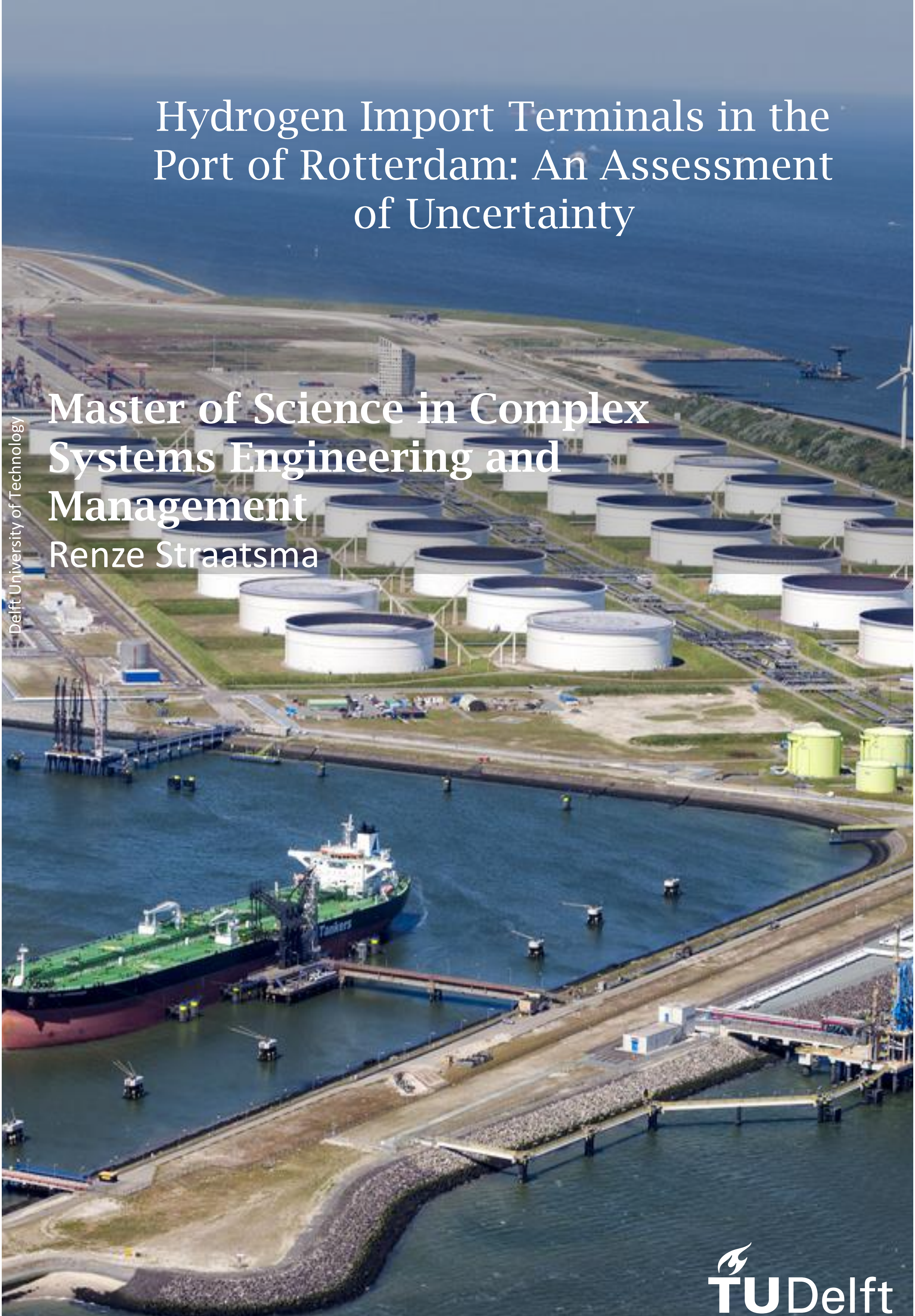


Hydrogen Import Terminals in the Port of Rotterdam: An Assessment of Uncertainty

Master of Science in Complex Systems Engineering and Management

Renze Straatsma

Delft University of Technology

TU Delft

Hydrogen import terminals in the Port of Rotterdam: An assessment of uncertainty

by

Renze Straatsma

Master thesis submitted to Delft University of Technology
in partial fulfilment of the requirements for the degree of
MASTER OF SCIENCE
in Complex System Engineering And Management (CoSEM)
Faculty of Technology, Policy and Management
to be defended on Wednesday December 1 , 2021 at 10:30 AM.

Student number:	4441184	
Project duration:	April 15, 2021 – December 1, 2021	
Thesis committee:	Dr. R.M. Stikkelman,	Chair & First supervisor
	Dr. A.F. Correljé	Second supervisor
	C. Ponsioen	Mentor

Summary

Hydrogen is widely considered an essential energy carrier that has the potential to accelerate the energy transition. However, large-scale production and the corresponding infrastructure are critical barriers that hinder hydrogen's diffusion. The Netherlands does not have the resources to fulfil the expected hydrogen demand by domestically produced hydrogen. To alleviate this, the Port of Rotterdam could play a significant role in the large-scale import of hydrogen. Hydrogen import terminals are required to facilitate large-scale hydrogen import. By realising hydrogen import terminals, the Port of Rotterdam can maintain its dominating position as the (renewable) energy port in North-West Europe. This study, in which the Port of Rotterdam is used as a case study, focuses on the uncertainties hampering the realisation of hydrogen import terminals.

While earlier studies have been conducted on hydrogen import, we identify two research gaps: 1) the necessity to optimise the scaling of hydrogen import terminals and 2) the inclusion of hydrogen use in multiple sectors. The scaling of import terminals is uncertain as many factors influence the optimal scaling, such as the uncertain hydrogen demand in multiple sectors. Therefore, this study aims to address both knowledge gaps by answering the following research question:

"How does uncertainty impact the realisation of hydrogen import terminals in the Port of Rotterdam?"

Through a literature review, three categories of uncertainty have been identified that are often present in hydrogen systems; economic, technical, and geopolitical uncertainties. Economic uncertainty relates to future markets and prices. Technological uncertainty predominately relates to the development of niche technologies aiming to evolve to their maximum potential. Geopolitical uncertainty is present in the emergence of new interdependencies between states and regions due to renewable energy production. Subsequently, three approaches were identified to deal with uncertainty; sensitivity analysis, scenario analysis, and probability-based assessments. This study used the first two methods to deal with uncertainties in this study. The latter method has been disregarded because of its prolonged computational times. The categories of uncertainty have been used as a guideline to identify uncertainty present in assessing the integrated hydrogen system in the Port of Rotterdam. Performing the case study resulted in a conceptual design of the integrated hydrogen system in the Port of Rotterdam. Figure 1 shows this system.

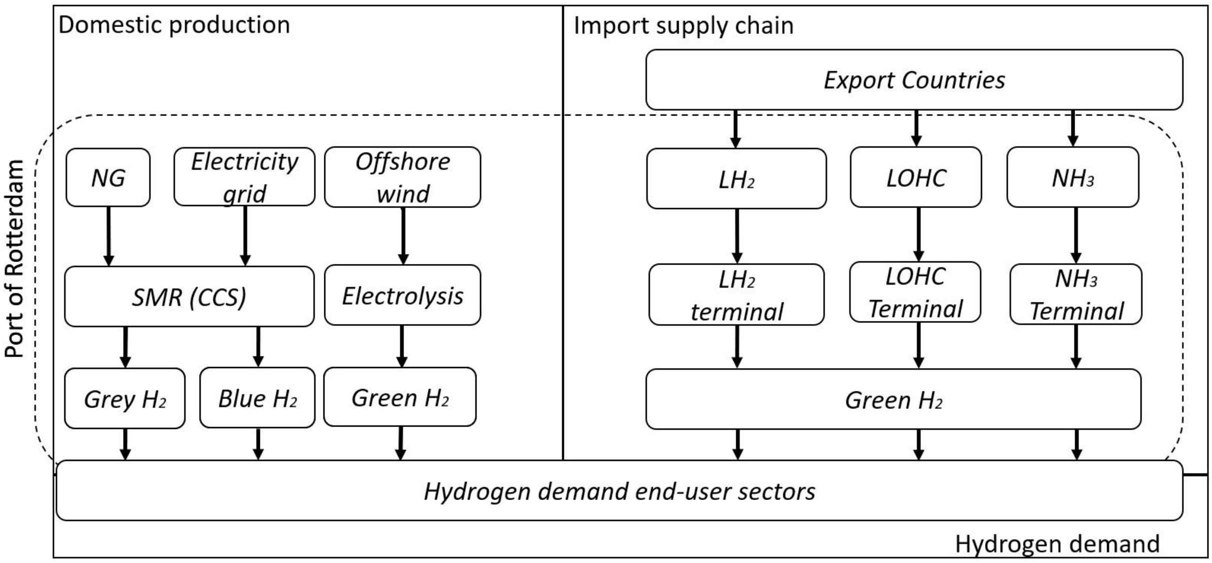


Figure 1: Systematic representation of integrated hydrogen system in the Port of Rotterdam.

The system includes three hydrogen carriers that can be imported (e.g. Liquid hydrogen (LH_2), Liquid Organic Hydrogen Carrier (LOHC), and Ammonia (NH_3)), two domestic hydrogen production methods (e.g. electrolysis and Steam Methane Reforming (SMR)), and eight hydrogen end-user sectors. A model that represents this system has been developed in Linny-R. Linny-R is a graphical specification language to solve Mixed-Integer Linear Programming problems. This model allowed us to adjust input parameters such as production capacities and prices, hydrogen demand, and infrastructural changes to study the identified uncertainties through sensitivity analyses and scenarios.

The results of this research illustrate the need for hydrogen import to meet the projected hydrogen demand. However, hydrogen import is not cost-competitive compared to domestically produced hydrogen. This study highlights the potential to reduce costs in the production, conversion to the carrier, and shipping stage of the supply chain. Currently, Ammonia (NH_3) is the cheapest hydrogen carrier followed by Liquid Organic Hydrogen Carrier (LOHC), and Liquid hydrogen (LH_2). Long-term contracts are required to manage the hydrogen import transactions to resolve economic uncertainty. However, we argue that this type of contracting can be quickly replaced by short-term contracting due to the current presence of aggregators in the hydrogen market. Technical uncertainty relates to the scaling of hydrogen import terminals and the end-user sectors' preferences for a specific hydrogen carrier. Each hydrogen carrier requires its specific infrastructure to be produced, stored, transported, and regasified. Based on the technical characteristics of the three hydrogen carriers, LH_2 shows the highest potential to supply all end-user sectors. However, LOHC and NH_3 also have advantages in specific areas. Moreover, the early stage of development in LH_2-technology fuels the need for LOHC and NH_3, leaving the debate on which hydrogen carrier is preferred open. Furthermore, the scaling of hydrogen import terminals is complicated by the presence of salt-caverns in the northern part of The Netherlands because they provide a cheap alternative for large-scale hydrogen storage. Finally, this research discusses both uncertainties and opportunities from a geopolitical perspective. Uncertainties related to the hydrogen import supply chain processes are highly dependent on the production capabilities in the export countries and the distance of those countries to the Port of Rotterdam. Additionally, other nearby ports can also realise import terminals, attracting hydrogen import, diminishing the potential dominant position of the Port of Rotterdam. However, a first-mover position could manifest the Port of Rotterdam as a dominant player in the global hydrogen market. More generally, hydrogen import terminals could provide security against geopolitical forces as it safeguards the diversity of the Dutch energy mix.

We identified several avenues for future research. First, researchers interested in expanding the model's functionalities could focus on 1) modelling a variable renewable electricity price to more precisely analyse its impact on the production costs of the electrolysis process, 2) including salt-caverns and specific hydrogen export countries to more comprehensively analyse the relevant aspects that are influencing the scaling of hydrogen import terminals, 3) adjusting our model by allowing only filled vessels to arrive which enables the performance of better analysis of the scaling of hydrogen import terminals, 4) including the Willingness To Pay (WTP) of various end-user sectors to sketch a more reliable picture of the expected hydrogen demand, 5) applying a method that allows the investigation of numerous possible futures. In that way, a complete overview can be created of different scaling designs of hydrogen import terminals. A more general recommendation is to add a new model to analyse investments and support companies' business cases by integrating hydrogen end-user sectors' WTP. Finally, we especially encourage policymakers to explore and support the possibility to realise one or more hydrogen import terminals, even in case of a lacking business case, to improve the strategic position of the Port of Rotterdam with regards to economic and geopolitical advantages.

List of Figures

List of Tables

Acronyms

BEV Battery Electric Vehicle.

CAPEX Capital Expenditures.

CCS Carbon Capture Storage.

CO_2 Carbon Dioxide.

DP Dynamic Programming.

LH_2 Liquid hydrogen.

LNG Liquid Natural Gas.

LOHC Liquid Organic Hydrogen Carrier.

NH_3 Ammonia.

OPEX Operational Expenditures.

PoR Port of Rotterdam.

RES Renewable Energy Sources.

SMR Steam Methane Reforming.

TCE Transaction Cost Economics.

TSO Transmission System Operator.

WTP Willingness To Pay.

Contents

1 Research Introduction

1.1 Port of Rotterdam's need for hydrogen

The Port of Rotterdam currently is the largest energy port in North-West Europe. Annually, nearly 8.800 petajoules (PJ) are imported and exported overseas (Port of Rotterdam, 2020c). To put this in perspective, that amount is equal to three times the energy demand in the Netherlands and covers approximately 13% of the total energy demand of the European Union (IEA, 2020). Currently, the import and export of this energy are almost entirely comprised of fossil fuels (Samadi et al., 2016). Many energy-intensive sectors use the Port of Rotterdam to cover their energy demand. Logically, the PoR does not want to lose its business and, therefore, aims to maintain its dominating position as an energy port in North-West Europe by shifting towards renewables. Hydrogen has the potential to be widely used as an energy carrier and has applications in industry, transport, built environment and power generation (IEA, 2019; Hydrogen Council, 2020).

The Netherlands cannot produce the potential hydrogen demand required for the decarbonisation of energy-intensive sectors. Moreover, hydrogen can be produced cheaper in world regions that have lower renewable energy source production costs (Port of Rotterdam, 2020c). These regions are predominantly located outside of Europe, making overseas hydrogen transportation necessary (IEA, 2019). Several scholars have advocated large-scale hydrogen import into The Netherlands, primarily through the Port of Rotterdam (Wijk and Hellinga, 2019; Detz et al., 2019a; Notermans et al., 2020). Hydrogen import terminals are required to facilitate hydrogen import. More specifically, Wijk and Hellinga (2019) states that an import terminal in Rotterdam could not only provide sustainable hydrogen for the Netherlands but, due to the strategic geographical location of Rotterdam's port, also to the rest of West-Europe. In that context, hydrogen is seen as a critical enabler to both fulfil the energy-intensive sectors' sustainable energy demand and to safeguard the dominant position of the Port of Rotterdam by using the port as a hydrogen hub (Notermans et al., 2020).

However, uncertainties are hampering the realisation of hydrogen import terminals. Hence, it is uncertain to what extent the role of sustainable hydrogen will be prominent in the energy transition (IEA, 2019). Therefore, companies are indecisive about investing in hydrogen import terminals. Nevertheless, Notermans et al. (2020) emphasise the urgency for action: *"Regardless of how understandable the hesitations for decisions under uncertainty, the window of opportunity for a leading role (for the Port of Rotterdam as hydrogen hub) is closing fast"*. This study aims to explore and analyse the uncertainties related to large-scale hydrogen import, hoping to modestly contribute to driving forward the decision-making process.

1.2 Background information

This thesis is conducted in collaboration with Gate Terminal. Gate Terminal's core business is the storage and distribution of liquefied natural gas (LNG). Despite the growing LNG business, the company aims to increase its sustainability by seeking a future business that is less carbon-intensive. The storage and distribution of sustainable hydrogen is, among others, an option for Gate Terminal to make their business sustainable. The hydrogen would be, similar to LNG, transported overseas, stored, regasified, and transported to the customers. Earlier studies by Gate Terminal point out Liquid hydrogen (LH_2) as the most promising hydrogen carrier since the similar operational process philosophy to LNG (Ban, 2020; Kolff, 2021). The notion of LH_2 as a hydrogen carrier will be further explained in section 1.3.2.

1.3 Research gaps related to hydrogen import

This sub-section aims to find knowledge gaps related to hydrogen import through a short review of the existing literature. A hydrogen import terminal will be highlighted as a core concept to introduce this research topic further. Then, literature regarding hydrogen import supply chains and their corresponding infrastructure will be reviewed. Subsequently, the identified knowledge gaps are used to formulate the main research question.

1.3.1 Core concept: hydrogen import terminal

A hydrogen import terminal facilitates the import of hydrogen from the sea. Generally, two options of hydrogen import are suggested, either by pipeline or by ship. The presence of the PoR as a large energy port facilitates the required knowledge on the handling of large energy imports and exports from sea (Notermans et al., 2020). We acknowledge that pipelines are required to distribute hydrogen and, possibly, import hydrogen from closer located export countries. However, we focus on overseas hydrogen import as we use the perspective of the Port of Rotterdam in this study. The far-located potential export countries strengthen our choice to focus on overseas hydrogen import as the use pipelines would be economically not viable (IEA, 2019).

The hydrogen import supply chain is presented in Figure 2. The first stage of the supply chain is the production of hydrogen in an export country. The next element is the conversion to the hydrogen carrier, whereby hydrogen can be converted to various hydrogen carriers (further explained below). The third element is the transportation of hydrogen overseas; shipping. The fourth element of the supply chain is the hydrogen import terminal. We distinguish between the two functions of an import terminal: the hydrogen carrier's storage and throughput. Throughput refers to the process where the hydrogen carrier is reconverted to gaseous hydrogen. The last element of the supply chain is the consumption of hydrogen.

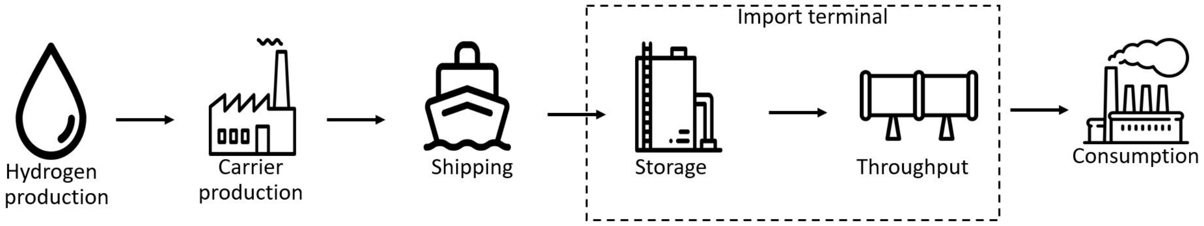


Figure 2: Hydrogen import terminal located in the hydrogen import supply chain

1.3.2 Overseas hydrogen import

Hydrogen transport by ship is more complicated than pipelines since gaseous hydrogen can be injected into a pipeline network like natural gas. Hydrogen is pressurised or attached to other components to increase the volumetric energy density to make hydrogen transportation by ships more efficient, so-called hydrogen carriers (Scott et al., 2013). Research has been conducted on various hydrogen carriers that are used to store and transport hydrogen. Liquid hydrogen (LH_2), Liquid Organic Hydrogen Carrier (LOHC), and Ammonia (NH_3) are the most common hydrogen carriers because of their characteristics, economics and applicability for different usages. Each carrier requires its specific infrastructure (He et al., 2016). Technical differences between the carriers result in advantages and disadvantages in use, regasification, and production (Papadias et al., 2021). This is also observed in studies that investigate overseas hydrogen supply chains. Ishimoto et al. (2020) considered a supply chain from Norway to Japan and Rotterdam. They considered two hydrogen carriers; NH_3 and LH_2- in their work, NH_3 was found to be the cheapest of the two due to a fixed amount of demand. However, NH_3 also resulted in the largest ecological footprint, due to the energy-intensive regasification process of NH_3. Roobeek (2020) considered a hydrogen import supply chain from Oman to Rotterdam. In this research, only

LH_2 was used as a hydrogen carrier. A relatively cheap supply chain cost was found (below 2,0 €/kg H_2). Wijayanta et al. (2019), and IEA (2019) researched the transportation of hydrogen from Australia to Japan. All three carriers were considered, and a fixed hydrogen demand was assumed. Lanphen (2019) conducted a study on the supply chain of hydrogen from various export and import countries. In her model, the costs of the supply chain, from export terminal to import terminal, depend on both countries' characteristics (import and export). However, her study also assumed a fixed demand and omitted specific end-use.

It can be observed that these studies do not emphasise the import infrastructure that is required to receive the hydrogen. Optimal capacity parameters of specifically import terminals were assumed rather than being the central focus of a study. In other words, the fixed amount of import could always be processed by the importing country or port as sufficient hydrogen infrastructure was assumed. However, it is essential to consider the scaling of a hydrogen import terminal as the upfront investment costs are incredibly high (Hong et al., 2021). An import terminal with a too high capacity for the import volumes suffers from these high upfront investment costs. On the other hand, an import terminal that is too small will not facilitate the volumes of hydrogen required. The previous paragraphs found that literature does not suffice in work on hydrogen import terminals. The suitable scaling of a hydrogen import terminal could resolve this mismatch. Now, we take one side-step away from hydrogen import to identify how hydrogen infrastructure (e.g. production, storage and distribution networks) in general is used to solve the mismatch of demand and supply.

1.3.3 Hydrogen supply chain infrastructure

Dayhim et al. (2014) investigated the planning of a sustainable hydrogen supply chain infrastructure for refuelling stations. They integrate hydrogen demand uncertainty based on consumer classification. Demand uncertainty is one of the most vital concepts since it determines supply chain and infrastructure scales (Nunes et al., 2015). The work of Nunes et al. (2015) includes an optimisation model that is focused on optimising the hydrogen supply chain while including the uncertainty in demand for hydrogen. Additionally, they included criteria to identify safety risks along with the hydrogen supply chain infrastructure. Moreno-Benito et al. (2017) use an optimisation model in which they combine different infrastructure components throughout different time phases to minimise the net present value of the infrastructure costs. Also, Robles et al. (2020) analysed a hydrogen supply chain under demand uncertainty. Konda et al. (2011) developed a framework that analyses the transition towards a hydrogen-based transport system. Caglayan et al. (2021) used a minimisation cost approach to investigate a 100% renewable European energy supply system with hydrogen infrastructure. A comprehensive study is the work of Reuß et al. (2017). In their work, they modelled a hydrogen infrastructure, including storage, in Germany combined with a supply chain study. This study focused on the application of hydrogen in the transportation sector, not considering several other hydrogen applications. Other scholars studied the hydrogen infrastructure used to supply refuelling stations for Fuel Cell Electric Vehicles (FCEV) (Samsatli et al., 2016; Parker et al., 2010; Brey et al., 2017). Their studies also focused on the transport sector rather than considering the supply process in a sea-port setting.

It can be observed that hydrogen infrastructure is often designed through optimisation studies. Moreover, most of the studies focus on the transportation sector and do not address other hydrogen end-user sectors.

1.3.4 Definition of existing knowledge gaps

From this short literature review, we observed two knowledge gaps. First, studies regarding hydrogen import supply chains often assume fixed demand and production volumes, disregarding the necessity to scale hydrogen import terminals based on variable parameters. The second knowledge gap refers to the scope of the studies, which included only a tiny variety of hydrogen end-user sectors. For instance, the import factor was not included. Therefore, the second knowledge gap is the limited scope of hydrogen consumption in studies that focus on hydrogen infrastructure. We aim to address both knowledge gaps in this research.

1.4 Research question

Now that the knowledge gaps are determined, the research questions can be formulated. The questions related to this research consist of one main research question and five sub-questions. Please note that hydrogen infrastructure refers to the infrastructure regarding the hydrogen import supply chain as indicated in Figure 2. The following main research question is formulated:

> *"How does uncertainty impact the realisation of hydrogen import terminals in the Port of Rotterdam?"*

To answer this central research question, multiple sub-questions will be answered. The sub-questions are:

1. What suitable methodology can be applied to study hydrogen infrastructure?
2. Which types of uncertainties are present regarding hydrogen infrastructure?
3. How to best deal with uncertainty in the context of hydrogen infrastructure?
4. What are relevant inputs to model an integrated hydrogen system located in the Port of Rotterdam?
5. Which uncertainties are present regarding an integrated hydrogen system in the Port of Rotterdam?
6. How can an integrated hydrogen system of the Port of Rotterdam be formalised in a working model?

1.5 Scope and research approach

This sub-section addresses the research scope and research approach. First, we describe the research scope. The Port of Rotterdam is selected as a case study. Therefore, the addressed problem in this thesis will be approached from the Port's perspective. From our short literature review, it became clear that LH_2, LOHC and NH_3 are the most promising hydrogen carriers for import. As such, only these three hydrogen carriers will be included in this study. This study considers the hydrogen demand that could potentially be met by hydrogen produced in or imported via the Port of Rotterdam. The hydrogen demand in end-user sectors could be located outside of the Port of Rotterdam itself. Regarding the time scope, we aim to explore the hydrogen infrastructure system between 2030 and 2050.

Now, we shift our focus to the research approach. The three first sub-questions will be answered in the literature review in chapter 2. We aim to find a suitable methodology to study hydrogen infrastructure design and its corresponding uncertainties. Sub-questions 4 and 5 will be answered through a case study. As shortly touched upon in the introduction, the PoR is selected as the topic of our case study. A conceptual model of an integrated hydrogen system in the PoR is made based on the case inputs. This conceptual design will be the foundation for formalising a model used to answer sub-question 6. In Linny-R, we found a suitable program to implement the MILP method. More information related to Linny-R is provided in chapter 4. Please note that hydrogen supply chain infrastructure has never been modelled in Linny-R. Hence, this requires an innovative approach to represent the real-time world in Linny-R. A model allows the modeller to test different assumptions and hypotheses to provide valuable insights (Leijnse and Majid Hassanizadeh, 1994). As a result, an answer to the main research question will be provided. The methodology is captured in a research flow diagram. The research flow diagram is presented in Figure 3.

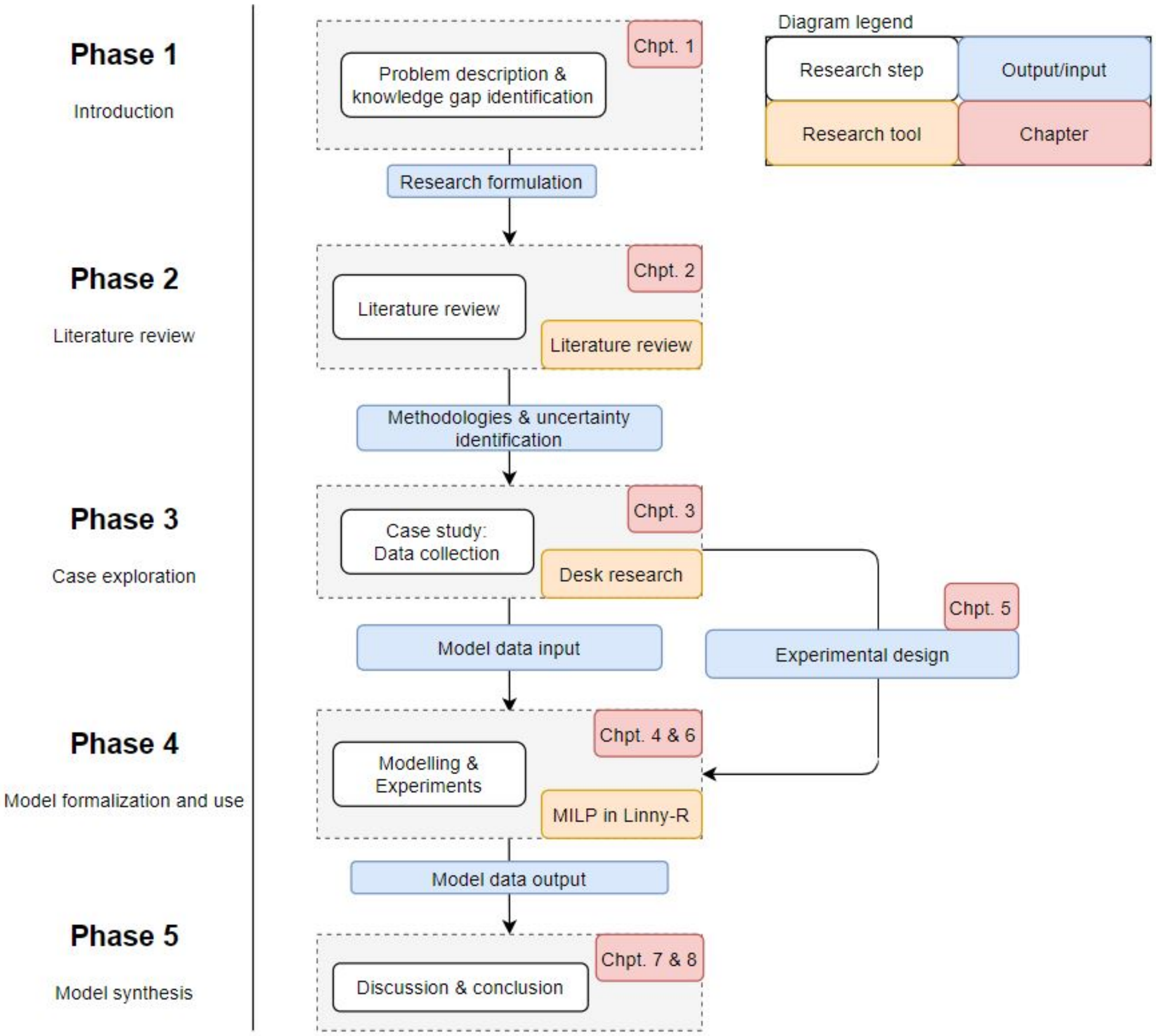


Figure 3: Research flow diagram

1.6 Research outline

This report has the following structure. Chapter 2 will cover a literature review that aims to find suitable approaches to study hydrogen infrastructure design and identify uncertainties related to them. Chapter 3 explores the case study for the Port of Rotterdam. Here, we identify case inputs and uncertainties related to an integrated hydrogen system in the PoR. Chapter 4 presents the formalisation of the case study into a model that will be used to experiment. In chapter 5, an experimental design is presented that introduces the experiments that will be conducted. Chapter 6 comprehends the results of these experiments. Chapter 7 discusses the results, methodology, and the contributions of this study. Finally, conclusions and recommendations will be given in chapter 8.

2 Literature review

This chapter aims to review the existing literature on hydrogen infrastructure and the uncertainty regarding hydrogen infrastructure. Again, do note that hydrogen infrastructure refers to the infrastructure regarding the hydrogen import supply chain as indicated in Figure 2. The following sub-questions are answered in this chapter:

- What suitable methodology can be applied to study hydrogen infrastructure?
- Which types of uncertainties are present regarding hydrogen infrastructure?
- How to best deal with uncertainty in the context of hydrogen infrastructure?

2.1 Literature review on hydrogen infrastructure modelling techniques

This section dives deep into the existing literature on hydrogen supply chain infrastructure. For this literature review, the following keywords have been used both separately and in combination with each other in the databases of Google Scholar & Scopus:

- hydrogen infrastructure
- hydrogen supply chain
- hydrogen import terminal

Some articles have been found through the so-called 'Snowball Sampling Method' (SSM). This approach uses a method of finding articles where one article gives the researcher other articles by citing them in those articles (Cohen and Arieli, 2011). Especially Agnolucci and McDowall (2013) was used as a starting point. Via their extensive literature review, many other articles were found.

Various studies have been conducted related to the modelling of hydrogen infrastructure. In an extensive literature review, Agnolucci and McDowall (2013) identified three methods that are applied generally in this field of research; spreadsheet model calculation, Dynamic Programming (DP) and Mixed Integer Linear Programming (MILP). First, a spreadsheet model can calculate the infrastructure price, the hydrogen price and environmental emissions. However, in this method, the hydrogen supply chain infrastructure configuration is assumed instead of optimised. Moreover, the results of such a static approach are hard to interpret in the context of transitions as it represents single time-points (Ogden, 2004). Second, dynamic programming is used only in three studies related to hydrogen supply chain infrastructure studies (Lin et al., 2006; Qadrdan et al., 2008; Lin et al., 2008). The reason for this limited use is the use of simplified constraints compared to MILP. These simplified constraints are used to limit the computational times (Agnolucci and McDowall, 2013; Lin et al., 2008). The utilisation of MILP models is the most common method in this field of research. According to Almansoori and Shah (2009), a MILP model allows the modeller to optimise the hydrogen supply chain infrastructure configuration based on the minimisation of costs. Other studies, already addressed in Chapter 1, also used MILP to study hydrogen infrastructure (Dayhim et al., 2014; Nunes et al., 2015; Moreno-Benito et al., 2017; Konda et al., 2011; Reuß et al., 2017).

2.2 Uncertainty in hydrogen infrastructure

This section aims to identify, through literature study, different categories of uncertainty that could impact hydrogen infrastructure. We refer to hydrogen infrastructure as the infrastructure that is required throughout the whole supply chain as indicated in Figure 2 in chapter 1. Therefore, future supply and demand is a critical factor in hydrogen infrastructure design. Moreover, Piyatrapoomi et al. (2004) argue that uncertainties have economic, technical and (geo)political natures. Therefore, this section will provide an assessment of these categories.

2.2.1 Economic uncertainties

Economic uncertainties are often present when investments are considered. Infrastructure requires huge investments and carries, therefore, risks. Moreover, infrastructure investment is subject to additional uncertainty as it is subjective to the chicken-egg problem. This problem refers to a lock-in situation between the infrastructure developer and the consumer. This section introduces two theories that address infrastructure developer- consumer risk: agency theory and transaction cost economics theory (TCE). The two theories will be explained by using natural gas examples. Natural gas and hydrogen are similar commodities based on their properties. Natural gas and hydrogen can both be transported overseas in liquid form. With natural gas, this happens through Liquid Natural Gas (LNG). Hydrogen is converted into (liquid) hydrogen carriers before being transported. For those two reasons, the supply chains are highly comparable, resulting in similar infrastructures and similar market structures (Aguilera, 2020). We aim to explore the economic uncertainties of hydrogen infrastructure based on those similarities with natural gas,

The agency theory describes the problems between two actors, the principal and the agent. The problem arises when the principal and agents have different interests, and the principal's management of the agent's activities is expensive. Even if the principal's interest and the agent align, they can disagree on which actions to take since their tolerance of certain risks differs. According to the theory, a contract can solve these problems (Eisenhardt, 1989). In other words, a contract can hedge the risk between a principal and an agent.

Applying this theory to the chicken-egg problem of the infrastructure developer and the consumer, one can argue that a contract between them could resolve the lock-in situation. For instance, a contract assures a specific consumption by the consumer that (partly) covers the investments costs and, thus, the risk of the infrastructure developer. On the other side, without a contract, the consumer has the risk of being unable to purchase the commodity required. Thus, a contract can hedge the risk for both parties.

Contracts are widely used in the LNG market. In the last decade, the LNG market has sharply increased in volumes and actors. This growth led to other forms of markets and contracts. Traditionally, major international oil companies have dominated the LNG market since they had the financial strength to undertake such capital intensive projects. Long-term contracts dominated the LNG market, driven by the necessity for significant investments in liquefaction plants, specialised LNG vessels, and regasification plants Wood (2012). The agency theory explains the essence of contracts. However, the theory is unsatisfactory in explaining why especially long-term contracts are present. Therefore, the transactions cost economics theory is used.

In the TCE, transactions are characterised by three dimensions; the degree of transaction-specific investment, the frequency of the transaction, and uncertainty. "Transaction costs are expenses incurred when buying or selling a good or service. Transaction costs represent the labour required to bring a good or service to market, giving rise to entire industries dedicated to facilitating exchanges" (Williamson, 1979). To illustrate, to buy LNG, the buyer searches for the lowest priced LNG available. This search comes with associated costs since this search requires time, labour, and, thus, money. Assuming the basic economic principle of profit maximisation, companies try to minimise these transaction costs. One option to minimise these costs is contracting (Church and Ware, 2000). The type governance to facilitate transactions is a result of the asset specificity that is used in a transaction and the frequency of these transactions (Williamson, 1979). This is illustrated in Figure 4

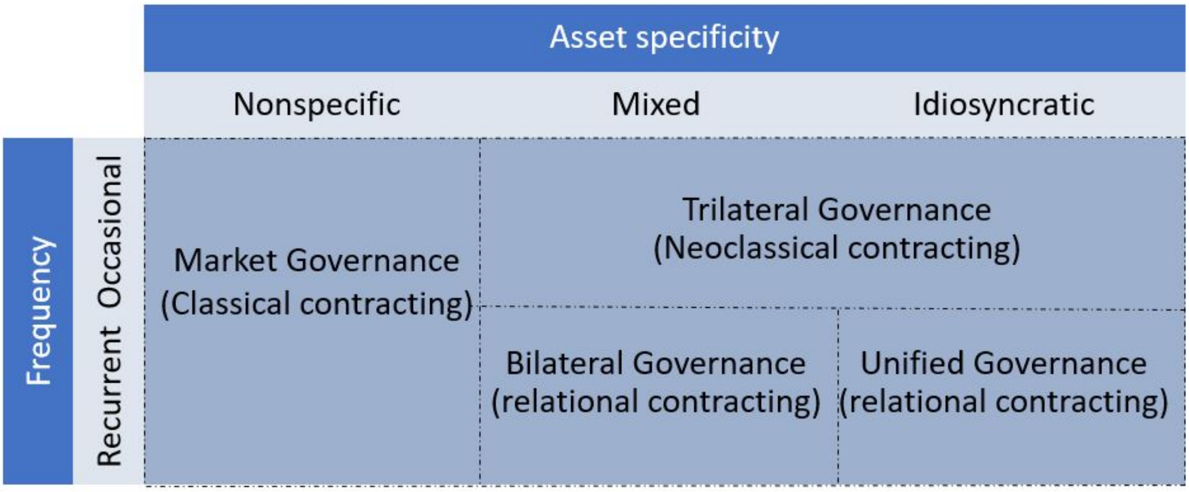


Figure 4: Matching governance structure with commercial transactions. Adapted from Williamson (1979).

Both LNG and hydrogen supply chains require highly specific investments (Arora, 2018). Furthermore, the transaction frequency, the purchase or sale of a specific amount of the commodity, is high. For those reasons, the type of contract is relational contracting (e.g. bilateral and unified governance). The difference between bilateral governance and unified governance has its foundation in the way companies are organised. Bilateral governance refers to contracting between two actors, in this case, the buyer and seller of either LNG or hydrogen. Note that contracts are constructed to minimise the transaction costs. Another form is unified governance, also known as vertical integration, where different stages of the supply chain are integrated into one firm to eliminate transaction costs (for example, natural gas production, liquefaction, and shipping LNG) (Williamson, 1979). Though uncertainty is not displayed in Figure 4, it does affect the governance of these transactions. Williamson (1979) states that a higher specificity of required investments increase the uncertainty of a transaction. Consequently, it is critical that both parties of the transaction organise a contractual structure to cope with these uncertainties. Also, Williamson (1979) argues that often uncertainty decreases as a result of an industry that matures leading to a more market governance of transactions instead of bilateral or unified governance.

In the last decade, a reduction of uncertainty combined with a shift of governance has been visible in the LNG market. Ruester and Neumann (2006) argue that large investments in LNG infrastructure, motivated by the growing natural gas demand, LNG, became a common traded commodity reducing the costs. As a result, the LNG market has seen a shift from long-term contracts to contracts more short-term. Already in 2006 Weems (2006) argued that these long-term contracts have become more and more flexible. In 2015, Hartley (2015) stated that *“the proportion of LNG-traded spot or under short-term contracts has grown substantially. (. . .). Long term contracts are likely to continue evolving toward offering much greater volume and destination flexibility.”*. The probable cause for the steer towards short-term contracts is the reduction in uncertainty of the transactions due to the increase in buyers and sellers in the market.

Due to the growing demand for spot traded or short-term contracts in the LNG market, the traditional LNG ‘players’ disappeared. Instead, ’portfolio actors’ (also called aggregators) have appeared (Ruester and Neumann, 2009). These actors either buy much LNG or hold various assets along the supply chain. In this way, they can supply different markets more efficiently than just using long-term contract types, resulting in higher profits. Currently, these portfolio players maintain approximately 75% of the total long-term contracts (Poten & Partners, 2015).

In the previous sections regarding contracts in the LNG market, a theoretical explanation has been presented for contracts and how they evolve during the maturity of a market or industry. To summarise, in the early stages of the LNG market, long-term bilateral contracts between buyer and seller are required to justify the significant specific investments made by the LNG producers and the investments done at the demand side (e.g. regasification companies). Unexpected shocks and events like the nuclear disaster in Fukushima increase, among other reasons, the demand for a spot or short-term traded LNG. Moreover, more buyers and sellers reduce the uncertainty of transactions which lead to other governance structures. However, a complete market governance is yet to be realised since relatively few players are in the LNG market despite the growth in the last years.

