DESIGNING A TRANSMISSION PIPELINE FOR THE DECARBONIZATION OF INDUSTRIAL CLUSTERS

A FLEXIBLE DESIGN APPROACH

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DESIGNING A TRANSMISSION PIPELINE FOR THE DECARBONIZATION OF INDUSTRIAL CLUSTERS; A FLEXIBLE DESIGN APPROACH

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by

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Dear reader,

This report represents the conclusion of my Master thesis and thereby finishes my master Complex Systems Engineering and Management at the Delft University of Technology.

Working on this project for the past six months was a challenging but also fun experience. I think that the fact that the main topic of my thesis: flexible pipelines, is a so called "contradictio in terminis" illustrates the complexity. The result of this project would not nearly be the same without the guidance of my graduation committee, which I would like to thank. First, I would like to thank my first supervisor, Petra Heijnen. Your sense of control and planning helped me to get back on track when I was confused and uncertain about the next step. Our meetings always gave me a clear sense of direction. Secondly, I would like to thank my second supervisor, Martijn Warnier. Thank you for your feedback, reassurance and an alternative view on my work.

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EXECUTIVE SUMMARY

Industrial clusters are facing major challenges in transitioning away from their carbon-intensive activities in order to accelerate the energy transition away from fossil fuels. Therefore, the industrial clusters; the Port of Rotterdam, Chemelot, North-Rhine Westphalia (NRW) and Transition System Operator (TSO) GasUnie are planning to develop a pipeline connection for the transportation of renewable fuels between one another (Port of Rotterdam, 2020b). However, this pipeline connection operates in a very uncertain environment with regard to the technology required to decrease greenhouse gas emissions and the future policies that impact on the investment decisions by the industries that will make use of this connection. Therefore, there is much uncertainty about the requirements of the pipeline, making the way in which this new pipeline connection is to be constructed a complex question. Designing a flexible pipeline with capabilities to pro-actively deal with uncertainty could reduce the financial risk and support investment in the pipeline connection. Even so, there is a lack of knowledge about the specific costs and benefits of flexible pipelines and the question arises of how efficiently these flexible pipelines will perform. Therefore, this research is aimed to analyse the performance of various flexible pipeline designs for the connection of Rotterdam, Chemelot and North-Rhine Westphalia and answers the research question:" How do flexible pipeline designs perform for the transportation of sustainable fuels between the Port of Rotterdam, Chemelot and North-Rhine Westphalia from 2025 until 2050?".

To identify a suitable research approach for the analysis of flexible pipeline designs to connect Rotterdam, Chemelot and North-Rhine Westphalia, the literature regarding flexible pipeline design was consulted. The flexible design approach by Melese et al. (2017) was selected to be the most suitable for this research. This approach varies the flexibility of the pipeline by defining various flexibility options for pipeline designs and calculates the Net Present Value (NPV) of the flexible pipeline designs under different future demand scenarios in order to evaluate their performance. However, the NPV model of Melese et al. (2017) is not comprehensive enough for the analysis of the flexible pipeline designs in the context of this study. Therefore, thist study expands the NPV model of Melese et al. (2017). Based on the approach of Melese et al. (2017), the research method of this study was established, which is presented in figure 0.1.

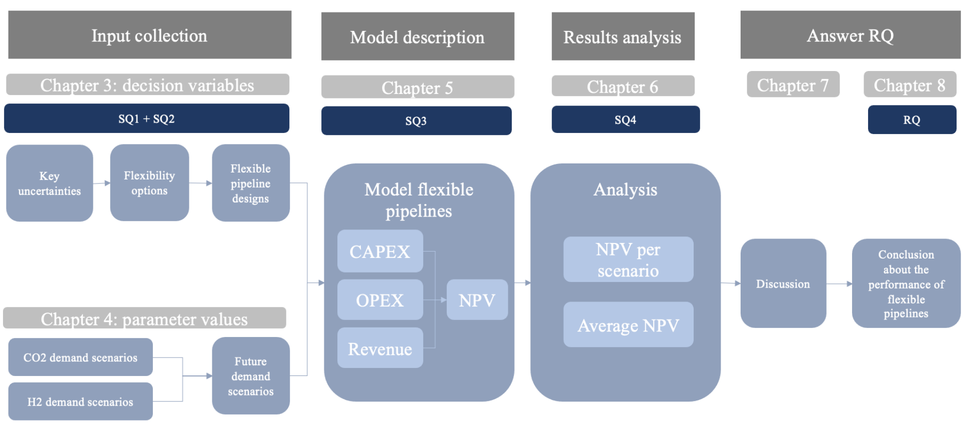

Figure 0.1: The research flow diagram

The first step of this approach was to identify possible flexible pipeline designs for the pipeline connection between Rotterdam, Chemelot and North-Rhine Westphalia. Therefore, first, the key uncertainties regarding the pipeline connection between these clusters were identified. An analysis of the requirements and objectives of the actors involved established three key uncertainties:

- Should the pipeline transport hydrogen or carbon dioxide?
- What should the capacity of the pipeline be?
- What hydrogen purity level should it deliver?

