the future.

6.4 Production Abroad

The previous experiment shows that when looking purely at the hydrogen production costs, a price of less than 2000/tonne could be possible for some countries in the MENA region. The superior conditions and potential scaling benefits lead to an unprecedentedly low hydrogen price. Based on the discussed results from the previous experiment, it is most likely that in the short term, imported hydrogen will not directly be significantly cheaper than locally produced hydrogen. Still, it will most likely become cheaper in the future.

A third option would be to incorporate the synthetic fuel system into the local industrial complex in the MENA region and then transport it to Rotterdam. Whether this is a better option than the local production of synthetic fuels mainly depends on two factors. Firstly, the ability of the MENA region to live up to the expectation in terms of cost reduction for green hydrogen production.

Secondly, synthetic fuels need to be transported to Rotterdam, which costs money and potentially causes transport emissions. Bensebaa et al. call the MENA region "a key area for a new start to a global deployment of hydrogen economy", highlighting the potential for synthetic fuels to compete with alternatives that are already more common, like fuel cell cars and biofuels [97]. The international collaboration responsible for the 25GW renewable energy project is already expecting the integration of green fuels in the project, preparing to export green hydrogen and 'green hydrogen derivatives' like synthetic fuels [98]. In the Middle East, large amounts of blue hydrogen and subsequent blue ammonia are being produced and transported. In research on the potential of sustainable energy production in the Middle East, the RVO calls synthetic fuels one of the solutions to large quantities of captured CO2 and acknowledges the potential of synthetic fuel as a mid-term option to decarbonize aviation. The availability of space, industry infrastructure, and most importantly, a high level of renewable energy availability will inevitably lead to a lower synthetic fuel price than local production in Rotterdam. One thing that is less easily available is biogenic CO2. If production abroad becomes a realistic option, the CO2 must be biogenic in order to maximise the positive environmental impact. If not enough is available, the import of biogenic CO2 could be an option. As discussed, the Fischer-Tropsch process is a proven concept and is already done in industrial areas worldwide. Although scaling up will require some investments, no investments in completely new infrastructure are needed because of the compatibility of synthetic fuels with the existing fossil fuel infrastructure. But, the synthetic fuels do have to be transported to Rotterdam as well. The main differences between production locations are the hydrogen costs and the transport costs.

6.4.1 Transport

The main advantage of local production is that the product that needs transportation is a hydrocarbon fuel instead of hydrogen. With hydrogen transport, the hydrogen needs to be converted before transported and converted back to hydrogen after transport. The costs of the conversion, export terminals and import terminals add up and mitigate the positive effect of the lower energy prices. As *Figure 27* showed, this can add up to almost the same costs as the production of hydrogen. The transport costs for hydrocarbon fuels are much lower. Studies from Fasihi (2016) and Agora (2018) estimated that the transport costs for liquid synthetic fuels are around 0,067 €ct/kWh [99] [100]. For kerosene, this amounts to about 85 €/tonne. Another study of Kalavista commissioned by the Dutch Ministry of Economic Affairs calculated shipping costs for synthetic fuels like DME and OME, which were discussed in Sections 4.2.2 and 4.2.3. They calculate a price between 30 and 40 €/tonne. All of the studies above base their calculations on a wide variety of factors such as the Capex and Opex of the ships, the fuel consumption, the fuel costs, the distance covered, the speed of the ships and more. Based on these studies, it may be assumed that the transport costs will not exceed 100€/tonne.