A similar trend can be expected with hydrogen. Hydrogen production needs particular and expensive investments for specialised assets such as liquefaction plants and specialised vessels. If hydrogen follows a similar trend to LNG, the shift from long-term contracts to short-term, it will take time to reduce the uncertainty of its transactions. However, the call for climate change combined with international and national regulation can accelerate the transfer of the hydrogen market from long-term to short-term trading and contracting. Similar to the LNG market, aggregators are expected to play a significant role in the hydrogen market. Already, large companies with high hydrogen demand seek opportunities to incorporate hydrogen production processes in their company (Shell, 2021).

In short, the realisation of hydrogen import terminals bears much uncertainty due to its asset-specificity characterisation. Also, production facilities and specialised vessels that transport hydrogen carriers are asset-specific. To illustrate, the literature showed that many hydrogen carriers have the potential to supply a hydrogen system. However, all hydrogen carriers require their own specific infrastructure. More hydrogen carriers are presumably simultaneously imported to establish a hydrogen market. However, no clear 'winner' is indicated. Therefore, long-term contracts will probably appear to justify expensive investments in the early stages of a future hydrogen market. However, based on regulations concerning the pressure for sustainability and the early signs of aggregators, the shift to a more short-term hydrogen market could come earlier than it came to the LNG market. Furthermore, due to the non-geographical boundaries of hydrogen production, more actors can enter the market, making a spot market more likely to occur.

2.2.2 Technological uncertainties

The realisation of hydrogen infrastructure has many technical difficulties that hinder large-scale projects. To illustrate this, commercially used LH_2-vessels do not exist. This section aims to identify the technical uncertainties corresponding to the design of import terminals. Geels (2004) developed a framework that seeks to capture the multiple aspects that influence the success of a specific technology to breakthrough and become the new standard. The framework consists of three levels; the technological niche, the regime and the socio-technological landscape. The three levels interact with each other. The framework is presented in Figure 5.

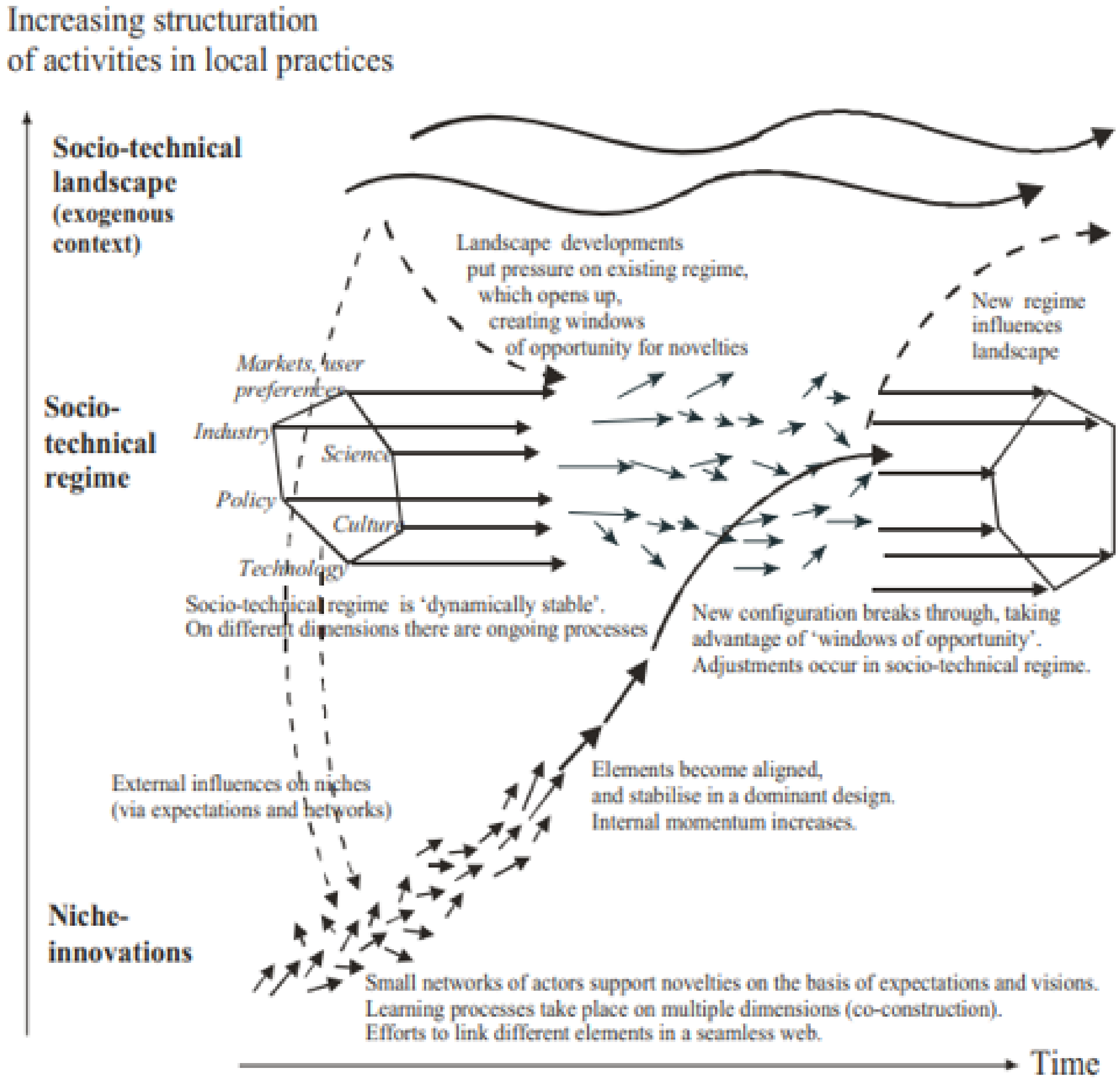


Figure 5: Multi-level perspective by Geels (2002)

Starting at the top of the framework, the socio-technical landscape is displayed. This layer should be explained as an exogenous layer that sets the context for the layers below. The landscape includes environmental issues, physical infrastructure, fossil fuels reserves and political visions. Changes or developments in this layer could pressure the regime and create windows of opportunities for technologies to breakthrough from a technological niche. Changes on this level usually do not happen overnight (Geels, 2002).

The second layer is the regime. According to Geels (2004), this layer refers to the role of institutions in processes. Said, it encompasses the current status of markets, technologies, users, policies, industries and many more. These institutions influence the possibility that a niche innovation can play a role at the regime level. Despite that, Geels (2004) refers to this layer as relatively stable, ongoing interactions that occur between actors, markets, users and their preferences, also at a political level. Both the landscape and the niche level influence the status quo at the regime level.

The lowers layer specifically involves niche innovations. *Niches* are novelties that are aiming for a breakthrough in the regime (Geels, 2011). Niches are often expensive. However, changes in the landscape can accelerate their development. The most straightforward example of a niche is a start-up aiming to release its new product into the market. High risks and high costs characterise niche innovations because their technology is non-mature by nature. Logically, it does occur that a niche innovation is not able to break through to the regime in a window of opportunity (Geels, 2002).

Without diving into a detailed description, the three layers of the framework are discussed regarding hydrogen infrastructure. At the landscape level, we see that the need for Renewable Energy Sources (RES) is rising as we more and more experience the effects of climate change. As a result, the landscape level pressures the current regime that uses conventional fuels and technologies to transition to renewable hydrogen. Moreover, as indicated by Figure 5, the landscape level externally influences niches by expectations and networks. When we apply this part of the framework on hydrogen, we, as indicated in Chapter 1, see growing attention, research and niche innovations regarding various hydrogen carriers that make overseas transportation of hydrogen viable.

Shifting our focus to the regime level, we identify different end-user markets that often use conventional fuels to fuel their production processes. The low prices for the currently used technologies and fuels block the penetration of more expensive sustainable alternatives like hydrogen. However, regulations like the CO_2 ETS are already present and influence the markets and actors at this level of the framework. Both the landscape level as the niche-innovation level are trying to force changes at the regime level.

The technologies and innovations that hope to break through to the regime are located at the niche-innovations level. The niche innovations include studies, like this study, that research innovations like hydrogen import and technological developments in terms of the infrastructure required for the hydrogen import and the storage & operational processes of these hydrogen carriers. Moreover, new technologies are developed to facilitate the broader use of hydrogen in many end-user sectors. To illustrate, research is conducted on integrating hydrogen in the natural gas network to heat the building environment. Moreover, a pilot project has been started to transport liquid hydrogen from Australia to Japan (Kawasaki Heavy Industries, 2021). In short, the developments at the niche-innovations level combined with the pressure of the socio-technical landscape on the regime level could create a window of opportunity that allows niche innovation to enter the regime.

The main take-away of this analysis is that various forces influence the success of breakthrough of a specific technology. These forces exist on separate levels but can interact with each other to create a window of opportunity. Geels (2002) does not mention the concept of uncertainty. However, we put his multi-level perspective in context of technological uncertainty related to the topic of our study. Moreover, the framework is used as guideline to identify different technological aspects and uncertainty present in our case study in chapter 3. Hence, the multi-level perspective has proved to be useful tool in case studies (Geels, 2005).

2.2.3 Geopolitical uncertainties

Recent reports showed that the versatility of hydrogen adoption in many end-user sectors leads to a higher projected demand which most countries will not be able to meet using local production (Hydrogen Council, 2020; IEA, 2019). Nevertheless, many countries and companies located in those countries show rising green hydrogen usage. Large international hydrogen supply chains are required to meet this demand. Therefore, it is relevant to look at more recent literature from a geopolitical perspective.

For this literature review, the following keyword has been used in the database of Google Scholar: "*geopolitics renewable energy*". The work of Vakulchuk et al. (2020) has been used to find most articles thanks to its extensive literature review.

Various scholars have discussed the implications of the future energy landscape in which renewables, including hydrogen, will play a significant role. Scholten et al. (2020) argued that the geopolitics of renewables would vastly differ from the power relations that currently exist in the energy systems that are based on oil and gas. Their conclusions have their foundation in the characteristic of renewables to be produced anywhere in the world. Contrarily, former energy systems, based on oil and gas, are dependent on access and availability of often geographical bounded oil and gas production locations. Vakulchuk et al. (2020) identified two groups with different perspectives on the geopolitics of renewables. The first group argues that the introduction of renewables will reduce the conflicts regarding energy security. The other group foresees a renewed conflict as renewables do not significantly change the current power relations. Scholars from the first group argue that in the case of renewables, influencing the price level by fluctuating production will be more challenging since, other than in oil and gas, hydrogen production is not limited to geographically bounded resources. In turn, this will result in greater independence and, thus, less conflict (Johansson, 2013; Paltsev, 2016; Verrastro et al., 2010). However, critical materials are required to facilitate the production of renewable energy. To illustrate, platinum is required in electrolysers. This could start conflicts triggered by the limited availability and accessibility of these critical materials (Stern, 2016; Jaffe and Soligo, 2008).

The other group claims that renewables have similar problems to fossil fuels (e.g. interdependence between countries due to geographically bounded resources). Hence, Capellán-Pérez et al. (2017) argues that the problem of energy security remains under the condition that consumers will have a high energy consumption. Moreover, Noussan et al. (2021), and Scita et al. (2020) argue that despite decentralisation of energy production, some countries have comparative advantages regarding renewable energy production due to favourable climate conditions. Shortly said, the geopolitics of renewables will be different compared to fossil fuels. However, the question remains if it will be with less conflict or not. Vakulchuk et al. (2020) concludes that some current geopolitical balances will be broken, but other challenges will appear. The literature argues that energy security can be resolved by more decentralised energy production. However, due to the comparative advantages of some countries over others, tensions between states will remain as they did with fossil fuels.

Another theme in the literature regarding geopolitics is the determination of ′winners′ and ′losers′. Various scholars argue that countries that always have leaned on their enormous oil and gas reserves will be left empty-handed, making them the losers of the energy transition (van de Graaf et al., 2020; Scholten et al., 2020; Sweijs, 2014). Contrarily, countries with beneficial climate conditions could become the winners. Focusing our scope on hydrogen, Pflugmann and Blasio (2020) put down three parameters to identify the country's renewable hydrogen potential: (1) renewable energy sources endowment; (2) renewable freshwater resource endowment; and (3) infrastructure potential. Countries that fulfil all three parameters are likely to become significant exporters and, therefore a winner, in a global hydrogen market. Countries in the Middle East, which dominate the international oil trade, seek to maintain this position by becoming major hydrogen exporters. However, lacking access to freshwater hinders the realisation of this ambition. The lost revenues from the oil and gas sector could damage their economies, resulting in destabilisation of that region (Pflugmann and Blasio, 2020). Moreover, these countries could potentially disrupt a hydrogen market by lowering the oil prices to make hydrogen economically less attractive for end-user sectors.

Another type of actor in the geopolitical game are developing countries. Developing countries with an abundance of RES are vulnerable to ′green colonialism′ (van de Graaf et al., 2020). In other words, countries or companies without the resources to invest in setting up hydrogen production assets could be left with simply providing the ′raw materials to more wealthy countries and companies. The work of Scholten and Bosman (2016) puts more focus on the infrastructural potential of a country or region. In that context, they argue that renewable energy should refer to, for example, wind and solar power and infrastructure. Central to this infrastructure is the availability of storage. Scholten et al. (2020) point out six clusters of renewables geopolitics. They suggest a possible future where countries are not, by definition, categorised into groups of winners, losers, importers or exporters. They sketch an alternative outcome, based on microeconomics, in where countries are *prosumers* (both producer as a consumer). In that context, they expect countries to strategically try to optimise the balance between domestic production and a cheap import.

In short, five observations stand out. First, the literature suggests a change in geopolitics for renewables compared to fossil fuels. It remains unclear if the geopolitics of renewables includes less conflict. Secondly, some scholars argue that the geopolitics of renewables and hydrogen can result in winners and losers based on their production potential. Other scholars instead speak in terms of exporters and importers of renewable energy. Third, former dominating oil and gas countries can be a disruptive factor in the rise of a global renewable energy market if they reduce their prices, making hydrogen less attractive. Fourth, apart from the production potential of countries, the infrastructure to import, distribute, and trade energy becomes an essential factor in establishing interdependences between countries. Finally, Scholten et al. (2020) point out that *prosumers* will occur during the emergence of a global renewables market which will go back and forth between importing and relying on domestically produced renewable energy. Economics is expected to play a significant role in the optimisation strategies of these countries.

2.3 Assessment of uncertainty

Previous sections identified three different categories of uncertainty regarding hydrogen infrastructure; economic, geopolitical and technical. Three approaches to analyse, among others, these types of uncertainties are broadly adopted; scenario analysis, sensitivity analyses, and probability-based assessment (Piyatrapoomi et al., 2004). This section analyses the three approaches and aims to find a suitable approach to study uncertainties regarding hydrogen infrastructure.

The first approach is to analyse uncertainties in scenario analysis. Scenario analysis is a primary tool to analyse risks and uncertainties about future forecasts and alternatives (Walker, 2000). Different scenarios are constructed to analyse the impact of the given alternatives on the considered system or problem. Scenarios do not calculate the probability of some occurrence. It rather indicates what will happen given different alternatives (Piyatrapoomi et al., 2004).

A second approach that analyses uncertainties are sensitivity analysis. The central notion of sensitivity analysis is the identification of vital variables that have more impact than other variables on future occurrences (Piyatrapoomi et al., 2004). Sensitivity analysis is often used in the verification and validation of a model (Christopher Frey and Patil, 2002). To illustrate, uncertainties regarding future (hydrogen) prices could be analysed to observe the impact of different price ranges on the import amount. By applying a sensitivity analysis, data errors and forecasting errors could be mitigated (Piyatrapoomi et al., 2004).

The third approach is a probability-based assessment. This method is solely based on statistics (Piyatrapoomi et al., 2004). A famous application of a probability-based method is the Monte Carlo method. It can solve deterministic problems by simulating large numbers of scenarios or experiments. The outcome of such approaches is often a distribution of output parameters, referred to as the solution space. The main disadvantage of the method is the significant computational times (Papadopoulos and Yeung, 2001).

Volumes and prices are important input parameters for our model given our intention to model an integrated hydrogen system. Among others, these input parameters contain uncertainty as it concerns a future hydrogen system. Scenario analyses enable the study of the implications given different amounts of hydrogen import or throughput regarding our hydrogen system. Furthermore, uncertainties in input parameters, such as prices, could be examined by performing sensitivity analysis to analyse the implications of a certain price range. Therefore, we conclude that both scenario and sensitivity analyses are suitable methods to deal with uncertainty in the context of hydrogen infrastructure. Probability-based assessment increase the robustness of the results. However, it significantly increases the computational time which becomes problematic given the time-scope of this study. Moreover, Linny-R does not enable the use of this method. As such, this method will be disregarded.

2.4 Choice for methodology

In this chapter, the literature concerning hydrogen infrastructure and uncertainty regarding a green hydrogen supply chain has been studied to answer the following sub-question:

- What suitable methodology can be applied to study hydrogen infrastructure?
- Which types of uncertainties are present regarding hydrogen infrastructure?
- How to best deal with uncertainty in the context of hydrogen infrastructure?

Regarding the first sub-question, MILP seems to be a fruitful approach to model hydrogen infrastructure. The TU Delft, and more specifically Dr P.W.G. Bots, provided us with a program Linny-R. In Linny-R, we found a suitable MILP solver that enables Mixed-Integer Linear Programming to be used in a visually attractive environment using modelling instead of hard-coded programming (Bots, 2021). Moreover, the broad adoption of MILP in the hydrogen supply chain & infrastructure design indicates its relevance. The availability of Linny-R as a modelling tool for MILP problems strengthens our choice for MILP. As such, this research will utilise this approach combined with Linny-R.

Regarding the second sub-question, the realisation of hydrogen import terminals has economic, technical, and geopolitical uncertainties. The reviewed studies showed that economic uncertainties are often hedged through contracts. To justify the huge financial investments that must be made to realise hydrogen infrastructure, usually, long-term contracts are constructed to alleviate the owner from the risk. Insights from the TCE theory will be used to reflect on the results of this study. Technical uncertainties relate to the breakthrough of technologies into the socio-technical regime. In other words, the uncertainty that technology develops to its potential. The Multi-level Perspective framework of Geels suggested that to realise these breakthroughs, a window of opportunity need to appear. Apart from developing the technology itself, the socio-technical landscape must influence the socio-technical regime to create a window of opportunity for the technology to settle itself in the established markets, society, and industries. The multi-level perspective will be used as guideline to identify technological aspects and uncertainties in our case study. Finally, geopolitical uncertainties are extensively discussed in the literature. Scholars are divided into two camps that distinguish themselves on assessing the geopolitical risks related to hydrogen. One group predicts a reduction of conflicts as hydrogen production is not restricted by bounded geographical resources. The other group argues that the risk of conflict remains as RES energy production is not guaranteed at all times due to fluctuating weather conditions. Moreover, geographical areas with favourable climate conditions could out-compete other regions without these conditions. In this context, the problem is only replaced by another. Storage options are crucial to tackling these risks. The insights provided by this literature review will be used to reflect on the results of this study.

Regarding the question of finding a suitable methodology to study uncertainties, three approaches have been identified. A combination of the first two, the scenario and sensitivity analysis, will be used for this research. The third approach, probabilistic based assessment, is excluded on account of its significant computation times.

This research aims to fill the knowledge gaps presented in chapter 1. These knowledge gaps are largely case-specific. However, they could provide insights that can be adopted outside of the case. From this literature review, we identified potential methodologies to study hydrogen import infrastructure. Moreover, we identified different categories of uncertainties that could impact hydrogen import terminals. The uncertainty categories are used as a guideline to identify relevant uncertainties for our case study. Moreover, general uncertainties related to hydrogen import infrastructure are used to reflect on the results of our research. Finally, three different approaches were identified to study the impact of these uncertainties on hydrogen infrastructure.

3 Case study: The Port of Rotterdam

This chapter aims to use the PoR as a case study to answer the following sub-questions:

- What are relevant inputs to model an integrated hydrogen system located in the Port of Rotterdam?
- Which uncertainties are present regarding an integrated hydrogen system in the Port of Rotterdam?

The structure of this chapter is as follows. First, the hydrogen import supply chains of the three carriers are analysed. Second, the domestic hydrogen production methods and their potential are examined. Third, the hydrogen demand in end-user sectors and the distribution infrastructure is analysed. Fourth, the uncertainties regarding our system are outlined. Fifth, the conceptual system is presented and discussed. Finally, the findings of this chapter that will be used for our model are described.

3.1 Hydrogen import via three hydrogen carriers

This section assesses different stages of the supply chain that will be imported into the PoR (see Figure 6). The green hydrogen supply chain starts with the production of hydrogen in an export country. This hydrogen is subsequently converted to a hydrogen carrier. Then, the hydrogen is shipped by a vessel, for each hydrogen carrier a different type, from the export country to Rotterdam. This thesis does not include transport by pipeline as it is expensive over longer distances and becomes highly complex in cross-border networks. Once arrived in the PoR, the hydrogen carriers are unloaded and stored in an import terminal. At last, the hydrogen is retrieved and distributed to the end-users. At the end of this section, the costs for the import supply chain is described in more detail.

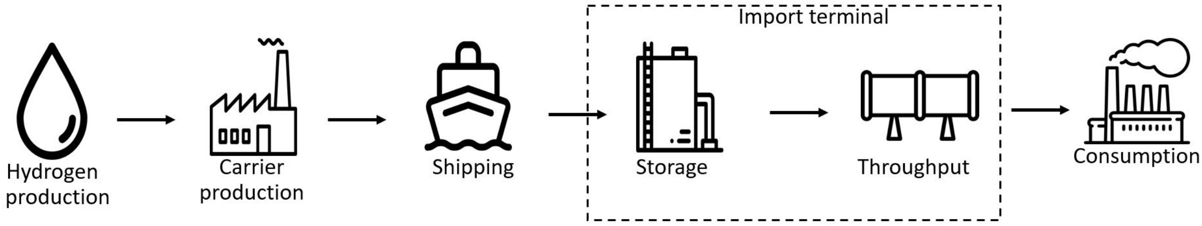


Figure 6: Different stages of the hydrogen import supply chain

3.1.1 Production

The most common method to produce sustainable hydrogen is water electrolysis. RES must be the energy input of electrolysis for the hydrogen produced to be called sustainable or green. The production costs of green hydrogen are dependent on the investment costs of the renewable energy source capturing method (i.e. wind turbines or solar panels), the price of electrolysers and the price of water (8 litres of water is required for the production of 1 [kg] hydrogen) (Turner, 2004; Esposito, 2017; IEA, 2019). It is important to mention that the hydrogen production costs can be highly volatile due to the intermittent production of renewable energy sources. This volatility is predominantly determined by the geographical location of the production of hydrogen. This is shown in Figure 7.

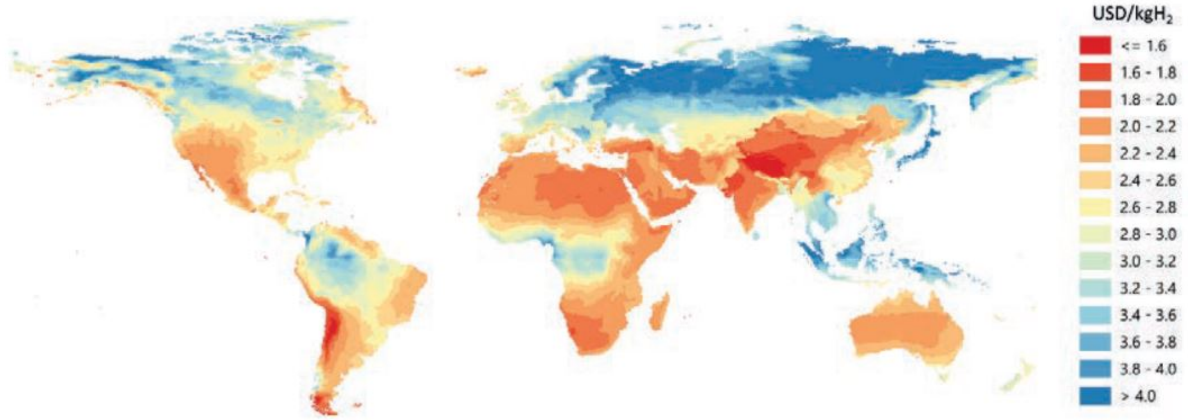


Figure 7: Hydrogen production costs determined by geographical location. Adapted from IEA (2019)

The production locations that would supply the PoR are still uncertain. As a consequence of that uncertainty, also the choice of the carrier is uncertain. The PoR has already signed various Memorandum of Understandings (MoU) with governments to formalise the intention for a hydrogen import supply chain into the PoR (Port of Rotterdam, 2020a). Among others, Australia, Chile, Oman, and Portugal are linked to the PoR. However, the choice for a specific location and/or carrier has not been made. Moreover, the carrier production capacities in those countries are still to be determined. This leaves some uncertainty regarding the availability of large-scale hydrogen import.

3.1.2 Conversion to carrier

Hydrogen is converted to a hydrogen carrier because hydrogen's low volumetric energy density (gaseous) makes transporting it overseas without conversion to a hydrogen carrier inefficient. The hydrogen carriers included in this research are Liquid hydrogen (LH_2), LOHC, and NH_3 since literature has shown their great potential (Wijayanta et al., 2019; IEA, 2019; Niermann et al., 2019). Converting hydrogen to such a hydrogen carrier reduces the volume, making it more efficient to transport.

LH_2 has many similarities with LNG. Significantly, the production and transportation of both commodities are similar. The main difference is the hydrogen' lower boiling point (minus 253 °Celcius) versus LNG's boiling point (minus 162 °Celcius). The extremely low boiling point makes the liquefaction process energy-intensive, and therefore, expensive (Deltalinqs, 2019). Approximately 45% of the energy brought by hydrogen is lost during the liquefaction process (Wijayanta et al., 2019).

LOHC is a name for different chemical bonds to which hydrogen can be attached. These bonds typically have one, and in some cases, two six-membered ring compounds in their chemical structure. This is illustrated in Figure 8. Toluene-MCH is the most widely used LOHC. In this thesis, the characteristics and properties of toluene-MCH will be used as LOHC. Through the process of hydrogenation, hydrogen is attached to the LOHC (Gonda et al., 2014). In this process, approximately 30% of the energy brought by hydrogen is lost (Wijayanta et al., 2019).

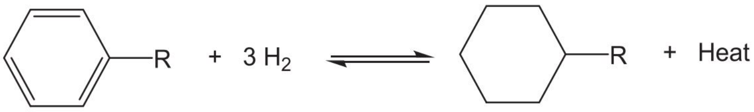


Figure 8: Systematic representation of the conversion of hydrogen to LOHC. Adapted from Reuß et al. (2017)

To convert hydrogen into NH_3, it will be combined with nitrogen (see formula below). In this process, approximately 13% of the energy brought by hydrogen is lost (Wijayanta et al., 2019). NH_3 is highly toxic and must, therefore, be carefully handled and stored. Fortunately, NH_3 can easily be detected, reducing safety issues. NH_3 has a higher volumetric hydrogen density than LOHC and LH_2. Also, NH_3, like LOHC, can make use of existing infrastructure and vessels (Wijayanta et al., 2019).

$$N_2 + 3H_2 \leftrightarrow 2NH_3$$

To summarise, the properties of the three carriers have been caught in Table 1. Note that both LOHC and NH_3 hold very little H_2 per kg (e.g. low gravimetric H_2 density). Hydrogen is only 6% of LOHC while 18% of NH_3. These low gravimetric densities have significant implications for the shipment and the hydrogen retrieval of the carriers. This will be discussed in the proceeding sections.

Table 1: Properties of the three hydrogen carriers. Adapted from Wijayanta et al. (2019) and Tijdgat (2020)

Hydrogen carriers				
Properties	**Unit**	**LH_2**	**LOHC**	**NH_3**
Density	kg/m^3	70,9	769	682
Boiling point	°C	-253	101	-33,34
Gravimetric H_2 density	wt%	100	6,16	17,8
Volumetric H_2 density	$kg\ H_2/m^3$	70,9	47,1	120,3
H_2-retrieval temperature	°C	-253	200-400	350-900
Conversion efficiency to H_2	-	0,98	0,70	0,79

3.1.3 Shipping

After the conversion of gaseous hydrogen to a hydrogen carrier, it is transported overseas. The three hydrogen carriers have their characteristics and properties. For that reason, they each require a specific type of vessels (Salmon and Bañares-Alcántara, 2021; Kamiya et al., 2015; Tijdgat, 2020; Niermann et al., 2019):

- LH_2 vessels have not been commercialised yet. However, Kawasaki Heavy Industries has built a small vessel (1250 m^3) as a pilot. It is planning to build larger vessels (up to 25.000 and 160.000 m^3) in the future.
- LOHC will be transported in chemical tankers under ambient pressure and temperature. It is assumed the vessel's capacity can vary from 20.000 to 220.000 ton LOHC
- NH_3 is transported in an LPG vessel. This vessel's capacity is assumed to be between 10.000 and 266.000 m^3.

It is important to mention that the hydrogen carrier mass of a specific vessel is not equal to the, eventually, the mass of the delivered hydrogen. This is true for two reasons. First, for LOHC and NH_3 the ratio between the volumetric H_2 density and the standard density (see Table 1) is very small. As a consequence, only 6,16% and 17,8% of the mass of respectively LOHC and NH_3 is hydrogen. The second reason relates to the conversion efficiency of the dehydrogenation process. This is further explained in section 3.1.4. The above is captured in the following formula and illustrated in Figure 9:

$$\text{Mass of hydrogen delivered [ton } H_2\text{]} =$$

$$\text{Delivered hydrogen carrier mass [ton } H_2 \text{ carrier]} * \text{Conversion Efficiency [-]} * H_2 \text{ content [-]}$$

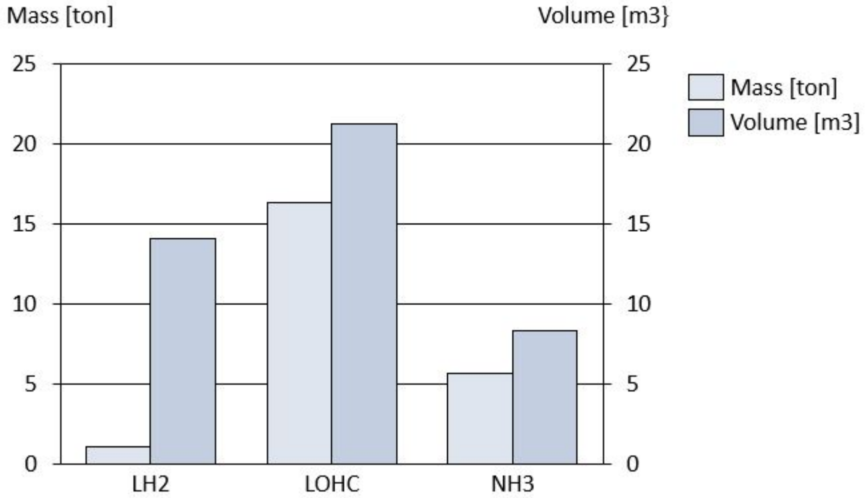


Figure 9: Volume and mass needed to deliver 1 [ton] of hydrogen based on Table 1

Capacities of hydrogen carrier vessels determine the amount of hydrogen that can be delivered by one shipment. A larger vessel capacity is expected to provide more flexibility regarding the import of hydrogen due to the possibility of storing the carrier in the import terminal. To test this hypothesis, different vessel capacities will be used. The vessel capacities that will be used are based on the literature (Salmon and Bañares-Alcántara, 2021; Kamiya et al., 2015; Tijdgat, 2020; Niermann et al., 2019). The vessel capacities are shown in Table 2

Table 2: Capacities hydrogen carrier vessels

	LH_2		**LOHC**		**NH_3**	
	Mass [tonne]	Mass H2 [tonne]	Mass [tonne]	Mass H2 [tonne]	Mass [tonne]	Mass H2 [tonne]
Low	89	87	20.000	868	6820	970
Medium	1.773	1.737	75.000	3.255	57.970	8.243
High	11.344	11.117	220.000	9.548	109.120	10.668

3.1.4 Import terminal: storage and throughput

This section aims to explore the process in and around the import terminal. First, we discuss the aspect of storage. Then, the throughput, or, in other words, the regasification processes, will be discussed. Finally, two aspects regarding the regasification and utilisation of the carriers are discussed. The first aspect regards the energy input for the regasification processes of LOHC and NH_3. The second aspect relates to the direct use of the carriers.

Once arrived by vessel, the carriers are stored in the terminal. Each hydrogen carrier requires specific storage tanks. Hydrogen carrier storage tanks and terminals vary in maximum capacity, depending on the state and form of the hydrogen (Detz et al., 2019b). LH_2 must be stored in a well-insulated tank as its boiling temperature is -253 °Celcius. LOHC can use the existing storage infrastructure of crude oil derivatives and can be stored at atmospheric pressure (Niermann et al., 2019). Also, NH_3 can potentially use the existing storage infrastructure that currently is used for propane (Wijayanta et al., 2019).

Another option for storage is the use of salt caverns. This technique is a promising option since it has low upfront investment costs, the sealing of the salt cavern has high potential, and it has a low cushion gas requirement (Caglayan et al., 2020). Gabrielli et al. (2020) argue that salt caverns are suitable for long-term storage of hydrogen. In the Netherlands, there is some potential for hydrogen storage in salt caverns. In the Northern part, nearby the small village Zuidwending, currently, five salt caverns are exploited as a natural gas reserve, with each a capacity of 1.000.000 m^3. For hydrogen a salt cavern of 500.000 m^3 could potentially store 3.733 [ton H_2]. Salt caverns will not be included in our model. However, it is important to mention their potential.

Now we shift our focus to the second function of an import terminal; throughput. Generally, two options are widely known for how to import terminals are operating; base-load and peak-shaving. A base-load operating terminal usually has a throughput of several thousands of tons per day. Therefore, the throughput is constant and predictable, and the throughput capacity has to be relatively high to facilitate the base-load. On the other hand, peak-shaving facilities have comparatively low throughput capacity as they aim to cope with the mismatch in supply and demand at only a few particular moments (Finn et al., 2000). It is vital to be aware of the different roles an import terminal could take on. If domestic production can mainly meet the demand, small import, and therefore small terminal throughput capacities are required. On the other hand, in case of a higher hydrogen demand, the domestic production will probably not be sufficient, and thus larger import volumes will need to be processed. In that case, import terminals likely adopt the function as a base-load terminal. However, large salt-cavern in the Northern part of the Netherlands influence this role as they could be used as large-scale hydrogen storage. Another factor is known as the chicken-and-egg problem. Large import volumes will only flow if the import terminals are in place and high local demand for hydrogen is present. On the other hand, a large import terminal could attract large import volumes. However, significant upfront investments are needed leaving the question of what needs to come first? In short, different technical, economical and even political aspects determine the most suitable role for an import terminal.

Throughput refers to the amount of carrier that can be dehydrogenated in one period of time (e.g. hour, day or year). Dehydrogenation is the process where the three hydrogen carriers are reconverted to gaseous hydrogen. The three carriers can be used directly (without re-conversion) in some cases. However, this is not included in this research. The gravimetric H_2 density (see Table 1 and Figure 9) determine the amount of H_2 that can be retrieved from a certain amount of hydrogen carrier. Once retrieved, the hydrogen has a specific purity degree. A higher purity degree a higher quality of hydrogen (see A for more information). Below, the three hydrogen carriers are discussed concerning their dehydrogenation process (reconversion to gaseous hydrogen).

LH_2 has a relatively easy and cheap dehydrogenation process because of the low boiling point. Therefore, the vaporisation of LH_2 requires little energy input (Wijayanta et al., 2019). This is crucial, especially when one considers that LH_2 is transported from a geographical area with an energy surplus to an area with a deficit. This characteristic of LH_2 is precious and unique compared to other hydrogen carriers. The purity of this vaporised hydrogen is higher than 99,99% making it available for every application in any end-users sector (see Appendix A for more information regarding hydrogen's quality) (Ishimoto et al., 2020).

LOHC is cracked at a temperature of approximately 300 °Celsius. This process consumes approximately 30% of the hydrogen energy (Wijayanta et al., 2019). After the dehydrogenation process, hydrogen purification methods are required, like pressure swing adsorption or membrane separation, increasing the costs (Niermann et al., 2019). Generally, the hydrogen purity retrieved from this process is lower compared to LH_2. The relatively easy storage handling and operations make LOHC applicable for export to Germany or other countries after arriving in Rotterdam.

To retrieve hydrogen from NH_3, *NH_3* must be cracked in a catalytic process, after which the hydrogen is purified (Ishimoto et al., 2020). This process requires a very high energy input (temperature above 800 °Celsius), resulting in a loss of approximately 13% of the hydrogen energy (Wijayanta et al., 2019; Giddey et al., 2013). Generally, the hydrogen purity retrieved from this process is lower compared to LH_2 and comparable with LOHC.

As identified, the regasification process of both LOHC and NH_3 require significant energy input. Two aspects regarding this energy input are important to address; sustainability and availability. Ishimoto et al. (2020) stated that the cracking process of NH_3 produces significant CO_2-emissions as it requires approximately 0,4 [MWh/ton H_2]. Their work advocates using waste heat to reduce the climate impact. Contrarily, as mentioned, LH_2 requires none to little energy input, and thus, is the ecological footprint of this process negligible (Wijayanta et al., 2019).

Another important aspect is the direct use of the carriers. LH_2 and LOHC do not yet have commercialised forms of direct usage. NH_3 is used directly in the fertiliser industry. Sustainable NH_3 can easily replace the carbon-intensive NH_3 used nowadays, creating a market for the imported NH_3. Moreover, NH_3 shows potential to be used in the maritime shipping sector and for combustion applications (Wijayanta et al., 2019). It is expected that the direct use of NH_3 will take priority over hydrogen retrieval from NH_3 since the dehydrogenating process requires a large amount of energy (Deltalinqs, 2019). Moreover, the purity of the hydrogen retrieved from NH_3 is significantly lower than hydrogen retrieved from LH_2. In the case of converting NH_3, expensive process equipment is required to retrieve a higher hydrogen purity, resulting in higher costs. Direct use eliminates the regasification process and makes the total supply chain of NH_3 more efficient (Aziz et al., 2019). Please note that the direct use of the carriers is not included in this research as we consider pure hydrogen demand. However, the notion of direct utilisation becomes relevant when the demand for a specific hydrogen carrier drives the need for a supply chain.

3.1.5 Hydrogen carrier supply chain costs

Apart from the advantageous or less beneficial characteristics of the three hydrogen carriers, costs are presumably the most critical factor in a decision to import a particular hydrogen carrier. The costs are usually a build-up of different stages in the supply chain. These stages are production, conversion, transportation, receiving and retrieval to hydrogen. In this research, we categorise the costs into three categories. First, the import price [€/tonne H_2 carrier], this entails the production of the carriers, including the shipment to the Port of Rotterdam. Second, the storage costs [€/tonne H_2 carrier], and finally the regasification costs [€/tonne H_2 carrier] for retrieving gaseous hydrogen.

In this study, no specific export countries have been mentioned. For that reason, the import prices used in the experiments and scenarios are determined based on our interpretation. Various studies showed a wide range of import prices, so choosing one specific study was not feasible. However, we always cross-checked our interpretations with other studies (Terwel and Kerkhoven, 2018; IEA, 2019). To illustrate, Terwel and Kerkhoven (2018) calculated the total supply chain costs of the three different carriers from 144 different countries. Please note that Terwel and Kerkhoven (2018) emphasised that their work entails large uncertainty and should not be treated as explicit or exact. The average supply chain costs of respectively LH_2, LOHC, and NH_3 are 8.481, 5.150, and 4.868 [€/tonne H_2] (8.311, 224, 692 [€/tonne carrier][1]). Therefore, we assume that NH_3 will generally be the cheapest carrier. However, for experiments, adjustments to this assumption can be made.

For both the storage and regasification costs, the work of Wijayanta et al. (2019) has been used as a source. The costs [€/tonne H_2 carrier] are presented in Table 3. Please note that the different hydrogen carriers have different volumetric densities as presented in Table 1 resulting in different ranges of costs per tonne H_2 carrier. Also, note that the storage costs for LH_2 are expected to decrease drastically in time due to economies of scale and technological development.

---

[1] Please refer to Table 1

Table 3: Storage and regasification costs for LH_2, LOHC and NH_3 in [€/tonne H_2 carrier]

		2030	2040	2050
Storage costs	LH2	638,8	468,4	298,0
	LOHC	5,4	5,4	5,4
	NH3	23,7	23,7	23,7
Regasification costs	LH2	0,0	0,0	0,0
	LOHC	30,8	27,7	24,6
	NH3	77,1	69,4	61,7

Generally, there are three business models known concerning a storage & regasification terminal; the (mixed) integrated project model, the merchant project model and the tolling project model (Tavares et al., 2018). Gate Terminal applies an adjusted tolling project model.

An essential notion in the tolling project model is the ownership of the gas being processed in the terminal. In the standard tolling structure, the terminal operator does not own the gas at any time the gas goes through the terminal (Tavares et al., 2018). The tolling fee paid to a terminal by its customers typically consists of two components; a fixed and variable component. The fixed component regards the reserved capacity. To clarify, a customer pays a fixed amount to the terminal owner to reserve the capacity if required by the customer. The variable component is the fee a customer pays for the actual unit of gas processed by the terminal. Such a model implicates that the terminal owner reduces the price risk since the fixed component is a stable income. However, the terminal is partly vulnerable to volume risk (Tavares et al., 2018). In other words, the terminal owner is independent of market price but dependent on market activity.