Next, possible flexibility options that can reduce the effect of the uncertainties on the performance of the pipeline are identified as follows:

- a multi-purpose pipeline that has the option to first transport carbon dioxide and later switch to the transport of hydrogen
- a single purpose hydrogen pipeline that is able to deliver 100 % pure hydrogen
- a pipeline that has the option to expand the capacity of the connection where the existing natural pipeline is reassigned for the transport of hydrogen alongside a new pipeline for sustainable fuels
- a pipeline that can expand by increasing the pressure, or
- a pipeline that can expand by installing an increased diameter.

These flexibility options are the decision variables involved in the flexible pipeline design. In total, almost 2,500 combinations can be formed. These 2,500 pipeline designs are used as input for the model. Thereafter, the hydrogen and carbon dioxide demand estimations of Rotterdam, Chemelot and North-Rhine Westphalia are used to developed eight demand scenarios to analyse and compare the performance of the flexible pipeline designs.

The next step in this research was to develop a NPV model that is able to analyse and compare the performance of the flexible pipeline designs. As pointed out above, the literature review regarding flexible pipeline analysis established that that the NPV model of Melese et al. (2017) was not suitable for the analysis of the flexible pipelines that can connect Rotterdam, Chemelot and North-Rhine Westphalia. The flexible design approach of Melese et al. (2017) is focused on uncertainty about the location of the participants and the flow of the participants. Therefore, the NPV analysis model of Melese et al. (2017) aims to optimise the path and the capacity of the network. However, the cost equation of this NPV model is not able to give a comprehensive analysis of the costs that are associated with the flexibility options of this study. Therefore, the literature regarding the cost models of the flexible pipelines of this research is reviewed. While there is existing research about separate hydrogen and carbon dioxide pipeline designs, no model exists that determines the design and the associated costs of a multi-purpose pipeline. Such a model is necessary to analyse the performance of the flexible pipeline designs to connect Rotterdam, Chemelot and North-Rhine Westphalia. This research therefore synthesizes the findings in the literature and uses the characteristics of hydrogen, carbon dioxide and natural gas reassignment to develop a NPV optimization model that is able to determine the optimal design and the associated costs of a pipeline based on the gas that flows through the pipeline. This model is used to calculate the NPV of the flexible pipelines designs to connect Rotterdam, Chemelot and North-Rhine Westphalia under the eight future demand scenarios.

The results of this NPV-analysis highlighted that a design that combines the construction of a multi-purpose pipeline with the construction of a separate single purpose pipeline and reassigns the natural gas pipelines for the transportation of hydrogen is the best performing pipeline design for the pipeline connection between Rotterdam, Chemelot and North-Rhine Westphalia in all future scenarios. Analysing the performance of the separate flexibility options concluded that the option to switch between the transport of carbon dioxide and hydrogen presents significant advantages in the average NPV. The analysis of the option to expand revealed that it is more economical to install a pipeline that is able to increase the pressure than it is to install a pipeline with a greater diameter. In addition to this, it was found that expanding the design with the capacity of the natural gas pipeline is a profitable option to include in the connection. When considering to include the flexibility to deliver 100% pure hydrogen, it is concluded that this option only has a good performance when it is combined with the option to switch between carbon dioxide and hydrogen. However, this combination involves high investment costs. Furthermore, the sensitivity analysis illustrated that the performance of a design that combines a multi-purpose and a single purpose pipeline is dependent on the demand of the industries that require 100% pure hydrogen.

With respect to the next steps, this research makes various recommendations. First, it is recommended to further investigate the costs of a multi-purpose pipeline. This research made a first attempt to estimate the costs of a pipeline that is able to first transport carbon dioxide and subsequently switch to the transportation of hydrogen. Such a pipeline has significant advantages. Therefore, the next step would be to further specify the costs of installing a multi-purpose pipeline between Rotterdam, Chemelot and North-Rhine Westphalia. Secondly, it is recommended to search for active collaboration with the industries that require 100% pure hydrogen. Investigating this option further could lead to reducing the investment risk of installing a combination of a multi-purpose pipeline and a single-purpose hydrogen pipeline. Furthermore, researchers can improve the proposed model by expanding the scope of the model and investigating the associated distribution pipelines that will be connected to the transmission pipeline. Finally, this research could be supplemented by an institutional analysis. This would allow one to determine the possibilities of contracting new industries in order to decrease the financial risk of installing a second pipeline. The model could then be expanded in order to evaluate the impact of these new contracts on the NPV and to decide which institutional arrangements would be most suitable.