6.5 Integrated approach

The results focused on visualizing the impact of scenarios on the whole system. Through this while research, the focus has been on providing a clear overview on the individual factors as well as how all the elements are connected with each other. Building on the PESTEL-analysis, the factors with the highest impact were highlighted in experiments using scenarios and showing the effect of future uncertainties. An important aspect of the model and the experiments was the integrated approach of the system. The complexity that is part of renewable energy production, hydrogen production and synthetic fuel production creates interdependencies between factors and create multiple outputs that are important. That is why the experiments not only focused on the effect of a lower price on the synthetic fuel price, but also on the capacity factor of the electrolyzer. That is also the reason that when looking at using green or blue hydrogen for synthetic fuel production for the cheapest production route, it is important to take into account the carbon emissions associated with blue hydrogen production. When looking at the synthetic fuel system and its uncertainties, it doesn't suffice to look at one factor at the time. The PESTEL-analysis showed the multitude of factors that can impact the development of synthetic fuels, and the model was constructed in a way to take as much of these factors into account. As shown in the scenarios, the energy price is heavily linked to the capacity factor of the electrolysis. Showing the trade-off is essential for understanding the challenges for the synthetic fuel system. Another example is that when using pricing instruments like carbon policy, this not only influences the fossil fuel price, but also the price and process of blue hydrogen and potentially even the transport costs of hydrogen or synthetic fuels from abroad. The model looks at feedstock prices, process prices, policy effects, import and different production routes, all of which are connected. Concluding, when looking at the synthetic fuel system, an integrated approach is much more valuable than looking at individual factors.

6.6 Conclusions

This chapter added quantitative insights to the qualitative insights from the PESTEL analysis. By looking at the system with an integrated approach, the results show not only the impact of certain important factors on the synthetic fuel price, but also how the factors influence each other. The chapter started by making a comparison between green and blue hydrogen. This is relevant, as blue hydrogen is widely regarded as a better short term solution due to lower costs, but green hydrogen is viewed as a better solution for the long term as there is no need for CO2 storage and it is completely carbon free. Showing the tipping point is interesting information for synthetic fuel development. The results then showed the trade-off between the capital costs of the electrolyzer and the energy costs. It is a huge challenge, but it is clear that to become cost-competitive, low energy costs in combination with a high capacity factor are essential. Another important development will be the technological developments for the essential processes of the system, most notably the electrolysis. Improvements in efficiency and cost reductions as a result of technological innovation and scalability will significantly decrease the costs of hydrogen. Efforts in achieving these improvements are mage globally, but some areas have more potential than others. The results of this study and comparison with other studies showed that the location of the hydrogen production and the synthetic fuel production have a huge impact on the price due to renewable energy availability. Based on the results, production abroad in combination with transport is a cheaper option than producing locally. However, this also brings uncertainty, as countries become dependent on hydrogen-producing countries and also want local production. A combination of local production and imported hydrogen or fuels will probably prove to be the best combination.

7

Discussion

This chapter aims to reflect on the research methods and discuss the results of this research. Specific sections will discuss the results from Chapter 6 and then reflect on the research method. Furthermore, the relevancy of the research as a part of the MSc. Complex Systems Engineering and Management will be highlighted. Lastly, the added value of this research will be discussed from a societal and scientific point of view.

7.1 Cost-parity for synthetic fuels

The experiments started by exploring the potential future prices of fossil kerosene, based on its two main cost drivers, the crude oil price and the CO2 emission price. The results showed that the possible range is big. The scenarios with low oil prices, low ETS prices or both result in a low fossil fuel price, making it almost impossible for synthetic fuels to reach cost-parity. This shows the importance of policy instruments focused on reducing carbon emissions. Another alternative is bio-kerosene. But this has the major disadvantage of needing large amounts of water and arable land. For example, supplying Schiphol with bio-kerosene would require at least half the Dutch farmland and a water equivalent of 22 times all Dutch households [93].

7.1.1 Synthetic fuel price

After exploring the fossil fuel price, the experiments focused on the synthetic fuel price. Firstly, the impact was measured of the two most important cost drivers of synthetic fuels, the energy price and the electrolyzer Capex. The experiment was done using the current conditions of the specified system of synthetic fuel production in the Port of Rotterdam. As expected, under current conditions in the Port of Rotterdam, there are no realistic scenarios with conditions where there is enough renewable energy constantly available to guarantee a high capacity factor.

The experiments show the potential of green hydrogen becoming much cheaper than it is now, and it will most likely become the preferred hydrogen feedstock over blue hydrogen. But the experiment also shows that in the current conditions, the costs of green hydrogen are substantially higher than the price needed for cheaper synthetic fuels. In the short term, green hydrogen will remain more expensive than blue hydrogen in every scenario.