In the case of Gate Terminal, the variable component is left out of the payment structure. Gate has signed long-term contracts with four customers, Shell, Orsted, Uniper, and congas. These companies have contracted approximately 11 out of the 12 available cm (billion cubic meters) storage capacity. Customers of Gate Terminal only pay a fixed fee for its services. Therefore, Gate Terminal eliminates the volume risk. This elimination has been one reason Gate Terminal has remained operating since the terminal has processed few LNG volumes in the first operational years. If Gate Terminal carried this volume risk, it would probably have been bankrupt.

A future business model regarding an LH_2, LOHC, or NH_3 terminal could have similarities with the current model for LNG. Note that the LNG terminal has been realised because the storage & throughput capacity was contracted before the terminal's construction. Logically, to justify investments, this would be an ideal situation in case of a possible LH_2-terminal. Nevertheless, the development of import supply chains is in its preliminary stages, and only a few large-scale end-users of hydrogen are present compared to natural gas. For these reasons, it is reasonable that smaller capacities will be contracted via long-term contracts than occurred with LNG. In smaller reserved capacities, one should consider other business models to be more profitable compared to the current model used for LNG.

In short, this study includes three different types of costs within the supply chain: import, storage, and regasification costs. Import costs include foreign hydrogen production, the conversion to a carrier, and the shipment into the Port of Rotterdam. As described, the import costs bear the most significant uncertainty. Storage and regasification costs are adapted from Wijayanta et al. (2019) and will be used accordingly (see Table 3).

3.2 Domestic hydrogen production

This section aims to explore the domestic hydrogen production located in the Port of Rotterdam. Note that we aim to explore potential production capacities for the coming decades. This research includes SMR (including CCS) and water electrolysis as production methods. First, we address SMR and CSS, followed by electrolysis.

3.2.1 Production of hydrogen using SMR and CCS

Steam Methane Reforming (SMR) is a method where natural gas is combined with steam to create syngas (a mixture of gaseous hydrogen and monoxide) from which hydrogen is produced due to the presence of a catalyst (Holladay et al., 2009). Blue hydrogen is produced if the CO_2 is captured and stored during the process of steam methane reforming. Assuming a hydrogen demand of around 14 [Mton/year], Gigler and Weeda (2018) calculated that approximately 2250 [PJ] natural gas is required in case SMR (including CCS) completely covers the demand. To put this in perspective, the total natural gas use in the Netherlands currently is 1200 [PJ]. Apart from the enormous amount of natural gas, storage capacity for the captured CO_2 is required. Using CCS to meet the 14 [Mtonne/year], would require a storage capacity of 128 [Mtonne CO_2/ year]. To put this in perspective, PORTHOS is a pipeline that transports the captured CO_2 to depleted gas reservoirs underneath the North Sea. PORTHOS will be the largest of its sort in the world with a capacity of 2,5 [Mtonne CO_2/year] (PORTHOS, nd). The current production capacity of SMR combined with CCS is 400 [ktonne/year]. However, including new projects, this amount would increase to nearly 800 [ktonne/year] (Port of Rotterdam, 2020c). For production costs of SMR and CCS, please refer to Appendix B.1.

Note that hydrogen production via SMR is subjective to the European Union Emission Trading System (EU ETS). For every tonne, CO_2 emitted while producing; a payment has to be made. Logically, a higher ETS price will stimulate the use of green or blue hydrogen. Vice versa, a lower ETS price makes the application of conventional fossil fuels attractive. As can be seen in Figure 10, the ETS price is doubled in the last two years, exceeding a price of 50 [€/tonne CO_2] in June 2021. Moreover, a law has been proposed to apply a minimum ETS price of 125 [€/tonne CO_2] in 2030 (PWC, 2020). However, this law still needs to be passed by the Dutch Government.

Figure 10: EU ETS price in the last two years. Adapted from EMBER (2021)

3.2.2 Electrolysis

This section provides an exploration of the potential of the use of water electrolysis. Two factors are needed for hydrogen production by electrolysis. First, a sufficient supply of renewable energy, and second sufficient electrolysis capacity. We assume that there will be a sufficient amount of water for any production capacity.

Recently, a few projects have been initiated to scale up the capacity of electrolysers in the Netherlands. In Delfzijl, Nouryon and Gasunie are on the edge of the realisation of a 20 [MW] electrolyser to produce up to 3.000 [tonne] green hydrogen per year. Also, a technical feasibility study is conducted for an electrolysis plant with a capacity of 1 [GW] in Zeeland, called Hydrogen Delta. A feasibility study regarding a 100 [MW] green hydrogen plant is ongoing in the Port of Amsterdam. Likewise, RWE is investigating a 100 [MW] green hydrogen plant nearby Eemshaven (De Laat, 2020). Shifting our scope to the PoR, Nouryon and BP are planning to build a 250 [MW] electrolysis plant that could be able to produce 45.000 [tonne] of green hydrogen annually. In addition, Shell aims to have 200 [MW] electrolyser capacity running by the end of 2030. The Port of Rotterdam has the ambition to increase the electrolysis capacity to 2 [GW] by 2030 ($\approx$ 360 [ktonne H_2/year]) (Port of Rotterdam, 2020c). The Dutch climate agreement aims for an electrolyser capacity of 3-4 [GW] by 2030 in the Netherlands (van Soest and Warmenhoven, 2019). Please refer to Appendix B.1 for the hydrogen production costs via electrolysis.

The second factor that needs to be taken into account when considering electrolyser capacity is the available RES for hydrogen production. In 2020, the Netherlands produced nearly 17 [TWh] sustainable electricity (CBS, 2020). This number is expected to rise to 128 [TWh] by the end of 2030 (Hammingh and Hekkenberg, 2017). In this thesis, it is assumed that sustainable electricity is generated by offshore wind (Gasunie, 2020). Gasunie (2018) argue that the amount of installed wind capacity on the Dutch North Sea approaches 40 [GW] by 2050 with a maximum of 80 [GW] in total (Gigler and Weeda, 2018; Gasunie, nd; Notermans et al., 2020). Port of Rotterdam (2020c) narrows down this number by arguing a maximum installed capacity of 60-72 [GW]. Depending on the operational hours, this could approximately produce 200 [TWh]. However, one should consider that electricity is widely used in various applications. Moreover, the most efficient way to use it is in its primary form. In other words, only a tiny part (the surplus) of the available electricity will be used to produce hydrogen.

3.2.3 Potential for domestic hydrogen production

The above paragraphs show a brief description of the domestic hydrogen production capacity in the PoR. In the PoR 800 [ktonne/year] is expected to be produced by SMR (including CCS). This would lead to a production of approximately 2.000 [tonne H_2/day]. Regarding electrolysis, a minimum of 2 [GW] is expected to be realised in 2030. However, the available wind capacity is uncertain as no specific pat of the available wind capacity is yet assigned to hydrogen production.

3.3 Hydrogen demand

This section aims to explore three topics. First, the possible future hydrogen demand in various end-user sectors. Second, quality considerations of the various end-user sectors will be described. Finally, the transportation infrastructure to these end-user sectors will be discussed. In the end, we will determine which end-user sectors and what transportation infrastructure will be included in this study.

3.3.1 Hydrogen demand in end-user sectors

The attention given to hydrogen has various reasons. Apart from possible sustainable production methods, its wide range of applications is the primary driver of hydrogen's recognition. However, a vast global debate is held between scientists, scholars and media about the potential of hydrogen in this range of applications. Note that this section evaluates the current status and knowledge regarding hydrogen applications and is mainly based on climate and technology outlooks. The perspective could change drastically in the coming years and decades.

In the work of Hydrogen Council (2020) four major sectors are mentioned; mobility, heat and power for buildings, heat and power for industry and industry feedstock. Narrowing our scope down to the Netherlands, a few studies have been conducted regarding hydrogen in different applications. Noteworthy is that most studies have used 2050 as a reference year (Jepma et al., 2019; Detz et al., 2019a; Samadi et al., 2016; Gigler and Weeda, 2018; Detz et al., 2020; van den Noort et al., 2017). The reason for this is the high uncertainty of the development of techniques that must facilitate hydrogen use. Samadi et al. (2016) only focused on industrial processes in the PoR. Jepma et al. (2019) research the impact of a hydrogen economy in 2050 on the employment rate, climate change impact and the energy system costs. Gigler and Weeda (2018) indicated a possible demand of 1690 PJ/year in 2050 (or 14,1 Mtonne H_2/year). Gigler and Weeda (2018) use similar sectors compared to Hydrogen Council (2020), such as heat and power for industry, industry feedstock, mobility, heat and power for buildings. Peculiar is the attention for hydrogen demand for synthetic fuels. For example, synthetic fuels could be used for the maritime shipping and aviation sector. van den Noort et al. (2017) did not include these sectors in their work, resulting in a maximum hydrogen demand in 2050 of 710 PJ/year (approximately 6,0 Mtonne H_2/year). The potential of synthetic fuels is enormous. Another major study is the work of Detz et al. (2020). They evaluated several scenario studies for various sectors regarding hydrogen use in 2030, 2040, and 2050. The result is presented in Figure 11.

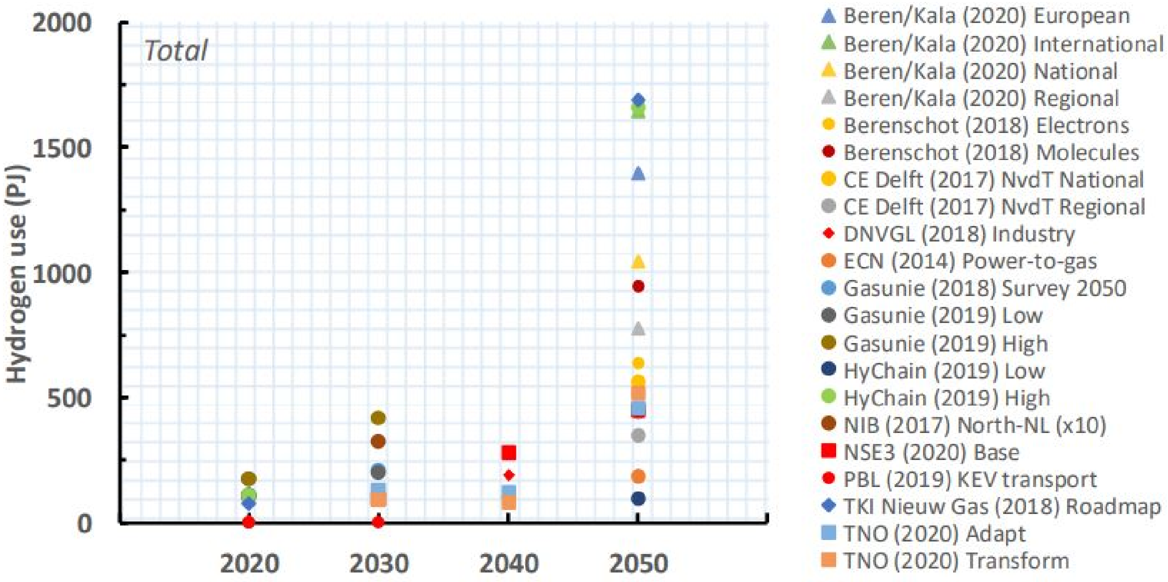


Figure 11: Hydrogen demand according to various studies in the years 2030, 2040, and 2050. Adapted from Detz et al. (2020).

Remko Detz is a leading scholar in this field of work. In another work, he and his colleagues found a potential hydrogen demand of 14 [Mtonne/year] in 2050. Their results are shown in Table 4.

Table 4: Dutch hydrogen demand in 2050 in the Netherlands. Aggregated overview from Detz et al. (2019b) & Port of Rotterdam (2020c).

End-user sectors	PJ	Mton/year	Ton/day
Feedstock chemicals	97	0,8	2192
Process heat industry	127,5	1,1	3013
Build environment	13,5	0,1	274
Mobility over land	102,5	0,8	2191
Aviation (H2 in synthetic fuels)	115	1,0	2739
Maritime shipping (H2 in liquid fuels)	375	3,2	8767
Export to Germany	960	8,0	21918
Export to NWE	600	5,0	13699

Note that the studies discussed above focus on the hydrogen demand that could replace current energy use (accounted for by fossil fuels). In the study of Port of Rotterdam (2020c), the potential hydrogen export is measured based on the current energy export. Please refer to Appendix B for more detail on the hydrogen used in these end-user sectors.

An essential aspect of stimulating hydrogen demand is cost-competitiveness. Hydrogen Council (2020) argue that advancements in technology developments will result in low-cost and, in some cases, even competitive prices compared to conventional fuels. The projections above regarding hydrogen demand are relevant. However, one must consider that maximum demand scenarios only can be reached if technology achieves such maturity that the costs will be competitive to conventional fuels. However, policies and regulations imposed by, for instance, governments could stimulate the use of the more expensive but also more sustainable hydrogen technologies.

The work of Detz et al. (2019b) and Port of Rotterdam (2020c) based their findings on the current energy imports and exports in the PoR. Geopolitical aspects related to the hydrogen demand are not included in their findings. As shortly discussed in the introduction of this thesis, the window of opportunity for the PoR to become a large hydrogen hub is closing. According to Notermans et al. (2020), other ports (e.g. the Port of Antwerp or the Port of Hamburg) could facilitate extensive hydrogen import infrastructure and absorb a significant amount of hydrogen demand that is allocated to the PoR in the work of Detz et al. (2019b) and Port of Rotterdam (2020c).

3.3.2 Quality considerations

It is important to consider that hydrogen can be perceived with various qualities. The quality of hydrogen is directly linked to its purity[2] Requirements per application of hydrogen can vary greatly. In general, the quality of hydrogen is divided into three groups (Cappellen van et al., 2018):

1. Fuel cell quality: This hydrogen has a purity of >99,99% and, thus, has no contamination of other gases.
2. Industrial quality: This hydrogen must have a purity of above 99,95%. This type of quality is usually used for feedstock in industrial processes.
3. Energy production quality. This category consists of hydrogen with low purity (>95%). This quality is produced with the SMR production method.

The higher the purity, the higher the investment costs of production methods. Ideally, the hydrogen with the highest purity will be used for the fuel cell and industrial feedstock. As discussed, LH_2 has the

---

[2] From now on this thesis will refer to this as hydrogen quality

highest quality grade among the three hydrogen carriers. LOHC and NH_3 require expensive process equipment to increase the purity of the hydrogen retrieved. Regarding the hydrogen backbone in the Port of Rotterdam, it is yet to be decided what the minimal hydrogen quality has to be. In Appendix B the use of hydrogen in the end-user sectors is explained in more detail. In short, the 'feedstock chemicals' and the mobility sector' require the highest hydrogen quality. The 'maritime shipping' and 'aviation' sectors require similar standards if synthetic fuels are produced. However, for the 'maritime shipping' sector NH_3 can be directly applied, and for the 'aviation' sector, the direct use of LH_2 is possible. Lower hydrogen quality standards are sufficient for the 'process heat industry' and the 'building environment' sector. The export sectors do not have specific technological requirements. However, it does bring some additional complexities. This will be discussed in the following section.

3.3.3 Local distribution

Hydrogen distribution refers to the transportation from the PoR towards the end-user sectors. This can occur through two forms; as the carrier or as (gaseous) hydrogen. Do note that the first form is not included in our model. Nevertheless, it is important to discuss. If the carriers are transported, the PoR is used only as a transit port. The carriers can be transported via pipelines, smaller barges, trains or trucks. For LOHC and NH_3 pipelines can be built. However, LOHC transportation by pipeline is inefficient as the residual LOHC must be returned to its original location after the cracking process. NH_3 transportation by pipeline is complex as NH_3 is highly flammable and toxic resulting in environmental and social issues. LH_2 (e.g. -253 °C) is too cold for transportation by pipeline. Where NH_3 and LOHC can largely build on existing barges, trains, or trucks to be transported, LH_2-barges and LH_2-rail tankers are still at the development stage. LH_2-trucks are already in use (Reuß et al., 2017; Office of Energy Efficiency & Renewable Energy, 2021; Elishav et al., 2021). However, a big disadvantage of truck-transport is the CO_2-emissions are higher, and it is usually expensive when large volumes are transported over long distances (Nayak-Luke et al., 2021). In the case of export via gaseous hydrogen, the carriers are reconverted in the PoR. Subsequently, the hydrogen is transported via pipelines. We do acknowledge that gaseous hydrogen transportation could also raise environmental and societal issues. However, there is nowadays already a large hydrogen pipeline network present and managed by the company Air products (Gasunie, 2021).

Due to the projected growth in hydrogen demand, a new hydrogen distribution infrastructure is planned to be constructed. The Port of Rotterdam and Gasunie are finalising the last phase of the construction of a hydrogen backbone in the Port of Rotterdam. The hydrogen backbone is a pipeline (diameter = 600 mm) in which hydrogen will be transported. This hydrogen backbone will be an open-access pipeline. In other words, companies or organisations that want to produce or consume hydrogen can be connected to these pipelines. Also, import terminals, refuelling stations, and the building environment can be connected to this pipeline. Finally, in the following years, the pipeline in the Port of Rotterdam will be connected to the national hydrogen backbone. In this way, the industrial cluster of Rotterdam can be connected with other industrial clusters like Chemelot and Antwerp (Gasunie, 2021). The project of the national hydrogen backbone is called; Hyway27. A project name has been chosen to emphasise the ambition to realise the national hydrogen backbone by 2027. Delta corridor is another project to expand the hydrogen infrastructure. This project, initiated by the Port of Rotterdam, the Dutch Government, and Chemelot, aims to realise a pipeline system including four commodities, C4-LPG, propane, hydrogen, and CO_2. A feasibility study concluded that the execution would cost more than 1 billion euros. A connection to the industrial clusters of Antwerp and North Rhine-Westphalia would increase the usage. A connection is essential to recover the investment costs (Delta Corridor, 2021). It is unknown in what year this project is envisaged to be accomplished.

3.3.4 Overview hydrogen demand and distribution

This thesis will include the following end-use sectors: feedstock industry, process heat industry, build environment, mobility (overland), synthetic fuels (aviation & maritime shipping), and export. For an elaboration on how hydrogen will be used in these sectors, please refer to Appendix A. The data in the work of Port of Rotterdam (2020c) will be used as a reference point. Because these data refer to the year 2050, we will use that data to interpolate data for the earlier years (for more explanation, see Appendix B.2). Quality considerations in various end-user sectors could potentially result in a sector's preference for a specific carrier. However, this is still uncertain. Geopolitical uncertainty is related to the presence of nearby located ports that could consume a large part of the projected hydrogen demand in and around the PoR. In our model, we assume that the carriers are reconverted in the PoR, and gaseous hydrogen is transported towards the end-user sectors.

3.4 Summation of case inputs

This section aims to provide a clear overview of the valuable case information used as input for our model. Please note that the uncertainties addressed in the previous section align with these case inputs. The case inputs are categorised into hydrogen import supply chain, domestic production, and hydrogen demand. An overview is presented in Figure 12.

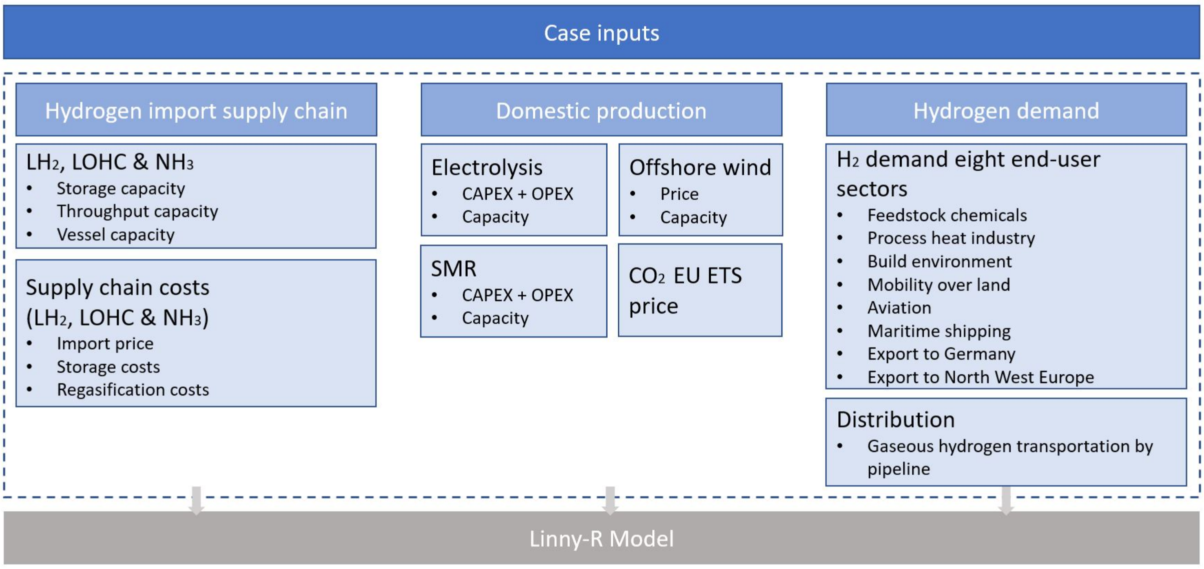


Figure 12: Overview of most important case inputs.

3.5 Uncertainties related to hydrogen in the Port of Rotterdam

This section aims to emphasise the uncertainties related to our system, which has been examined in the previous sections. Due to our analysis in chapter 2 and the case exploration in this chapter, we were able to identify economic, technological, and geopolitical uncertainty related to the hydrogen system in the Port of Rotterdam. We acknowledge that some uncertainties are uncertainties related to the hydrogen system in general. Nevertheless, these uncertainties are included due to their relevance to our case study. The structure of this section is as follows. First, the uncertainties related to the hydrogen import supply chain will be discussed. Second, uncertainties related to domestic production are evaluated. Third, uncertainty in the hydrogen demand will be discussed. Finally, an overview of the uncertainties is presented.

Uncertainty in the hydrogen supply chain is widely present. The PoR already signed numerous Memoranda of Understanding with various countries to develop a hydrogen supply chain to the PoR. However, potential export countries have not yet made any decision on what carrier they will produce. Moreover, the production capacities in those countries are still unknown as excessive RES capacities must be examined. These uncertainties inherently cause the uncertain import prices of the three hydrogen carriers identified by (Terwel and Kerkhoven, 2018). Other uncertainties relate to the technology required for the supply chain. Where LOHC and NH_3 can primarily rely on existing infrastructure. The vessel capacities, storage tanks and other process equipment of LH_2 are still in an early stage of development, resulting currently in high prices. However, future cost reductions depend on the technology development in the coming years (Wijayanta et al., 2019). The uncertainty in the prices of the three hydrogen carriers makes the realisation of the import terminals for a specific hydrogen carrier rather complex. Hence, as described in chapter 2, they require enormous investments and is highly asset-specific, making investment decisions complicated. Furthermore, the uncertain hydrogen demand in various sectors makes designing suitable scaled import terminals complicated as requested storage and throughput capacities are hard to determine. Again, technology developments are crucial as they determine how efficient and, thus, against what price hydrogen can be used in the end-user sectors. Geopolitical forces are also causing uncertainty in the import supply chain. Firstly, former oil and gas countries could disrupt the emergence of a global hydrogen market as they keep their production levels up and, therefore, lower fossil fuel prices. In turn, the relatively expensive hydrogen import supply chain would be economically less attractive (Pflugmann and Blasio, 2020). Second, international supply chains are inherently subject to uncertainty. Last year, the Suez canal was blocked for a few days resulting in significant disruptions in various supply chains. Uncertainty in a hydrogen supply chain could affect the security of supply in the Port of Rotterdam. Finally, establishing a supply chain for only one specific carrier into the Port of Rotterdam could make the Port and the Netherlands vulnerable to geopolitical forces.

Uncertainties regarding domestic hydrogen production are present in production methods and their capacities, policies and regulations. Economic uncertainty would relate to the production costs of the electrolysis and SMR methods. However, many scholars have already projected future production costs for these methods (IEA, 2019). Therefore, we used these production costs as case-input rather than as uncertainty. In section 3.2, we identified several potential projects that would lead to an expansion of both offshore wind and electrolysis capacity. However, uncertainty remains in what actually will be realised regarding hydrogen production capacity in the coming years. Another factor of uncertainty is the availability of 'green' electricity that is available for hydrogen production. This thesis assumes that offshore wind will be used as an energy input for electrolysis. However, the work of Gigler and Weeda (2018) also argued that most electricity produced by offshore wind would directly be used instead as an energy input for electrolysis. Moreover, the production output of electrolysis fluctuates if only wind energy is used as energy input. This could be troublesome in case end-user sectors require a constant inflow of hydrogen. The renewable electricity price is uncertain. Other uncertainties are related to policies and regulations. In section 3.2, we identified that hydrogen production via SMR (CCS) is subject to the EU ETS price. The projection is that the EU ETS price will only increase. This would lead to significantly higher prices for SMR and CCS. In the coming years, other policies could affect the use of SMR as hydrogen production as it uses fossil fuels as energy input. A realistic future policy would be a total exclusion of SMR, leaving the role of SMR in the security of supply doubtful (PWC, 2020). To conclude, uncertainty in the domestic hydrogen production affects hydrogen supply chain infrastructure, as it is unknown what volumes can be produced domestically against what price. In that context, it remains unknown what import volumes are required, and thus, what infrastructure is required for this hydrogen import.

Unknown technological developments cause uncertainty in the hydrogen demand in end-user sectors. To clarify, if new technologies could reduce conventional fuels in many sectors, the hydrogen demand could rise exponentially, especially if this could be established in energy-intensive sectors like the aviation and maritime shipping sectors. However, if technology developments in those energy-intensive sectors are lacking, hydrogen demand could remain at a relatively small scale due to high costs. Uncertainty is also present in the sector's preference for a specific carrier. These preferences could completely shift the hydrogen import if, for instance, the hydrogen demand for one specific carrier is very high compared to the other two carriers. Another aspect of uncertainty in hydrogen demand is related to time. To establish the security of supply, hydrogen must be available at any point in time. Hydrogen production by electrolysis could be subjective to weather conditions. Also, hydrogen import is subjective to the arrival of vessels. For that reason, storage and throughput capacities are vital to respond to hydrogen production and demand fluctuations. In turn, this makes designing hydrogen import terminals highly complicated as higher volumes provide more flexibility and correspond to more significant up-front investments. Therefore, optimising hydrogen import terminals is critical to establishing hydrogen security of supply against minimal costs. Another aspect of uncertainty is the presence of other nearby located hydrogen clusters that could consume some of the hydrogen demand that is projected for the PoR.

An overview of the uncertainties related to our three sub-systems is presented in Figure 13. Please note that the uncertainties identified in this chapter are not used as case inputs, except for one; hydrogen demand. How hydrogen demand uncertainty is used as case-input, and therefore not presented in Figure 13, is further explained in section 4.2.3. Other uncertainties are analysed through sensitivity and scenario analyses.

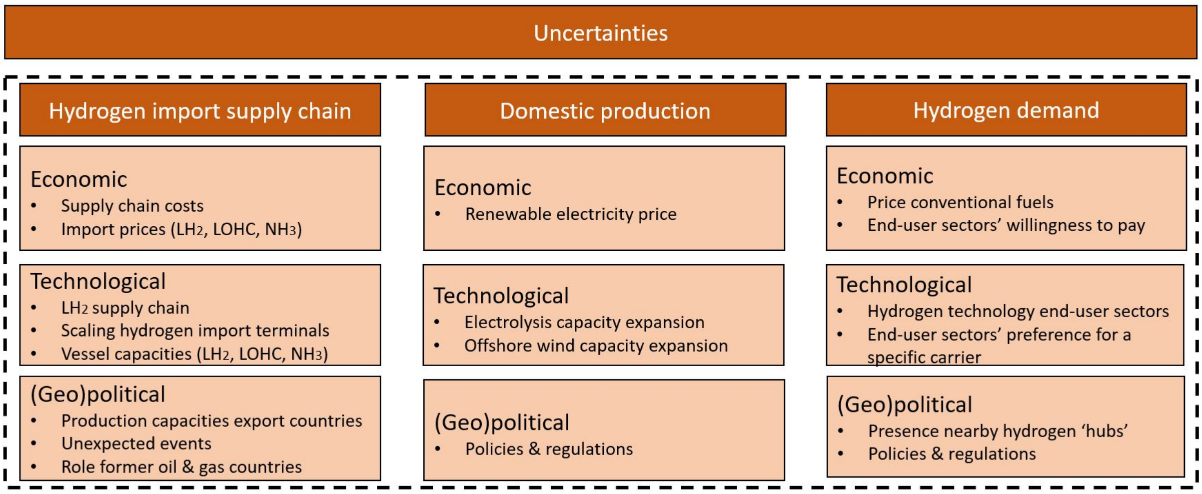


Figure 13: Overview of economic, technological, and geopolitical uncertainties related to the three sub-systems in the Port of Rotterdam.

3.6 Conceptual design

Based on the previous sections, a conceptual design is made that will provide the foundation for our model. The conceptual design is shown in Figure 14. Please note the supply and demand concept present in Figure 14. We assume the demand is either met by domestic production or via import.

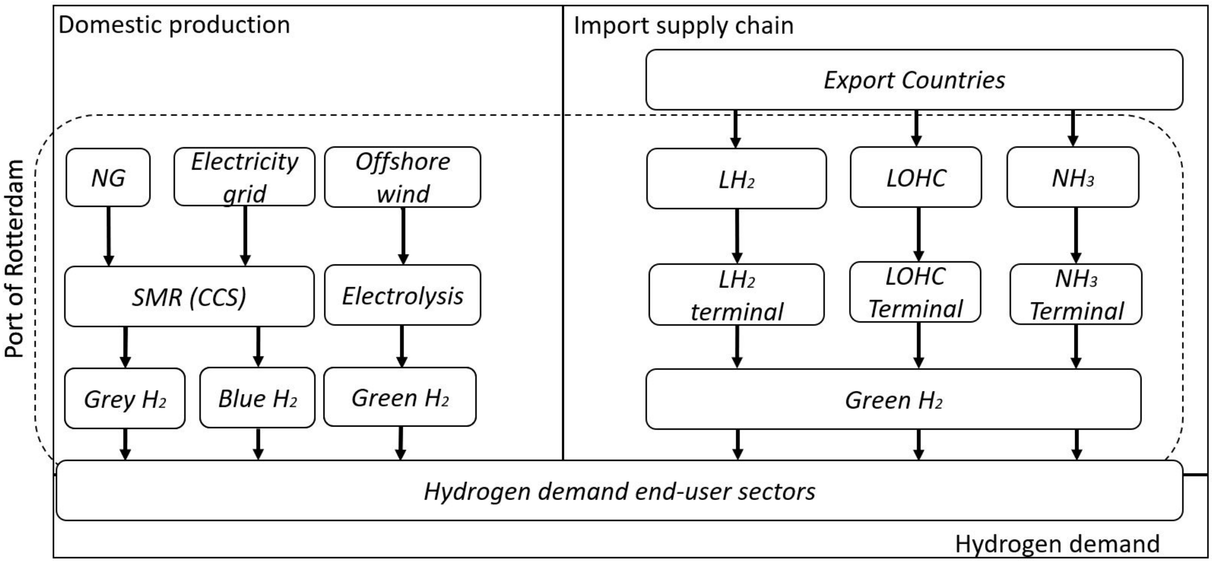


Figure 14: Systematic representation of hydrogen system in the Port of Rotterdam

On the right-hand side in Figure 14, the hydrogen import supply chain is shown. Export countries produce a surplus of hydrogen, making a share of their hydrogen production available for export. No specific export countries are included in this study. We assume that the hydrogen can be shipped via three different carriers; LH_2, LOHC, and NH_3 with each of their supply chain costs. These carriers are assumed to be produced sustainably, and therefore, 'green'. The three carriers are shipped in carrier-specific vessels. Once arrived in the PoR, the carriers are stored in an import terminal. An import terminal has two functions: storage & throughput. Storage refers to the receiving of the carrier and its storage in the terminal. Throughput refers to the re-conversion from the carrier back to gaseous hydrogen. Note that each carrier has its specific infrastructure. The direct use of the hydrogen carriers is not included in this study.

In Figure 14, the domestic production of hydrogen is presented on the left side. The two production methods included in this system are water electrolysis and Steam Methane Reforming (SMR). The energy input for electrolysis is provided by offshore wind. Therefore, hydrogen is only produced when electricity from offshore wind is available. Consequently, the production capacity of electrolysis is variable. Regarding SMR, a choice is made to capture a part of the produced CO_2 by applying Carbon Capture Storage (CCS). The production capacity of SMR (with or without CCS) can be varied as it is not dependent on fluctuating renewable energy production. Electrolysis, SMR, and SMR, including CCS, generate the three types of hydrogen; grey, blue, and green. Note that this study uses a system perspective. As a result, the total production capacities of the production methods are considered rather than several smaller production units.

Finally, the hydrogen produced or imported into the PoR is distributed to various end-user sectors by hydrogen distribution infrastructure (pipelines). These end-user sectors can be located either within or outside of the geographical boundaries of the PoR.

3.7 Case study as reference for model

In this chapter, the case of the Port of Rotterdam has been explored and analysed. The following two sub-questions have been answered:

- What are relevant inputs to model an integrated hydrogen system located in the Port of Rotterdam?

- Which uncertainties are present regarding an integrated hydrogen system in the Port of Rotterdam?

To summarise, first, the three sub-systems have been discussed; hydrogen import supply chains, domestic hydrogen production, and hydrogen demand. Then, case inputs are collected in section 3.4. This data will be used to formalise a working model in Linny-R. Then, the identified uncertainties related to the respective sub-systems have been described. Subsequently, a conceptual design is presented in the last section that will function as the blueprint for our model. Through our model, we aim to analyse the identified uncertainties to answer the main research question.

4 Modelling

In this chapter, the processes in the defined system are formalised in a model. In that way, the following sub-question, as stated in Chapter 1, can be answered:

- How can an integrated hydrogen system of the Port of Rotterdam be formalised in a working model?

As outlined in chapters 1 and 2, Linny-R will be used as a modelling environment that enables solving MILP problems. Gurobi is the solver that powers Linny-R. Pieter Bots, the developer of Linny-R, introduced the Gurobi-solver to replace the lp_solve solver which we used at the beginning of our study. The Gurobi solver reduced the computational times by roughly a factor of 10. The conceptual design and the case exploration in chapter 3 will be the foundation of our modelling process and philosophy. The outline of this chapter is as follows. First, Linny-R and its working are shortly described. Second, the model will be described by first presenting an overview of the complete model. Then, in more detail, the three sub-models will be elaborated upon. Third, our model will be verified and validated. Finally, a model test run will be conducted, and the results will be presented to understand how our model works and how the results can be interpreted.

4.1 Linny-R

The model is made in Linny-R. Basically, Linny-R is developed to represent (industrial) production systems reflected by basic concepts such as: e.g. *processes*, *products*, *levels*, and *rates* Bots (2021). The components in a model (processes, products, levels and rates) are used as decision variables and constraints. A short description of part of the model is described below to illustrate the basic working of Linny-R.

Linny-R is ideal for production systems in industrial clusters (Bots, 2021). A production system involves a production process that can convert input (e.g. energy, water) into output (e.g. H_2) to add more value to the production chain. A process often involves an artefact (e.g. an electrolyser or a steam methane reformer) that has a certain Capital Expenditures (CAPEX) and Operational Expenditures (OPEX). The number in the upper left corner of the process indicates the maximum production capacity. The above is visualised in Figure 15.

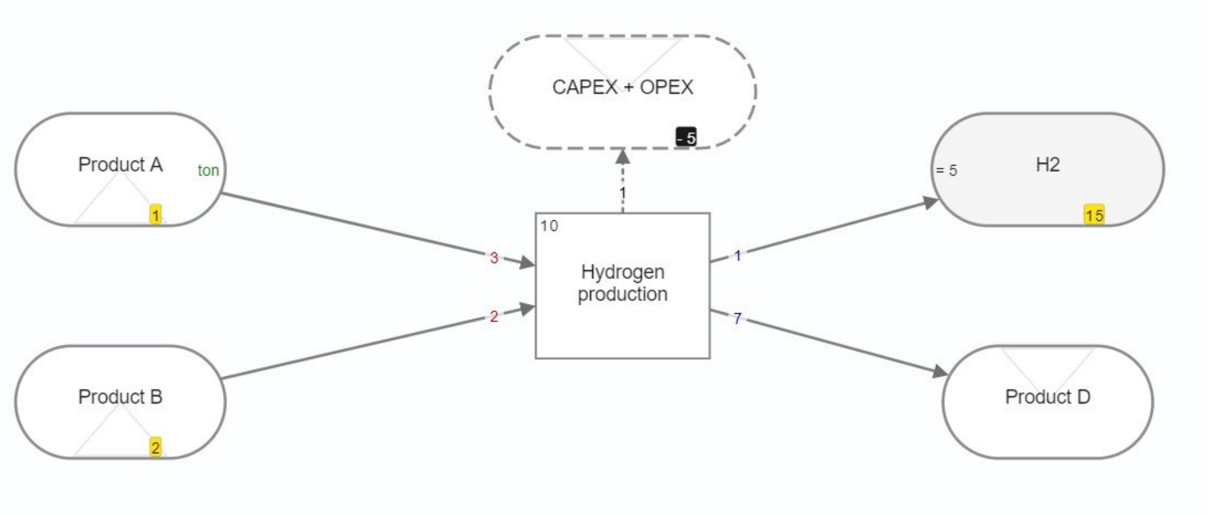


Figure 15: Hydrogen production system in Linny-R

The illustration, presented in Figure 15, shows a hydrogen production process. In the case of hydrogen production, we assume two methods; electrolysis and SMR. Both methods rely on the same principle discussed above. The inputs for electrolysis are green electricity and raw water, and the outputs are hydrogen and oxygen. The links connecting the products with the process are given weight, corresponding with the required input or output. SMR is the other hydrogen production option considered in our system. Natural gas, electricity and water are the inputs for this process. Hydrogen, wastewater, and CO_2 are the outputs (Cappellen van et al., 2018).

4.2 Model description & model objective

This section presents our model in Linny-R. First, a complete overview of the model is presented. Then, the modelling process of each sub-model is explained. Additionally, data inputs and assumptions are mentioned.

Figure 16 shows a complete overview of our model in Linny-R. Similar to our case exploration, the model is divided into three sub-models; hydrogen import (green), the domestic production of hydrogen (blue), and hydrogen transportation to the end-user sectors (grey). Please note that this is not an investment-based model. This model is built to analyse daily operations. In other words, investment costs for, say, import terminals are not included. This stems from our perspective that, as touched upon in the introduction, we aim to analyse what infrastructure is required to design a reliable hydrogen infrastructure system in the Port of Rotterdam that enables the transition towards sustainable hydrogen, regardless of the costs.

For our model, the following settings are used. First, the model has a daily time resolution. To clarify, every time step represents a single day. In this way, the arrival of hydrogen carrier vessels, the hydrogen production by SMR and electrolysis, and the hydrogen demand in the end-user sectors could appropriately be analysed. For the same reason, the second setting is the run-length equal to 368 time steps. Three extra days are simulated for two reasons. First, hydrogen import can not occur in the first two days, as hydrogen import is delayed by two days. This is further explained in the following section. Second, due to the optimising nature of Linny-R, it will release all hydrogen stored in the terminals as it notices that will be the last day of the run for cost-minimisation reasons. However, in reality, after the last day, a new year starts. Therefore, an extra day is added to the simulation to 'trick' Linny-R and stop the model from performing unwanted behaviour. For the results, only the data of t=3 till t=367 are used. The third setting refers to the block length, which is set at three time-steps and the look-ahead, which is set at five time-steps. This represents available information of eight days. The most important reason to apply this configuration of settings is to represent available information regarding weather conditions which are often given for a weekly basis.