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NOMENCLATURE

List of abbreviations

CCS	Carbon Capture and Storage
CCSU	Carbon Capture Storage and Utilisation
LNG	Liquefied Natural Gas
NPV	Net Present Value
NRW	North-Rhine Westphalia
PoR	The Port of Rotterdam
TSO	Transmission System Operator

List of Greek symbols

α	Connection fee
ϵ	The mean height roughness
η	Efficiency
μ	The viscosity
ρ	Density

List of Roman symbols

CA	Corrosian Allowance
$CAPEX$	Capital Expenditures
$C_{compCO2}$	Carbon dioxide compression costs
C_{compH2}	Hydrogen compression costs
$C_{construction}$	Construction costs
C_{labor}	Labor costs
$C_{material}$	Material costs
$C_{miscellaneous}$	Miscellaneous costs
C_{Pump}	Pumping costs
$C_{Reassignment}$	Capital expenditures for the reassignment of the natural gas pipelines
C_{RoW}	Righ of Way costs
C_{steel}	The steel price
D	The diameter
D_{NG}	The diamater of the natural gas pipeline
E	Longtidinal joint factor
F	Design factor related to the terrain
ff	The friction factor
L	Length of the new pipeline connection
L_{NG}	Length of the natural gas pipeline connection
M	Molar mass
n	Project lifetime
OPEX	Operation and Maintenance costs
P1	Compressor outlet pressure
P2	Compressor inlet pressure

P_{ave}	The average operation pressure
P_{in}	The inlet pressure
P_{max}	Maximum pressure
P_{out}	The outlet pressure
Q	The yearly flow
r	The discount factor
Re	Reynolds number
S	Minimum Yield Stress
t	Year
T	Temperature
v	Velocity
W	Compressor capacity

1 RESEARCH INTRODUCTION

1.1 BACKGROUND INFORMATION

"Human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years" (IPCC, 2021)

This is a quote of the IPCC Sixth Assessment report that was published in August 2021. This report states that humanity has caused the last four decades to be successively warmer than any decade previously since 1850 (IPCC, 2021). Furthermore, it finds that averaged over the next 20 years, global temperature is expected to reach or exceed 1.5°C of warming (IPCC, 2021). With these findings, this report stresses the need for immediate measures against climate change, of which decarbonization is a major focus (IPCC, 2021).

An important area to focus on is the energy sector since this sector has been relying on carbon-based energy sources for over 2 centuries. Although the share of alternative energy carriers is increasing, oil, gas and coal still account for the primary energy source (BP, 2021). This indicates how difficult and revolutionary in scope a transition to a decarbonized energy system will be (Dorian et al., 2006).

The industry is responsible for 30 % of total carbon emissions. This makes industrial clusters critical players in accelerating the decarbonization of the energy sector (Accenture, 2021). Industrial clusters are geographic areas where industries are co-located. This provides for opportunities of scale, sharing of the risks and resources and the possibility to optimize the demand (Accenture, 2021). In order for the industrial clusters to decarbonize, they have to adjust their processes and invest in renewable technologies. However, currently, the industrial sector faces three barriers to do so: uncertainty about policy support, uncertainty about technological development and the absence of infrastructure (Accenture, 2021).

This thesis focuses on this last barrier: the need for an energy transportation infrastructure, because this plays an important role in the decarbonization of the energy system. Infrastructure is essential in connecting the customers to the producers and thus form a secure link in the energy chain. Implementation of a new energy infrastructure has three complex components. First, the development of an energy infrastructure requires high capital investment - potentially hundreds of millions or billions of dollars might be involved with the construction of a pipeline network - and because of the long lifespan, it has a relative delayed return on investment (Melese et al., 2017). Secondly, many actors are involved in the construction of the pipeline connection with both private and public interests (Ligtvoet, 2013). These actors have different interests and requirements which makes cooperation challenging (Melese et al., 2017). Thirdly, renewable energy infrastructure operates in a very uncertain environment. There is uncertainty about which actors will connect to the network, what requirements they have, how technology develops in the future and what policies will be set. Because of these uncertainties, infrastructure developers get afraid to 'bet on the wrong horse', become risk averse and consequently make sub-optimal decisions (McCarter et al., 2010). This thesis focuses on decreasing the complexities of infrastructure implementation by analysing the construction of a renewable fuel pipeline connection between three industrial clusters, Rotterdam, Chemelot and North-Rhine Westphalia. The next sections introduce this case study, specify the research objective and finally identify the main research question.

1.2 CASE STUDY DESCRIPTION

In order to support the decarbonization of the industry in Northwest Europe, the industrial clusters Port of Rotterdam (PoR), Chemelot, North-Rhine Westphalia(NRW) and Transmission System Operator (TSO) GasUnie are planning to develop a transmission pipeline connection for the transportation of renewable fuels between these industrial clusters (figure 1.1) (Port of Rotterdam, 2020b). This project is intended to develop a public-private partnership and fulfil an important role in the transformation of these industrial clusters to carbon-neutral clusters.