The option to use only excess renewable energy and thus reduce energy costs will lead to an increase in Capex per tonne and total hydrogen costs. The last policy scenario shows that cost reduction are possible with cheaper electricity prices, but the total costs of hydrogen per ton remain too high. The experiment showed the difficulty of producing synthetic fuels, as none of the scenarios led to the substantially low hydrogen costs needed for synthetic fuels to become more competitive. An important takeaway is that it is most likely necessary to build renewable energy capacity specifically for hydrogen production for the cheapest hydrogen. The affordable production of green hydrogen is essential to decrease the production costs of synthetic fuels. The price of green hydrogen is heavily dependent on two factors, the price of electricity and the capital costs of the electrolyzer. The capital costs of the electrolyzer, in their turn, are the result of the initial investment costs and the capacity factor. In other words, the availability of green electricity is equally or even more important than the price of green energy. This means that more renewable energy is needed for a good price.

Based on the assumptions and results from the experiments, it is highly unlikely that locally produced synthetic fuels will reach cost-parity with fossil fuels in the short term. In the long term, it is evident that significant cost improvements will occur due to technological developments and efficiency gains. On the synthetic fuel side, increasing RES capacity will decrease renewable energy costs, and technological developments will reduce electrolyzer costs. On the fossil fuel side, pricing instruments and high oil prices could increase the price of fossil kerosene, making low-carbon alternatives more interesting.

Policy instruments like blending quota en subsidies will create demand and increase production. It could be possible that cost-parity may never be reached, but even that scenario might not lead to synthetic fuels being completely absent in the future energy mix. For example, Japan is buying 'blue ammonia' from blue hydrogen at prices twice as high as the conventional ammonia market, just for environmental reasons [101]. Discussed social PESTEL-factors could further increase demand and stimulate relevant actors to purchase more sustainable fuels. The demand for synthetic kerosene is expected to grow, no matter the price. However, for the large-scale use of synthetic fuels, more cost reductions are still needed. Other opportunities could be to import cheaper hydrogen or produce synthetic fuels abroad. In the next sections, the research aims to provide insights into these possibilities.

7.1.2 Alternatives Abroad

It is interesting to look at the impact of hydrogen import, as the Port of Rotterdam is expected to import large quantities of hydrogen in the future. However, the experiment was focused on showing the potential price difference between imported hydrogen and locally produced hydrogen. Two elements stand out. Firstly, the price of imported hydrogen is highly dependent on assumptions. The results (Section 6.2) showed the high sensitivity for energy and Capex costs. The values for these essential parameters fall in an extensive range in literature. Based on the majority of the literature taken into account, including internationally recognized organisations like the International Energy Agency, the assumptions on the low part of the spectre are too optimistic, as is more often the case with emerging technologies.

However, there is no question about the potential of hydrogen production in, for example, the MENA region. Excellent renewable energy conditions lead to relatively low hydrogen prices. Even with shipping, imported green hydrogen is expected to be cheaper than locally produced green hydrogen and cost-competitive with local blue hydrogen. And while the prices seem to be on par with locally produced blue hydrogen, the increasing amount of hydrogen available could still lead to a decrease in price and more opportunities for synthetic fuel producers. Production prices of 3000 €/tonne are without a doubt possible, and prices until less than 2000 €/tonne could be possible under the right conditions and due to scalability and technological developments. With prices this low, it will be tough for countries with less favourable conditions to compete. But, countries don't want to be completely dependent on imports if they can prevent it. The uncertainties of relying on foreign production are significant, especially with Middle-Eastern countries where the diplomatic ties are not strong. Because of this, it is expected that the Dutch government will continue to invest in and stimulate local hydrogen production, even with higher prices.