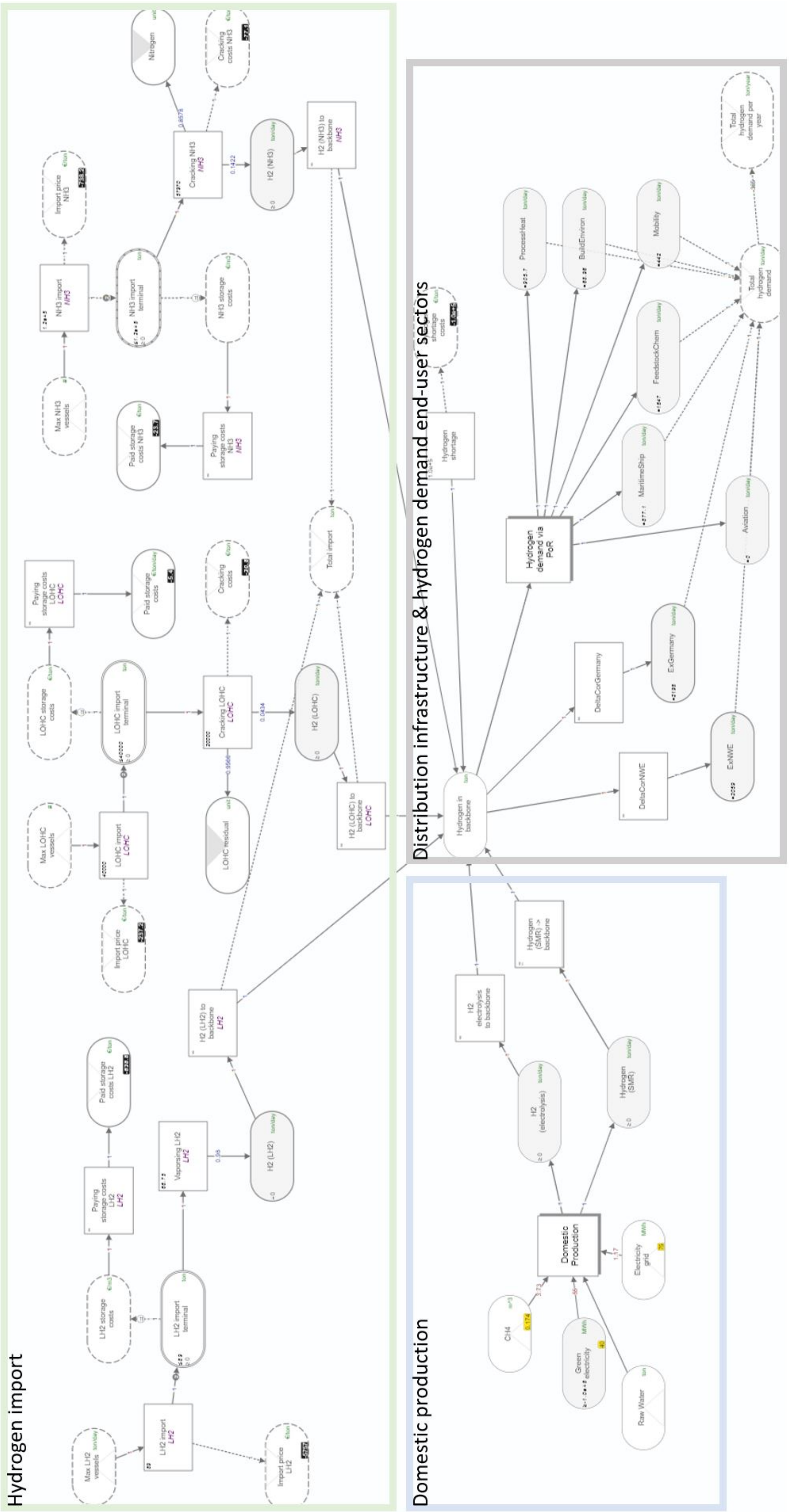


Figure 16: Overview model in Linny-R. This figure is also presented, in higher resolution, at the end of this thesis report.

4.2.1 Representing hydrogen import in Linny-R

This section describes the sub-model related to hydrogen import. An overview is presented of how the import of LH_2 is modelled.

This model simplifies the infrastructure as it consists of only a storage tank (import terminal) and a regasification process. In Figure 17 the LH_2-import is illustrated. Based on this illustration, the modelling of import is explained as the LOHC, and NH_3 import follow the same modelling philosophy.

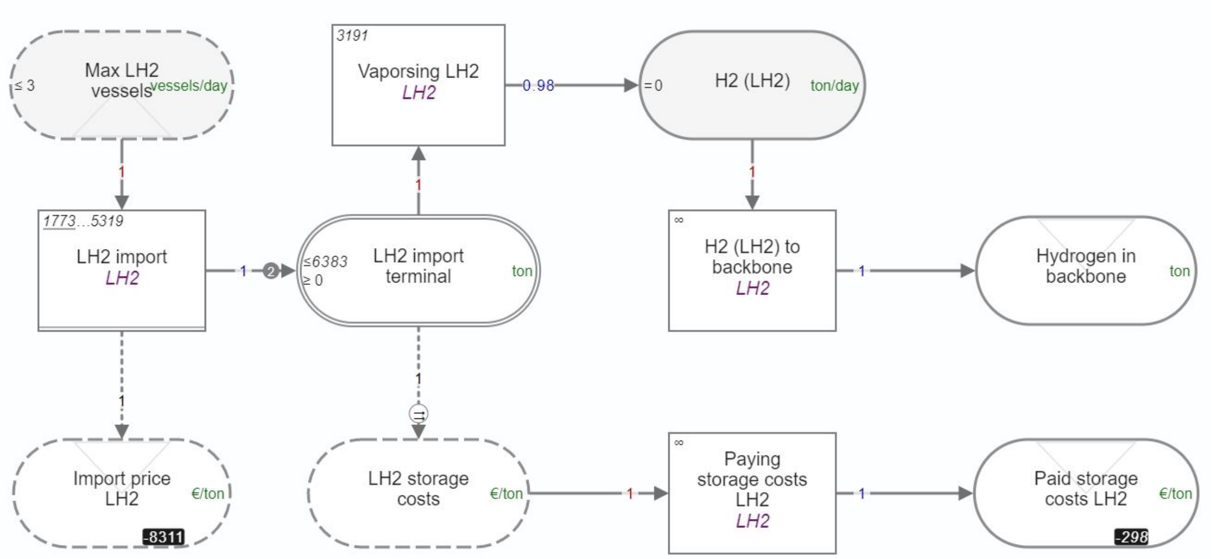


Figure 17: LH_2-terminal modelled in Linny-R

At the left side of Figure 17, hydrogen is imported via process ‘LH_2 import’. Every ton that is imported is taxed with the import price (underneath ‘LH_2 import’). Please note that an upper- & lower bound can be added to this process. The extra line underneath process ‘LH_2-import’ allows the model to ‘shut down the process if the optimised solution is constrained by the lower bound of the process. In our model, the lower bound is set at the maximum capacity of a LH_2-vessel. In this way, we prevent the model from representing the arrival of less than one completely filled vessel per time-step. However, we were not able to only allow the arrival of completely filled vessels. As a result, the model does allow for the arrival of, say, one and a half-filled ship in a single time-step or the arrival of hydrogen equal to, say, 2.3 times the capacity of a vessel in a single time step. This results in somewhat unrealistic behaviour of our model. The upper bound of the process ‘LH_2-import’ is determined by the upper-bound (UB) data-product ‘Max LH2 vessels’. To clarify, the upper-bound of ‘LH_2-import’ is modelled as *[Capacity LH2-vessel] * [MaxLH2vessel | UB]*. In this way, the modeller can easily adjust import constraints.

Subsequently, the imported LH_2 is stored in product ‘LH_2 import terminal’. The upper bound of this product can easily be adjusted and varied by the modeller. The model even allows an upper bound set at unlimited. Logically, the lower bound can not be lower than zero as this would imply that the LH_2-terminal could produce LH_2. For every ton that flows through the storage, storage costs are taxed. To clarify, data product ‘LH_2 storage costs’ reads the amount of LH_2 that flows through product ‘LH_2 import terminal’. Consequently, for each amount of LH_2 process ‘Paying storage costs LH_2’ produces a new product (e.g. ‘Paid storage costs LH_2’) associated with a negative price. In that way, costs are attributed to the storage of LH_2. Note that the import and storage tank link is labelled with the number ’2’. The link represents the delay of import. In this way, the solver can ’purchase’ LH_2 at, say, t=1, and only receives the LH_2 at t=3, instead of ’purchase’ and delivery on the same day. By modelling this in such a way, we aim to approach real-world processes. After storage, LH_2 is converted to gaseous hydrogen with an efficiency of 98% please recall Table 1 in section 3.1.2. Note that, only in the case of LH_2, the regasification process has no corresponding costs, contrarily to LOHC and NH_3 that do have regasification costs. After the vaporisation process, gaseous hydrogen is transported via the backbone to the end-user sectors.

It is essential to address the implications of this modelling method. Be aware that this model in Linny-R uses MILP as a method. Therefore, the model solves the problem by finding the most optimal (e.g. the cheapest) solution given a specific set of constraints (e.g. storage and throughput capacity). In that context, the way import occurs is determined by these two factors. This could result in the following behaviour of the model. The cheapest hydrogen carrier will account for all hydrogen imports up to its level of storage and throughput capacity. Then, the second cheapest hydrogen carrier is addressed. If this carrier, and its corresponding infrastructure, cannot meet the demand, the most expensive hydrogen carrier in that scenario is used.

Finally, the following assumptions are made regarding this sub-model:

- Hydrogen import is always available if required by the optimal solution of our model. In that context, we do not include the production capacities in export countries.
- Hydrogen import is delayed by two days.
- All hydrogen carriers are reconverted to gaseous hydrogen. Therefore, no direct use of hydrogen carriers is included.

4.2.2 Representing domestic hydrogen production in Linny-R

This section describes the sub-model 'Domestic hydrogen production. First, an overview of the model in Linny-R is presented. Then, we explain in more detail how offshore wind is modelled in Linny-R.

Two domestic hydrogen production methods are included; electrolysis and SMR. The latter method also involves the option of capturing CO_2 through CCS. If the CO_2 is captured, it will be stored via PORTHOS, in case CCS is not applied, the produced CO_2 will be emitted in the air. The CO_2 that is not captured is subject to the EU ETS price. Through optimising, Linny-R always chooses the cheapest option. The hydrogen produced will be transported to the end-users by the hydrogen backbone. An overview of this sub-model in Linny-R is presented in Figure 18. Please note that no price is allocated to offshore wind as this is incorporated in the CAPEX of electrolysis. This is based on the research of IEA (2019). Other input values and data for the two production methods are presented in Appendix B.1. We assume an electricity price (grid) equal to 75 [€/MWh] and a natural gas price equal to 0,3 [€/m^3] (IEA, 2019).

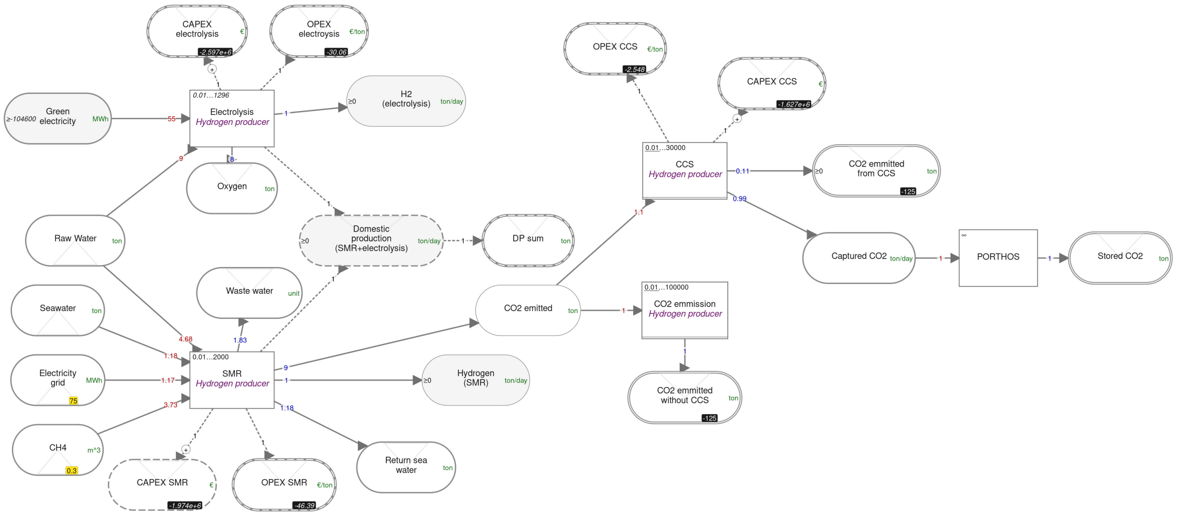


Figure 18: Domestic hydrogen production sub-model in Linny-R. This figure is also presented, in higher resolution, at the end of this thesis report.

Now we shift our focus to the modelling of offshore wind in Linny-R. The energy input of the electrolysis process is generated by offshore wind. Offshore wind has a volatile production output because it relies on wind. A capacity factor has been used to replicate the volatile production output. The capacity factor times the installed offshore wind capacity results in the produced electricity available for hydrogen production. In this way, the modeller can easily vary the installed offshore wind capacity and the installed electrolysis capacity. The capacity factor profile is presented in Figure 19.

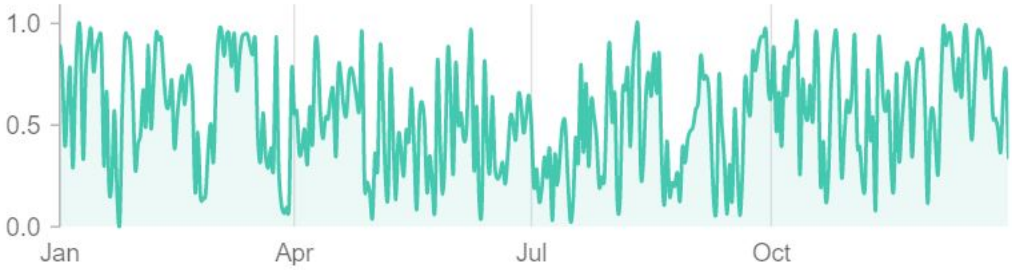


Figure 19: Offshore wind capacity factor

The offshore wind turbine that has been used to generate the capacity factor is the Vesta V164 7000. This wind turbine has a hub height of 125 [m] and an average capacity factor of 53,11 [-] (Renewable Ninja, nd). Therefore, the capacity factor in Figure 19 is a result of such a wind turbine located approximately 150 km off the coast of the Netherlands. Note that this wind profile is used to show the varying wind conditions for a representative year. Further note that in the future, innovation regarding wind turbines can lead to better-performing wind turbines.

4.2.3 Representing hydrogen demand in Linny-R

The last sub-model that we will discuss is the hydrogen demand of the end-user sectors. First, an overview of this sub-model is presented. Then, we explain in more detail how uncertainty in hydrogen demand is modelled.

The hydrogen demand, spread over eight different end-user sectors, must always be met, regardless of the costs. The hydrogen, domestically produced or imported, is transported via the hydrogen backbone in the PoR to the end-user sectors. The transportation is facilitated by either the pipeline in the PoR, the delta corridor, or the national hydrogen backbone. We do not assume distribution costs. The overview of this sub-model is presented in Figure 20. As can be seen in Figure 20, the hydrogen distribution infrastructure that transports hydrogen to Germany and North-West Europe is labelled as Delta Corridor. However, we acknowledge the possibility that also the national hydrogen backbone will be used for these export streams.

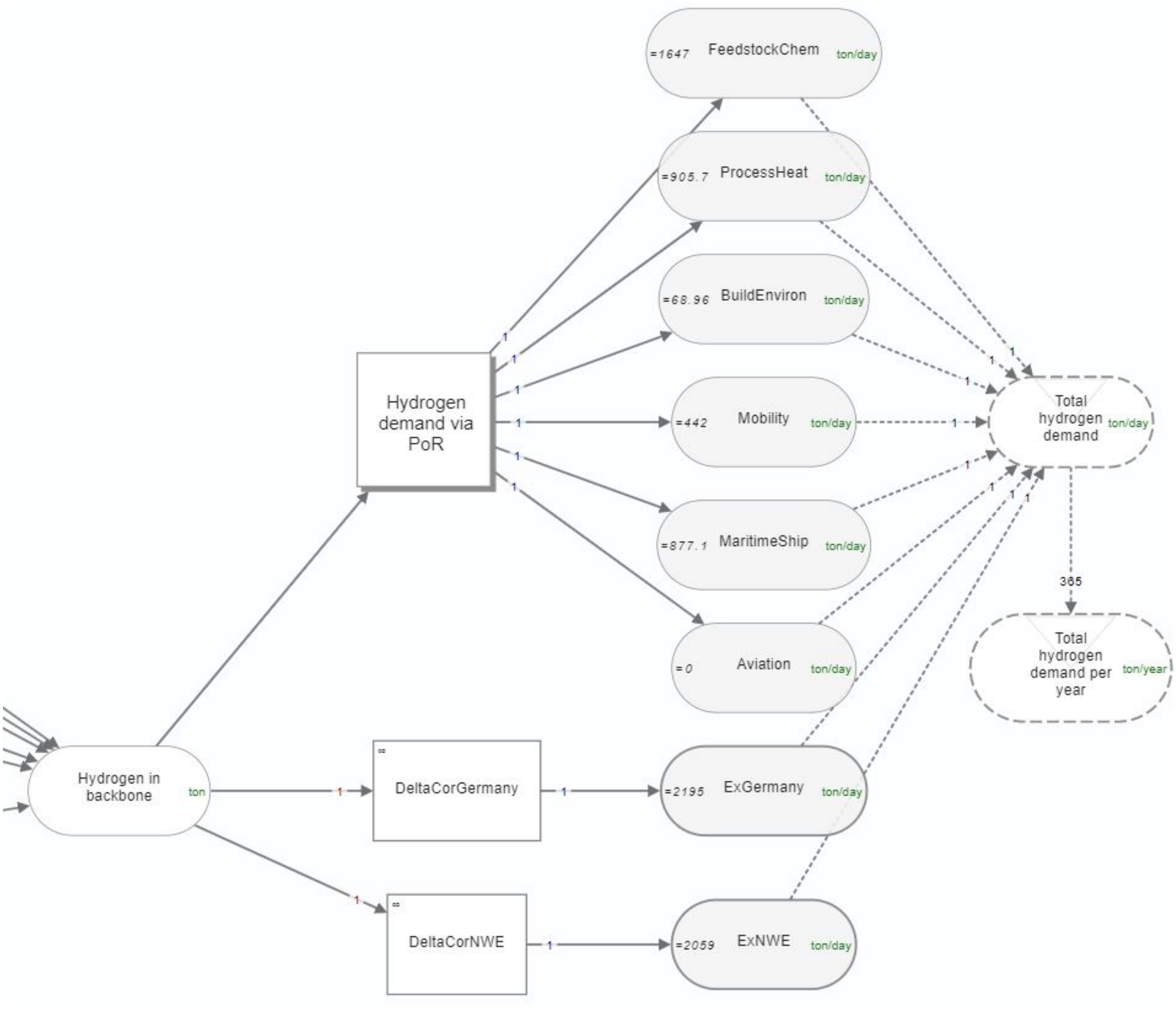


Figure 20: Hydrogen demand sub-model in Linny-R

The following assumptions are made regarding this sub-model:

- Hydrogen demand must always be fulfilled at any cost.
- For the distribution of hydrogen to the end-user sectors, no cost has been accounted for.
- The hydrogen backbone in the PoR has an unlimited capacity. The same goes for the Delta Corridor to Germany and the rest of North-West Europe.
- No distinction is made between different levels of hydrogen quality.
- For each time-step outside of a block, an extra uncertainty factor of 1% is added for the hydrogen demand (see section 4.2.3).

We acknowledge the simplicity in the way hydrogen demand and the local distribution are modelled due to these assumptions. In reality, the Willingness To Pay (WTP)[3] essentially decides the amount of hydrogen demand. Moreover, the distribution costs could be significant for the WTP. Additionally, the capacity of distribution pipelines could be constraining the supply of enormous volumes of hydrogen. The level of hydrogen quality is not included in the model. However, the results will discuss the implications of different degrees of quality. Nevertheless, this sub-model is a vital part of the integrated model as it allows the modeller to include uncertainty in the hydrogen demand. This is explained in the following paragraphs.

Hydrogen demand uncertainty

The data that has been used to represent the hydrogen demand is given in [tonne/year]. We converted this data to [tonne/day] as our model runs with a daily time resolution (see Appendix B.2 for more information). However, modelling this hydrogen demand would result in a flat and constant hydrogen demand every day. Therefore, we added two factors to vary this constant value; fluctuating and uncertainty factors. First, the fluctuating factor is explained, after which the uncertainty factor is described.

The fluctuating factor is modelled to approach real-world hydrogen demand. We acknowledge that some activities in sectors have a constant and stable hydrogen demand. Nevertheless, we assume that some fluctuations are observed as we model the hydrogen demand for an entire industry. Figure 21 shows how these fluctuations could look over a time period of 365 days.

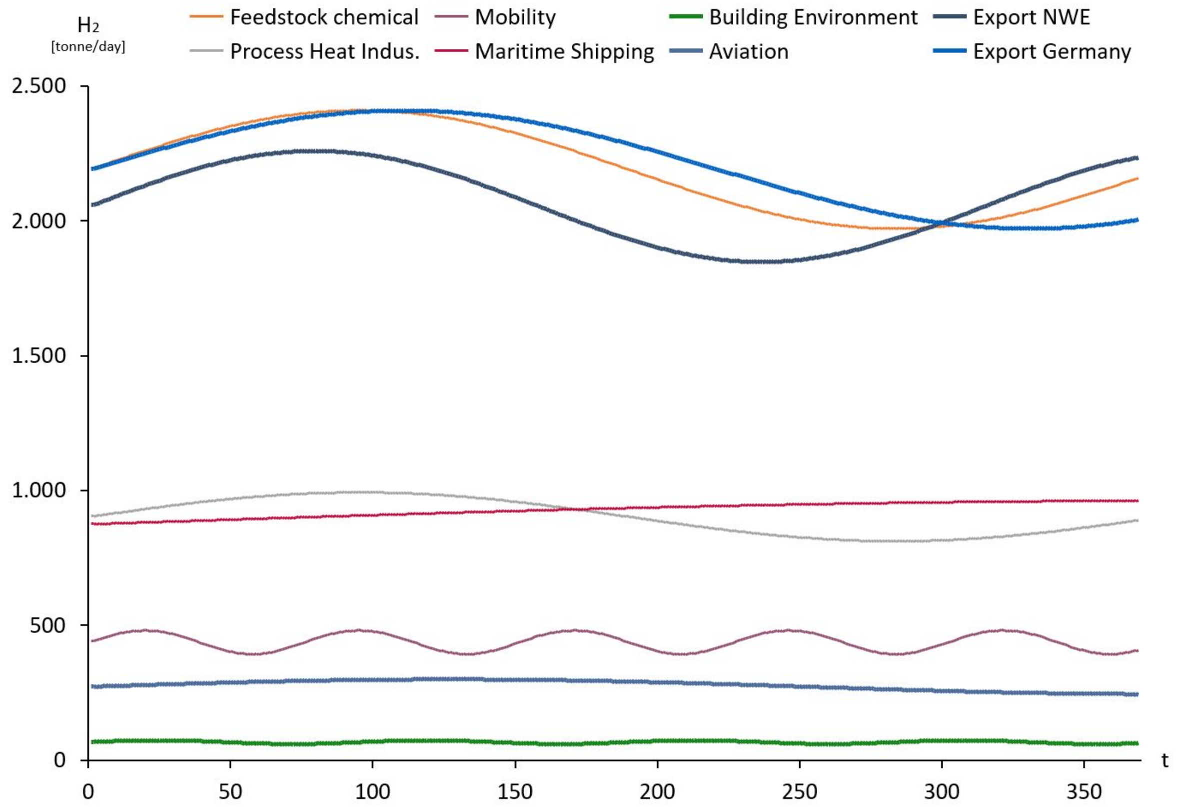


Figure 21: Hydrogen demand fluctuations throughout a representative year in eight end-user sectors

Another essential aspect that has been modelled regarding hydrogen demand is uncertainty. The hydrogen demand for one specific process or even a factory can be adequately predicted. However, pre-

---

[3] The maximum price a customer is willing to pay for a product or service.

dicting the precise hydrogen demand for an entire sector is highly challenging, especially for individual days. Therefore, uncertainty regarding the hydrogen demand for various end-user sectors is included in the model. To explain how hydrogen demand is modelled, we must explain how the MILP-solver in Linny-R works. Linny-R is a cost-optimisation model. Therefore, running a model will always look for a feasible solution in which profit is maximised or the costs are minimised over a certain amount of time steps. This method is called the ’rolling horizon approach and illustrated in Figure 22.

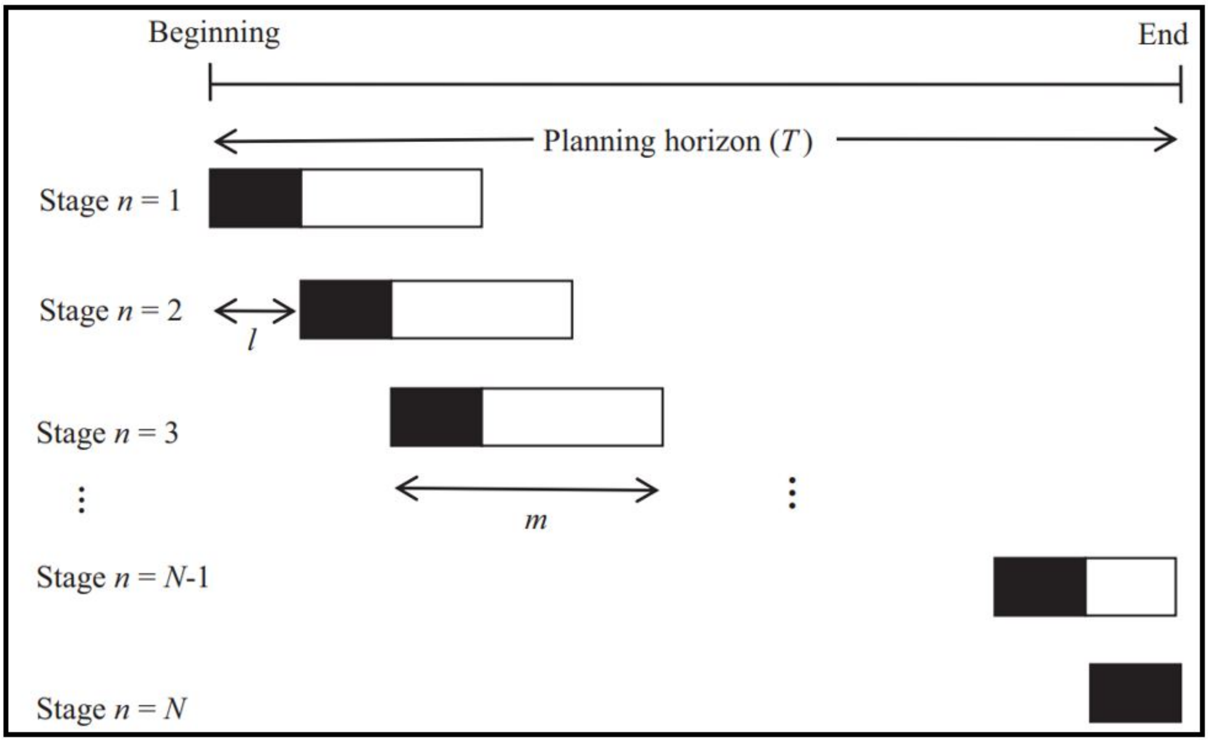


Figure 22: Rolling horizon approach. Adapted from Lu et al. (2016).

The black boxes, called ‘blocks’ in Linny-R, represent the period in which all information is completely known. Often this is a short-term time period. The white boxes, called ‘look-ahead’ in Linny-R, represent the non-short-term time spans in which the model can ‘look ahead’ in the future. Before each stage, the information for both types of boxes and their corresponding time spans are made available. When the problem is solved for one stage, the solution is determined only for the time period for the black boxes. Then, the next stage arrives, and the solution is determined for the next black box for which the information will become completely available, which was not the case before. This method is repeated till the end of the problem’s total time span (Lu et al., 2016). This approach shows its relevance, among other examples, when weather forecasts are used in models. In our model, offshore wind energy is used as an energy input factor for electrolysers. Thus, using the block length and the look-ahead function could help to resemble real-life wind predictions. For example, if one knows that the production by electrolysis is relatively low due to wind in the coming days, one could take action by importing hydrogen. The rolling horizon approach is verified for our model. This is shown in Appendix C. To clarify how hydrogen demand uncertainty is modelled, we refer to the rolling horizon approach. As mentioned before, within a ’block’, the model has complete information. To model uncertainty, we include a specific range of uncertainty in the look-ahead time span. This is illustrated in Figure 23. As in real life, the uncertainty increases as we look further into the future. This is shown in the formula presented below. Please note that “*bt*" is short for time-step within block length, “*n*" represents the number of time steps within a single block. Also, note that this formula is presented as an illustration. Other numbers can be used within the model.

```
IF bt $\leq$ n
  $THEN$
    [Hydrogen demand]
      $ELSE$
        [Hydrogen demand] + (random<0?1:-1)* (0,05+(bt-n)$*$0,01$*$[Hydrogen demand])
```

Through this formula, Linny-R[4] adds an uncertainty factor, in this example 5[%], to the first time step outside of the block (inside the look-ahead time span). The factor '(random<0?1:-1)' determines whether the hydrogen demand is overestimated or underestimated by randomly generating either '-1' or '1'. For every time-step further in the horizon, 1[%] is added to the uncertainty factor. Figure 23 illustrates a larger uncertainty space as we look further in time.

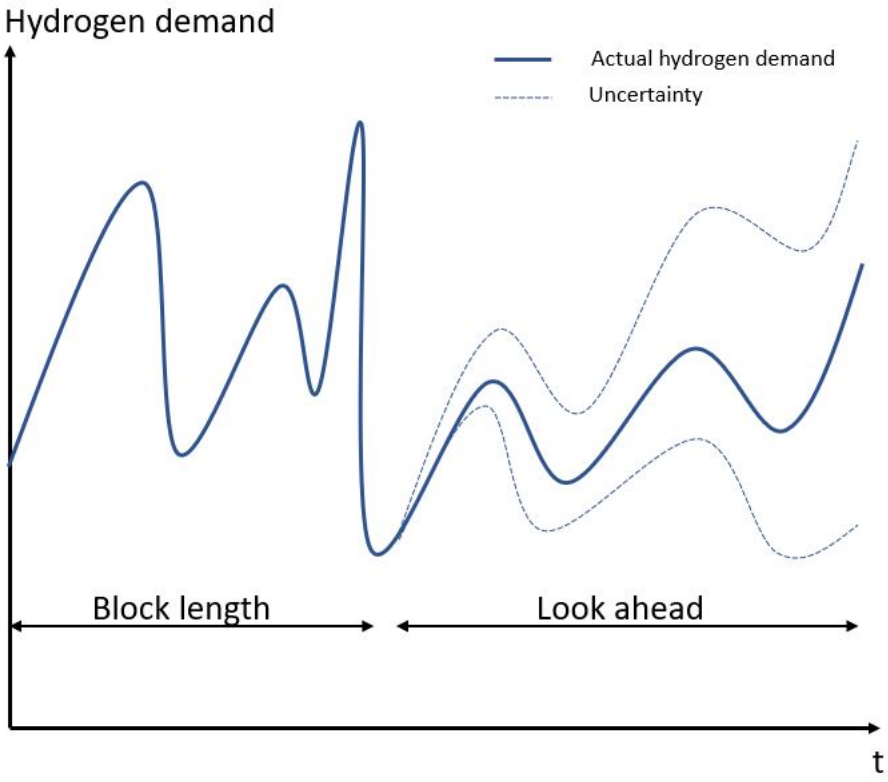


Figure 23: Illustration of the uncertainty factor in hydrogen demand

To clarify, we illustrate the uncertainty by an example, assuming a block length *n* equal to 3 and a look ahead *l* equal to 15. If we start at time-step 1, Linny-R has complete information regarding the first three-time steps. However, for t=4, an uncertainty factor is added. For t=5, an ever-larger uncertainty factor is added, until t=18 where the most significant uncertainty factor is added. At the start of the second block (at t=4), time steps 4 till 6 become the new black boxes. As a result, Linny-R is provided with full information regarding these time-steps. Moreover, the uncertainty factors for t=9 until t=6 is not as large as in the first block.

The following can happen if we apply this uncertainty factor to our case. At t=1, Linny-R notices that the domestic hydrogen production is insufficient to meet the hydrogen demand in t=10. Therefore, Linny-R decides to import hydrogen at a particular time-step at which the import price is relatively low.

---

[4] Linny-R is only the name of the program. The solver behind Linny-R solves the problem. However, for illustration, we mention the solver as 'Linny-R'

However, once arrived in the second block, the model conveys the complete information for the second block and concludes that the actual hydrogen demand, for t=10, is lower than initially foreseen at t=1, resulting in excessive hydrogen import and higher costs.

4.3 Verification & validation

Model verification refers to the procedure to determine if the model performs as it should do according to the modeller. Verification is conducted to identify any modelling errors. In other words, experiments are done to analyse if the model behaves as expected. Where verification aims to analyse the model's behaviour, validation checks if the results correspond with the expected results. In any case, the model should have sufficient accuracy of the real-world system it intends to represent. Sufficient accuracy is subjective; however, in this case, we mean that it can represent a real-world system to experiment, analyse, and apply scenarios (Carson, 2002).

4.3.1 Verification

Three different experiments have been conducted to verify the model according to the *Extreme Conditions Tests* (Sargent, 2010). Extreme values are used as input to observe if our model behaves as expected. The verification experiments have been caught in Table 5.

Table 5: The three experiments performed to verify the model in Linny-R

Experiment	Expectations
Unlimited electrolysis and wind capacity	No import required
Increment of import prices LOHC and nh3 by 100%	The import should totally be accounted for by LH2
Look-ahead function	Reducing negative cash flow as look-ahead increases

The three experiments have been successful. In other words, the expected behaviour of the model is verified by performing these experiments. For a more detailed description and the results of the verification experiments, please refer to Appendix C.

4.3.2 Validation

Two experiments were conducted to validate our model. The first experiment focuses on a smaller sub-model in which we validate the calculations of the CCS process. We increased the CO_2 price every time step. Via a spreadsheet calculation, we determined at which time-step the SMR should use CCS instead of emitting the produced CO_2. Corresponding to our expectation, the model started to utilise CCS at the right time-step. The second experiment externally validated our model results as we examine if its capacity to reproduce the projects of hydrogen import in 2050 by Port of Rotterdam (2020b). As expected, our model determined that approximately 18 [Mtonne H_2/year] would be required given the domestic production capacities indicated by Port of Rotterdam (2020b). Therefore, both experiments produced the expected results. For a detailed description and experiment results, please refer to Appendix C.

4.4 Reference model & test run

The reference model will be described in this section, and a test run will illustrate its use. The reference model is the foundation for many experiments. However, the reference model can be slightly adjusted to perform experiments. This will be further explained in Chapters 5 & 6.

4.4.1 Reference model

The reference model is used as a standard set-up and represents the year 2030. The input values of the reference model are categorised into three domains; hydrogen import, domestic hydrogen production and hydrogen demand. The input values are presented in Table 6. Please note that the three domains directly correspond with the case-inputs presented in Figure 12 in section 3.4. Assumptions that have been made for the input values regarding Table 6b are presented in Appendix B.1. Please note that the reference model assumes a variable hydrogen demand. Both volatility and uncertainty factors are added to the values in Table 6c. For more information, please refer to section 4.2.3.

Table 6: Input values reference model categorized into the three sub-models.

(a) Hydrogen import

Input values	Unit	Value
Import price LH_2	8.311	€/tonne LH_2
Storage costs LH_2	636,8	€/tonne LH_2
Regasification costs LH_2	0,0	€/tonne LH_2
Capacity vessel LH_2	89	tonne LH_2
Import price LOHC	224	€/tonne LOHC
Storage costs LOHC	5,4	€/tonne LOHC
Regasification costs LOHC	30,8	€/tonne LOHC
Capacity vessel LOHC	40.000	tonne LOHC
Import price NH_3	692	€/tonne NH_3
Storage costs NH_3	23,7	€/tonne NH_3
Regasification costs NH_3	77,1	€/tonne NH_3
Capacity vessel NH_3	57.970	tonne NH_3

(b) Domestic hydrogen production

Input values	Unit	Value
Electrolysis (CAPEX)	2.004	€/tonne H_2
Electrolysis (OPEX)	30,0	€/tonne H_2
Electrolysis capacity	3	GW
Offshore wind capacity	5	GW
SMR (CAPEX)	987	€/tonne H_2
SMR (OPEX)	46,4	€/tonne H_2
SMR capacity	2.000	tonne H_2/day
CCS (CAPEX)	488	€/tonne H_2
CCS (OPEX)	22,9	€/tonne H_2
CCS capacity	30.000	tonne CO_2/day
CO2 price	125	€/tonne

(c) Hydrogen demand

Input values	Unit	Value
Feedstock chemicals	1.657	tonne/day
Process heat industry	906	tonne/day
Building environment	69	tonne/day
Mobility sector	442	tonne/day
Maritime shipping	877	tonne/day
Aviation	0	tonne/day
Export Germany	2.195	tonne/day
Export North-West Europe	2.059	tonne/day
Total	2.99	Mtonne/year

4.4.2 Model test run

A model test run is performed to illustrate the working of our model. The run consists of 365 time steps. A snapshot of our model at t=3 is presented in Figure 24. The figure shows the flow of hydrogen through our model. On the right side are the end-user sectors towards which the hydrogen is transported. From the domestic production cluster (square at the bottom left corner), the hydrogen produced by electrolysis and SMR is visible. In this time-step, 815,5 and 2.000 [tonne H_2] are produced by respectively electrolysis and SMR. However, domestic production is not able to meet the demand. Therefore, NH_3 is important, as this is the cheapest carrier in this run. In this time-step, 38.045 [tonne NH_3] is cracked into 5.411 [tonne H_2]. The sum of the three sources of hydrogen production is equal to the hydrogen demand in this time step (e.g. 8.226,5 [tonne H_2]. It is important to realise that Linny-R solves the problem under the condition that the hydrogen demand is met at every time step against the lowest costs.

Figure 24 illustrate how the three sub-models discussed in this chapter are interacting. To clarify, the amount of hydrogen import depends on the production of hydrogen domestically. In turn, the electrolyser relies on the wind as energy input resulting in a fluctuating production output resulting in fluctuating import. In this case, only NH_3 is imported as its infrastructure capacity is large enough to suffice for the remaining hydrogen demand. In case of lower infrastructure capacity or a higher hydrogen demand, other carriers are imported. Again, in such a way that the hydrogen demand is met against the lowest costs.

The model allows the modeller to vary the parameters and analyse their implications easily. For example, among other options, import prices of the three hydrogen carriers can be varied to analyse the hydrogen import. Likewise, the domestic production capacities can be increased to analyse how much import is required when a certain amount of electrolysers is installed. Also, the hydrogen demand in a specific end-user sector can be lowered to analyse the implications if that sector chooses to use another energy carrier other than hydrogen to fulfill its energy demand.

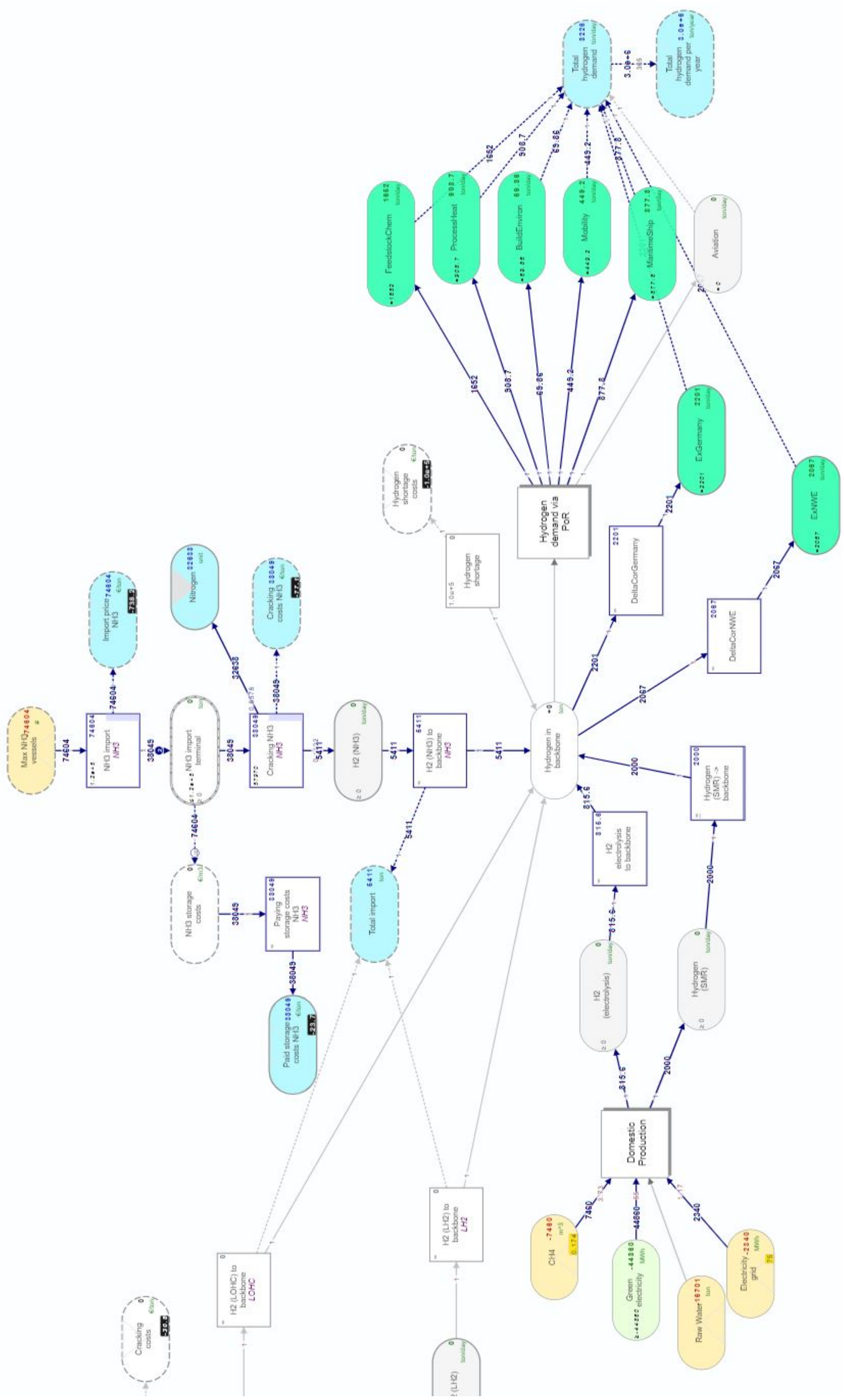


Figure 24: Snapshot integrated model in Linny-R after test run. This figure is also presented, in higher resolution, at the end of this thesis report.