The Port of Rotterdam is an industrial cluster, located next to the North Sea and is currently the leading energy cluster in Northwest Europe. However, more than half of the total throughput originates from fossil fuel resources (Drift, 2020). This has created the current strong economic position for the Port of Rotterdam but simultaneously has put this position in danger in the future. Drift (2020) stated that if Rotterdam wants to remain in this position, it has to become pro-active and search for other, renewable, alternatives to use, import, produce and transport energy. Chemelot is an industrial cluster, located in the south of the Netherlands. This industrial cluster is mostly focused on the production of chemical products such as fertilizers and plastics. North-Rhine Westphalia is located in Germany, just across the border with the Netherlands and has many different industries located in its cluster such as oil refineries, steel construction industries and power plants. Both clusters want to decarbonize their activities but due to limited domestic potential for renewable energy generation or storage capacity, they are not able to foresee their own demand (Drift, 2020). Since currently both clusters are already connected to the Port of Rotterdam for energy transportation, the situation offers good entry points for future collaborations (Drift, 2020).

In the Netherlands and the northern part of Germany, GasUnie is in charge of building and maintaining the infrastructure for the large-scale transport of natural gas. The main duty of GasUnie is the maintenance of the natural gas network. However, in a renewable energy future, GasUnie also wants to retain the function of Transmission System Operator and intends to become responsible for the construction of reliable and safe pipelines for the transportation of sustainable gasses.

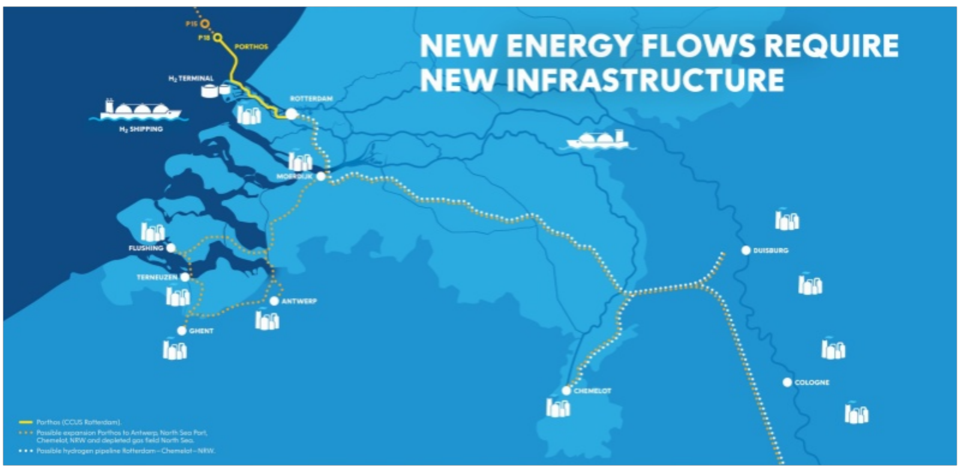

Figure 1.1: An overview of the future pipeline connection between Rotterdam, Chemelot and North-Rhine Westphalia (Port of Rotterdam, 2020b)

The previous section established that a reliable infrastructure is an essential component in accelerating the decarbonization of industrial clusters. In order to illustrate the need for a new transmission pipeline connection between clusters, the current pipeline connections are analysed first. Figure 1.2 presents the natural gas network in the Netherlands. This network could serve for the transportation of renewable gasses (Cerniauskas et al., 2020). However, there are three significant disadvantages of using the current pipelines. First of all, the natural gas pipelines have been constructed to meet the natural gas demand instead of the demand of renewable fuels. Therefore, the pipelines flow from the natural gas hub, Groningen, in the North of the Netherlands to the industrial clusters in the south. However, East-West pipelines are preferred for a renewable fuel pipeline as this gives the shortest connection. Secondly, assuming an immediate change from natural gas to hydrogen is not a realistic scenario and applying a mixture of hydrogen and natural gas might not have the required effects regarding emission reductions (Cerniauskas et al., 2020; Kovač et al., 2021). Lastly, the natural gas pipelines between Rotterdam, Chemelot and North-Rhine Westphalia do not have the optimal design to transport renewable gasses. For example, with regard to the transportation of hydrogen, the capacity of the pipeline only allows for a yearly flow of 1.4 Mton hydrogen, while the yearly hydrogen demand could potentially increase to 20 Mton in 2050 (Port of Rotterdam, 2020a). Considering the transportation of carbon dioxide, the design of the pipeline does not deliver the most economical way to transport carbon dioxide over long distances. As liquid carbon dioxide is most economical for transport over long distances, the pipeline pressure should be 8MPa or above (Knoope, 2015). However, the natural gas pipelines allow a maximum pressure of 7MPa thus it is not recommended to use the old natural gas pipelines (Cerniauskas et al., 2020). These disadvantages show the limitations of the current pipeline network between the Port of Rotterdam, Chemelot and North-Rhine Westphalia and the need for a new pipeline connection that helps the decarbonization of these industrial clusters. In order to get a better understanding of the design of the new pipeline connection, the critical pipeline components of this case study will be discussed in section 1.2.2. But first, to clarify these critical variables, the possibilities to decarbonize in the industrial sector are shortly discussed in the next section.