The Middle East has an excellent location for producing hydrogen-based fuels. The most important factor is the availability of abundant renewable solar and wind energy, but the location also has a big strategic advantage as they can export to Asia as well as Europe. The excellent wind and solar conditions are already leading to very large-scale hydrogen projects with an outspoken ambition to use hydrogen for synthetic fuel production as well. From the PESTEL-analysis and the experiments in Section 7.2, it became clear that the energy price and the Capex costs of the electrolyzer are among the most important cost-drivers for synthetic fuels. The energy costs are significantly lower (a factor 2-3). The Capex costs also decrease gradually with scale. This means that large-scale hydrogen projects (such as the new project of 25GW) are working with almost ideal conditions. In the experiments in Section 6.2, in the best-case scenarios, the synthetic fuel price for 2030 and 2050 were 1669 and 925 €/tonne, respectively. With these numbers, the advantages of the conditions in the MENA region seem to outweigh the additional transport costs of 100€/tonne significantly. Additionally, transporting synthetic kerosene is easier and cheaper than transporting hydrogen. Because the rest of the production process, including the Fischer-Tropsch synthesis and fuel upgrading, is comparable, production abroad seems to have a high potential. However, importing countries lose some authority over the process and might face competition from local demand, which faces even fewer transport costs. This means that the possibility of importing synthetic fuels on a large scale does not depend only on price but also on the stable availability of synthetic fuels. The higher risk will lead to a higher rate of return, which increases the synthetic fuel price some more.

7.1.3 Importance of assumptions

The PESTEL-analysis and the experiments showed multiple factors that had a high impact on future prices. Unfortunately, in literature, there is little consensus about the future values of these factors. Overall, the results of this research are at par with the average expectations in literature. As shown and discussed in Section 7.3, extreme assumptions on electrolyzer Capex can lead to significantly lower prices than the best-case scenarios from the model experiments and could lead to cost-parity with fossil fuels in the short term (2030). However, renowned institutions like the IEA estimate the developments significantly less optimistic. With new technologies, quite often they are accompanied by hype, leading to optimistic literature. Because of this, the results of this research probably reflect the potential of synthetic fuels more realistically than some literature.

7.2 Discussion on the research approach

In this section, the use of the PESTEL-analysis in combination with MILP will be discussed. The combination of research methods provides an opportunity to characterize and quantify important identified factors. The combination of methods has strengthened the fulfilment of the research objective, as the quantitative part is essential for understanding how big the impact of some factors is. The experiments also help show how the numbers could develop over time, make comparisons between policy options and production locations, and shed new light on the identified factors from the PESTEL-analysis.

However, the factors PESTEL-analysis are not always easily compatible. For example, social factors like environmental awareness and environmental factors like climate change were found to have a huge impact on the development of synthetic fuels. But, these factors are difficult to directly incorporate into the model, as they are difficult to quantify. As was argued in Section 4.9, this is not necessarily a bad thing. Climate change and environmental awareness have an impact as they accelerate the transition to solutions like synthetic fuels. They are the reason that there is so much technological development that, for example, the Capex costs of electrolyzers will fall so significantly. In conclusion, following up PESTEL-analysis with experiments to quantify identified uncertainties can definitely add value to research. However, the compatibility of the two methods for all factors is limited.

7.2.1 Limitations

The model and data input have been constructed and collected with the greatest care and from reliable sources. However, higher-quality data is always aspired, especially after the experiments showed the large differences between important assumptions in literature. Looking back, this heavyweight on assumptions has a significant impact on the model results, as the model is a simplified representation of the system. By focusing on the most important factors, the weight of these assumptions further increased. This could lead to an indiscriminate view of the results.

It was difficult to determine the right price for carbon feedstock. Most other data was based on multiple sources, but since the carbon trading has not yet led to a market for CO2, the carbon is traded via bilateral contracts, where there is little information. The weight of this feedstock is significantly smaller than hydrogen. However, better estimates would increase the validity of the model. In any case, the estimate is not far off. Direct Air Capture is a factor 3-10 times more expensive, dependent on the literature source and the location. According to the authors' insights, this difference is so large that it is ruled out for the short term. If costs can be reduced over time, the environmental potential of DAC could make it a more interesting option.

7.3 CoSEM relevance

This study involves discussing the complex socio-technical process of developing and optimizing a system for synthetic fuels. The multi-disciplinary nature of this subject is highlighted by the PESTEL research method. Synthetic fuel production requires considering technical, economic, institutional and social aspects rather than focusing on just one of them.

The work has a clear technology component by addressing the synthetic fuel process as a whole and specific parts like electrolysis and Fischer-Tropsch synthesis. Technical issues are addressed by highlighting the importance of technological developments like DAC and efficiency gains. The research also goes beyond the technical aspect of synthetic fuel production by addressing the changes in perception and looking at strategic decision-making such as the production of cheap hydrogen in areas with favourable conditions.