To further explain the working of our model, a small experiment is conducted to illustrate what results can be derived. This experiment aims explicitly to show the minimisation costs method of Linny-R. Please note that this illustrative experiment does not correspond with the model snapshot in Figure 24. For this experiment, the import prices of LH_2, LOHC, and NH_3 are varied to analyse how hydrogen import occurs given variable import prices. The results are presented in Figure 25.

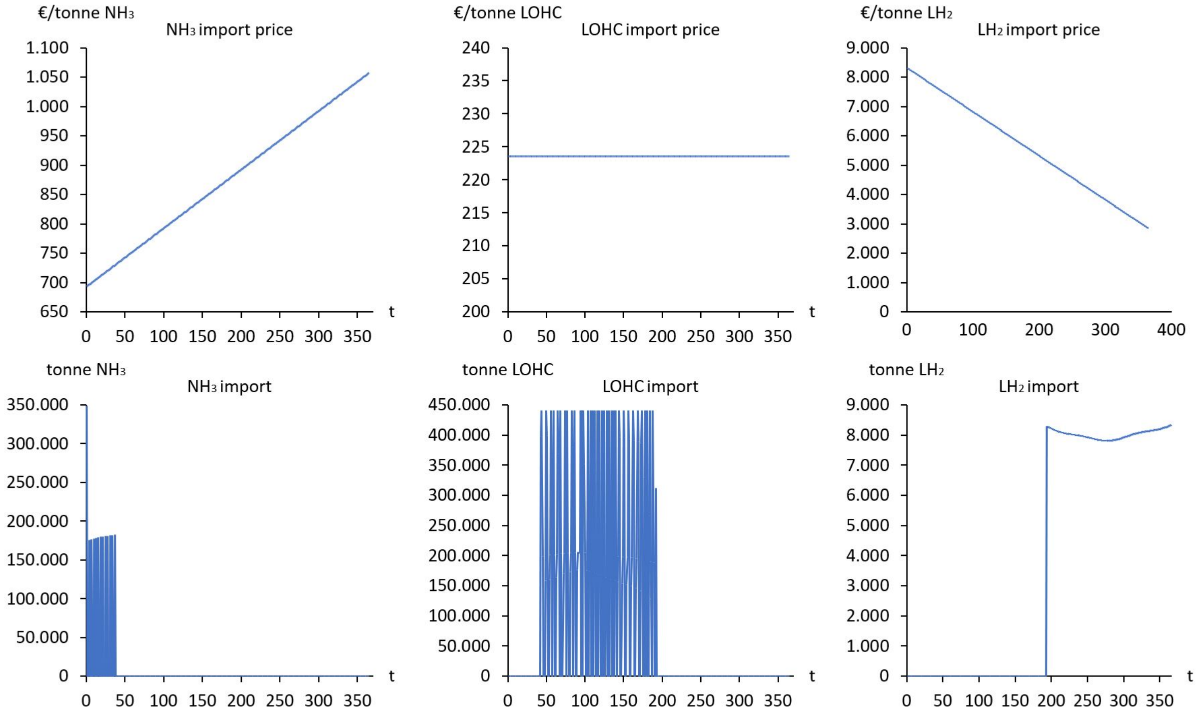


Figure 25: Hydrogen import under variable import prices

The upper-left graph in Figure 25 shows a decreasing NH_3 import price. The bottom-left graph shows the corresponding NH_3 import. Please note that the lower graphs represent the arrival of vessels in the Port of Rotterdam. This explains the volatile lines in the 'NH_3-import' and 'LOHC-import' graphs. At t=43, the total supply chain costs of NH_3 exceed the total supply chain costs of LOHC due to the rising import price, resulting in LOHC import instead of NH_3. Till t=193, LOHC remains the cheapest carrier. Then, the decreasing import price of LH_2 results in a lower supply chains costs of LH_2 compared to LOHC, which make the hydrogen import shift to LH_2. Do note that the import prices are presented in [€/tonne carrier]. Please recall the different properties of the three carriers (see Table 1 in section 3.1). In Figure 25 the import prices are not intersecting at the time-steps of the tipping points. However, translating these import prices to [€/tonne H_2] would give more converging import prices. Moreover, storage and regasification costs are also impacting the total supply chain costs of import.

5 Experimental design

In this chapter, the experiments will be introduced. Our experiments use two types of methods; sensitivity analysis and scenario analysis. First, a short overview of the experiments is presented, then the experiments are introduced in more detail.

We aim to analyse how uncertainties impact the realisation of hydrogen import terminals. Figure 26 shows which uncertainty is analysed by which experiment. Specific uncertainties that are not analysed by an experiment will be discussed in chapter 7. Experiment 1 compares four supply and demand scenarios for 2050 to analyse the technological uncertainties related to domestic production and hydrogen demand. Experiments 2 and 3 explore the economic uncertainties of the hydrogen import supply chain. Experiment 4 focuses on the technological uncertainty of the hydrogen import supply chain. Finally, experiment 5, 'Power of information', does not analyse one identified uncertainty. Instead, we illustrate what impact information regarding future market prices could make on an integrated hydrogen system.

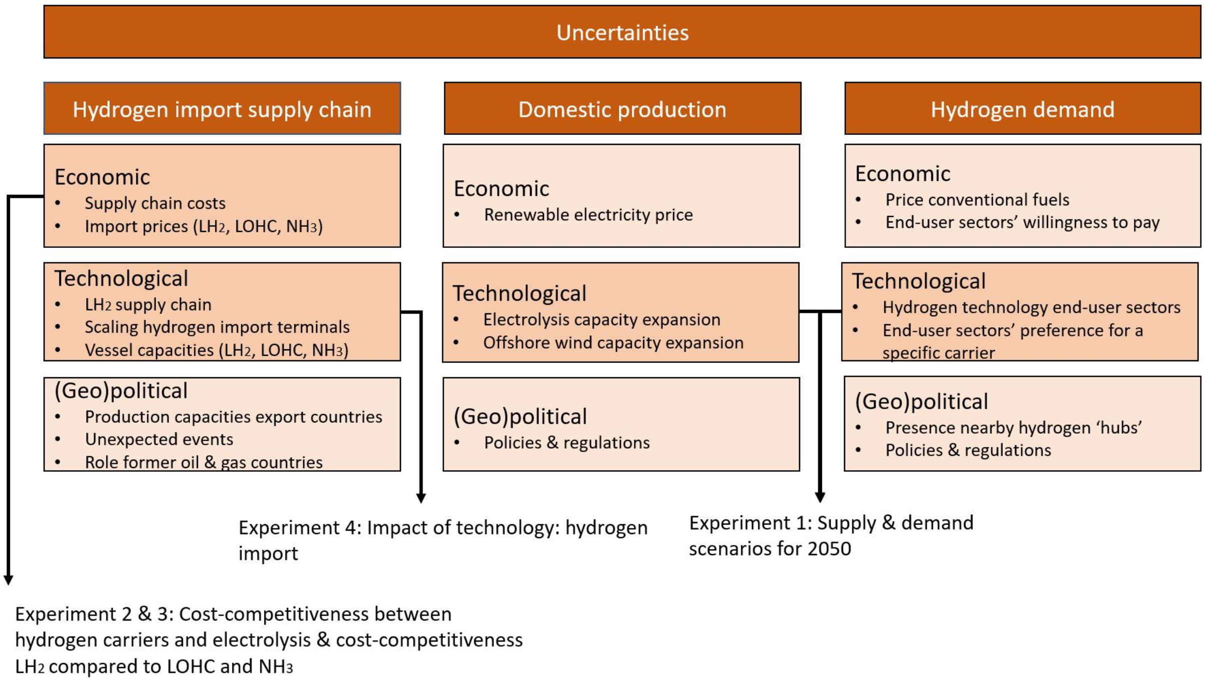


Figure 26: Overview uncertainties analysed by experiments.

5.1 Supply and demand scenarios for 2050

Scenarios have always been a building block that is used at different levels of political decision making. In the case of the energy transition, techno-economic scenarios are used to point out different futures and their implications (Poganietz and Weimer-Jehle, 2020).

Previous experiments focused on uncertainties concerning the import supply chain infrastructure in the PoR. This experiment uses four scenarios to analyse the uncertainties of domestic production and hydrogen demand forecasts. Each scenario sketches a possible future for 2050. Please note that these scenarios are nowhere meant to describe an exact future. Instead, they aim to show the implications of our system given varied conditions.

The scenarios are constructed through the variation of two factors; domestic production and hydrogen demand. Within the four scenarios, these two factors are described in more detail. Domestic production is accounted for by electrolysis (fueled by wind energy) and SMR. Eight different end-user sectors account for the hydrogen demand. In addition, distribution networks must be in place to transport the hydrogen from the PoR to the end-user sectors. The four scenarios are presented in Figure 27. Finally, an overview of the input values is provided.

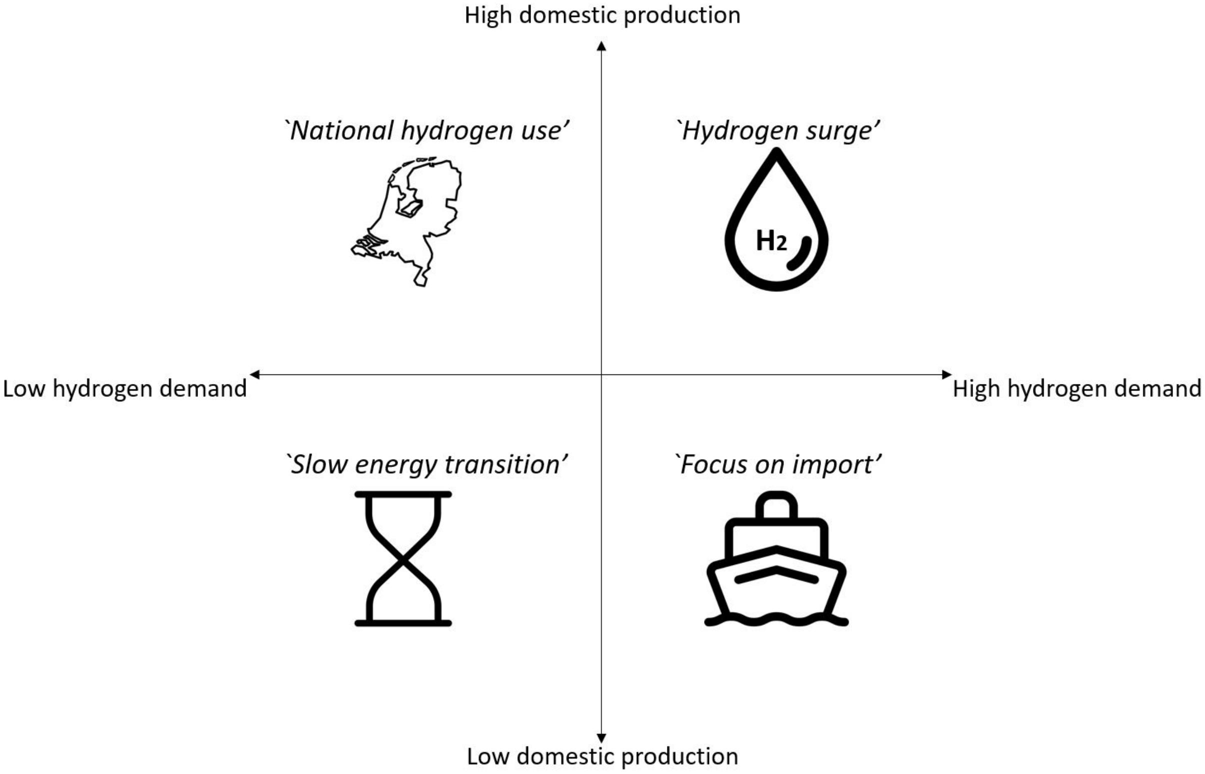


Figure 27: The four supply and demand scenarios for 2050.

5.1.1 Hydrogen surge (HS)

Hydrogen has become the leading commodity under renewables. The Netherlands have significantly expanded their hydrogen production capacity. The PoR is the hydrogen hub of North-West Europe. Distribution networks from the PoR towards large industrial clusters in Germany and Belgium have been realised, facilitating large-scale hydrogen export. The large industry sectors are fully transitioned to sustainable hydrogen. Moreover, hydrogen use in the build environment and mobility sector is growing.

5.1.2 Focus on import (FI)

Growing attention for hydrogen leads to a significant boost in hydrogen demand. The hydrogen production capacity has only slightly increased and remained at the level of 2030. A distribution network to facilitate export is realised. The feedstock chemical industry and the process heat industry have primarily transitioned to sustainable H_2 as expected. In the building environment and mobility sector, electrification has the upper hand. As a result, large-scale use of hydrogen remains absent. The aviation and the maritime shipping sectors keep their options open to determine which fuel will be future. H_2 is one of the options, and small hydrogen pilot projects in these sectors are starting to appear.

5.1.3 Slow energy transition (SET)

Sustainable hydrogen has not achieved the dominating role that has been projected. Electrolysis and offshore wind remained low. Hydrogen production via SMR is still in use as a result of the slow energy transition. Hydrogen distribution networks towards Germany and NWE have not been realised, eliminating the possibility for export. Also, the delta corridor is not realised excluding hydrogen transportation from the PoR towards the industry cluster Chemelot. Hydrogen accounts for a tiny part of end-user sectors like shipping, aviation, building environment, and mobility.

5.1.4 National hydrogen use (NHU)

The Netherlands has established itself as a hydrogen country. Large-scale offshore wind parks have been dedicated to hydrogen production via electrolysis. Nearly all national end-user sectors have reached the level of hydrogen use that has been projected. Extensive distribution networks have been realised in the Netherlands. However, other nearby countries have shifted to other renewables, leaving a low potential to export hydrogen.

5.1.5 Overview input values

This section summarises the input values of the four scenarios described above. Moreover, the similarities and differences between the input values are discussed. First, the capacity of the local hydrogen production methods is discussed, followed by the hydrogen demand per end-user sector in the scenarios.

The input values for the local hydrogen production methods are presented in Table 7. The scenarios HS and NHU are characterised by high domestic hydrogen production. The scenarios FI and SET are characterised by low domestic hydrogen production. In scenario HS, the production capacities are somewhat higher compared to scenario NHU. Hence, in HS, hydrogen is globally adopted, while in scenario NHU, especially the Netherlands, is convinced of hydrogen's potential. As a result, international companies in the Netherlands are less drawn to make investments in hydrogen production methods. The contrast between the scenarios FI and SET is a result of the stage of the energy transition. In FI, the energy transition is in an advanced stage. However, the strategy of the Netherlands is to import its energy demand predominantly. The storyline of SET describes an earlier stage of the energy transition. The role of hydrogen is marginal, and non-sustainable production methods as SMR are still in practice.

Table 7: Overview input values local hydrogen production methods for four scenarios

		Scenarios			
Input parameter	Unit	Hydrogen surge	Focus on import	National hydrogen use	Slow energy transition
Electrolysis capacity	GW	15	5	12	2
Offshore wind capacity	GW	25	9	18	4
SMR capacity	tonne H2/day	0	0	0	2.000

The hydrogen demand in the four scenarios is based on the work of Detz et al. (2019b) (for more information, please refer to Appendix B.2). The scenarios 'Hydrogen surge' and 'Focus on import' are characterised by a high hydrogen demand. The scenarios 'National hydrogen use' and 'Slow energy transition' are characterised by low domestic hydrogen production. Below, context related to the hydrogen demand in the scenarios is presented.

What strikes is the same hydrogen demand for the sectors feedstock chemicals and process heat industry in the scenarios HS, FI, and NHU. At the moment, the hydrogen use in these sectors is already significant. Various reports argue that the energy demand in these sectors will be entirely accounted for by sustainable hydrogen. Therefore, this sector's hydrogen reaches its full potential in terms of demand. Also, the demand in the aviation sector is the same in these three scenarios. The reasoning behind this input variable is the expectation that hydrogen can only be applied in this sector in 2045. Therefore, we argue that in all scenarios the aviation sector just starts using hydrogen leading to the small but equal use of hydrogen in these scenarios. In scenario HS, the hydrogen demand is somewhat higher than scenario FI due to a lower hydrogen demand in the export sectors. Hence, in the storyline of FI, other countries are also focusing on hydrogen import, leading to other hydrogen import infrastructure projects in nearby located ports. Consequently, the projected hydrogen demand that would transit the Port of Rotterdam is absorbed by other ports in other countries. Therefore, the hydrogen demand in other sectors is the same. In the scenario, NHU, the sectors 'building environment' and 'mobility sector', are slightly higher than HS and FI due to their role as leading sustainable energy carriers in the Netherlands. Logically, the scenario SET represents a lower hydrogen demand in each end-user sector compared to the other three scenarios.

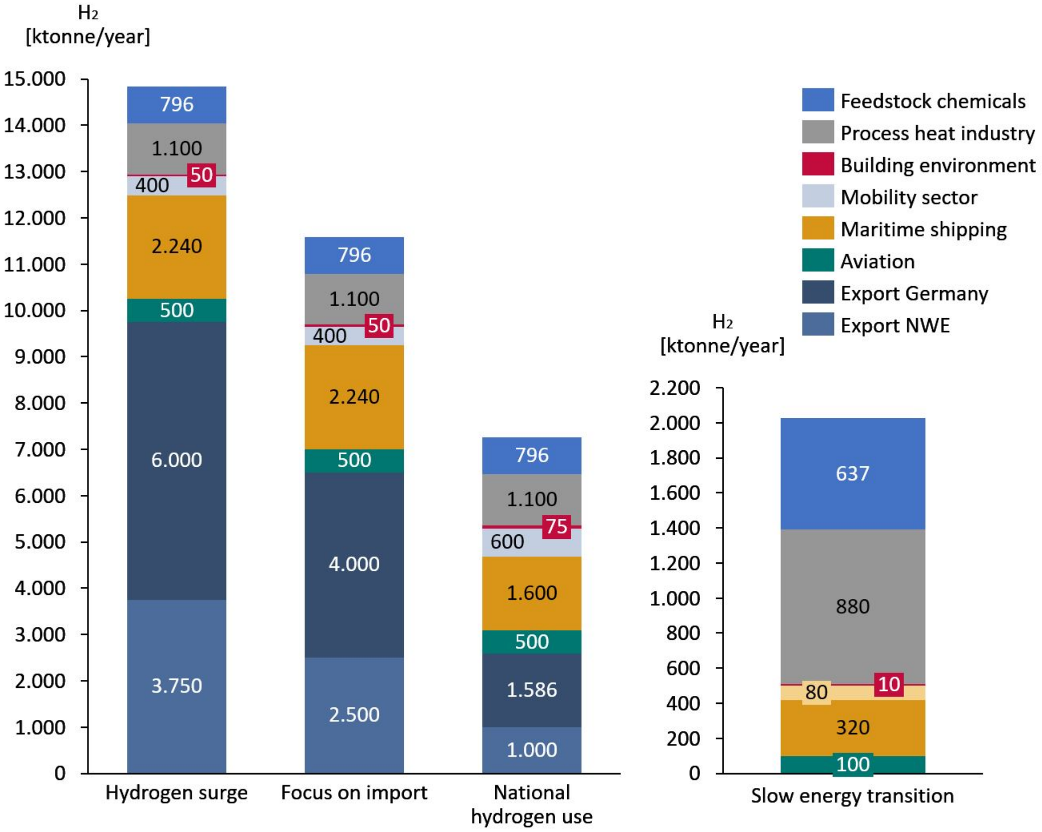


Figure 28: Overview hydrogen demand in the four scenarios

5.2 Cost-competitiveness between hydrogen carriers and electrolysis

This experiment aims to analyse the cost-competitiveness of the three carriers (e.g. LH_2, LOHC, and NH_3) compared to water electrolysis in the years 2030, 2040 and 2050. The look-ahead function is disabled as this experiment regards a sensitivity analysis. First, the electrolysis production process's cash flow (CF) is estimated for each year while constraining the model to cover the demand by hydrogen produced via electrolysis (e.g. no import and no SMR is allowed). Please refer to Appendix B.1 for the production costs of electrolysis in the years 2030, 2040, and 2050. The CF is then estimated for each of the three carriers. The model is constrained only to cover the demand by one specific carrier. Then, the import price is manipulated. It is decreased over the year to identify the point where the CF of a carrier drops below the CF of the electrolysis process. In such a manner, we determined at what import price the import of hydrogen is economically more beneficial than using locally produced green hydrogen. A certain margin reduces the import prices of the three carriers through the following formulas:

- LH_2 = 8.311 - 75 * $(x - 1)$ [€/tonne LH_2][5]
- LOHC = 224 - 2 * $(x - 1)$ [€/tonne LOHC]
- NH_3 = 692 - 6 * $(x - 1)$ [€/tonne NH_3]

5.3 Cost-competitiveness LH_2 compared to LOHC and NH_3

This experiment aims to address the uncertainty related to the supply chain costs between the three different carriers. In section 3.1.5, the uncertainty for the production, conversion and shipping of carriers has been mentioned. Terwel and Kerkhoven (2018) determined the supply chains costs at 8.311, 224, 692 [€/tonne carrier] (8.481, 5.150, and 4.868 [€/tonne H_2]) for LH_2, LOHC, and NH_3, respectively. For this experiment, we assume that these prices exclude storage and regasification costs. Projections for cost reductions regarding storage and the regasification processes have been adopted from Wijayanta et al. (2019) and are once again presented in Table 8. The studies point towards NH_3 as the cheapest carrier, followed by LOHC and LH_2. Based on the import prices found by Terwel and Kerkhoven (2018) and the costs for storage and regasification found by Wijayanta et al. (2019), we aim to determine the tipping point at which import price LH_2 will replace NH_3 as the cheapest carrier. The look-ahead function is disabled as this experiment regards a sensitivity analysis.

Table 8: Storage and regasification costs for LH_2, LOHC and NH_3 in [€/tonne H_2 carrier]

		2030	2040	2050
Storage costs	LH2	638,8	468,4	298,0
	LOHC	5,4	5,4	5,4
	NH3	23,7	23,7	23,7
Regasification costs	LH2	0,0	0,0	0,0
	LOHC	30,8	27,7	24,6
	NH3	77,1	69,4	61,7

To determine the tipping point, we disregarded domestic hydrogen production. In other words, the hydrogen demand is only met by import. Three runs have been performed to simulate the costs in 2030, 2040, and 2050. The import prices of LOHC and NH_3 have been held at a constant level to be able to compare the results. In addition, the price for LH_2 has been lowered through the following formula: LH_2 = 8.311 - 80 * $(x - 1)$ [€/tonne LH_2] where the starting point is $x = 1$ and the end at $x = 100$.

5.4 Impact of technology: Hydrogen import

The two previous experiments analysed the economic uncertainties related to hydrogen import. This experiment addresses the technological uncertainties related to hydrogen import. Furthermore, we discuss how geopolitical uncertainty could impact hydrogen import infrastructure.

In this experiment, we quantify developments in-vessel technologies and analyse vessels' different impacts on an import supply chain and its corresponding import infrastructure. This experiment uses the reference model. However, one adjustment is made. The hydrogen import is allocated to only one

---

[5] To clarify, at, say, t=10 the import price for LH_2 = 8.311 - 20 * $(10 - 1)$ = 7.931 [€/tonne LH_2]

hydrogen carrier in each run, disregarding the other two. As a result, in each run, the hydrogen demand (e.g. 2,99 [Mtonne/year]) is met by the domestic production and one hydrogen carrier. In total, nine runs are performed, three runs for each carrier. In each specific run, the maximum vessel capacity is varied. Table 9 shows the nine different vessel capacities corresponding to the nine performed runs. Please note that Table 9 is a duplicate of Table 2 in section 3.1.

Table 9: Capacities hydrogen carrier vessels

	LH2		**LOHC**		**NH3**	
	Mass [tonne]	Mass H2 [tonne]	Mass [tonne]	Mass H2 [tonne]	Mass [tonne]	Mass H2 [tonne]
Low	89	87	20.000	868	6820	970
Medium	1.773	1.737	75.000	3.255	57.970	8.243
High	11.344	11.117	220.000	9.548	109.120	10.668

5.5 Power of information

This experiment aims to analyse the impact of information on the processes of hydrogen import. For this experiment, we used our reference model. However, in this experiment, we use a volatile market price for NH_3. To simulate price volatility, we define the market price for NH_3 as [Market price NH_3] + (0,1 $*$ [Market price NH_3] $*$ sin(t / 20)). Figure 29 shows the resulting price over 365 time steps.

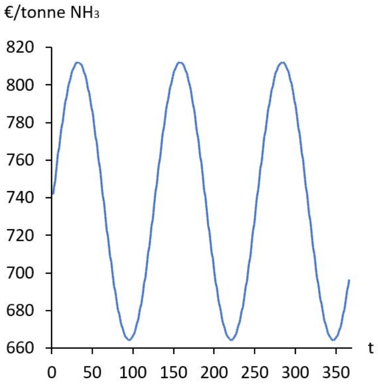


Figure 29: Volatile market price NH_3

In each run, the look-ahead was increased, while the block length remained equal to 3 time steps. Logically, the run 'Full info' used a block length of 365 time steps and a look ahead equal to zero as in this run. In other words, Linnny-R provides our model with complete information.

6 Results

This chapter presents the results of the experiments described in chapter 5. Note that solely the results are presented in this chapter. Their implications will be discussed in chapter 7. Since this study is conducted in collaboration with Gate Terminal, the results predominantly focus on LH_2. Each sub-section presents the findings of a specific experiment.

6.1 Supply and demand scenarios for 2050

This sub-section compares the four scenarios introduced in the previous chapter and evaluates their results. This experiment is conducted to understand the necessity of hydrogen import in different scenarios. Despite its simplicity it is vital to understand what implications certain production capacities have on the required hydrogen import. Moreover, through this experiment one get a better grasp on what volumes of import are required. The results are presented in Figure 30. Please note that the left side of Figure 30 presents an overview of the input data for this experiment. To promote clarity these input values are added to the results on the right side of the figure.

The first notion that stands out is the small share that is accounted for by electrolysis. The reason for this is the relatively low production capacity of electrolysis. This study assumes that offshore wind will provide the electricity used as input for the electrolysis process. Due to the fluctuating wind production, the electrolysers do not produce at full capacity each day. An option to increase the electrolysis output is using the electricity grid to produce hydrogen when wind production is low. However, one must consider that the hydrogen produced by electrolysis is supposed to be 'green'. Using the electricity grid does not guarantee sustainable hydrogen considering the fact the energy mix of The Netherlands is not 100% accounted for by renewable electricity. If the share of renewable electricity increases over the coming years, one could consider the electricity grid as the energy input to produce hydrogen.

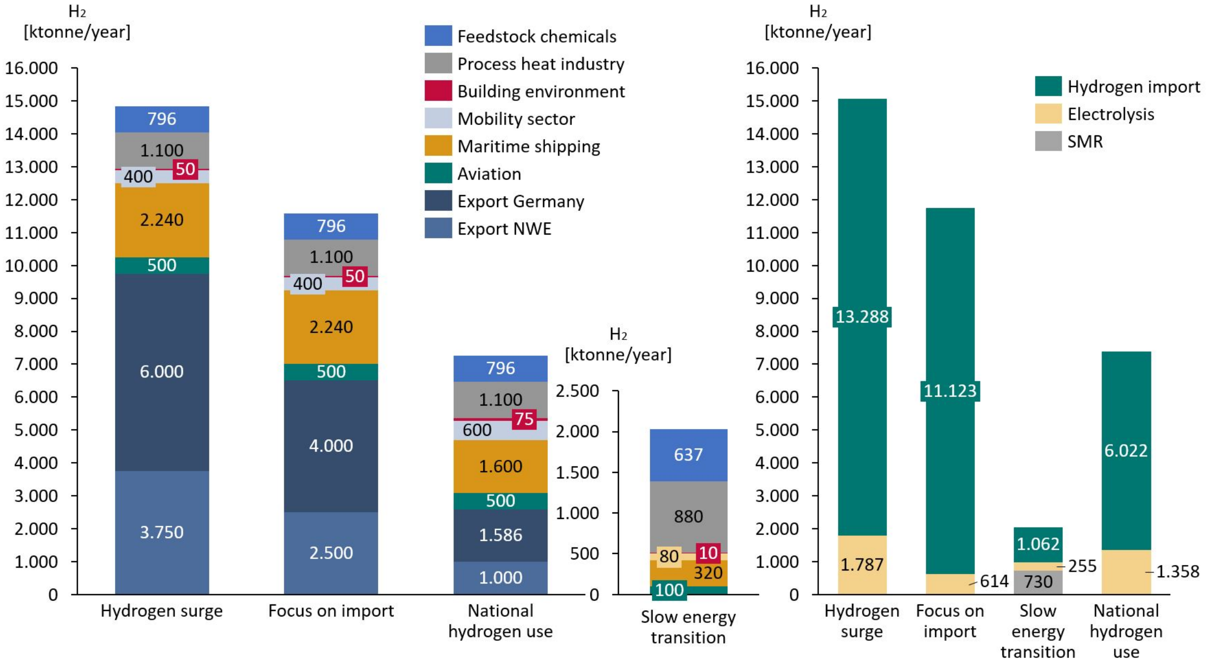


Figure 30: Overview hydrogen sources in the four scenarios. Hydrogen import is required in every scenario to meet the demand.

The second notion that stands out from Figure 30 is that the results do not consider the three different hydrogen carriers. Instead, the total hydrogen import is shown. The reason for this is that if the hydrogen import were separated into the three carriers, the cheapest hydrogen carrier would account for the largest share of hydrogen import, followed by the second cheapest and the most expensive carrier. Through this experiment, the hydrogen import potential for each carrier is analysed based on the technological characteristics of each end-user sector instead of looking at the hydrogen carrier's economics. Technical characteristics refer to the hydrogen quality and the distributions methods of the three hydrogen carriers. The considerations regarding hydrogen quality are addressed in section B.2. Moreover, that section described what quality considerations are of interest for the various end-user sectors and which issues arise during the distribution of the hydrogen carriers towards these end-user sectors. Section B.2, Table 4 indicates which end-user sectors have the most significant potential hydrogen demand. It shows that maritime shipping and the two export sectors have the largest hydrogen potential. The feedstock chemicals and the process heat industry sectors are smaller, but these sectors show great potential for a complete transition towards sustainable hydrogen based on policies and the current hydrogen use, (Hydrogen Council, 2017; Detz et al., 2019a). The question of which carrier will likely, supply which end-user sector is discussed in chapter 7.

In each scenario, a dominant share of hydrogen import over electrolysis and SMR has been identified. Furthermore, based on technical requirements of the end-user sectors, due to its high quality, the share of LH_2-import would be significant. However, LOHC and NH_3 are needed now due to the early stage of development of LH_2-technology. NH_3 can be of great importance as it can supply the sector 'maritime shipping', which has a significant hydrogen demand. LOHC suffers no transportation losses, which can benefit the 'export' sectors as the transportation requires more days. However, the residual LOHC must be returned to its original destination once the hydrogen is retrieved. An import scenario in which all three hydrogen carriers play their role is expected.

6.2 Cost-competitiveness of the three hydrogen carriers

The results of this experiment have been captured in Figure 31, Figure 32, and Figure 33. Please note that the CFs are negative. Also, note that each run consists of 365 time steps. However, we do not want to simulate a representative year. Instead, the time-steps are explicitly used to lower the hydrogen carrier import prices.

At the left half of each figure, the cash flows of electrolysis (in 2030, 2040, and 2050) and the specific carrier are presented. At the left half of each figure, the carrier's cash flow corresponds with the decreasing import price at the figure's right. Moreover, the intersections at the left half of each figure correspond with the intersections at the right half of that exact figure. The intersections mark the import price at which importing a specific carrier becomes cheaper compared to electrolysis. These intersections are labelled with the corresponding import price, shown at the utter right half of each figure.

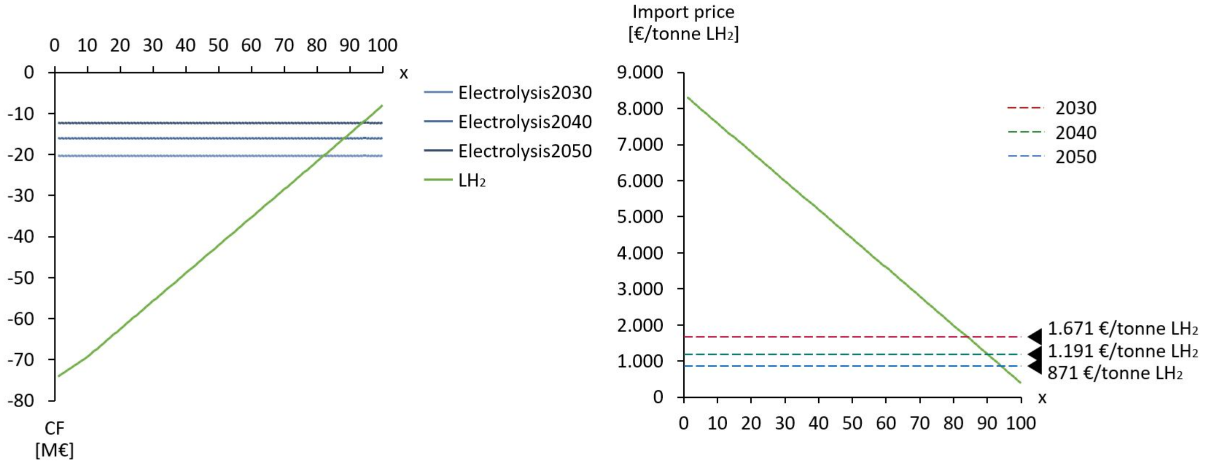


Figure 31: Comparison electrolysis CF and LH_2-import CF given a decreasing LH_2-import price (left) & import price at which electrolysis CF equals LH_2-import CF (right). The LH_2 import price must be reduced by almost almost 80% to be cost-competitive with electrolysis in 2030.

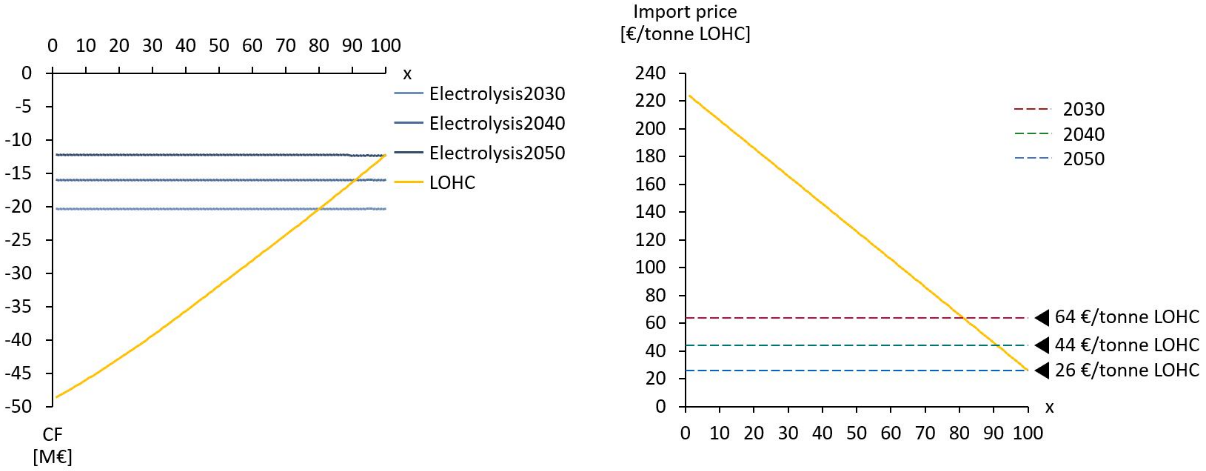


Figure 32: Comparison electrolysis CF and LOHC-import CF given a decreasing LOHC-import price (left) & import price at which electrolysis CF equals LOHC-import CF (right). The LOHC import price must be reduced by almost 71% to be cost-competitive with electrolysis in 2030.

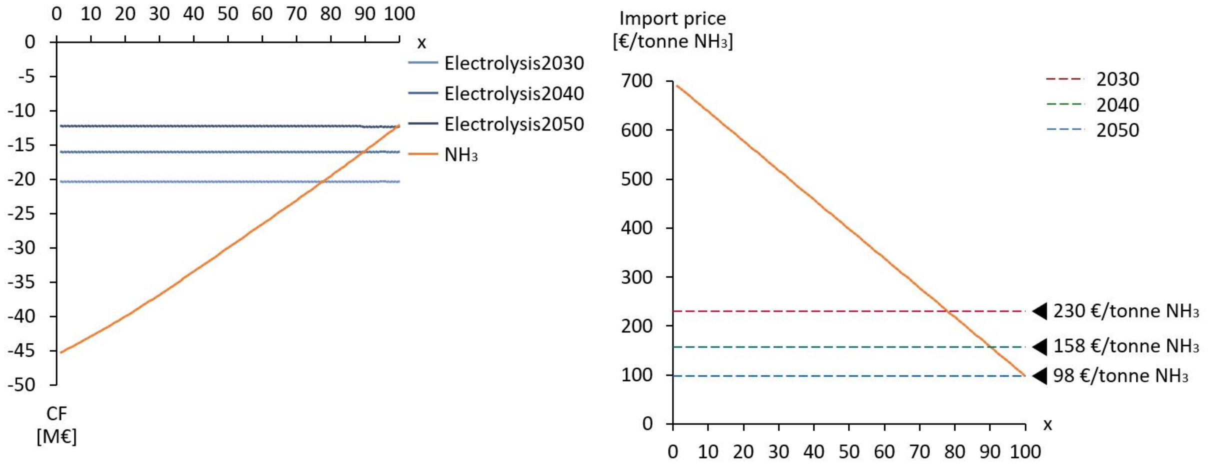


Figure 33: Comparison electrolysis CF and NH_3-import CF given a decreasing NH_3-import price (left) & import price at which electrolysis CF equals NH_3-import CF (right). The NH_3 import price must be reduced by almost 73% to be cost-competitive with electrolysis in 2030.

The results of this experiment show each carrier's import price to be cost-competitive to electrolysis. When comparing our results to the average supply chain costs found by Terwel and Kerkhoven (2018) (e.g. 8.311, 224, 692 [€/tonne carrier] (8.481, 5.150, and 4.868 [€/tonne H_2]) for LH_2, LOHC, and NH_3, respectively), one can recognise the significant cost reduction required for each carrier to be cost-competitive, compared to electrolysis. For each carrier, the import price must drop by at least 70%. This percentage even increases when looking at 2040 and 2050.

Not surprisingly, significant reductions are required to be cost-competitive with electrolysis. Hence, the difference between the hydrogen production in the Netherlands and the hydrogen production in an export country must be equal to the costs of the rest of the import supply chain.

6.3 Cost-competitiveness LH_2 compared to LOHC and NH_3

The results are presented in Figures 34 and 35. Figure 34 represents the tipping point of LH_2 compared to LOHC. Figure 35 represents the tipping point of LH_2 compared to NH_3. On the left side of each figure, the amount of import is presented corresponding to the projected supply chain costs in the years 2030, 2040, and 2050. The right-hand side of the figures shows the decreasing import price of LH_2 and labels the tipping points. Note that x-axes in both graphs do not represent days in a year. Instead, they are explicitly used as reference points to indicate the decrease of the LH_2 import price. Also, note that shown results shown in Figures 34 and 35 are zoomed in at the tipping point where LH_2 becomes cheaper than the alternative hydrogen carrier (e.g. LOHC or NH_3). As indicated in the previous chapter the whole x-axis spans from $x = 1$ till $x = 100$.

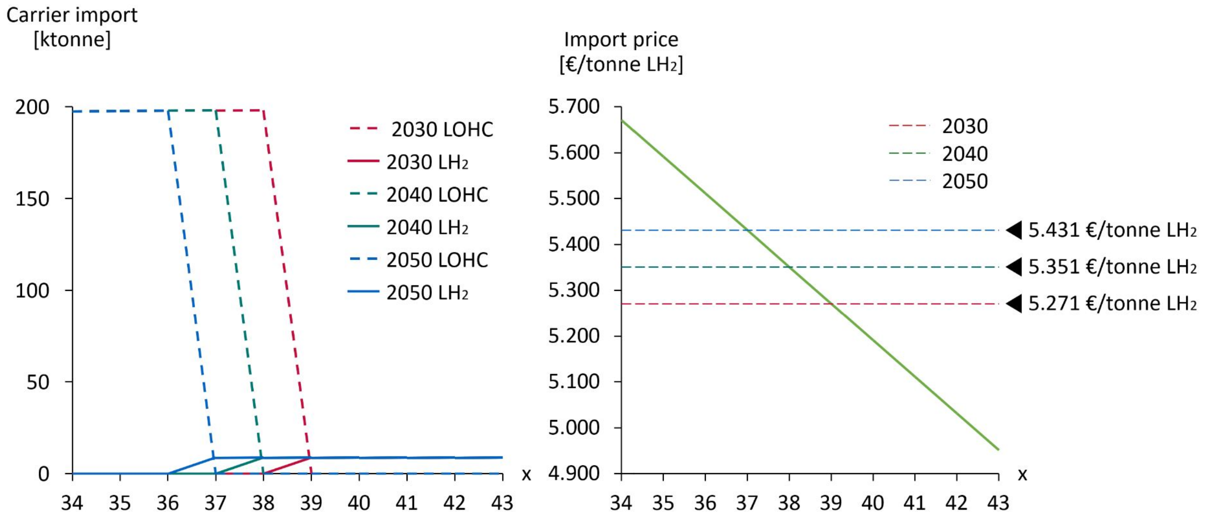


Figure 34: Amount of LH_2 and LOHC import (left) & LH_2 import price at which LH_2 becomes cheaper than LOHC (right). The LH_2 import price must be reduced by 36,5% to be cost-competitive with LOHC in 2030.