Figure 1.2: Natural gas infrastructure in the Netherlands

1.2.1 Decarbonizing industrial clusters

The industrial sector has several options to decrease its carbon emissions. However, no single technology or action represents a silver bullet. Therefore, a combination of options is necessary to reach zero carbon emissions (Bellona Europe, 2018). Bellona Europe (2018) described the various options, which are presented in the figure below.

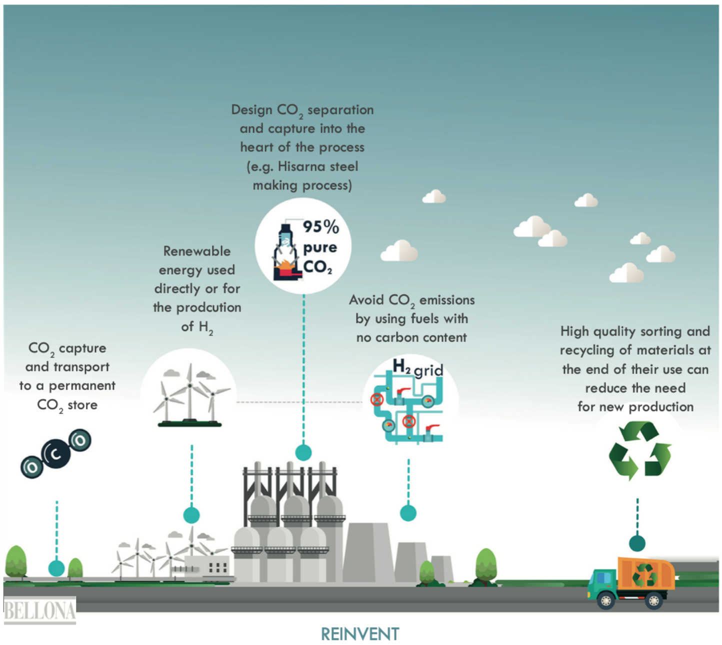

Figure 1.3: The options to decrease green house gas emissions in industrial clusters (Bellona Europe, 2018)

Reducing, recycling and up-cycling

Industrial products are produced and consumed in significant quantities and thus they play an important role in CO2 emissions of industrial clusters (Bellona Europe, 2018). Therefore, a natural first step to decrease the carbon emissions would be to reduce the use of industrial products. As well as carefully considering the number of industrial products, sorting and recycling of materials at the end of their use can further decrease the need for new production. By improving the efficiency of the designs and the production of industrial products, the waste and resources used can be decreased. Apart from recycling, up-cycling is also a possible concept, where the resources are not reused to make inferior products, but reused in high quality manufacturing (Bellona Europe, 2018). However, this requires advances in both production and end-of-life separation but not an energy transportation infrastructure. Therefore, these options to decrease greenhouse gas emissions are left out of the scope of this study.

Electrification

Many amendments have been made to shift from the conventional fossil fuel electricity production to renewable electricity production. In Europe the share of renewable electricity generation is slowly increasing. However, electricity presents only 20 % of the total societal energy consumption meaning that other energy sources account for the majority of the final energy use (Bellona Europe, 2018). In order to reach non-carbon industrial clusters with renewable electricity, their processes have to be electrified. Electrification of the industrial processes is possible and certainly plays an important role in reducing industrial emissions. One of these possibilities is the implementation of green hydrogen. Green hydrogen is produced from renewable electricity and can be easily implemented in certain industrial processes (Bellona Europe, 2018). The applications of hydrogen will be further discussed below. However, the analysis of Bellona Europe (2018) shows that solely relying on renewable electricity is a high-risk strategy. The amount of electricity needed when the industrial clusters only rely on electricity is extensive and seems to be beyond all reality. This shows that electrifying the industry is one of the options to decrease the greenhouse gas emissions, but not enough to foresee the transition to a non-carbon cluster.

Carbon Capture Storage and Utilisation (CCSU)

Carbon Capture Storage and Utilisation is a method to decrease carbon dioxide emissions by capturing the carbon dioxide in pre-, post- and oxyfuel combustion and transport it to deep underground CO2 storage, such as old gas and oil fields. In these storage facilities CO2 binds with the surrounding salty water molecules and remains stored between impermeable layers of rock for thousands of years (Bellona Europe, 2018). Besides storage, re-use of carbon-dioxide is also possible. When CO2 storage is combined with biomass, carbon negative products can be produced, such as heat, electricity and industrial products (Bellona Europe, 2018). However, for this purpose, it is important that any biomass used for energy or heat, with or without CCS, should be sourced in a sustainable way. Whereas other options show limitations of feasibility, scale, costs and time, CCS is ready to be implemented and can provide effective emission reductions (Bellona Europe, 2018). However, in order for it to be implemented, first an infrastructure for the storage facilities is necessary. This illustrates that CCS is an essential part of the solution but is in critical need of a transportation infrastructure.