The work uses a systematic approach of multiple research methods, and the subject is highly relevant for the public and the private domain. Synthetic fuels will become part of a multi-billion dollar hydrogen economy in the coming years. On the other hand, governments will be essential for accelerating and facilitating that economy. The multi-actor network, the high level of uncertainty and the complexity make the subject very suited for a CoSEM thesis.

7.4 Societal Relevance

The present study provides insights into the driving forces for the development of synthetic fuels in the future. To do this, potential future scenarios have been considered and analyzed, and the macro-environment of the synthetic fuel system has been categorized in PESTEL-factors. Firstly, it is clear that governments and regulators are required to play a role in the transition towards more sustainable fuel technologies. As can be concluded from the results, the path to cost-parity is long and financial incentives are essential for accelerating the process. Furthermore, accelerating the transition from fossil fuels to sustainable alternatives will have a very positive impact on the climate by reducing CO2 and other greenhouse gas emissions. It is therefore not the responsibility of one actor but governments, producers and customers. Inciting a paradigm shift is difficult. Globalisation has led to pushing boundaries in terms of costs, efficiency, speed and comfort. But is without question necessary to 'give in' on some of these points to reach the climate ambitions set in the Paris Agreement. Lastly, a shift away from fossil fuels towards hydrogen and hydrogen derivatives would create opportunities for countries with renewable energy sources and create a large number of technology-driven jobs. It is up to those countries to seize the opportunities and up to all countries to work together to benefit the world the most. Without actions from all actors involved and well-structured collaboration, e-fuels will struggle to become competitive. [3]

7.5 Scientific Relevance

The scientific relevance of this research is related to the identified knowledge gap in Section 2.2. The discussed knowledge gap can be summarized in two items:

- There was a lack of literature showing the 'complete picture' of important factors for the development of synthetic fuels in the future
- Extant literature was either qualitative of nature or focused on specific technical parts of the production process

First, a PESTEL-analysis was done, which was, by the authors' knowledge, the first PESTEL-analysis on synthetic fuels. The core of the research gap is the absence of research that looks at the impact uncertainties of the electric fuel system. This study adds to the extant literature by looking at the future of electric fuels beyond only the environmental impact or the technical process. The study does this by exploring the system and identifying the 'PESTEL' factors. This qualitative part of the research provides a comprehensive overview of the driving forces instead of only highlighting technical possibilities or environmental gains related to the use and production of synthetic fuels. By doing so, it provides a view of synthetic fuels from multiple perspectives. Secondly, the research adds value to the PESTEL-analysis by quantifying important factors. It is essential that the Linny-R model enables to look at the system with an integrated approach, taking into account feedstock prices, process prices, policy effects, import and different production routes and more, all of which are connected. This means that when looking at the scenarios, the impact on multiple metrics can be reviewed and their interdependencies are taken into account. The research looks at internal factors like process efficiency but also at external factors like policy. To ensure a complete overview, the potential development of the fossil fuel price is also taken into account. Scenarios over time and other locations provide a practical view and possibilities for synthetic fuel production in the future. The results provide information useful for various involved actors and could create incentives investments and policy decisions.

8

Conclusions and recommendations

In this section, the research question will be answered and the results of the qualitative and quantitative analyses will be summarized in the conclusion.

8.1 Conclusions

In order to reach the climate goals set by the Paris Agreement of 2015, the transport sector needs to decarbonize. Next to solutions as hydrogen-powered vehicles and electrification, synthetic fuels could be part of the solution. The International Energy Agency expects multiple transport modes to use synthetic fuels as part of the medium-to long-term solution. However, due to high costs and many uncertainties, the future potential of synthetic fuels is still unclear. Additionally, the macro-environment of synthetic fuels is insufficiently covered in the literature. To fulfil this research gap, the following research question was formulated:

"What is the potential of synthetic fuels and what is the impact of the most important internal and external uncertainties in the synthetic fuel system?"

To answer the research question, four sub-questions were formulated and answered. By addressing the sub-questions, the answer to the main research question was found step by step. The methods to fulfil each sub-question and the key conclusions will be discussed in the sections below. After the conclusions, recommendations will be given for further research.