As expected, the tipping point is different in those three years due to the cost reductions for the storage and regasification processes. The import price at which LH_2 becomes the cheaper than LOHC is 5.271 [€/tonne LH_2] in 2030, and 5.351 and 5.431 [€/tonne LH_2] in the years 2040 and 2050, respectively.

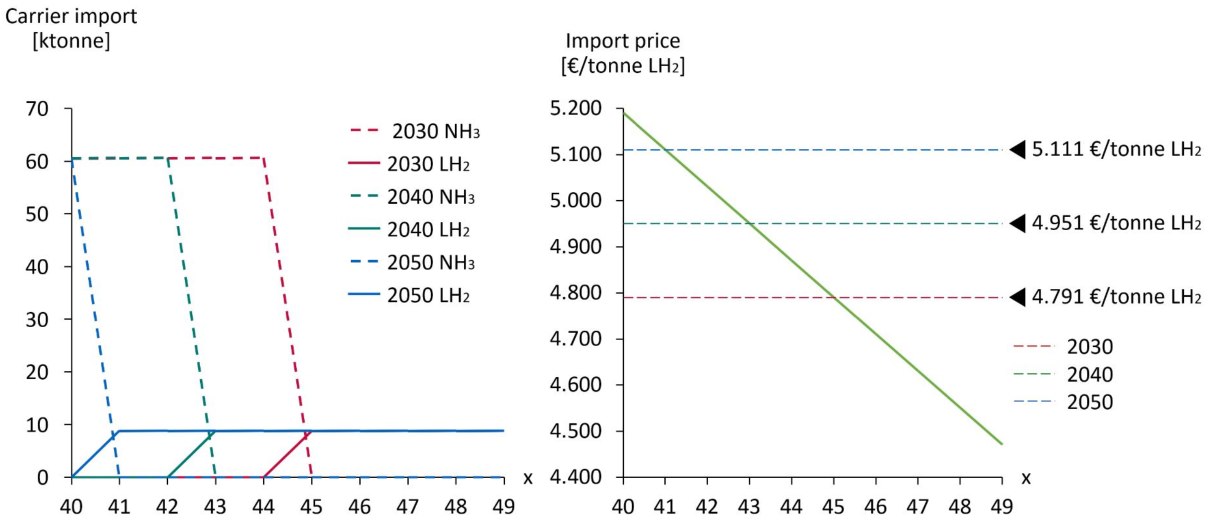


Figure 35: Amount of LH_2 and NH_3 import (left) & LH_2 import price at which LH_2 becomes cheaper than NH_3 (right). The LH_2 import price must be reduced by 42,4% to be cost-competitive with NH_3 in 2030.

Similar results can be observed for the comparison with NH_3. The tipping point is different in those three years due to the cost reductions for the storage and regasification processes. The corresponding import prices at which LH_2 becomes the cheaper than NH_3 is 4.791 [€/tonne LH_2] in 2030, and 4.951 and 5.111 [€/tonne LH_2] in the years 2040 and 2050, respectively.

What stands out from Figures 34 and 35 is the relatively small difference between the tipping points in 2030, 2040, and 2050. Especially when one considers that the regasification costs for LH_2 in 2050 decrease by more than 400 [€/tonne LH_2] compared to 2030. Thus, the reduction in the regasification costs of LOHC and NH_3 has a marginal impact on the total supply chain costs. Also, it is important that the ‘tipping point prices’ are not the exact prices at which LH_2 becomes cheaper than the alternative hydrogen carrier (e.g. LOHC or NH_3). The reason for this is the use of a step-function to decrease the LH_2 import price. Every step the price is lowered by 80 [€/tonne LH_2]. As a result the given ‘tipping point prices’ could be higher than the actual ‘tipping point prices’ till a maximum of 79 [€/tonne LH_2] above the presented prices in Figures 34 and 35.

6.4 Impact of technology: Hydrogen import

The overall results of this experiment are shown in Table 10. Logically, the number of vessels needed to guarantee security supply lowers as vessel capacity increases. To illustrate this, when LH_2 is solely responsible for covering the demand, an average of 61,7 vessels per day is required when the technology offers only a maximum of 89 [tonne LH_2/vessel]. This amount significantly decreases to an average of 3 vessels per day if the technology advances and enables a maximum capacity of 1.733 [tonne LH_2/vessel]. In case of a high LH_2-vessel capacity, the average is even reduced to 0,5 vessels per day combined with no import on most of the days. The number of required vessels in case of low vessel capacities for LOHC or NH_3 as import carriers are significantly lower.

Table 10: Required number of vessels per day to guarantee hydrogen security of supply given the allowance for only one specific hydrogen carrier to cover the hydrogen demand.

Required vessels per day		Low	Medium	High
LH_2	Average	61,7	3,0	0,5
	Median	60,9	3,0	0,0
LOHC	Average	6,1	1,6	0,6
	Median	5,5	1,5	0,0
NH_3	Average	5,5	0,6	0,4
	Median	4,8	0,0	0,0

The results shown in Table 9 are in line with the expectation that higher vessel capacities result in fewer required vessels per day. Also, Table 9 shows that many vessels are necessary in case of low vessel capacities for each carrier. In that case, establishing a reliable import supply chain would be extremely difficult. To illustrate this, say, each vessel takes two days to arrive in the PoR from an export country. If approximately six vessels are required per day, the import supply chain must consist of at least 24 vessels that are continuously in operation. As outlined in section 3.5, unexpected events, say malfunctioning vessels or extreme weather conditions, could disrupt such import supply chain leading to more uncertainty. Moreover, unforeseen circumstances regarding the production of the specific carrier in an export country would inherently lead to a disrupted supply chain. In short, many vessels are required from, desirably, more than one export country to create a robust import supply chain. Larger vessel capacities are significantly increasing the robustness of import supply chains.

Apart from the robustness of the import supply chain, the results of this experiment reveal important information for import terminal owners. To clarify, the arrival times of vessels have direct implications for the required hydrogen import infrastructure. Figure 36 show the distribution of needed LH_2-vessels over a year. The upper graph shows the distribution of arrival in case of low capacity for LH_2-vessels, the middle graph in case of medium capacity, and the bottom graph in case of high capacity of these vessels. Please note that our model does allow the arrival of half-filled vessels. The minimum amount to arrive is one vessel, as explained in section 4.2.1. The distribution of vessel arrivals, as shown in Figure 36 has implications for both the storage capacity and the throughput capacity. First, the implications for storage capacity will be discussed, followed by the implications for throughput capacity. Finally, the results are discussed, considering the geopolitical uncertainty factor. To explain these implications, we focus on the bottom graph in Figure 36.

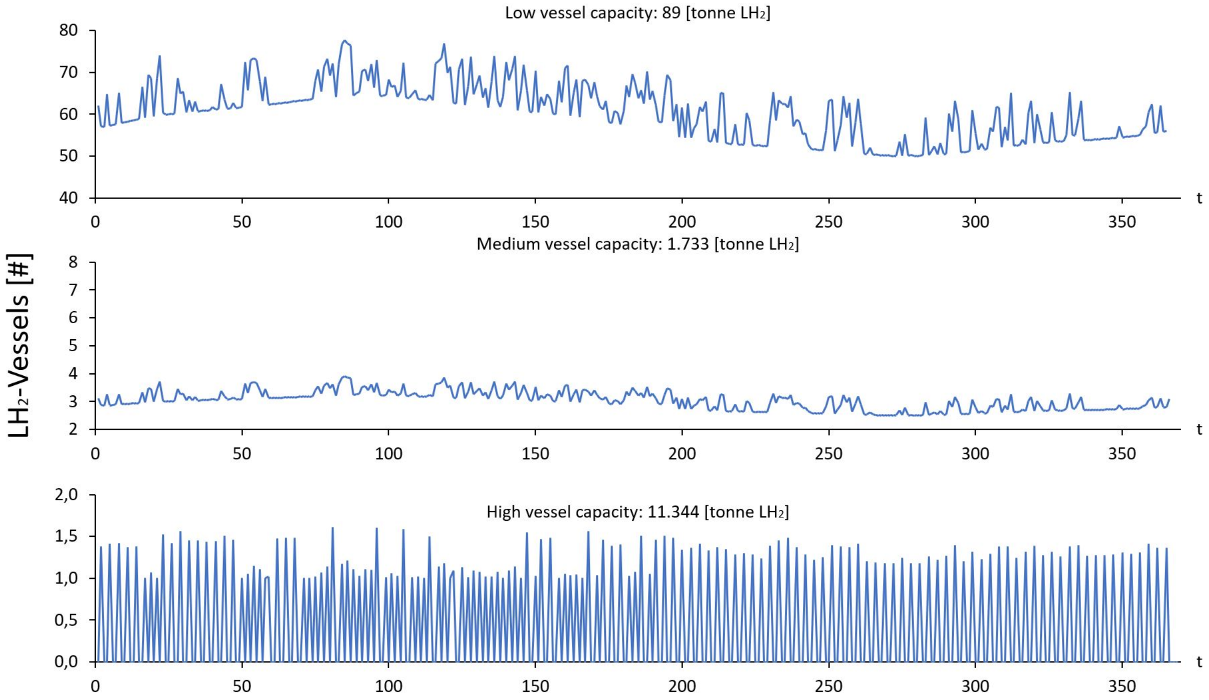


Figure 36: Required LH_2-vessels per day throughout the year in case LH_2 is the only imported carrier. In case of low and medium vessel capacities, unrealistic import frequencies are required. Please note the different ranges on the y-axis for each sub-graph

As can be seen in the bottom graph of Figure 36, many peaks represent the arrival of at least 1,0 to 1,5 vessels in those specific time-steps. In real life, on these days, two vessels would arrive to guarantee the security of supply instead of the arrival of, say, 1,5 vessels for obvious efficiency matters. In that case, the storage capacity required to facilitate the arrival of these ships would be equal to at least two times the capacity of a large LH_2-vessel (e.g. 2 * 11.344 = 22.688 [tonne LH_2]). To put this amount in perspective, Kamiya et al. (2015) stated that current technology of LH_2 storage tanks allow for a capacity of 50.000 [m^3] which is equal to 3.540 [tonne LH_2]. Hence, more than 6 of these storage tanks would be required to guarantee the security of supply. Please note that a hydrogen demand of only 2,99 [Mtonne/year] is considered in these runs. Logically, a higher hydrogen demand would require more infrastructure. However, these runs only allow one carrier to be imported in each run instead of combining the three carriers. Combining three carriers would lead to less required hydrogen infrastructure per carrier.

The distribution of vessel arrivals, shown in Figure 36, also has implications for the required throughput capacity of a terminal. The recurrent peaks in the bottom graph of Figure 36 represent an almost continuous arrival of vessels. A large throughput capacity is required to cope with these volumes. Coping entails providing the end-user sectors with gaseous hydrogen and emptying the storage as new vessels are incoming. Looking closely at the bottom graph of Figure 36, ‘import cycles of approximately three days can be observed. This would imply a throughput capacity that can process the full storage capacity in three days. Assuming the 22.688 [tonne LH_2] storage capacity from above paragraph, a throughput capacity of approximately 7.562 [tonne LH_2/day] (e.g. 22.688/3) would be required. To verify this, we conducted the same run of the bottom graph in Figure 36. Now the storage capacity and the throughput of the LH_2-terminal have been observed. The results are presented in Figure 37.

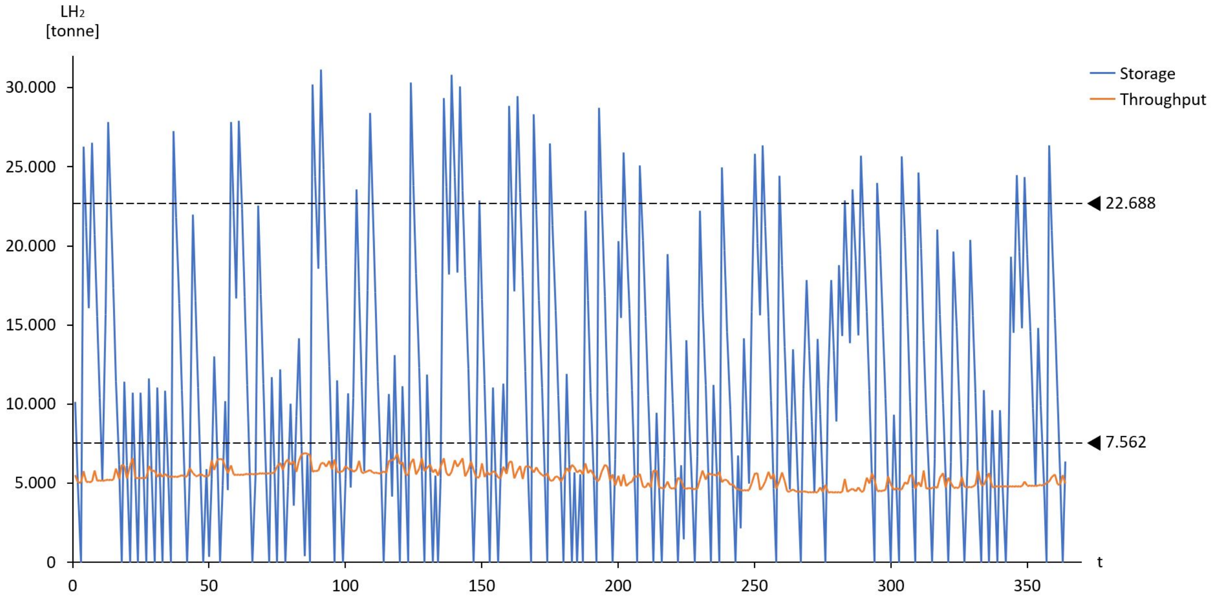


Figure 37: The level of the LH_2-storage tank content and the level of throughput by LH_2-terminal. The highly fluctuating storage level indicates a low average storage time per volume of LH_2.

Please note that an optimisation model has produced the results of this experiment. The model finds the optimal solution, which, in this case, is to meet the hydrogen demand against minimal costs, and thus, to import the minimum required amount of hydrogen. This is illustrated by many peaks in time steps where the amount of LH_2 is equal to a range between 1,0 and 1,5 times the LH_2-vessel capacity. Applying this to the real world, the results show the minimum amount of required hydrogen import, and therefore, the minimum necessary import infrastructure. In real life, larger storage & throughput capacities are required to cover for disruptions in the supply chain or unexpected events that suddenly increase the hydrogen demand.

To create a more realistic overview of the required storage and throughput capacity, we conducted another run. Similar to previous runs, this run uses *high* LH_2-vessel capacities (e.g. 11.344 [tonne LH_2/vessel]) and the import of LOHC and NH_3 is not allowed. However, now we set the lower bound of LH_2-import at a minimum of two vessel capacities per day. As such, we prevent our model from importing an amount of LH_2 that equals the capacity of more than one but less than two LH_2-vessels. The results are presented in Figure 38.

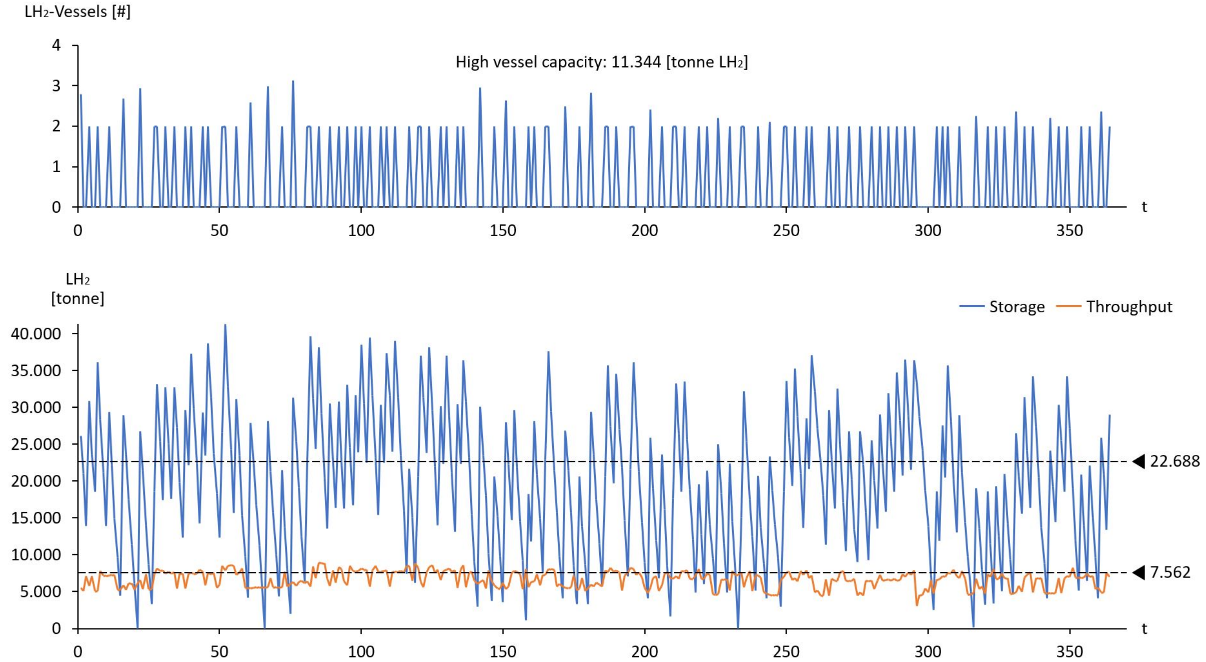


Figure 38: (Upper graph) the arrival of vessels per day throughout the year, (lower graph) the level of the LH_2-storage tank and the level of throughput by LH_2-terminal. The storage - throughput capacity ratio is approximately 3:1.

The first graph in Figure 38 shows the arrival of LH_2-vessels over 365 days. In comparison, in Figure 36 a more constant supply of LH_2 is observed. Hence, in only a few days, the amount of imported LH_2 is exactly equal to 2 times the LH_2-vessel capacity. Comparing the bottom graph in Figure 38 to Figure 37 one can observe an important role for storage capacity. To clarify, contrarily to Figure 37, in Figure 38 the LH_2-storage is rarely empty. Moreover, the storage content rarely moves below the amount of 7.500 [tonne LH_2]. What stands out is that in Figure 37 and Figure 38 the required storage capacity is approximately three times the throughput capacity. In the LNG terminal operated by Gate Terminal, a similar ratio is observed (Gate Terminal, 2020). Again, to put these amount in perspective, Kamiya et al. (2015) stated that current technology of LH_2 storage tanks allow for a capacity of 50.000 [m^3] which is equal to 3.540 [tonne LH_2]. To be able to facilitate the amount of import as indicated in figure 38, approximately nine storage tanks are required. Moreover, each day the level of throughput equals the storage capacity of two storage tanks (of 50.000 [m^3]). It is important to be aware of the magnitude of these amounts. To illustrate, a disruption in the import supply could lead to a situation where arrivals cannot arrive for, say, seven days. In that case, the amount of storage must be equal to approximately 14 storage tanks of 50.000 [m^3] to prevent a hydrogen shortage. Please be aware that this experiment only allows the import of LH_2 and disregard the presence of LOHC and NH_3. Nevertheless, the results of this experiment provide valuable insights related to the role of storage capacity.

6.5 Power of information

The results of this experiment are shown in Figure 39. A drop of more than 6% can be identified if the model receives complete information at the start of the run compared to runes with a look ahead of 20 time-steps or less.

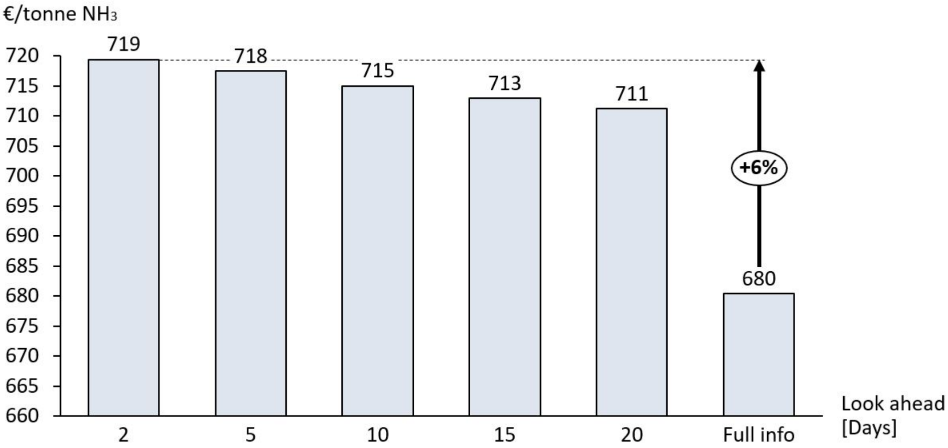


Figure 39: Average import price NH_3. The larger the look-ahead horizon, the lower the average NH_3 import price.

This can be explained as follows: Our model receives more information regarding the future in a run with a greater look-ahead horizon than a previous run. To clarify, a model with complete information knows the periods corresponding with the lowest market prices. In these periods, large amounts of NH_3 can be imported to establish a buffer for moments the market price increases. However, one must realise that a decrease of 6% in costs is not that significant because this can only be achieved if the exact import price is known for 365 days. Moreover, in this experiment, the import capacities were set at unlimited. Adding import constraints would decrease the efficiency of the look-ahead function as the solution space is smaller which can result in less optimal solutions. In that context, we argue that more information does provide possibilities to reduce costs, however, only to a limited extent.

The results of this experiment are highly sensitive to the input data. Hence, more cost reduction would be achieved if we add a more extensive range (e.g. between -20% and +20%) to the market price. However, one should also consider that the possibility to react to a fluctuating price is limited. To illustrate, if one knows that the import price significantly drops tomorrow, this short time frame will not allow for the sudden arrival of more hydrogen carrier vessels. Nevertheless, our model enables the modeller to analyse how information could contribute to more efficient hydrogen import. Additionally, one should consider that market price does not necessarily have to exist. As pointed out in chapter 2, long-term contracts are often constructed to protect infrastructure developers from fluctuating prices in an emerging market, like the hydrogen market. As such, this experiment would be more useful in the context of a more mature market.

7 Discussion

In this chapter, the most important results of this research are discussed. Please recall Figure 26 in chapter 5. This figure illustrates which uncertainties are analysed by experiments and which are not. This chapter discusses all uncertainties. Furthermore, we evaluate the applied research methodology by discussing the approaches we used to answer each sub-question. Finally, this study is put into context to discuss its scientific and societal contribution.

7.1 Discussion of results

Hydrogen is widely considered an essential energy carrier that could accelerate the energy transition. However, the development of large-scale production and the corresponding infrastructure are critical barriers that hinder hydrogen's potential. The Netherlands does not have the resources to fulfil the expected hydrogen demand by domestically produced hydrogen. Our results, in section 6.1 demonstrated the necessity for hydrogen import. We considered four supply and demand scenarios for 2050. In each scenario, the role of hydrogen import has been significant (>50% of the total demand). Our study considered only four scenarios. Therefore, other studies could apply a Monte Carlo method which enables the investigation of thousands of possible futures to create a more robust overview of the implications of different scenarios. Furthermore, this study considered three promising hydrogen carriers that could potentially be imported. Which hydrogen carrier, or combination of hydrogen carriers, will eventually be seen as the to-go-to form of hydrogen import revolves around technical, economic and geopolitical determinants. The added value of this study is that it analyses the technological, economic, and geopolitical uncertainties that hamper the realisation of hydrogen import terminals. Subsequently, the results will be discussed in light of the three categories of uncertainty (e.g. technological, economic, and geopolitical).

7.1.1 Technological uncertainty

Our results in the previous chapter did not include all technological uncertainties. However, based on our literature review, and our case study, we argue that the characteristics of each hydrogen carrier and the end-user sectors' technical preferences are the most critical technological determinants that determine which hydrogen carrier is imported. End-user sectors with presumably high hydrogen quality requirements are the feedstock chemical industry, mobility (transportation), and aviation. For these sectors, LH_2 is suited due to its high hydrogen quality after vaporisation. Other sectors can, presumably, use lower hydrogen qualities which allows the use of LOHC and NH_3. Please note that the quality of LOHC and NH_3 can be increased by expensive purification methods. Moreover, LOHC and NH_3 can make use of existing infrastructure, while LH_2-technology is in an early stage of development. Additionally, LOHC can be stored without cooling and has no losses during transportation, favouring LOHC compared to other hydrogen carriers. Finally, one aspect makes the use of LOHC and NH_3 less attractive compared to LH_2; their regasification process. The cracking of LOHC and NH_3 into hydrogen require a high energy input which must be made available in the PoR. In section 3.1.4, we indicated that waste heat could be used for these cracking processes. In the case of cracking using fossil fuels, the sustainability of both carriers would become questionable. This study does not include CO_2-emissions. However, it is crucial to consider that a guaranteed availability of sustainable energy input for the regasification of processes of both LOHC and NH_3 is not apparent. The consideration of environmentally harmful emissions opens a new avenue for future research. Nevertheless, in sectors where NH_3 can directly be used (e.g. maritime shipping sector and process heat industry), NH_3 could be advantageous as the total energy efficiency of the NH_3 supply chain is increased because the energy-intensive regasification process is not required anymore. The same goes for the aviation sector in which LH_2 can, presumably, directly be used. The two export sectors probably include more hydrogen applications than described here, which leave uncertainty of which those sectors prefer hydrogen carrier. The required inland transportation towards the export sectors complicates the debate for their preferred carrier even more. Section 3.3.3 described in detail how pipelines, barges, trains, and trucks could be used to transport the hydrogen or hydrogen carriers towards these sectors. Each hydrogen carrier has its own barriers related to inland transportation. LH_2 inland transport is relatively expensive as it can only be transported by trucks or specialised containers on trucks or barges. The inland transportation of LOHC is complicated as the residual LOHC must be transported to its original location after the cracking process, leading to twice as many transportation movements. NH_3 can make use of existing infrastructure for its inland transportation. However, NH_3 is highly flammable and toxic, which can result in societal opposition if transported through residential areas.

Furthermore, our results in section 6.4 considered the impact of technology on hydrogen import terminals. More specially, we observed important aspects that determine the scaling of an import terminal. A critical technological factor that impact the realisation of hydrogen import terminals is the development of technologies in the supply chain of hydrogen import. Especially the technology regarding the specialised vessels of each hydrogen carrier is essential to consider since larger vessel capacities inherently mean larger import terminals. We quantified this technology development using different sizes of the three hydrogen carrier vessel's capacities. Our results show the number of vessels required given a scenario in which only one specific hydrogen carrier is included. In reality, more hydrogen carriers will be imported simultaneously, resulting in a lower number of vessels required per hydrogen carrier. Moreover, the different sizes of vessel capacities were derived from projections in the literature. In that context, the exact future sizes of the vessels are uncertain, which makes our results less reliable. Nevertheless, our results show the importance of technology development. Our model enables the modeller to experiment with different vessels sizes. This is a vital addition as it provides a tool to quantify technology development. As such, the model's user can analyse the impact of the technology development.

Finally, another factor that affects the scaling of a hydrogen import terminal is the mismatch between supply and demand. Hydrogen import can contribute to matching the supply and demand accordingly. More specifically, the hydrogen import terminals' storage capacity provides flexibility to the supply of hydrogen demand to the end-user sectors. Our results, in section 6.4, offered valuable insights related to how import terminals operate to distribute the right amount of hydrogen at the right time towards the end-user sectors. The combination of storage and sufficient throughput capacity provides a reliable supply source for end-user sectors requiring constant hydrogen supply. Contrarily, the electrolysis' fluctuating hydrogen production complicates the (production) processes in end-user sectors that rely on a continuous hydrogen supply. In that context, hydrogen import could provide a more reliable hydrogen source than domestically produced hydrogen. Another option to cope with the mismatch of supply and demand is demand management. Some end-user sectors have more flexible processes and can, therefore, quickly ramp up or ramp down their operations. To clarify, these specific sectors can downscale their (production) processes to decrease their hydrogen demand, enabling other sectors to continue their (production) processes. Our study did not include the concept of demand management. However, it is important to consider during the design of a hydrogen import terminal as it can impact its scaling. Other studies could focus on demand management of specific sectors and analyse the role of demand management in the scaling of hydrogen import terminals.

7.1.2 Economic uncertainty

Now that technical uncertainties have been discussed, we focus on the economic aspects of the realisation of hydrogen import terminals. Our results, in section 6.2, analysed the cost-competitiveness of the three hydrogen carriers compared to hydrogen production via electrolysis given projected production costs in 2030, 2040, and 2050. The import price of all three hydrogen carriers needs to be significantly reduced to be cost-competitive compared to electrolysis. This is essential to mention since import terminal owners must consider that imported hydrogen will presumably be more expensive, which increases the uncertainty of using import terminals. However, noteworthy to mention is that our study considered a renewable electricity price of 40 [€/MWh], which was adapted from the work of IEA (2019). Since we were not able to model the renewable electricity price as an input value, the data of IEA (2019) has been used. Hence, their work offered hydrogen production costs, including the renewable electricity price, which made their data applicable to our model. However, their work is not explicitly focused on The Netherlands. To put into context, the energy transition model by Quintell (2010) is specifically focused on The Netherlands and uses higher productions costs for offshore wind (e.g. 75 - 125 [€/MWh]). An increase in the renewable electricity price would significantly increase the costs of the electrolysis process. As a result, hydrogen carriers could be sooner cost-competitive to electrolysis as the production costs of hydrogen via electrolysis are presumably higher than indicated by our study. This would decrease the uncertainty for import terminal owners. Furthermore, the cost-competitiveness between the three hydrogen carriers have been analysed in section 6.3. These results have three important implications. First, the LH_2 import price must be reduced by 3.040 [€/tonne LH_2] to be cost-competitive, compared to LOHC, in 2030, and even 3.520 [€/tonne LH_2] to be cost-competitive, compared to NH_3, in 2030. To put this in perspective, that equals a decrease of nearly 40%. Second, the level of an import price entails more uncertainty than the storage and regasification costs. Since the results included cost reductions for storage and regasification, the 40% cost reduction must be achieved in the production, conversion to the carrier, or shipping stage of the supply chain. Third, our results, on this matter, did not include technology development of LOHC and NH_3. This is not realistic as technology development between 2030 and 2050 will probably lower prices for these two carriers due to technology development. In reality, the import price of LH_2 needs to be reduced even further to be cost-competitive compared to the other two carriers. The relatively undeveloped LH_2-technology has more potential to reduce supply chain costs compared to LOHC and NH_3 as their technologies are already well developed and optimised (Wijayanta et al., 2019). However, our results require some discussion related to the reliability as the import prices that were used to come to the results have been derived from Terwel and Kerkhoven (2018). Their work calculated the import prices of hydrogen carriers to the Port of Rotterdam from 144 different countries. The average import prices for the three hydrogen carriers from those 144 countries were taken as an input value (e.g. 8.311, 224, 692 [€/tonne carrier] for LH_2, LOHC, and NH_3, respectively). Taking the average prices seems a reasonable approach to obtain input values when no specific countries are considered. However, one must consider that, in reality, hydrogen will be imported only from countries that offer relatively low export prices. In that context, the import prices of all three hydrogen carriers will probably be lower than indicated in this experiment. Future research could include specific export countries. Using specific country parameters increase the reliability of the results. Nevertheless, these results showed the significant cost reduction that LH_2 needs to be cost-competitive compared to the other two hydrogen carriers. More specifically, it illustrates the need for long-term contracts to import LH_2. This is further explained in the next paragraph.

From a more theoretical perspective, the above results confirm the notion of the TCE theory by Williamson (1979). The TCE theory suggest that in a market with high asset specificity and a recurrent frequency of transitions, long-term contracts are a suitable approach to organise these transactions. Chapter 2 analysed, by using the TCE theory, how contracts have been used in the LNG market and how they evolved from long-term contracts, at the emergence of the market, to more short-term contracts in the last decades. Hydrogen import terminals are highly asset-specific and facilitate recurrent transactions (e.g. the storage and throughput of volumes of hydrogen). In that context, a similar path, compared to LNG, can be projected for hydrogen based on the similarities in the supply chain of the two commodities. Moreover, long-term contracts would fit the degree of uncertainty present in these transactions as the long-term aspect of the contracts can justify the expensive investments required for hydrogen import terminals. Our results showed that hydrogen import can not yet, economically compete with domestically produced hydrogen. More specifically, due to the supply chain price gaps between the three carriers, only the cheapest hydrogen carrier would 'survive' if a market mechanism regulated the hydrogen import. As earlier discussed, the technical characteristics of each hydrogen carrier and the end-user sectors' technical preference indicate that a combination of three hydrogen carriers is technically desirable. Moreover, a variety of hydrogen import options, instead of one, makes the Port of Rotterdam less vulnerable to geopolitical forces. In that context, realising hydrogen import terminals through long-term contracts provides a promising solution to cope with economic, technical, and geopolitical uncertainties. However, it is essential to discuss the differences between LNG and hydrogen and address corresponding implications for realising hydrogen import terminals.

The pressure for sustainability forces a rapid development of the hydrogen market. As a result, more actors are involved in the hydrogen market than the LNG market, where only a small number of players are active. Primarily since natural gas reservoirs geographically bound LNG production while hydrogen can be produced anywhere globally. According to Williamson (1979), the presence of more buyers and sellers in a market decreases the uncertainty in transactions which would alter the suitable contract form from long-term to short-term contracts. The number of actors in the LNG market increased in the last decade, resulting in another type of actor; the aggregator. To recall chapter 2, an aggregator either buy much LNG or hold various assets along the supply chain. This way, it can supply different markets more efficiently than long-term contract types, resulting in higher profits. These aggregators are already visible in the hydrogen market, which is remarkable since they appeared only after many decades in the LNG market. The presence of aggregators could have a critical impact on how contracts will be organised in the hydrogen market. More specifically, it could impact the way contracts related to hydrogen import terminals are organised. Hence, the presence of aggregators indicates a faster transition from long-term contracts to short-term contracts. This more immediate transition could endanger the realisation of hydrogen import terminals. In the LNG market, long-term contracts proved suitable to justify the expensive investments costs associated with the import terminals. If hydrogen import terminals owners can no longer rely on long-term contracts' safety, alternative ways to receive a return on the investments need to be found. This is closely related to the function of a hydrogen import terminal, a base-load or a peak-shaving function.

To clarify, section 3.1.4 describes that a base-load operating terminal usually has a throughput of several thousands of tons per day. Therefore, the throughput is constant and predictable, and the throughput capacity has to be relatively high to facilitate the base-load. Our results showed that, in the case of a base-load terminal, the ratio storage versus throughput capacity is approximately 3:1. The LNG import terminal, operated by Gate Terminal, has a similar ratio, strengthening our results' reliability. Considering a base-load operating import terminal, the terminal owner can quickly determine what customers need to pay for the terminal operations to justify the terminal investment costs. As such, our results provide valuable insights for terminal owners and designers. On the other hand, an import terminal, functioning as a peak-shaving facility, has less predictable operations. Compared to a base-load operating terminal, a peak-shaving facility has a low throughput capacity. Moreover, the peak-shaving function should have quick ramp-up time because it aims to cope with the mismatch in supply and demand at only a few particular moments to guarantee security of supply. In the electricity and natural gas market, balancing services are offered by a Transmission System Operator (TSO). It is expected that a similar approach will be applied for hydrogen. Without diving deep in a detailed assessment of the TSO's operations, invoke peak-shaving units to produce at times of a high demand (Oren, 2000). Therefore, a quick ramp up time is required for such operations. LH_2 is more suitable, than LOHC and NH_3, to function as a peak-shaving unit given its low energy demand during regasification, and therefore, quick ramp-up time (Wijayanta et al., 2019).

As required storage and throughput capacities are unknown, investments in peak-shaving terminals bear more risk if not realised through long-term contracts that justify the investment costs. If long-term contracts are not applied for such terminals, the profits need to be realised in the small window the terminal is operating. We already shortly discussed that some end-user sectors require a constant hydrogen supply as energy input for their production processes. To them, security of supply is of vital importance as a disruption in the hydrogen supply results in huge losses as expensive production processes can not continuously run. Here, the customer's WTP is essential to discuss. In our study, eight hydrogen end-user sectors are included as a potential customer. Their WTP has not been included in this study. However, the WTP is of absolute importance as it reflects the price a customer is willing to pay for a specific volume of hydrogen and their security of supply. More specifically, it reflects what a customer, or entire end-user sector, is willing to pay for the operations of a hydrogen import terminal to guarantee their security of supply. As such, future research could focus on the end-user sectors' WTP. Import terminal owners and designers are supported in their decision-making process if provided by insights into the WTP of the end-user sectors. Our contribution is that our model enables the simulation of the operations of import terminals given various scenarios. This is essential as it allows import terminal owners to optimise the scaling of hydrogen import terminals. Moreover, the systematic approach our study enables to investigate the security of supply of a hydrogen system. Future research interested in developing our model, could focus on integrating the WTP of various end-user sectors. As such, valuable insights can be generated related to the security of supply in a hydrogen system. More specific, this addition in combination with an investment model would create a fruitful model that can test the system adequacy of a integrated hydrogen system. The recommendation to build an investment model is further explained in the section 8.3.

7.1.3 Geopolitical uncertainty

Finally, three geopolitical aspects that impact the realisation of hydrogen import terminals need to be discussed. First, uncertainty is present in the country that exports hydrogen carriers. The hydrogen import supply depends on export countries with excessive renewable energy sources that could be used for hydrogen production. Moreover, Pflugmann and Blasio (2020) argued that renewable energy resources, freshwater availability and infrastructure potential are three critical criteria that determine the export potential of a country. To illustrate, Saudi Arabia, having an uncertain availability of freshwater, would be risky as an export country compared to countries like Norway or Australia where freshwater is abundantly available (Noussan et al., 2021). Furthermore, the distance to the PoR is a crucial aspect that holds uncertainty, especially if these distances are large. Hence, a disruption in the supply chain can quickly occur, as seen last year during the blockage of the Suez canal. Another disturbance is related to the production of fossil fuels. Former oil and gas countries that cannot shift to renewable energy or earn less profit could potentially hamper a global hydrogen trade. They keep the fossil fuel prices low by increasing their oil and gas production.

More geopolitical uncertainty is identified closer to the PoR. Notermans et al. (2020) emphasise the urgency of the realisation of hydrogen import terminals. Postponed decisions could result in other countries claiming this position. A hydrogen import terminal in, say, the Port of Antwerp could abduct a significant share of the predicted hydrogen demand. A 'first-mover' position could give the PoR considerable opportunities to develop knowledge and expertise related to hydrogen, which would be fitting to the position of The Netherlands as a knowledge economy. Moreover, even when not being used, hydrogen import terminals could contribute to the security of supply. We already discussed the working of a peak-shaving unit which becomes valuable in moments of an extremely high hydrogen demand or low domestic hydrogen production to unfavourable weather conditions. More general, the presence of a hydrogen import terminal provides the possibility to import hydrogen from various places around the globe. An exemplary example is the realisation of the LNG terminal, operated by Gate Terminal, in 2011. Until 2017 the LNG terminal has been used at a minimum level (Gate Terminal, 2020). However, due to its presence, the Netherlands, would be less vulnerable to geopolitical forces by, say, Russia, as it had another option to import natural gas. A similar function could be drawn to a hydrogen import terminal. Even without functioning or processing hydrogen, hydrogen import terminals could improve the strategic position of the PoR and the Netherlands.

Finally, we discuss the presence of salt caverns and their potential to store hydrogen. The presence of salt caverns has not been included in our model. However, it is relevant to discuss as salt caverns can account for storage which would replace the need for large-scale above-ground storage (e.g. storage tanks in import terminals) in the PoR. This would not only leave room for other industrial activities in the PoR but also requires less upfront investment (Caglayan et al., 2020). The operational hydrogen storage in salt caverns impacts the design and role of a hydrogen import terminal in the Port of Rotterdam. Hence, the infrastructure in the PoR should be able to facilitate the reception of the imported hydrogen and allow for sufficient throughput capacity to transport the hydrogen towards the salt caverns. This significantly impacts the business model of a terminal. Therefore, other studies could investigate the inclusion of salt caverns as a hydrogen storage alternative since it could alter the results obtained from our model.

7.2 Discussion of methodology

This section discusses the methodology applied in this study. First, we discuss the research methodology by evaluating how the sub-question contributed to answering the main research question. Then, the modelling methodology in Linny-R is discussed.