Hydrogen

Hydrogen is the most abundant element on earth and the practical implementations of hydrogen in industry are extensive (Drift, 2020). It can be used as feed stock for important chemical industries, as an energy carrier, but also as an emission-free fuel (Drift, 2020). Hydrogen can be produced through different processes. Therefore, different types of hydrogen can be distinguished : grey, blue and green hydrogen. The majority of hydrogen is produced by converting natural gas to hydrogen and carbon dioxide or as a by-product in industrial processes (Bellona Europe, 2018). This is called grey hydrogen. However, as the emission targets are becoming stricter, grey hydrogen production has to switch to the production of sustainable hydrogen. One form of sustainable hydrogen is blue hydrogen. Blue hydrogen is produced by capturing the emitted carbon dioxide of the grey hydrogen production and storing it. Another form of sustainable hydrogen is green hydrogen. Green hydrogen is produced by splitting water with green electricity through a process called electrolysis (Bellona Europe, 2018). The existing production of green hydrogen is limited, but is likely to increase in the future, especially in countries with relatively cheap renewable electricity production. The speed of the scaling up of hydrogen production will be dictated by the speed of the renewable electricity (Bellona Europe, 2018). Currently, blue hydrogen is cheaper than green hydrogen. However, if enough sustainable electricity is installed, the production of green hydrogen will become cost competitive with blue hydrogen and green hydrogen will become more attractive to use (Drift, 2020). Apart from the costs and carbon dioxide emissions, grey, blue and green hydrogen also differ in their purity (also referred to as quality). The purity of hydrogen is the mol fraction of contaminants in hydrogen. When hydrogen is produced from green electricity, 100% pure hydrogen is produced. Grey and blue hydrogen only have a level of 99.9 %. Some industrial processed require a certain purity level, the minimum percentage contaminants that can be tolerated to maintaining acceptable performance, durability, and cost requirements. The purity is dependent on the method of production, transportation or storage. Consequently, some industries require a specific colour of hydrogen or a specific transportation method.

1.2.2 The critical components of the design of the new pipeline

The previous sections established the need for a renewable fuel pipeline connection between Rotterdam, Chemelot and North-Rhine Westphalia. This section will discuss the design components of the new pipeline and identify the critical ones.

Pipeline design has various components which can be optimized according to the system they operate in. Normally, the path and the associated length of a pipeline is one of the most critical components of the design of a pipeline, because the length has a large influence on the total costs. Furthermore, it also is difficult to optimize the length in the design phase of pipeline construction as it is often uncertain who will join the network at the start of the project. However, in January 2021, the Port of Rotterdam and Chemelot conducted a study into the feasibility of different transmission pipeline routes for the connection of those clusters (Buck Consultants International, 2021). In this feasibility study, three possibilities for the pipeline route between Rotterdam and Chemelot were analysed, one route was established as being the optimal one. The path that the pipeline will follow in the Netherlands is illustrated in figure 1.4 (Buck Consultants International, 2021). This pipeline route can easily connect to NRW. It can thus be concluded that in this case study and in this phase of the project, the pipeline route is not the most critical issue that has to be addressed.

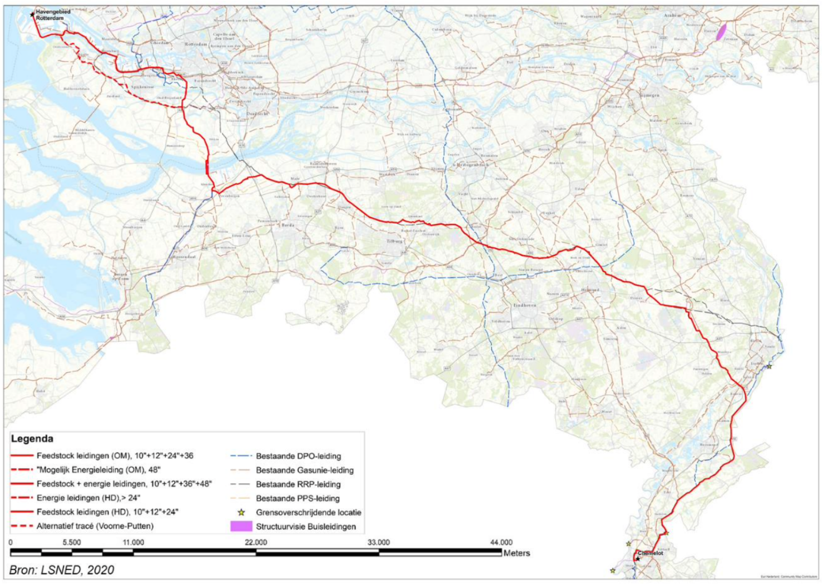

Figure 1.4: The pipeline route between Rotterdam and Chemelot (Buck Consultants International, 2021)