1. What does the synthetic fuel production process look like, and what are the potential fuel end-products?

The first sub-question was approached by doing a literature study on the synthetic fuel production process and possible synthetic fuel end-products. The research followed a clear sequence, firstly discussing the hydrogen and carbon feedstocks and a selection of high-potential synthetic fuels. As end-product, methanol, DME, OME, FT-gasoline, FT-diesel and FT-kerosene were discussed, their main characteristics were summarized. Positive aspects that stand out for synthetic fuels are the positive environmental impact and their compatibility with existing infrastructure. Negative aspects that were observed often were high costs and, in some cases, a low Technology Readiness Level (TRL). After discussing the process and the potential end-products, synthetic kerosene was chosen as fuel to zoom in on. Synthetic kerosene is unique because it is a potential decarbonizing solution for a sector with very few other promising alternatives. Hydrogen or battery-powered aeroplanes don't have the reach or the capacity to play a big enough role in the growing aviation sector. Additionally, the infrastructure and fleet are complicated and expensive to replace.

2. What are the internal and external uncertainties that impact the synthetic fuel system, and which of them are critical for the development of synthetic fuels?

The answer to the second sub-question was found by using a qualitative research method called PESTEL-analysis. This analysis focuses on the macro-environmental system and categorizes the synthetic fuel system's internal and external uncertainties into six groups of factors. These PESTEL factors represent the Political, Economic, Social, Technological, Ecological and Legal factors that impact the future of the system. The PESTEL-analysis was then combined with a SWOT analysis to show if the factors were related to Strength, Weakness, Opportunity or Threat for the synthetic fuel system. The PESTEL-analysis was started by a literature study of relevant literature to see which factors were named most often and to assess their impact. The literature study also showed some factors are getting less attention than others. For example, most scholars focus on technical aspects of the process. A comprehensive overview of the driving forces for synthetic fuel production was generated by analysing the full set of factors. The PESTEL-factors were then categorized in a PESTEL-impact map.