7.2.1 Discussion of research methodology

The literature review conducted in chapter 2 provided the foundation for our study. Through this literature study, the first three sub-questions, presented in chapter 1, are answered. First, three methods to study hydrogen infrastructure were analysed; MILP, DP, and spreadsheet modelling. MILP was chosen as it could facilitate the resolution of more complex problems. However, we acknowledge that some experiments that have been conducted in this study could also have been performed with DP or even spreadsheet modelling as not all experiments required optimisation. Nevertheless, creating a model in Linny-R allowed us to experiment with a large set of variables easily. More importantly, MILP as the method was required to analyse required storage and throughput capacities as we did in experiment 'Impact of technology: Hydrogen import'.

Second, three types of uncertainty have been identified using different theories or frameworks. Economic uncertainty has been analysed using both the agency theory and the transactions cost economics theory. Primarily, the latter theory provided valuable insights on how contracts occur and evolve in an industry. Those findings proved to be helpful to evaluate our model results. Technological uncertainty has been analysed through the use of the multi-level perspective by Geels (2002). The work by Geels (2002) and its peers provided insights into how forces on societal, technological, and political levels could contribute to a successful breakthrough of a specific technology. However, the multi-level perspective does not address the successful breakthrough of a new industry, such as hydrogen import. Geopolitical uncertainty has been identified through a literature review. The literature review provided valuable insights that could be used as a guideline to identify geopolitical uncertainties, specifically for the Port of Rotterdam. The theories and framework that have been used will be further elaborated upon in section 7.3.1.

The third sub-question aimed to reveal approaches that could deal with the uncertainty present related to hydrogen infrastructure. Three approaches have been identified in chapter 2; scenario analysis, sensitivity analysis, and a probability-based method. The latter method has been disregarded because of its significant computational times. However, we recognise that computational time has less of a limitation than thought beforehand. The reason for this is that, during the process of writing this thesis, we could replace the solver behind Linny-R with a more powerful solver, Gurobi (Gu et al., 2021). This solver significantly reduces the computational time and enables the modeller to solve more complex problems. We elaborate further on the possibilities offered by the Gurobi solver in section 8.3.

The fourth sub-question was used to identify aspects from our case that could be used as input for our model. Through a case study, we analysed an integrated hydrogen system located in the PoR. However, due to our system perspective, some elements could be analysed and modelled in more detail. Especially certain technical aspects of the import terminal have not been included for complexity reasons. An example of a process that is not included relates to the storage of LH_2. Hence, during the storage of LH_2, some LH_2 vaporises due to imperfect insulation. The vaporisation rate is equal to approximately 0,06 [%/day] of the content of the LH_2-storage tank in the import terminal (Kolff, 2021). Future research could add more technical information to these processes to provide more comprehensive results.

The fifth sub-question concerned the identification of the uncertainties that were specifically present for our the Port of Rotterdam through a case study. The degree to which economic uncertainty is present is straightforward due to unknown future prices and high specific investment costs. The degree of technological uncertainty has been somewhat difficult to capture. The reason for the complexity is the quantification of technological uncertainty. To cope with this, metrics have been used to quantify technological development. To illustrate, the technology development regarding the specialised vessels has been quantified by the metric 'vessel capacity. Quantifying technological development by only one metric is not entirely representative. Other studies could make use of more metrics to define technological developments. Geopolitical uncertainty has also been found through the case study. We argue that a case study is helpful to identify geopolitical uncertainty. However, the degree to which the geopolitical aspects are uncertain is, again, challenging to capture. A separate study would provide presumably insights into how geopolitical uncertainty impacts the realisation of hydrogen import terminals.

The sixth sub-question regards the formalisation of a working model in Linny-R. This is discussed in the following section.

7.2.2 Discussion of modelling methodology

The model in Linny-R has been built with the greatest care to represent reality as well as possible. Nevertheless, some assumptions are made to limit complexities in our model. First, we assumed that hydrogen import was always available. Also, no specific export countries were included from where hydrogen was imported. In that context, we neglected production capacities from export countries and the possibility that the hydrogen demand could exceed the domestic and foreign hydrogen production. Moreover, due to those assumptions, distances to the PoR were not included in our model. Though distances do not only significantly influence the import prices of the three carriers (Lanphen, 2019), longer distances do increase the chance of disruption in the supply chain and complicate quick reactions to disturbances. Other studies could include specific countries and analyse their production capacities to create a more comprehensive system overview. Another critical assumption that we made relates to supplying the hydrogen demand. We assumed that hydrogen demand must always be met at any cost. As such, we excluded the option that alternative fuels could replace hydrogen if hydrogen becomes too expensive. If the prices of hydrogen, either locally produced or imported, exceeds the WTP of the end-user sectors, their hydrogen demand will decrease or even be eliminated. Other studies should consider including the WTP to be able to have a more realistic hydrogen demand. Our data has been collected from reliable sources such as large, recognised institutions, for instance, the IEA, or literature cited often. However, we recognise that all input data contain some degree of uncertainty. Especially when it concerns data projections for 2030, 2040, and 2050.

Furthermore, we were not able to model the arrival of only filled vessels (e.g. vessels that are not loaded to maximum capacity, see section 4.2.1). This led to some results, see 6.4, where the amount of hydrogen import was equal to a range of 1,0 - 1,5 times the capacity of that specific vessel in many days of one particular run. In this case, relatively low storage capacity is required. However, more storage capacity was needed when a more realistic import distribution was modelled by constraining the model to only import a minimum amount of hydrogen carrier equal to two vessels in a time step. Other studies could develop a modelling method in which only totally filled vessels could arrive. This would represent a more realistic overview of hydrogen carrier import and provides more valuable insights. Nevertheless, our model enables the quantification of vessel technology derived from the differences between the characteristics of the three hydrogen carriers. Moreover, our model allows the modeller to explore the required storage and throughput capacities given various supply and demand scenarios. This provides valuable information for terminal owners and designers.

Finally, we used a daily time resolution to solve our problems in Linny-R. In this way, the arrival of hydrogen carrier vessels, the hydrogen production by SMR and electrolysis, and the hydrogen demand in the end-user sectors could appropriately be analysed. An hourly time resolution allows for a detailed analysis of the electrolysis process but would be too detailed for an analysis of the arrival of vessels. A weekly or yearly time resolution would not allow analysing the daily operations in an import terminal. Moreover, it would be less practical to include volatility and uncertainty in the hydrogen demand. Based on the choice for a daily time resolution and the use of the lp_solve solver at that time, we disregarded investments in our model. Hence, investments, especially large investments required for hydrogen infrastructure, need a horizon of multiple years to analyse. Therefore, including investments combined with a daily time resolution would lead to enormous computational times as thousands of time-steps must be optimised. We still do support the decision to apply a daily time resolution as it allowed us to analyse different components of our system. Nevertheless, we recognise that investments cannot be disregarded as investments are essential to support companies' business cases for hydrogen import terminals. Investments in Linny-R can be analysed by adjusting our model, especially when the Gurobi solver is used. This will be further explained in section 8.3. An investment model could provide additional insights into when returns on investments can be expected. Nevertheless, our model allows the analysis of several essential components related to the realisation of hydrogen import terminals.

7.3 Discussion of scientific and societal contribution

This section aims to discuss this study in perspective of its societal and scientific contribution. First, the scientific contribution is discussed, followed by a discussion of the societal contribution.

7.3.1 Scientific contribution

To the domain of hydrogen import infrastructure literature, this study is the first to include a combination of both hydrogen demand uncertainty and multiple hydrogen end-user sectors. This is a unique and vital addition to the hydrogen infrastructure literature primarily focused on the transportation sector. The included end-users sectors are the feedstock chemical industry, process heat industry, the building environment, the mobility sector (transportation), maritime shipping sector, the aviation sector, and two export sectors (e.g. Germany and North-West Europe). Including these end-user sectors is essential as the transportation sector accounts for only a marginal share of the projected hydrogen demand. As a result, this study provides a more comprehensive perspective on the role of hydrogen, and thus, on the role of hydrogen import in the energy transition. Furthermore, this study includes geopolitical aspects, which adds a novelty to the hydrogen import infrastructure literature. The unsettled debate in the literature regarding the geopolitics of renewables and hydrogen motivates the involvement of geopolitics in this study. On the one hand, this study highlighted the geopolitical uncertainties that hamper the realisation of hydrogen import terminals. On the other hand, this study suggests opportunities for the Port of Rotterdam to establish hydrogen import terminals to improve their strategic position. By including geopolitics into the scope of this research, a more comprehensive outlook on uncertainty related hydrogen import terminals is achieved.

As a more theoretical contribution, this study applies the TCE theory by Williamson (1979) and the multi-level perspective by Geels (2002) to a case study of hydrogen import terminals. First, we reflect on the use of TCE theory, then the appliance of the multi-level perspective is discussed. The similarities between LNG and hydrogen provided a promising foundation for the use of the TCE theory in the context of hydrogen import infrastructure as the TCE theory has been widely used to analyse market development and contracts in the LNG market. The TCE theory proved to be an excellent tool to analyse the governance structures and contracts in an emerging hydrogen market. Despite that we were not able to model the concept of contracts, our model results supported theoretical arguments suggested by the TCE theory. As such, our study underlines the applicability of the TCE theory in the context of renewable energy economics, and more specifically, hydrogen economics. Finally, we share the criticism of Ruester and Neumann (2009) on the TCE theory, as they argue that the TCE theory falls short in explaining how different types of contracts can be applied in a firm's strategy or vision. This is vital to provide insights for single companies, like Gate Terminal, about the uncertainties related to the realisation of hydrogen import terminals.

The use of the multi-level perspective has been less successful compared to the appliance of the TCE theory. Hence, the multi-level perspective is specifically focused on the success of one technology. Our study concerned an integrated hydrogen system using various technologies. Especially the variety of technological developments in different areas create uncertainty on a systematic level. Consequently, we argue that the multi-level perspective is not applicable from a system perspective in which more technologies are present but rather for analysing a specific technology within a system. The multi-level perspective should loosen its tendency to focus on one 'winning' technology to be more relevant in case studies such as ours. Our results suggested that the simultaneous development of more than one hydrogen carrier technology is desirable from a societal perspective.

On a more detailed level, this study has proposed the use of a model. The model that has been developed made use of MILP. To the author's best knowledge, no other model regarding hydrogen import has been built that uses MILP as a method, which adds a novelty to this research. Moreover, the model incorporates hydrogen demand uncertainty which is vital to represent an integrated hydrogen system from a more realistic perspective. As such, this study offers a modelling philosophy to model the import of other energy commodities combined with uncertain demand. This is a valuable contribution as supply and demand mismatch is an increasingly mentioned problem, especially in the context of the energy transition.

7.3.2 Societal contribution

This study provides valuable insights regarding uncertainty related to hydrogen import terminals. Through our model, we have been able to analyse the hydrogen carriers' cost-competitiveness compared to electrolysis. Moreover, the cost-competitiveness between the respective hydrogen carriers was analysed. Other results showed the importance of technology advancements and information regarding future market prices. In short, we developed a model to quantify the uncertainties related to hydrogen infrastructure. The quantification of uncertainties is helpful to companies and policymakers in decision-making processes. Companies want a certain degree of certainty before making an investment decision. However, we argue that the results of this study should not be used as the foundation for investment decisions. Hence, due to our system perspective, some aspects essential for individual companies are not included in detail. Moreover, we argue that an investment-based model would give more insight into economically feasible options. Nevertheless, our results point out what aspects are subject to uncertainty. Therefore, this study can be seen as a starting point on which future research can be built. Policymakers could derive essential conclusions from this study. Namely, the results showed that large-scale hydrogen import is required, but it also showed that hydrogen import must achieve significant cost reductions to be competitive with hydrogen produced locally. Moreover, as discussed, the realisation of hydrogen infrastructure could make The Netherlands less vulnerable to geopolitical forces as it contributes to a diverse energy mix. Policymakers could design tailored regulations and policies to stimulate hydrogen use and hydrogen import based on our results. To be more precise, the costs gap between import and domestically produced hydrogen is significant. The government could provide a subsidy similar to the support provided for the PORTHOS project, compensating for the cost gap between import and domestically produced hydrogen. As such, hydrogen use is stimulated, and business cases for hydrogen import terminals are strengthened. A more comprehensive overview would include the environmental emissions that are related to hydrogen import. This is not included in this study but should be studied in future research. Nevertheless, we modestly argue that this study contributes to the decision-making process regarding hydrogen import and the corresponding infrastructure.

8 Conclusion & Recommendations

This chapter presents the research conclusion. First, the sub-questions are answered. Then, the main research question is answered. Finally, recommendations for future research are given.

8.1 Answers to the sub-questions

This section answers the sub-questions defined in chapter 1. Each paragraph is dedicated to the conclusion of one sub-question.

A suitable methodology that can be applied to study hydrogen infrastructure has been found in MILP. Moreover, we found that often models are used in combination with MILP to investigate large energy systems, which strengthen our choice to develop a model. This answers the first sub-question.

Three categories of uncertainties are present regarding hydrogen infrastructure; economic, technological, and geopolitical uncertainties. Economic uncertainty relates to future markets and prices. Technological uncertainty predominately relates to the question development of niche technologies evolves to their maximum potential. Geopolitical uncertainty is present in creating new interdependence between states and regions as a consequence of renewable energy production. As such, the second sub-question is answered.

Three approaches were identified to deal with uncertainty in the context of hydrogen infrastructure; sensitivity analysis, scenario analysis, and probability-based assessments. This study used the first two methods to deal with uncertainties in this study. The latter method has been disregarded since its prolonged computational times and the inability of Linny-R to perform such a method.

The inputs to model an integrated hydrogen system located in the Port of Rotterdam can be categorised into three sub-systems; hydrogen import, domestic production, and hydrogen demand. The case-inputs are found in Figure 12 in section 3.4. As such, the fourth sub-question is answered.

The uncertainties present regarding an integrated hydrogen system located in the Port of Rotterdam are economic, technological, and geopolitical. The uncertainties have been categorised into three sub-systems; hydrogen import, domestic production and hydrogen demand. As such, the fifth sub-question is answered.

Finally, we found a suitable modelling environment in Linny-R to formalise the conceptual model into a working model. The three sub-systems from our case study have been translated into three sub-models. Subsequently, the three sub-models have been combined into one integrated model. In this way, sub-question six is answered.

8.2 Answering the main research question

Hydrogen seems to account for a dominant position in the future energy mix of the Netherlands. Hydrogen import is compulsory to match the projected hydrogen demand due to the limited hydrogen production capacity in the Netherlands. Specifically, a combination of economic, technical, and geopolitical uncertainty complicates the realisation of import terminals that would facilitate the hydrogen import. As such, the main research is as follows:

> *"How does uncertainty impact the realisation of hydrogen import terminals in the Port of Rotterdam?"*

Economic uncertainty is related to the cost-competitiveness of hydrogen import and investments in hydrogen import terminals. We conclude that hydrogen import is necessary to supply the hydrogen demand in various end-user sectors. However, hydrogen import is not cost-competitive compared to domestically produced hydrogen. Cost reductions in the import supply chain must be achieved in the production, conversion to the carrier, or shipping stage of the supply chain to improve the cost-competitiveness of hydrogen import. No specific carrier has been pinpointed as 'winner' to account for the entire required hydrogen import among the different hydrogen carriers. At the moment of writing this thesis, NH_3, and followed by LOHC, seem to be cheaper than LH_2. However, if LH_2 import would be scaled up due to technological developments, it could become a close race. This creates uncertainty for the investment in hydrogen import terminals as the possibility arises that high upfront investments are not returned if the market shifts towards another carrier. To resolve this economic uncertainty, we conclude that long-term contracts are required to organise the transactions related to hydrogen import. In this context, we argue that the LNG market provides valuable lessons that can be applied to the hydrogen market. However, a transition from long-term contracts to short-term is expected to occur faster compared to the LNG market due to the presence of aggregators in the hydrogen market and the global pressure for sustainability.

Technical uncertainty relates to the scaling of hydrogen import terminals and the end-users preferences for a specific hydrogen carrier. We conclude that the right scaling of hydrogen import terminals can resolve the mismatch between supply and demand. In turn, the scaling of hydrogen terminals depends on the development of the three hydrogen carrier technologies. Advanced technologies lead to economies of scale, higher vessel capacities and, thus, higher import capacities that the hydrogen import terminals must facilitate. Moreover, the scaling of hydrogen import terminals is subject to the role salt-caverns can take on to provide alternative storage options. If salt-caverns become a viable option for hydrogen storage, less hydrogen storage in the Port of Rotterdam is required. This bears uncertainty for hydrogen import terminals in determining what storage capacity must be constructed. Furthermore, we conclude that LH_2 has a high potential to supply each end-user sector due to its low energy requirement in its regasification process and its high hydrogen quality. However, LOHC and NH_3 are necessary due to the early stage in the development of LH_2-technology. Moreover, NH_3 will be vital if hydrogen becomes the primary energy carrier in the maritime shipping sector. Hence, that sector can directly use NH_3 which eliminates the expensive and energy-intensive regasification process and makes NH_3 the most efficient and cheapest hydrogen carrier for that sector. Also, LOHC has its advantages as it requires no cooling during storage and experiences no losses during transportation. Therefore, a combination of the three hydrogen carriers is needed to supply all end-user sectors.

Regarding geopolitical aspects, we conclude that the early stage of the global hydrogen market creates uncertainty as it is unclear which volumes, against what prices, and from which locations hydrogen can be imported. The global hydrogen market can significantly grow in the coming years due to the pressure of sustainability. However, former oil and gas countries could hamper the global hydrogen trade without decreasing their fossil fuel production. The realisation of hydrogen import terminals combined with stagnated global hydrogen trade could result in severe economic losses. Despite the uncertainty, opportunities are present for the Port of Rotterdam and the Netherlands to become a dominant player in the geopolitical field of hydrogen. The Port of Rotterdam as a hydrogen hub could lead to a dominating position as the port could act reference price-setting location, and hydrogen expertise could be gained. Moreover, the presence of hydrogen import terminals would make the Netherlands less vulnerable to geopolitical forces as it diversifies the energy mix.

8.3 Recommendations

This section outlines the recommendations. First, seven recommendations will cover the aspects that could be included in future research to improve and expand the findings of this research. Then, finally, a recommendation will be included, which is aimed explicitly at policymakers and companies.

- The first recommendation is related to hydrogen production by electrolysis. The electrolysis production costs are highly dependent on the price of renewable electricity. Other studies could consider the hydrogen production costs given a realistic and thus fluctuating renewable electricity price. This can be done by modelling the electrolysis process in such a manner that the renewable electricity price is an input value instead of including the price in the CAPEX as done in this study.

- The inclusion of specific export countries is the second recommendation for future research. Including specific export countries provide insight into their production capacities and, logically, their distance to the PoR. Insights in production capacities are required to analyse the availability of hydrogen import. Furthermore, insight in the location and distance to PoR helps to determine more precise import prices as the location largely determines the price for renewable electricity, and greater distances, to the PoR inherently lead to higher transportation costs.
- The third recommendation is related to the presence of salt caverns in nearby Groningen. Their inclusion in future research could provide valuable insights that concern the scaling of hydrogen import terminals. Hence, operational underground storage has fewer investments costs than above-ground storage like import terminals. As such, operational salt-caverns can replace the storage function of hydrogen import terminals.
- The fourth recommendation also relates to storage capacity. We were not able to allow the arrival of only filled vessels in our model. Nevertheless, the results showed that larger storage capacity is required if most of the arrived vessels were fully loaded than when most of the arrived vessels were only half-filled. Developing a method that allows the arrival of only fully filled vessels would provide more valuable insights into the required storage capacity.
- The fifth recommendation suggests the creation of an investment-based model. In this research, investments have not been included as it focused on exploring the scale of the required infrastructure given different circumstances. Now that the Gurobi solver powers Linny-R, investments can be more easily modelled as the computational time is significantly reduced. Without diving deep into modelling details, an investment can be modelled in Linny-R by linking a data product, representing CAPEX costs, to a ‘process’, representing an asset such as a hydrogen import terminal (e.g. similar to Figure 15. The link represents a start-up multiplier that can turn on the process if the investment is required to find the optimal solution. A study that includes an investment-based model could focus on the financial feasibility of hydrogen import terminals.
- The sixth recommendation is also related to economics. This thesis assumes that the hydrogen demand must always be met at any cost. However, actors who aim to profit will only use sustainable hydrogen if it is either imposed by regulations or economically attractive. Future research could investigate what the willingness to pay is for various end-user sectors. In that way, a more reliable picture could be sketched related to the total hydrogen demand based on the import price of hydrogen. Governments and international organisations like the EU could apply policies that raise the end-user sectors’ willingness to pay.
- The seventh recommendation relates to the number of experiments. A method like the Monte Carlo method would be fruitful as it allows the investigations of hundreds of thousands of possible futures. Moreover, it would enable actors to test their assumptions relating to the hydrogen system in the PoR. As such, import terminal owners could test different scaling designs of import terminals given in various scenarios. As Linny-R does not allow using a method, the MILP problem must be solved by another program.
- The last recommendation is aimed explicitly at policymakers and companies. Even if reliable business cases are lacking, realising hydrogen import terminals should be considered. Not only could a first-mover position contribute to making the PoR the most important hydrogen hub in Europe. Hydrogen import terminals would also make Rotterdam, the Netherlands and the rest of North-West Europe less vulnerable for geopolitical forces related to the energy security of supply.

References

Agnolucci, P. and McDowall, W. (2013). Designing future hydrogen infrastructure: Insights from analysis at different spatial scales. *International journal of hydrogen energy*, 38(13):5181–5191.

Aguilera, R. F. (2020). Global hydrogen market prospects. In *International Association for Energy Economics Podcast Series*.

Almansoori, A. and Shah, N. (2009). Design and operation of a future hydrogen supply chain: multi-period model. *International journal of hydrogen energy*, 34(19):7883–7897.

Arora, V. (2018). A note on natural gas market evolution in light of transaction cost theory. Retrieved from https://mpra.ub.uni-muenchen.de/54974/1/.

Aziz, M., Oda, T., and Kashiwagi, T. (2019). Comparison of liquid hydrogen, methylcyclohexane and ammonia on energy efficiency and economy. *Energy Procedia*, 158:4086–4091.

Ban, I. (2020). Synergies between lng and lh2 receiving terminals. (Unpublished report). TU Delft.

Billing, E. and Fitzgibbon, T. (2020). What shipowners, refiners, and traders should know about imo2020. Retrieved from https://www.mckinsey.com/industries/oil-and-gas/our-insights/what-shipowners-refiners-and-traders-should-know-about-imo-2020.

Bots, P. (2021). Linny-r documetation. Retrieved from https://sysmod.tbm.tudelft.nl/linny-r/docs/.

Brey, J. J., Brey, R., and Carazo, A. F. (2017). Eliciting preferences on the design of hydrogen refueling infrastructure. *International Journal of Hydrogen Energy*, 42(19):13382–13388.

Caglayan, D. G., Heinrichs, H. U., Robinius, M., and Stolten, D. (2021). Robust design of a future 100% renewable european energy supply system with hydrogen infrastructure. *International Journal of Hydrogen Energy*.

Caglayan, D. G., Weber, N., Heinrichs, H. U., Linßen, J., Robinius, M., Kukla, P. A., and Stolten, D. (2020). Technical potential of salt caverns for hydrogen storage in europe. *International Journal of Hydrogen Energy*, 45(11):6793–6805.

Capellán-Pérez, I., De Castro, C., and Arto, I. (2017). Assessing vulnerabilities and limits in the transition to renewable energies: Land requirements under 100% solar energy scenarios. *Renewable and Sustainable Energy Reviews*, 77:760–782.

Cappellen van, L., Croezen, H., and Rooijers, F. (2018). Feasibility study into blue hydrogen. Retrieved from https://cedelft.eu/reports/.

Carson, J. S. (2002). Model verification and validation. In *Proceedings of the winter simulation conference*, volume 1, pages 52–58. IEEE.

CBS (2020). Elektriciteit en warmte; productie en inzet naar energiedrager. Retrieved from https://www.cbs.nl/nl-nl/cijfers/detail/80030ned?q=duurzame20elektriciteitsproductie.

Christopher Frey, H. and Patil, S. R. (2002). Identification and review of sensitivity analysis methods. *Risk analysis*, 22(3):553–578.

Church, J. R. and Ware, R. (2000). *Industrial organization: a strategic approach*. Citeseer.

Cohen, N. and Arieli, T. (2011). Field research in conflict environments: Methodological challenges and snowball sampling. *Journal of Peace Research*, 48(4):423–435.

Dayhim, M., Jafari, M. A., and Mazurek, M. (2014). Planning sustainable hydrogen supply chain infrastructure with uncertain demand.

De Laat, P. (2020). Overview of hydrogen projects in the netherlands. retrieved from https://www.topsectorenergie.nl/sites/default/files/uploads /TKI%20Gas/publicaties.

DECHMA and FutureCamp (2019). Working towards a greenhouse gas neutral chemical industry in germany. Retrieved from https://www.vci.de/langfassungen/langfassungen-pdf/vci-study-greenhouse-gas-neutrality-in-the-german-chemical-industry.pdf.

Delta Corridor (2021). Haalbaarheidsstudie buisleiding(en) port of rotterdam - chemeleot - noordrijn-westfalen: Stevige impuls voor de veiligheid langs het spoor, de economie en de energietransitie. Retrieved from https://www.portofrotterdam.com/nl/nieuws-en-persberichten/studie-buisleidingen-rotterdam-chemelot-en-noordrijn-westfalen.

Deltalinqs (2019). Annexes to the h-vision main report. Retrieved from https://www.deltalinqs.nl/h-vision-en.

Detz, R., Lenzmann, F., Sijm, J., and Weeda, M. (2019a). Future role of hydrogen in the netherlands. a meta-analysis based on a review of recent scenario studies.

Detz, R., Weeda, M., Knoors, B., Katakwar, P., and Wirtz, A. (2019b). Hychain-i: Energy carriers and hydrogen supply chain: Assessment of future trends in industrial hydrogen demand and infrastructure. Retrieved from https://ispt.eu/media/SI-20-06-Final-report-HyChain-1.pdf.

Detz, R., Weeda, M., and Stralen, J. v. (2020). Hydrogen in the netherlands. a review of recent dutch scenario studies. Retrieved from https://energy.nl/en/publication/hydrogen-in-the-netherlands-a-review-of-recent-dutch-scenario-studies/.

Eisenhardt, K. M. (1989). Agency theory: An assessment and review. *Academy of management review*, 14(1):57–74.

Elishav, O., Lis, B. M., Valera-Medina, A., and Grader, G. (2021). Storage and distribution of ammonia. In *Techno-Economic Challenges of Green Ammonia as an Energy Vector*, pages 85–103. Elsevier.

EMBER (2021). Eu ets price. Retrieved from https://ember-climate.org/data/carbon-price-viewer/.

Esposito, D. V. (2017). Membraneless electrolyzers for low-cost hydrogen production in a renewable energy future. *Joule*, 1(4):651–658.

Finn, A. J., Johnson, G. L., and Tomlinson, T. R. (2000). Lng technology for offshore and mid-scale plants. In *79th Annual GPA Convention, Atlanta*.

Gabrielli, P., Poluzzi, A., Kramer, G. J., Spiers, C., Mazzotti, M., and Gazzani, M. (2020). Seasonal energy storage for zero-emissions multi-energy systems via underground hydrogen storage. *Renewable and Sustainable Energy Reviews*, 121:109629.

Gasunie (2018). Verkenning 2050. Retrieved from https://www.gasunie.nl/expertise/aardgas/energiemix-2050.

Gasunie (2020). Webinar hydroegn infrastructure. Retrieved from https://www.gasunienewenergy.nl/projecten/waterstofbackbone/marktconsultatie.

Gasunie (2021). Backbone voor waterstofinfrastructuur in haven rotterdam stap dichterbij. Retrieved from https://www.gasunie.nl/nieuws/backbone-voor-waterstofinfrastructuur-in-haven-rotterdam-stap-dichterbij.

Gasunie (n.d.). Home. Retrieved from https://www.gasunie.nl/.

Gate Terminal (2020). Gate termianl. operationele gegevens. Retrieved from https://www.gateterminal.com/commercial/operationele-gegevens/.

Geels, F. (2005). Co-evolution of technology and society: The transition in water supply and personal hygiene in the netherlands (1850–1930)—a case study in multi-level perspective. *Technology in society*, 27(3):363–397.

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research policy*, 31(8-9):1257–1274.

Geels, F. W. (2004). From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. *Research policy*, 33(6-7):897–920.

Geels, F. W. (2011). The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental innovation and societal transitions*, 1(1):24–40.

Gerbert, P., Herhold, P., Burchardt, J., Schonberger, S., Rechenmacher, F., Kirchner, A., Kemmler, A., and Wünsch, M. (2018). Klimapfade für deutschland. Retrieved from https://www.bcg.com/de-de/publications/2018/climate-paths-for-germany.

Giddey, S., Badwal, S., and Kulkarni, A. (2013). Review of electrochemical ammonia production technologies and materials. *International Journal of Hydrogen Energy*, 38(34):14576–14594.

Gigler, J. and Weeda, M. (2018). Contouren van een routekaart waterstof. *Topsector Energie, TKI Nieuw Gas, Maart*.

Gonda, M., Ohshima, M.-a., Kurokawa, H., and Miura, H. (2014). Toluene hydrogenation over pd and pt catalysts as a model hydrogen storage process using low grade hydrogen containing catalyst inhibitors. *international journal of hydrogen energy*, 39(29):16339–16346.

Gu, Z., Rothberg, E., and Bixby, R. (2021). Gurobi optimization. Retrieved from https://cdn.gurobi.com/wp-content/uploads/2021/02/Gurobi-Optimization-Product-Brochure-2021.pdf.

Hammingh, P. and Hekkenberg, M. (2017). Nationale energieverkenning 2017. Retrieved from https://www.pbl.nl/publicaties/nationale-energieverkenning-2017.

Hartley, P. R. (2015). The future of long-term lng contracts. *The Energy Journal*, 36(3).

He, T., Pachfule, P., Wu, H., Xu, Q., and Chen, P. (2016). Hydrogen carriers. *Nature reviews materials*, 1(12):1–17.

Holladay, J. D., Hu, J., King, D. L., and Wang, Y. (2009). An overview of hydrogen production technologies. *Catalysis today*, 139(4):244–260.

Hong, X., Thaore, V. B., Karimi, I. A., Farooq, S., Wang, X., Usadi, A. K., Chapman, B. R., and Johnson, R. A. (2021). Techno-enviro-economic analyses of hydrogen supply chains with an asean case study. *International Journal of Hydrogen Energy*, 46(65):32914–32928.

Hydrogen Council (2017). Hydrogen scaling up - a sustainable pathway for the global energy transition. Retrieved from https://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-scaling-up-Hydrogen-Council.pdf.

Hydrogen Council (2020). Path to hydrogen competitiveness a cost perspective. Retrieved from https://hydrogencouncil.com/wp-content/.

IEA (2019). The Future of Hydrogen The Future of Hydrogen. Retrieved from https://www.iea.org/reports/the-future-of-hydrogen.

IEA (2020). European Union 2020. Energy Policy Review. Retrieved from https://www.iea.org/reports/european-union-2020.

Ishimoto, Y., Voldsund, M., Nekså, P., Roussanaly, S., Berstad, D., and Gardarsdottir, S. O. (2020). Large-scale production and transport of hydrogen from norway to europe and japan: Value chain analysis and comparison of liquid hydrogen and ammonia as energy carriers. *International Journal of Hydrogen Energy*, 45(58):32865–32883.

Jaffe, A. M. and Soligo, R. (2008). Energy security: the russian connection. In *Energy Security and Global Politics*, pages 120–142. Routledge.

Jepma, C., Spijker, E., and Hofman, E. (2019). The dutch hydrogen economy in 2050. Retrieved from https://www.vno-ncw.nl/meer-informatie/dutch-hydrogen-economy-2050.

Johansson, B. (2013). Security aspects of future renewable energy systems–a short overview. *Energy*, 61:598–605.

Juan, A. A., Mendez, C. A., Faulin, J., De Armas, J., and Grasman, S. E. (2016). Electric vehicles in logistics and transportation: A survey on emerging environmental, strategic, and operational challenges. *Energies*, 9(2):86.

Kamiya, S., Nishimura, M., and Harada, E. (2015). Study on introduction of co2 free energy to japan with liquid hydrogen. *Physics Procedia*, 67:11–19.

Kawasaki Heavy Industries (2021). World's first liquefied hydrogen terminal complete. Retrieved from https://www.tankstoragemag.com/2021/01/25/worlds-first-liquefied-hydrogen-terminal-complete/.

Kolff, S. (2021). Converting an lng terminal to be fit for processing lh2. TU Delft. Retrieved from https://repository.tudelft.nl.

Konda, N. M., Shah, N., and Brandon, N. P. (2011). Optimal transition towards a large-scale hydrogen infrastructure for the transport sector: The case for the netherlands. *International Journal of Hydrogen Energy*, 36(8):4619–4635.

Lanphen, S. (2019). Hydrogen import terminal. Retrieved from http://resolver.tudelft.nl/uuid:d2429b05-1881-4e42-9bb3-ed604bc15255.

Leijnse, A. and Majid Hassanizadeh, S. (1994). Model definition and model validation. *Advances in water resources*, 17(3):197–200.

Lin, Z., Chen, C.-W., Ogden, J., and Fan, Y. (2008). The least-cost hydrogen for southern california. *International Journal of Hydrogen Energy*, 33(12):3009–3014.

Lin, Z., Ogden, J., Fan, Y., and Sperling, D. (2006). The hydrogen infrastructure transition model (hit) & its application in optimizing a 50-year hydrogen infrastructure for urban beijing.

Lu, C.-C., Ying, K.-C., and Chen, H.-J. (2016). Real-time relief distribution in the aftermath of disasters–a rolling horizon approach. *Transportation research part E: logistics and transportation review*, 93:1–20.

Ministerie van Economische Zaken en Klimaat (2020). Kamerbrief over kabinetsvisie waterstof. Retrieved from https://www.rijksoverheid.nl/documenten/kamerstukken/2020/03/30/kamerbrief-over-kabinetsvisie-waterstof.

Moreno-Benito, M., Agnolucci, P., and Papageorgiou, L. G. (2017). Towards a sustainable hydrogen economy: Optimisation-based framework for hydrogen infrastructure development. *Computers and Chemical Engineering*, 102:110–127.

Nayak-Luke, R., Forbes, C., Cesaro, Z., Bañares-Alcántara, R., and Rouwenhorst, K. H. R. (2021). Techno-economic aspects of production, storage and distribution of ammonia. In *Techno-Economic Challenges of Green Ammonia as an Energy Vector*, pages 191–207. Elsevier.

Niermann, M., Beckendorff, A., Kaltschmitt, M., and Bonhoff, K. (2019). Liquid Organic Hydrogen Carrier (LOHC) – Assessment based on chemical and economic properties. *International Journal of Hydrogen Energy*, 44(13):6631–6654.

Notermans, I., van der Have, C., van Raak, R., Rotmans, J., et al. (2020). Hydrogen for the port of rotterdam in an international context. Retrieved from https://www.portofrotterdam.com/sites/default/files/drift-hydrogen-for-the-port-of-rotterdam-in-an-international-context-a-plea-for-leadership.pdf?token=3ySt8rOD.

Noussan, M., Raimondi, P. P., Scita, R., and Hafner, M. (2021). The role of green and blue hydrogen in the energy transition—a technological and geopolitical perspective. *Sustainability (Switzerland)*, 13(1):1–26.

Nunes, P., Oliveira, F., Hamacher, S., and Almansoori, A. (2015). Design of a hydrogen supply chain with uncertainty. *International Journal of Hydrogen Energy*, 40(46):16408–16418.

Office of Energy Efficiency & Renewable Energy (2021). Liquid hydrogen delivery. Retrieved from https://www.energy.gov/eere/fuelcells/liquid-hydrogen-delivery.

Ogden, J. (2004). Hydrogen delivery model for h2a analysis: A spreadsheet model for hydrogen delivery scenarios. Retrieved from https://escholarship.org/content/qt8sw8m9cp/qt8sw8m9cp.pdf.

Oren, S. S. (2000). Capacity payments and supply adequacy in competitive electricity markets. *Sepope, May*.

Paltsev, S. (2016). The complicated geopolitics of renewable energy. *Bulletin of the Atomic Scientists*, 72(6):390–395.

Papadias, D. D., Peng, J.-K., and Ahluwalia, R. K. (2021). Hydrogen carriers: Production, transmission, decomposition, and storage. *International Journal of Hydrogen Energy*.

Papadopoulos, C. E. and Yeung, H. (2001). Uncertainty estimation and monte carlo simulation method. *Flow Measurement and Instrumentation*, 12(4):291–298.

Parker, N., Fan, Y., and Ogden, J. (2010). From waste to hydrogen: An optimal design of energy production and distribution network. *Transportation Research Part E: Logistics and Transportation Review*, 46(4):534–545.

Pflugmann, F. and Blasio, N. (2020). Geopolitical and market implications of renewable hydrogen. *New Dependencies in a Low-Carbon Energy World*.

Piyatrapoomi, N., Kumar, A., and Setunge, S. (2004). Framework for investment decision-making under risk and uncertainty for infrastructure asset management. *Research in Transportation Economics*, 8:199–214.

Poganietz, W.-R. and Weimer-Jehle, W. (2020). Introduction to the special issue 'integrated scenario building in energy transition research'.

Pollet, B. G., Staffell, I., and Shang, J. L. (2012). Current status of hybrid, battery and fuel cell electric vehicles: From electrochemistry to market prospects. *Electrochimica Acta*, 84:235–249.

Port of Rotterdam (2020a). Feasibility study on export of south australian green hydrogen to rotterdam. Retrieved from https://www.portofrotterdam.com/en/news-and-press-releases/feasibility-study-on-export-of-south-australian-green-hydrogen-to-rotterdam.

Port of Rotterdam (2020b). Hydrogen economy in rotterdam - handout. Retrieved from https://www.portofrotterdam.com/sites/default/files/2021-06/hydrogen-economy-in-rotterdam-handout.pdf.

Port of Rotterdam (2020c). Port of rotterdam becomes international hydrogen hub. vision port of rotterdam authority. Retrieved from https://www.portofrotterdam.com/sites/default/files/hydrogen-vision-port-of-rotterdam-authority-may-2020.pdf.

Port of Rotterdam (2020d). Waterstofeconomie in rotterdam factsheet. Retrieved from https://www.portofrotterdam.com/sites/default/files/waterstofeconomie-in-rotterdam-factsheet.pdf?token=BJLnJZST.

PORTHOS (n.d.). Porthos. Retrieved from https://www.porthosco2.nl/.

Poten & Partners (2015). Producers pass buck to portfolio players. Retrieved from https://www.poten.com/wp-content/uploads/2016/02/Producers-Pass-Buck-to-Portfolio-Players-Opinion.pdf.

PWC (2020). Wetsvoorstel co_2-heffing voor de industrie. Retrived from https://www.pwc.nl/nl/actueel-en-publicaties/belastingnieuws/pwc-prinsjesdag-special/belastingplan-2021-co-2-heffing.html.

Qadrdan, M., Saboohi, Y., and Shayegan, J. (2008). A model for investigation of optimal hydrogen pathway, and evaluation of environmental impacts of hydrogen supply system. *International journal of hydrogen energy*, 33(24):7314–7325.

Quintell (2010). Energy transition model. Retrieved from https://pro.energytransitionmodel.com/.

Renewable Ninja (n.d.). Home. Retrieved from https://www.renewables.ninja/.

Reuß, M., Grube, T., Robinius, M., Preuster, P., Wasserscheid, P., and Stolten, D. (2017). Seasonal storage and alternative carriers: A flexible hydrogen supply chain model. *Applied energy*, 200:290–302.

Robles, J. O., Azzaro-Pantel, C., and Aguilar-Lasserre, A. (2020). Optimization of a hydrogen supply chain network design under demand uncertainty by multi-objective genetic algorithms. *Computers & Chemical Engineering*, 140:106853.

Roobeek, R. (2020). Shipping sunshine: A techno-economic analysis of a dedicated green hydrogen supply chain from the port of sohar to the port of rotterdam. (Unpublished report). Retrieved from https://repository.tudelft.nl.

Ruester, S. and Neumann, A. (2006). Economics of the lng value chain and corporate strategies-an empirical analysis of the determinants of vertical integration. In *26th USAEE International Conference*.

Ruester, S. and Neumann, A. (2009). Linking alternative theories of the firm–a first empirical application to the liquefied natural gas industry. *Journal of Institutional Economics*, 5(1):47–64.

Salmon, N. and Bañares-Alcántara, R. (2021). Green ammonia as a spatial energy vector: a review. *Sustainable Energy & Fuels*.

Samadi, S., Lechtenböhmer, S., Schneider, C., Arnold, K., Fischedick, M., Schüwer, D., and Pastowski, A. (2016). *Decarbonization pathways for the industrial cluster of the port of Rotterdam*. Wuppertal Institute for Climate, Environment and Energy.