In order to establish which other components do play a critical role in this phase of the project, it is important to analyse what is desired from the pipeline (Enserink et al., 2010). In this case study, the industries located in the industrial clusters are the users of the pipeline and the TSO is the investor and constructor of the pipeline. In order to determine what is desired from the pipeline, the objectives of the various industries located in the industrial clusters and the TSO are analysed. A short summary of the objectives is presented in figure 1.5, chapter 3 elaborates on these objectives and requirements in more detail. The objectives of the industries are clear: they all want to decarbonize. However, research illustrates that the way they want to do this differs per industry (Bellona Europe, 2018). These differences result in different requirements of the pipeline. Furthermore, the exact requirements are still very uncertain due to lack of knowledge about technology and policy development in the future (IEA, 2019). Therefore, the pipeline is subject to great uncertainty about the future circumstances. Since the industries are the users of the pipeline, the different requirements of the industries determine the critical components of the pipeline. Accordingly, the new pipeline connection between Rotterdam, Chemelot and North-Rhine Westphalia has the following three critical components:

- The purpose of the pipeline: hydrogen or carbon dioxide transport
- The capacity of the pipeline
- The hydrogen purity level of the pipeline

In order to decide upon the optimal pipeline design, first, more information about future circumstances is necessary. Nevertheless, there is an urgent need for a new pipeline and it is not possible to wait and see how the future develops. In order to tackle this problem, the literature regarding pipeline design and uncertainty has been consulted and reviewed in chapter 2.1.1. The literature appears to focus on so-called flexibility designs, which are designs of pipelines with capabilities to pro-actively deal with uncertainty by changing these capabilities for a range of possibilities (Melese et al., 2017; Mudchanatongsuk et al., 2008). Flexibility is defined here as having a great range of adaptability. At first sight, a flexible pipeline might sound impossible, but with some further scrutiny one can identify multiple opportunities to meet this criterion. With respect to the requirements of the actors that are connected, multiple options for increased flexibility can be included in the design. For example, a flexible pipeline is a pipeline that has the ability to expand according to the demand of the industries or a multi-purpose pipeline that has the ability to switch if the type of gas required varies in future scenarios. Therefore, in order to deal with the three critical components and their uncertainties, a flexible pipeline design could be considered for the pipeline connection between Rotterdam, Chemelot and North-Rhine Westphalia.

Actor		**Objectives**
North-Rhine Westphalia & Chemelot	Chemical industry	Help to decarbonize by importing 99.9% green or blue hydrogen.
	Oil refinery industry	Help to decarbonize by either importing 99.9 % hydrogen or exporting carbon dioxide.
	Iron & steel industry	Help to decarbonize by exporting carbon dioxide to storage facilities.
	High temperature heat in industry	Help to decarbonize by exporting carbon dioxide to storage facilities.
	The mobility sector	Help to decarbonize by importing 99.999% green hydrogen.
	The power sector	Help to decarbonize by either importing 99.9 % hydrogen or exporting carbon dioxide.
Port of Rotterdam		Pro-actively supporting the use of renewable, alternatives to use, import, produce and transport energy.
TSO		Supporting decarbonization of the industries and remaining in the TSO position but without a high financial investment risk.

Figure 1.5: An overview of the objectives of the actors involved

1.2.3 Problem description and research objective.

The previous section established the benefits a flexible pipeline design that is not dependent on the identified uncertainties. However, a flexible pipeline might sound promising, but simultaneously might involve high investment costs (Melese et al., 2017). For example, when a pipeline is over-sized, the benefits of being able to meet future demand might not outweigh the risks of sunk costs. As the network operator is the one that carries the risk of investment, he might be reluctant to invest in a flexible pipeline. For the network operator, the investment cost should be low or he should be convinced that the benefits of flexibility outweighs the risks. This illustrates the need for more information about the performance of flexible pipelines in the context of the pipeline connection between Rotterdam, Chemelot and North-Rhine Westphalia.

It is in this field of innovations, changes and uncertainties that this study is situated. This thesis helps deciding on flexible pipeline designs by investigating flexible pipeline designs by varying among others the components that are critical in the context of the Port of Rotterdam, Chemelot and North-Rhine Westphalia.

This research aims to develop a model for the investigation of flexible pipelines in the context of the Port of Rotterdam, Chemelot and North-Rhine Westphalia and to order the various options of flexible pipeline design with respect to specific performance criteria, that will be explained later (chapter 4 and 5). As our review of the literature on flexible pipeline design in chapter 2 shows, this has not been done before. Therefore, this study fills in a gap in the current knowledge of flexible pipeline designs, as well as in the methodology for modelling/investigating these.

1.3 THE RESEARCH QUESTION

This research objective resulted in the following main research question:

"How do flexible pipeline designs perform for the transportation of sustainable fuels between the Port of Rotterdam, Chemelot and North-Rhine Westphalia from 2025 until 2050?"