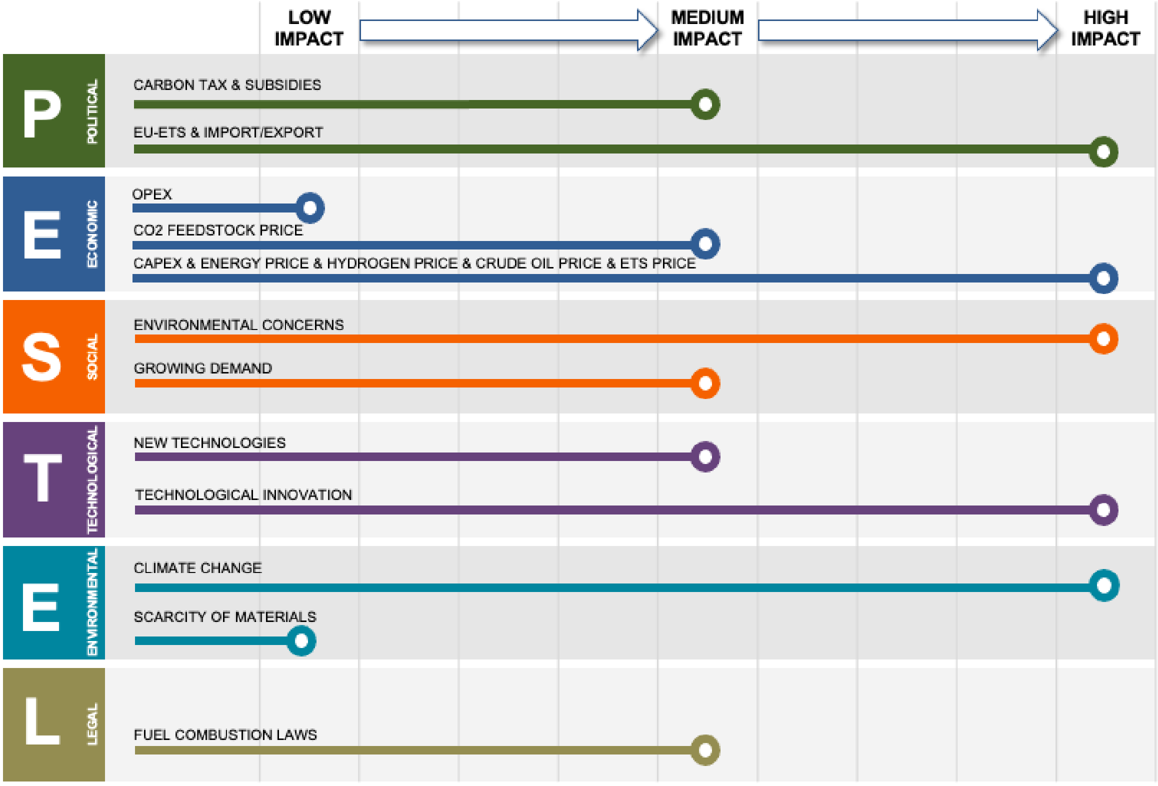


Figure 28: PESTEL Impact Map

3. How can the research add quantitative insights to the identified critical factors?

This sub-question was formulated to be able to use the results of the literature study and PESTEL-analysis. To do this, an optimization model in the MILP-program Linny-R was constructed. The aim of this question was to build a model that could show the impact of the identified uncertainties and show the dynamics of different scenarios for those uncertainties. The model is a simplified representation of the synthetic fuel supply chain in the Port of Rotterdam. The model provides an overview of the synthetic supply chain and shows the internal and external flows that influence the system. Relevant inputs and outputs include the CO2 emissions, the energy and Capex costs, fossil fuel costs and more. To ensure the model could be used for the experiments, it was verified using balance checks, extreme values, structured walk-throughs and logical interpretation of the results.

4. What are potential scenarios for synthetic fuel production, and what do the results mean for the development of synthetic fuels in the future

The fourth sub-question was focused on showing the impact of the identified uncertainties and their interaction. Firstly, the potential development of the fossil fuel price was discussed. The experiments showed that the oil price and carbon pricing instrument could add up to a price difference of factor 4. The low prices in the table show that the scenarios with lower prices will always lead to a fossil fuel price that is significantly lower than synthetic fuels. This is important because it confirms the fact that policy is needed that works both ways. Synthetics fuels need to be stimulated, and high-carbon technologies should be taxed.

The second part of the experiment was aimed at the cost drivers of synthetic fuels. It became apparent that there is a difficult trade-off between the most important cost drivers of synthetic fuels, the energy costs and the Capex costs. One important finding is that hydrogen production will be cheapest if the production is combined with a separate renewable energy park, without grid restrictions. Technological developments and economies of scale are expected to decrease important costs significantly, reducing important cost factors by more than 50%. However, the experiments show that it is hard to compete with fossil fuels even in the best-case scenarios. Under normal conditions, synthetic fuels are most likely 2 times more expensive than their fossil equivalent.

The third part of the experiments aimed to explore importing hydrogen or producing the fuels abroad and then importing the fuels. The first conclusion of this part is that there is no doubt that the favourable conditions for renewable energy generation in some parts of the MENA region, like Oman, will lead to unprecedentedly low hydrogen production prices. The attention for the regions' potential is growing rapidly, and the strategic location of, for example, the Middle East provides the opportunity to supply Asia as well as Europe with hydrogen or hydrogen derivatives. However, high prices for hydrogen transport will delay the competitiveness of imported green hydrogen. The discussion also shows the importance of the assumptions on different factors like the electrolyzer Capex. This confirms the results from the experiments in Section 7.2. Assuming that they are beneficial for the MENA region, imported green hydrogen is already cheaper than local blue hydrogen. It would therefore be a valuable addition to the synthetic fuel supply chain. Lastly, the possibility of integrating synthetic fuel production in renewable energy generation in the MENA region was discussed. Reviewing multiple literature sources on transport costs, the results show that it could be an excellent option to import synthetic fuels from regions with favourable conditions under the assumptions used in this research. The production costs are expected to be in the same league as locally, and the difference in hydrogen costs seems to be significantly higher than the added transport costs. As hydrogen costs are by far the biggest cost driver, importing synthetic fuels is likely a very interesting option. A disadvantage is increasing uncertainty, increasing competition and decreasing autonomy over the process for countries.