Samsatli, S., Staffell, I., and Samsatli, N. J. (2016). Optimal design and operation of integrated wind-hydrogen-electricity networks for decarbonising the domestic transport sector in great britain. *international journal of hydrogen energy*, 41(1):447–475.

Sargent, R. G. (2010). Verification and validation of simulation models. In *Proceedings of the 2010 winter simulation conference*, pages 166–183. IEEE.

Scholten, D., Bazilian, M., Overland, I., and Westphal, K. (2020). The geopolitics of renewables: New board, new game. *Energy Policy*, 138:111059.

Scholten, D. and Bosman, R. (2016). The geopolitics of renewables; exploring the political implications of renewable energy systems. *Technological Forecasting and Social Change*, 103:273–283.

Scita, R., Raimondi, P. P., and Noussan, M. (2020). Green hydrogen: the holy grail of decarbonisation? an analysis of the technical and geopolitical implications of the future hydrogen economy. *Fondazione Eni Enrico Mattei Working Papers*.

Scott, R. B., Denton, W. H., and Nicholls, C. M. (2013). *Technology and uses of liquid hydrogen*. Elsevier.

Sharples, J. (2019). Lng supply chains and the development of lng as a shipping fuel in northern europe.

Shell (2021). Shell wordt 100% eigenaar van het eerste nederlandse windpark op zee. Retrieved from https://www.shell.nl/media/nieuwsberichten/2021/shell-wordt-100-eigenaar-eerste-nederlandse-windpark-op-zee.html.

Stern, R. J. (2016). Oil scarcity ideology in us foreign policy, 1908–97. *Security Studies*, 25(2):214–257.

Sweijs, T. (2014). *Time to wake up: the geopolitics of EU 2030 climate and energy policies*. Hague Centre for Strategic Studies.

Tavares, F. B., Mitro, T., Maennling, N., and Toledano, P. (2018). Manual for the open lng regasification model. *Columbia Center on Sustainable Investment*.

Terwel, R. and Kerkhoven, J. (2018). The cost implications of importing renewable electricity, hydrogen and hydrogen carriers into the netherlands from a 2050 perspective. *Kalavasta, November*.

Tijdgat, J. (2020). Shipping renewable hydrogen carriers. Retrieved from https://repository.tudelft.nl/.

Turner, J. A. (2004). Sustainable hydrogen production. *Science*, 305(5686):972–974.

Vakulchuk, R., Overland, I., and Scholten, D. (2020). Renewable energy and geopolitics: A review. *Renewable and Sustainable Energy Reviews*, 122:109547.

van de Graaf, T., Overland, I., Scholten, D., and Westphal, K. (2020). The new oil? The geopolitics and international governance of hydrogen. *Energy Research and Social Science*, 70(April):101667.

van den Noort, A., Vos, M., and Sloterdijk, W. (2017). Verkenning waterstofinfrastructuur. Retrieved from https://www.topsectorenergie.nl/nieuws/waterstoftransport-gasnet-dichterbij.

van Soest, J. P. and Warmenhoven, H. (2019). Waterstof in het klimaatakkoord. Retrieved from https://www.klimaatakkoord.nl/documenten/publicaties/2019/01/25/achtergrondnotitie-elektriciteit-en-industrie-waterstof.

Verrastro, F., Ladislaw, S., Frank, M., Hyland, L. A., and Schlesinger, J. R. (2010). The geopolitics of energy. *Emerging trends, changing landscapes, uncertain times. CSIS energy and national security program.*

Walker, W. E. (2000). Policy analysis: a systematic approach to supporting policymaking in the public sector. *Journal of Multi-Criteria Decision Analysis*, 9(1-3):11–27.

Weems, P. R. (2006). Evolution of long-term lng sales contracts: Trends and issues. *Oil, Gas & Energy Law Journal (OGEL)*, 4(1).

Wijayanta, A. T., Oda, T., Purnomo, C. W., Kashiwagi, T., and Aziz, M. (2019). Liquid hydrogen, methylcyclohexane, and ammonia as potential hydrogen storage: Comparison review. *International Journal of Hydrogen Energy*, 44(29):15026–15044.

Wijk, A. and Hellinga, C. (2019). Naar een groene waterstofeconomie in Zuid-Holland Een visie voor 2030. Retrieved from https://userfiles.mailswitch.nl/files/3081-1f4a127529e22069d9d5b041baeb3842.pdf.

Williamson, O. E. (1979). Transaction-cost economics: the governance of contractual relations. *The journal of Law and Economics*, 22(2):233–261.

Wood, D. A. (2012). A review and outlook for the global lng trade. *Journal of Natural Gas Science and Engineering*, 9:16–27.

A Hydrogen end-user sectors

In this appendix, the hydrogen application in various end-user sectors is analysed. Moreover, projections for the timeline in which hydrogen could penetrate these markets are assessed.

A.1 Feedstock industry

The feedstock industry is the sector with the most significant hydrogen consumption nowadays. Over 90% of the hydrogen production is used for this sector. Processes like the production of NH_3, methanol require hydrogen. Also, refining accounts for a large part of the hydrogen consumption (Hydrogen Council, 2020). Due to future regulations and policies, the industry must reduce its carbon footprint by zero in 2050. Therefore, the role of sustainable hydrogen has considerable potential in this sector. Moreover, Hydrogen Council (2020) states that due to the few actors involved in these decision-making processes and no changes required in process equipment or operations, the sustainable hydrogen uptake can be accelerated. However, the question remains with what pace this uptake will be accompanied. The costs of these processes in this sector mainly depend on the (sustainable) hydrogen production costs. In that context, at the time, sustainable hydrogen will be cost-competitive with hydrogen produced by fossil fuels.

A.2 Process heat industry

Another application of hydrogen in the process heat industry. When writing this thesis, the heat in this sector is generated by the combustion of natural gas in power plants. Hydrogen can be injected into the natural gas grid (after making some adjustments to the natural gas grid) for this kind of process. This would significantly reduce its ecological footprint (Detz et al., 2019a).

A.3 Building environment

Hydrogen can provide a sustainable alternative to provide heat for the building environment. In short, there are two ways hydrogen can be used to deliver heat. The first regards the blending in hydrogen in a natural gas network. The other one is the direct heating of buildings via boilers (IEA, 2019). However, the application of hydrogen in the building environment has still a low maturity technology. In other words, technologies have to be further developed, safety aspects have to be tested, and the costs have to be identified (Gigler and Weeda, 2018).

A.4 Mobility (over land)

At the moment, gasoline and diesel are the dominant types of fuels in the mobility sector. Just like any other section, the mobility sector is shifting towards sustainable alternatives. Two options are often considered; Battery Electric Vehicle (BEV) and hydrogen driven vehicles (FCEV)s. Many think that hydrogen has already lost the battle in the mobility sector. The Battery Electric Vehicle (BEV) is expected to take account for a significant market share in this sector. However, some argue that heavy-duty vehicles benefit more from hydrogen due to their larger potential action radius. Moreover, the charging or reloading time of FCEVs is significantly lower than BEV which is an essential issue if the number of users of this technology is growing (Pollet et al., 2012; Detz et al., 2020; Juan et al., 2016). For the relatively small vehicles and short distances, BEV seems to remain the most competitive alternative (Hydrogen Council, 2020).

A.5 Aviation and maritime shipping

The aviation sector is one of the most carbon-intensive sectors in the world. This sector produces approximately 3% of the global emissions. Currently, the sector uses kerosene as fuel. The advantages of kerosene are its weight (very light) and volumetric energy density, requiring little storage. However, for the same reasons is the electrification of the aviation sector highly difficult. At the moment, few minor projects are executed experimenting with hydrogen and fuels cells for short flights in small aeroplanes; however, the vast majority of the CO_2 is emitted during long flights with large and heavy planes (Hydrogen Council, 2020). Another application is using hydrogen as a building block for synthetic fuels.

The maritime shipping sector is also looking for sustainable alternatives compared to conventional fuels. Smaller ships have the potential to be electrified. However, the same trend identified in the aviation sector applies to the maritime shipping sector; the more significant part of the CO_2 is produced by the larger container ships. Traditionally, heavy fuel oil and marine gasoil are the most common fuel types in the maritime sector. The usage of LNG is rising. However, only LNG accomplishes a CO_2-reduction of 20% compared to the other type of fuels (Billing and Fitzgibbon, 2020; Sharples, 2019). Therefore, a more sustainable fuel is required. According to Hydrogen Council (2020), the direct use of NH_3 could offer an opportunity for low-carbon maritime shipping fuel due to similarities in technology. Another option could be the direct use of LH_2. However, the lower energy density makes NH_3 a more viable option. Nevertheless, both options require sustainable hydrogen.

Hydrogen, as a building block for other fuels such as NH_3 or synthetic fuels, has the potential to replace the conventional fuels in both the aviation as the maritime shipping sector. However, the cost of producing these synthetic fuels is the main barrier to the adoption of hydrogen in these sectors.

A.6 Export

Nowadays, the Port of Rotterdam receives and distributes approximately 13% of the total energy demand of Europe. Germany accounts for a large share of this 13% (Port of Rotterdam, 2020d). In Germany, the demand for hydrogen is also likely to increase, according to (Gerbert et al., 2018). Their work stated that Germany needs to import hydrogen to achieve the climate targets set for 2050. Moreover, DECHMA and FutureCamp (2019) picture a sharp increase in the need for hydrogen to produce a synthetic feedstock. At last, the steel industry has indicated a significant increase in hydrogen to become more sustainable (Port of Rotterdam, 2020c).

B Data collection case study

In this appendix, the data required as input for the model is collected. Most data are projections from other scholars regarding the development of specific technologies and prices. In that case, a short overview of the leading publications is given, after which a choice is made regarding the input data for the model. The data collection is categorised into two parts; domestic production and hydrogen demand.

B.1 Domestic hydrogen production

The three production methods used for domestic production are SMR, SMR with CCS and water electrolysis. The input- & output variables of SMR (with and without CCS) and electrolysis are presented in Table 11.

Table 11: Input & Output variables SMR and electrolysis. Adapted from Cappellen van et al. (2018)

Input	Unit	SMR (including CCS)	Electrolysis
Inflow natural gas	$m^3/kg\ H_2$	3,73	0,0
Inflow raw water	$kg/\ kg\ H_2$	4,68	9,0
Inflow sea water	$m^3/kg\ H_2$	1,18	0,0
Electricity demand	$kWh/kg\ H_2$	1,17	53,6
Oxygen	$kg/kg\ H_2$	0,0	0,0
Output			
Hydrogen	kg	1,0	1,0
CO2 process emission	$kg/kg\ H_2$	9,0	0,0
CO2 capture rate (CCS)	%	90	0,0
Waste water	$kg/kg\ H_2$	1,83	0,0
Return sea water	$m^3/kg\ H_2$	1,18	0,0
Oxygen	$kg/kg\ H_2$	0,0	8,0

For the Capital Expenditures (CAPEX) of the technologies, we use IEA (2019) as source (see Figure 12. However, due to stricter environmental regulations and technological developments, the expected costs for electrolysis and SMR (if CCS is applied) are expected to reduce over time. Therefore, the production costs for electrolysers for 2030, 2040, and 2050 are presented in Figure 40.

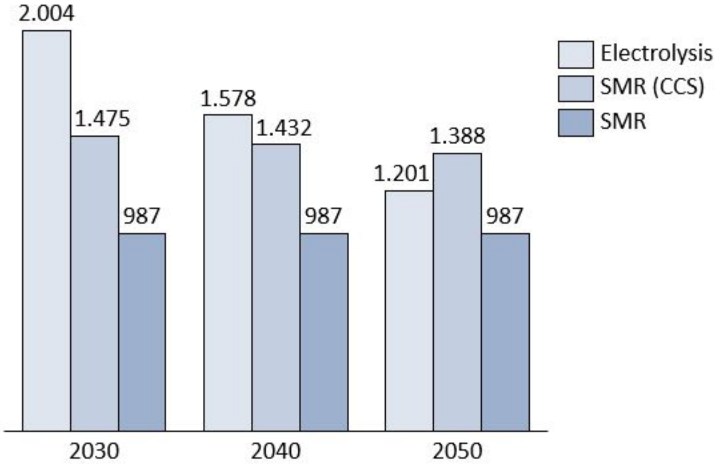


Figure 40: CAPEX [€/ton H_2] for different hydrogen production methods for 2030, 2040, and 2050.

Table 12: Assumptions hydrogen production costs. Adapted from IEA (2019).

General	**Value**	**Unit**
Conversion rate ($/€)	0,85	-
Operational hours	8000	h/year
LHV (H2)	33,3	kWh/kg H2
Discount rate	6	%
Depreciation time	-	
Electrolysis	10	year
SMR	25	year

Electrolysis

	Unit	**2030**	**2040**	**2050**
CAPEX	*USD/kWe*	700	545	450
Efficiency (LHV)	%	69	72	74
Annual OPEX	*% CAPEX*	1,5	1,5	1,5

SMR

	Unit	**2030**	**2040**	**2050**
CAPEX	*USD/kW* H_2	910	910	910
Efficiency (LHV)	%	76	76	76
Annual OPEX	*% CAPEX*	4,7	4,7	4,7

SMR including CCS

	Unit	**2030**	**2040**	**2050**
CAPEX	*USD/kW* H_2	1.360	1.320	1.280
Efficiency (LHV)	%	76	76	76
Annual OPEX	*% CAPEX*	4,7	4,7	4,7

B.2 Hydrogen demand end-user sectors

In this research, we use hydrogen demand for various sectors. For our model data input, we use the work of Detz et al. (2019b) as a source since also the Port of Rotterdam has adapted this source and used it for its own research and strategy. Additionally, for the export to the hinterland, the source of the Port of Rotterdam is used (Port of Rotterdam, 2020c).

Please note that this data, calculated by Detz et al. (2019b), is the maximum hydrogen demand that could transit through the Port of Rotterdam. Also, note that this data is used reference data. For experiments and scenarios, a fraction of this data is assumed as hydrogen demand. To illustrate, for a scenario representing the year 2040, we could assume that 10% of the maximum hydrogen for the aviation sector is fulfilled. This results in 0,1 [Mtonne/year] as the maximum potential is 1,0 [Mtonne/year]. The maximum hydrogen demand for the end-user sectors is presented in 13

Table 13: Potential hydrogen demand & through Rotterdam in 2050. Adapted from Port of Rotterdam (2020c) and Detz et al. (2019b)

End-user sectors	PJ	Mtonne/year	tonne/day
Feedstock chemicals	97	0,8	2.192
Process heat industry	127,5	1,1	3.013
Build environment	13,5	0,1	274
Mobility over land	102,5	0,8	2.191
Aviation (H2 in synthetic fuels)	115	1,0	2.739
Maritime shipping (H2 in liquid fuels)	375	3,2	8.767
Export to Germany	960	8,0	21.918
Export to NWE	600	5,0	13.699

C Model verification and validation

This section provides a more detailed description of the experiments that have been conducted to verify and validate our model in Linny-R. First, the verification experiments are presented, followed by the validation experiments.

C.1 Verification experiments

In this experiment, the electrolysis and wind capacity is set at unlimited. As hydrogen produced by electrolysis is cheaper than import, our model should not import any hydrogen. Moreover, all hydrogen production should come from domestic sources (electrolysis and SMR). This is shown in Figure 41.

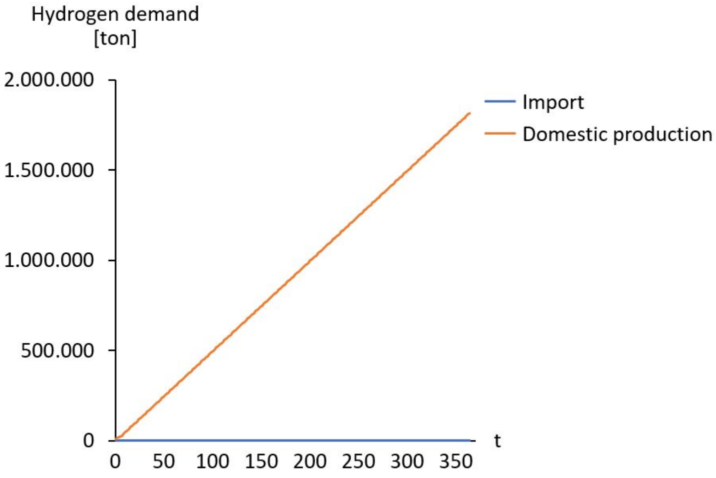


Figure 41: Total hydrogen import compared to domestic production given unlimited production capacity for electrolysis and SMR

In the second experiment, the import prices of LOHC and NH_3 are increased by 100%. The results are presented in Figure 42. As expected, the sole hydrogen import is accounted for by LH_2 while LOHC and NH_3 are not imported due to higher prices.

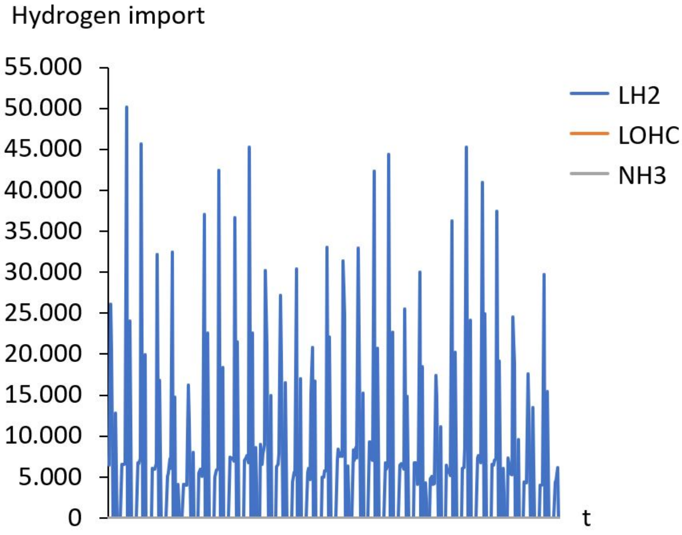


Figure 42: Hydrogen import given a lower price for LH_2 and unlimited import capacities

In the third experiment, various runs have been conducted with each a different look-ahead scope. The results are presented in Figure 43. Each run had a time horizon of 100 time steps. In case the model receives full information before solving the problem, NH_3 is imported in 22 days. As expected, this amount increases as the model gets less information (e.g.) the look ahead decreases) since the import is less efficient. The right-hand side of Figure 43 shows the average price at which NH_3 is imported. The average import price reduces by almost 9% compared to when the model runs with a look-ahead of two time steps.

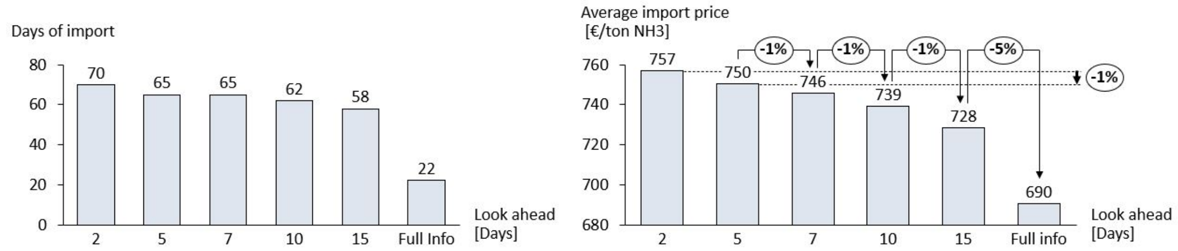


Figure 43: Verification of the look-ahead function: More information results in less days of import and a lower average import price.

Having successfully conducted three experiments, we can conclude that the model is verified.

C.2 Validation experiments

The first experiment regards the CCS process. Based on the level of the CO_2 ETS price, hydrogen produce can choose to either capture the CO_2 or emit it into the air. In this experiment the CO_2 ETS price is increased from 50 to 149 [€/tonne CO_2] over 100 time steps. In each time step, 29592 [tonne] CO_2 is produced by SMR as a result of hydrogen production. Assuming a CCS rate of 90[%]. The following formula is used to determine the level of the CO_2 ETS price at which the hydrogen producer should shift from emitting the CO_2 to CCS:

$$1708000 + 2{,}548 * (0{,}9*29592) + (0{,}1*29592) * CO_2\ ETS\ price = 29592 * CO_2\ ETS\ price$$

The CO_2 ETS price should be equal to 65,69 [€/tonne CO_2]. The CO_2 ETS price exceeds 65,69 [€/tonne CO_2] in time step 17 as it increases to 66,00 [€/tonne CO_2]. This is confirmed by the model and presented in Figure 44.

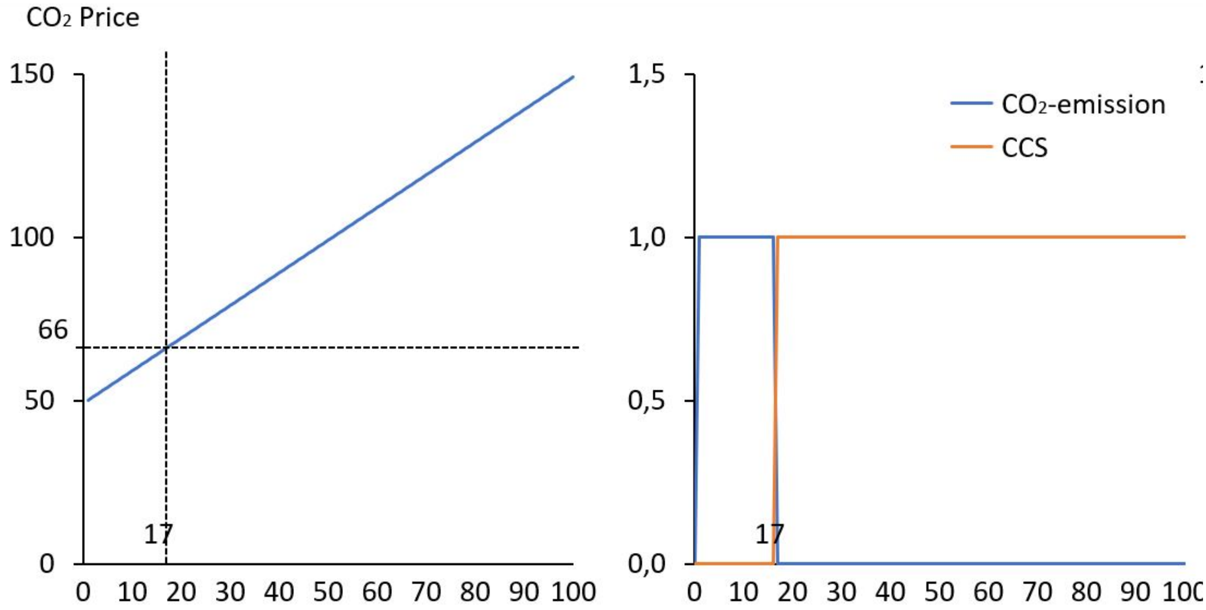


Figure 44: Tipping point where CCS becomes cheaper compared to emitting CO_2

The second experiment validates the entire work of our model. It aims to validate the accuracy of our model by reproducing the number of imports in 2050 as indicated by Port of Rotterdam (2020b). This report states that of the expected 20 Mtonne hydrogen demand, 18 [Mtonne/year] is provided by import and 2 [Mtonne/year] using domestic production. The domestic production capacities chiefly determine the need for import. Nevertheless, this experiment can show the accuracy of our model. The input values used for this model are presented in Table 14.

Table 14: Input values used for the second validation experiment

Input parameter	Unit	Value
Electrolysis capacity	[GW]	10
Offshore wind capacity	[GW]	20
SMR (including CCS)	[tonne/day]	1000

The input value for electrolysis capacity is 10 [GW]. However, there are no sources or policies published that indicate such electrolysis capacity by 2050. However, for 2030 an electrolysis capacity of 3-4 [GW] is indicated (van Soest and Warmenhoven, 2019). Furthermore, 10 [GW] by 2050 is more than reasonable, assuming a steady capacity growth. Port of Rotterdam (2020c) pointed out that between 18 and 24 [GW], wind could be available for hydrogen production in the Port of Rotterdam. Therefore, 20 [GW] has been chosen as an input value for this validation experiment. At last, 1000 [tonne/day] for SMR (including CCS) has been picked. Despite the climate targets to be carbon neutral by 2050, the policy regulations by Ministerie van Economische Zaken en Klimaat (2020) indicate that blue hydrogen will still be produced. Therefore, we assume a small (SMR including CCS) production capacity of 1000 [tonne/day].

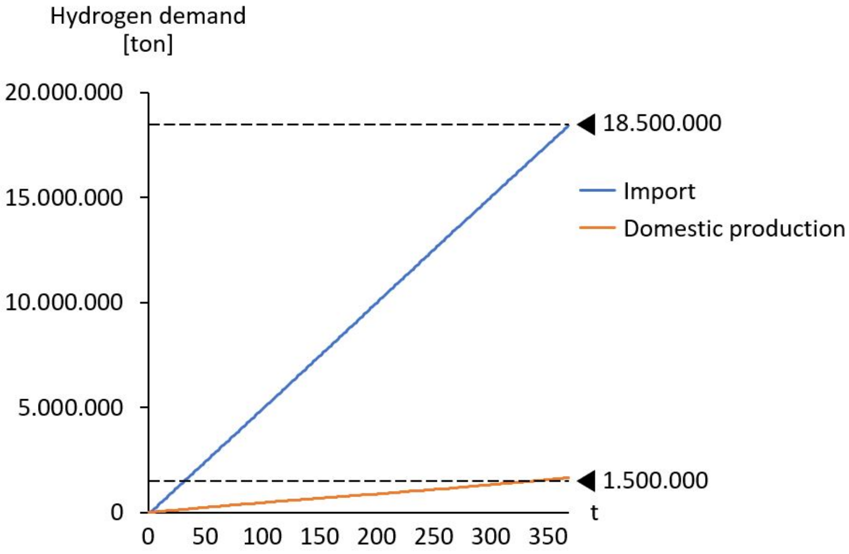
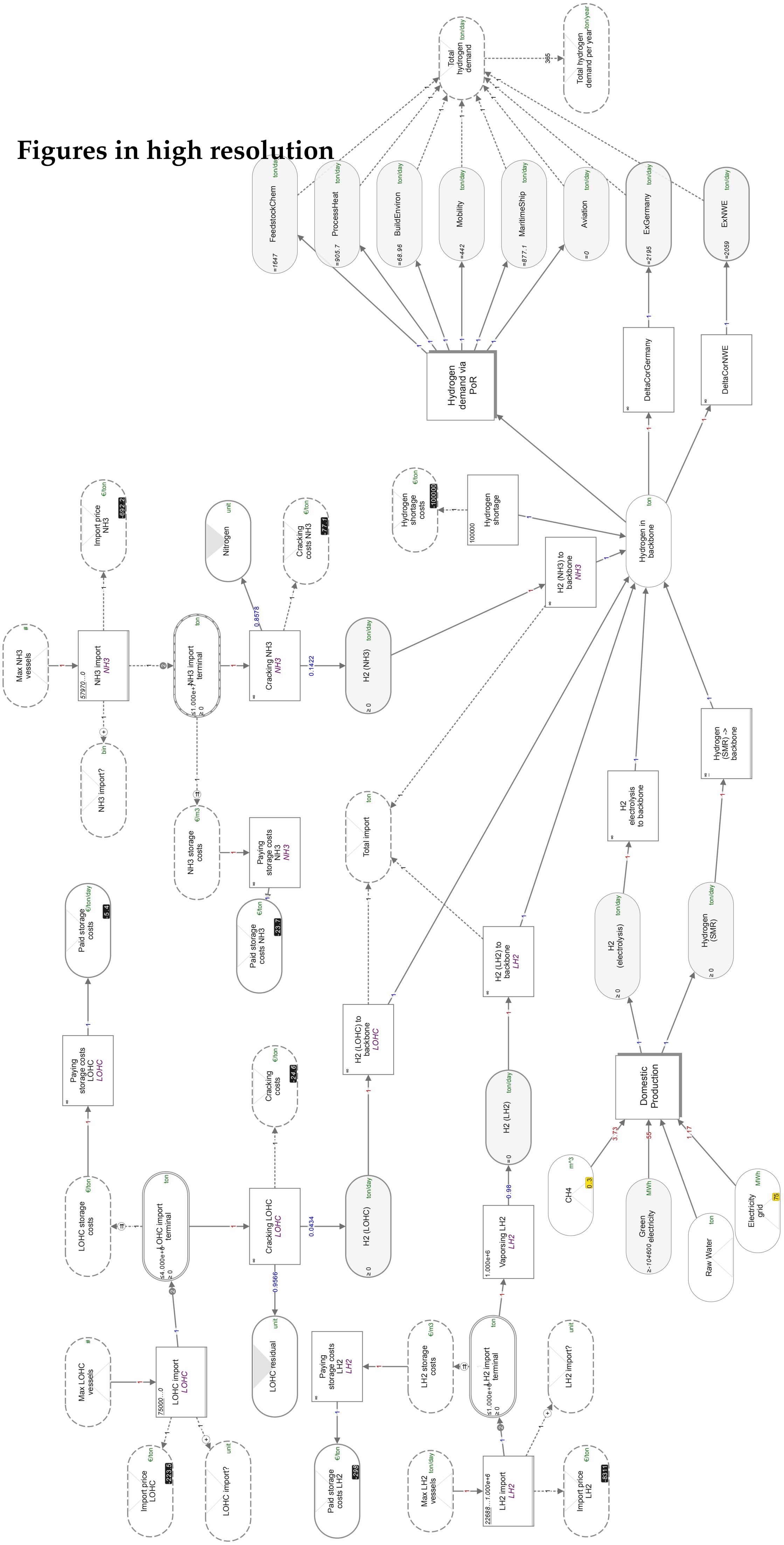
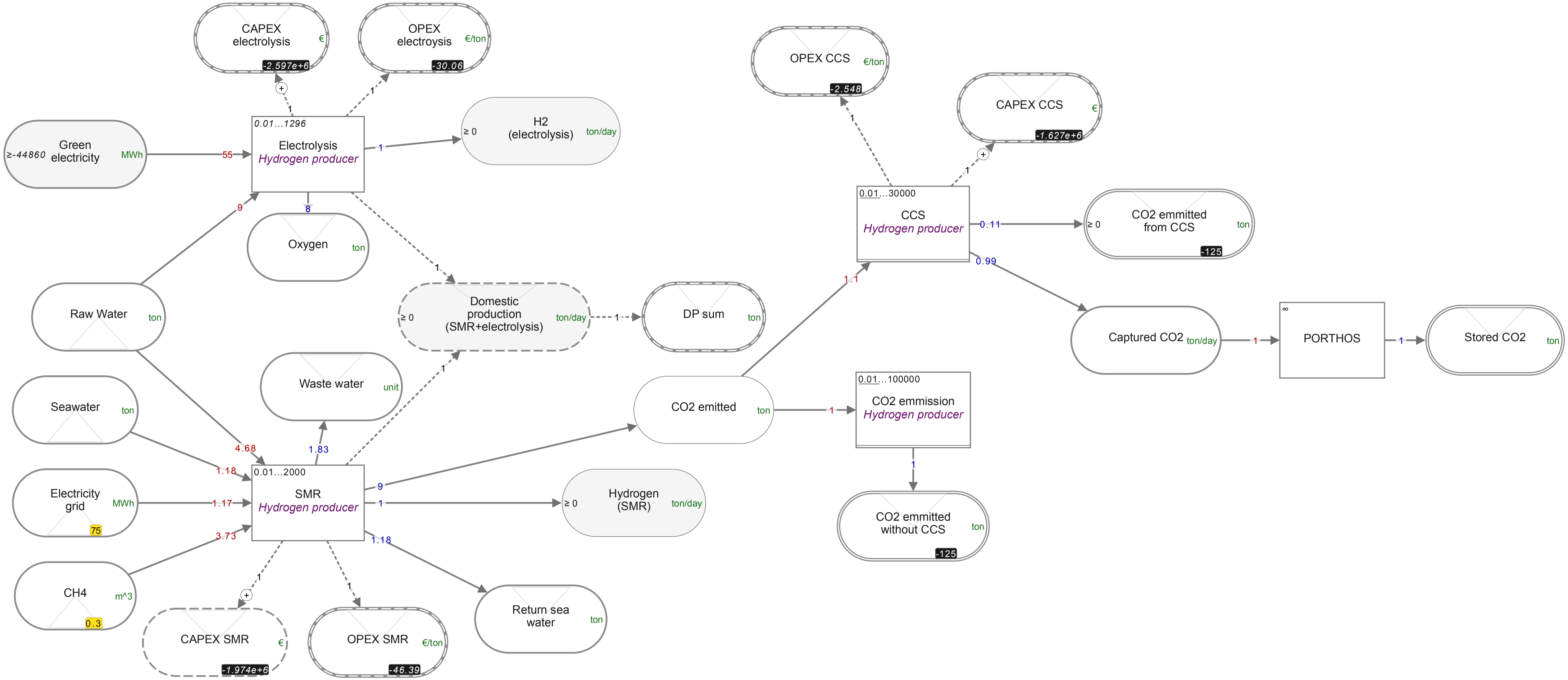


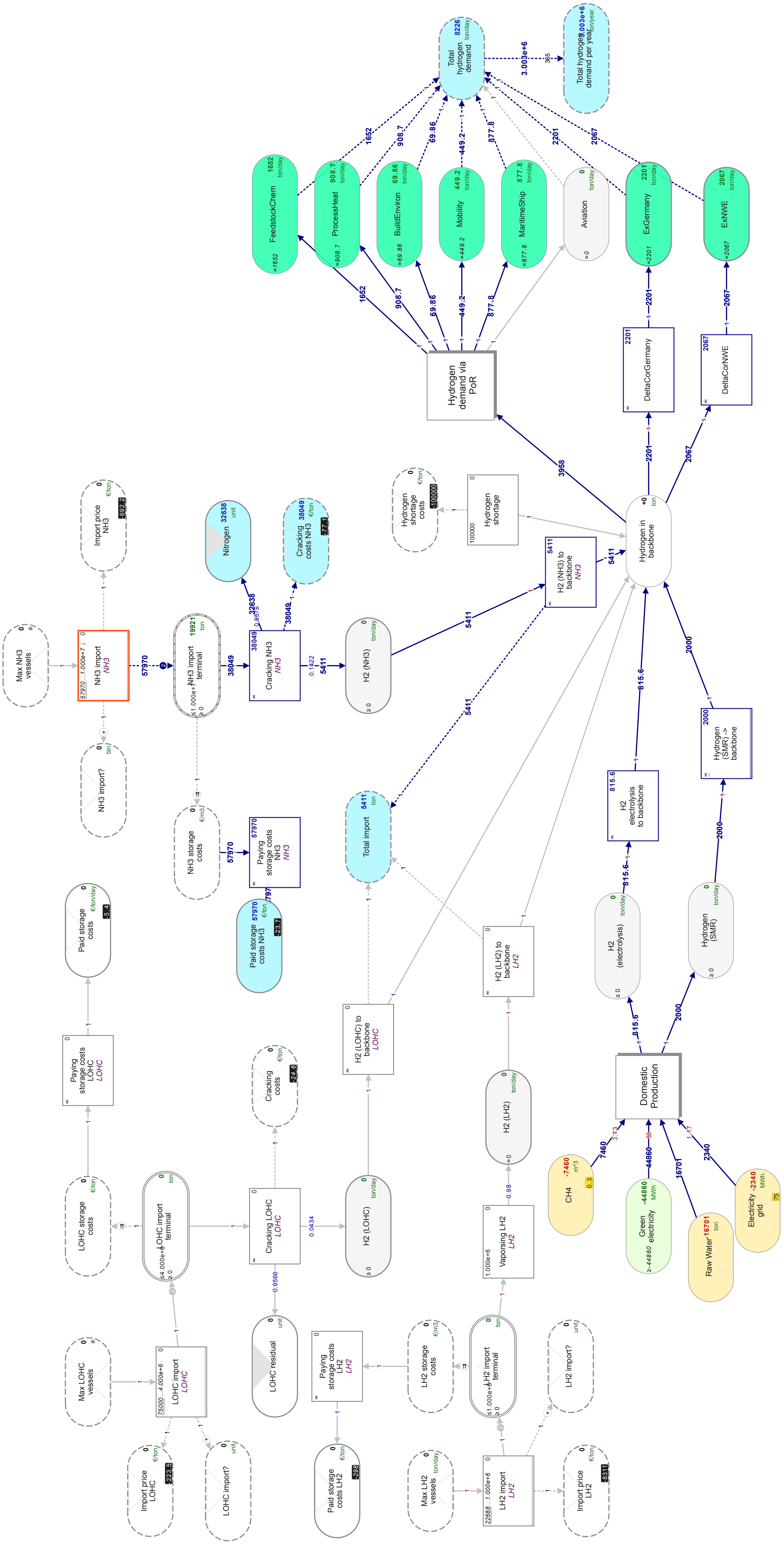
Figure 45: The yearly hydrogen import compared to the domestically produced hydrogen

The result of this validation experiment is satisfactory as it approaches the expectation. In Figure 45 the blue line indicates the import, and the orange line is the sum of both the electrolysis and SMR production. As can be seen, the import accounts for slightly more than 18 [Mtonne/year] (approximately 18,410 [Mtonne/year]) while the domestic production, justifies for somewhat below 2 [Mtonne/year] (1,655 [Mtonne/year]). Nevertheless, we conclude that our model is validated for two reasons. First, the experiment regarding the CCS option has successfully been conducted, and secondly, the latter experiment only differentiates 2,2 [%] from the estimations by Port of Rotterdam (2020b).

D Figures in high resolution




CAPEX electrolysis
€
-2.597e+6
OPEX electroysis
€/ton
-30.06
OPEX CCS
€/ton
-2.548
CAPEX CCS
€
-1.627e+6
Green electricity
≥-44860
MWh
55
0.01...1296
Electrolysis
Hydrogen producer
1
≥ 0
H2 (electrolysis)
ton/day
1
1
9
8
Oxygen
ton
0.01...30000
CCS
Hydrogen producer
0.11
≥ 0
CO2 emmitted from CCS
ton
-125
0.99
1.1
1
Raw Water
ton
≥ 0
Domestic production (SMR+electrolysis)
ton/day
1
DP sum
ton
Captured CO2
ton/day
1
∞
PORTHOS
1
Stored CO2
ton
Seawater
ton
Waste water
unit
1
CO2 emitted
ton
1
0.01...100000
CO2 emmission
Hydrogen producer
1
4.68
1.83
1.18
0.01...2000
SMR
Hydrogen producer
9
Electricity grid
MWh
75
1.17
1
≥ 0
Hydrogen (SMR)
ton/day
3.73
1.18
CO2 emmitted without CCS
ton
-125
CH4
m^3
0.3
1
1
CAPEX SMR
€
-1.974e+6
OPEX SMR
€/ton
-46.39
Return sea water
ton


Total hydrogen demand 8226 ton/day
Total hydrogen demand per year 3.003e+6 ton/year
3.003e+6
365
FeedstockChem 1652 ton/day
ProcessHeat 908.7 ton/day
BuildEnviron 69.86 ton/day
Mobility 449.2 ton/day
MaritimeShip 877.8 ton/day
Aviation 0 ton/day
ExGermany 2201 ton/day
ExNWE 2067 ton/day
Hydrogen demand via PoR
DeltaCorGermany 2201
DeltaCorNWE 2067
Hydrogen in backbone 0 ton
3958
2201
2067
Hydrogen shortage 100000
Hydrogen shortage costs 0 €/ton 100000
H2 (NH3) to backbone NH3 5411
Total import 5411 ton
H2 electrolysis to backbone 815.6
Hydrogen (SMR) -> backbone 2000
H2 (electrolysis) 0 ton/day
Hydrogen (SMR) 0 ton/day
Domestic Production
CH4 -7460 m^3 0.3
Green electricity -44860 MWh
Raw Water -16701 ton
Electricity grid -2340 MWh 75
7460
44860
16701
2340
Import price NH3 0 €/ton 692.2
Max NH3 vessels 0 #
NH3 import NH3 57970...1.000e+7
NH3 import? 0 bin
NH3 import terminal 19921 ton
57970
38049
Nitrogen 32638 unit
Cracking costs NH3 38049 €/ton 77.1
Cracking NH3 NH3 38049
H2 (NH3) 0 ton/day
0.1422
5411
NH3 storage costs 0 €/m3
Paying storage costs NH3 NH3 57970
Paid storage costs NH3 57970 €/ton 23.7
Paid storage costs 0 €/ton/day 5.4
Paying storage costs LOHC LOHC
LOHC storage costs 0 €/ton
LOHC import terminal 0 ton
Cracking LOHC LOHC
Cracking costs 0 €/ton 24.6
H2 (LOHC) 0 ton/day
0.0434
0.9566
H2 (LOHC) to backbone LOHC 0
H2 (LH2) to backbone LH2 0
H2 (LH2) 0 ton/day
0.98
Vaporising LH2 LH2
LOHC residual 0 unit
Paying storage costs LH2 LH2
LH2 storage costs 0 €/m3
LH2 import terminal 0 ton
LH2 import? 0 unit
Max LOHC vessels 0 #
LOHC import LOHC 75000...4.000e+6
Import price LOHC 0 €/ton 223.5
LOHC import? 0 unit
Paid storage costs LH2 0 €/ton 298
Max LH2 vessels 0 ton/day
LH2 import LH2 22688...1.000e+6
Import price LH2 0 €/ton 831