8.1.1 Conclusion main research question

Together, the conclusions of the four sub-questions make it possible to answer the main research question. The research aims to create additional insights into the impact of internal and external uncertainties on the synthetic fuel system. In doing so, it looks at the system with an integrated approach, to take into account interdependencies and look further than individual factors. Combining a qualitative and quantitative approach, the research highlighted the challenges and potential for synthetic fuels. The synthetic fuel system is a complex system, and the PESTEL-analysis highlights the multitude of important factors and their impact on the synthetic fuel system as well as each other. Then, the modelling part quantified the impact and showed how the different factors are related and also influence each other. It is clear that there are a lot of uncertainties surrounding synthetic fuels and in terms of potential it is definitely not certain that they will play a major role in the future energy system. However, the increasing demand and improving technologies do give synthetic fuels a good chance. The most important metrics are all 'moving in the right direction'. The prices of renewable energy and electrolysis are rapidly decreasing, which is leading to unprecedentedly low hydrogen costs. This cheap large-scale hydrogen production (abroad) will significantly reduce the synthetic fuel price. On the other side, economic policy instruments like carbon pricing are increasing the fossil kerosene price. Other stimulating policy instruments like blend-in quota and subsidies could create a minimal demand for synthetic fuels which would decrease investment risks and potentially increase synthetic fuel production. Overall, while cost-parity looks far away, the price gap between fossil fuels and synthetic fuels is decreasing. The demand for carbon-neutral solutions across all sectors is steadily growing, and for the aviation sector, where other alternatives are scarce, synthetic kerosene could be a viable alternative.

8.2 Next steps

This research shows that synthetic fuels' main barriers are insufficient stimulating policy and hydrogen costs. The renewable energy capacity must be increased significantly to ensure availability and decrease price. Technological developments need to bring down electrolysis costs and potentially make new technologies like DAC a viable alternative for point-sources. Governments should accelerate the transition towards synthetic fuels by stimulating policy and subsidies while taxing fossil alternatives. It should also provide a regulatory framework to incorporate synthetic fuels under alternative fuels, creating certainty for the actors involved. The results highlight the challenges but also the potential of synthetic fuels. To make them part of the inevitable transition to sustainable alternatives for the transport sector, governments, policymakers, international organisations and customers need to align their efforts to collectively (partly) shift towards synthetic fuels.

8.3 Suggestions for further research

One of the intentions of this research was to provide a complete overview of the macro-environmental factors influencing the development of synthetic fuels. The second intention was to show the most influential cost drivers and how their development would influence the chances of synthetic fuels and their chance to reach cost parity with fossil fuels. The assumptions in this research led to the conclusion that that will be very difficult. However, the growing environmental awareness could lead to a willingness to use synthetic fuels even with the price difference. An example was given about Japan buying more expensive but more sustainable ammonia. It would be very interesting to understand how large this factor is. There is some evidence that price will not be the only decisive factor.

The result of this research also highlights the potential of relatively low-cost production of synthetic fuels abroad. In the literature, there is very little information on the uncertainties surrounding a trade connection between, for example, Oman and Rotterdam. It is essential to know the scalability of the production there, the competition of local demand, and overall the possibility of a stable import line. Also, as the risk is higher, the required rate of return is most likely higher. This is also a factor that needs additional attention.

Further research could take into account more investing costs. This research focused mainly on the cost drivers of synthetic and fossil fuel production in terms of feedstock like gas, oil and renewable energy. It did not take into account the challenges of building huge amounts of renewable energy capacity. For example, it is expected that in the MENA region, it is easier to build this capacity in the desert than an off-shore wind farm next to the Port of Rotterdam.

Current policy is focused heavily on biofuels, while synthetic fuels arguably have equal or more potential. Synthetic fuels need fewer resources in terms of land use and can be scaled up more easily. There are already initiatives on incorporating CCU in the ETS, and the impact of that transition is discussed in the experiments. But more research on the best way to stimulate synthetic fuels is essential for their development. It is evident that without supporting policy, it is very difficult.

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