More specifically, it focuses on four sub-questions. First of all, the context of this thesis is characterized by a large range of uncertainties. The first sub-question tries to grasp the main uncertainties:

1. What are the key uncertainties regarding the pipeline connection between Rotterdam, Chemelot and North-Rhine Westphalia?

   These key uncertainties form a risk for the construction of a pipeline. A flexible pipeline reduces this risk, but within the category 'flexible pipeline' many options exist. The second sub-question addresses these options:

2. What are possible flexibility options to reduce the risk of these uncertainties?

   When the key uncertainties are determined and the flexibility options have been tracked down, the flexibility options can be investigated with respect to their performance. The third sub-question addresses the problem of how to measure the performance of flexible pipeline designs.

3. How can the performance of the flexible pipeline designs be measured?

   When the key uncertainties are determined and the flexibility options have been tracked down, the flexibility options can be investigated with respect to their performance. The third sub-question addresses the problem of how to measure the performance of flexible pipeline designs.

4. How do the flexible pipeline designs perform on the established criteria?

By taking the answers to all four sub-questions together, the general research question is answered.

1.4 ALIGNMENT TO COMPLEX SYSTEM ENGINEERING AND MANAGEMENT

This study addresses a complex system that fits the criteria of a Complex Systems Engineering and Management master thesis. The complexities of infrastructure design, the many stakeholders involved, the combination of technical and economic aspects and the link between the public and the private domain are all indicators of how this research is connected to the master program.

The study's engineering component is the energy system: a complex sociotechnical system. More specifically, this thesis focuses on energy transportation infrastructure implementation. The technological components include a hydrogen and carbon dioxide transportation pipeline with technical issues related to uncertainty of the environment it operates in and the costs of flexible pipelines. The social context is deliberated through an evaluation of the requirements and objectives of the many actors involved and an attempt is made to fit the pipeline design into their preferences. For these reasons, this study embodies a Complex Systems Engineering and Management thesis.

1.5 OUTLINE OF THE RESEARCH

The study is structured as outlined. In this first chapter, the societal relevance of this study is discussed. In the next chapter, the scientific relevance of this thesis is illustrated by analysing the current literature on flexible pipeline design and determining the research gaps regarding analysis methods. Chapter 3 and 4 describe the input of the model. First, in chapter 3 the pipeline designs that are tested in this research are presented. Chapter 4 discusses how the future can develop and determine possible demand scenarios that are used to analyse the performance of the pipeline designs. Next, chapter 5 discusses how the model for relevant cost comparison is developed and how it can be applied. Thereafter, chapter 6 presents the performance of the pipeline designs under different future scenarios. Finally, chapter 7 and chapter 8 address the discussion and the conclusion respectively. Ultimately a recommendation is given.

2 LITERATURE STUDY AND METHOD DESCRIPTION

The general question of this thesis is: "How do flexible pipeline designs perform for the transportation of sustainable fuels between the Port of Rotterdam, Chemelot and North-Rhine Westphalia?". The question this chapter aims to answer is: does the body of scientific knowledge contain leads that can be helpful in answering a part of this question, namely the part that concerns flexible pipeline designs? What is known about pipelines and more specifically about flexible pipelines, and how does this knowledge relate to this study?

Firstly, the academic literature on handling uncertainty in renewable fuels pipeline design will be analysed. The next section focuses on the flexible design generation and evaluation method by Melese et al. (2017). Synthesising this information results in a research gap in the model used to analyse the model to analyse flexible pipelines. The last section presents the way in which this study tries to fill the research gap by presenting the adaption of the flexible pipeline evaluation method by Melese et al. (2017).

2.1 STATE OF THE ART OF PIPELINE DESIGN

2.1.1 Pipeline design under uncertainty

The literature sets out the development of different methods that help to design the optimal pipeline connections. Most of the models focus on mathematical optimization including Mixed Integer Linear or Non-Linear programming (Reuß et al., 2019) and multi-objective programming (Baufumé et al., 2013). In these models, system topology and pipeline capacity are being varied in order to find the connection with the lowest costs. Some studies combine this with the use of a geographical information systems (GIS) in order to take the national and regional specific conditions into account, making the approach less generic (Baufumé et al., 2013; Marcoulaki et al., 2012). Other mathematical optimization studies use graph theory to find the optimal pipeline topology (Heijnen et al., 2020; Heijnen et al., 2014; Melese et al., 2014; Melese et al., 2015).

Apart from mathematical optimization, agent-based models have also been used in order to assess the interaction of individuals and groups in the hydrogen network to develop the optimal pipeline connection (Chappin and Dijkema, 2008; Heijnen et al., 2014; Nikolic et al., 2008). Maryam (2017) reviewed all the methods that have been used for the development of hydrogen infrastructure and concluded that most models are static models only limiting the behaviour of the hydrogen infrastructure to a snapshot or to very particular scenarios. Hence, the common engineering practice of designing pipelines is to find the optimal design that optimizes a fixed set of parameters such as minimum costs (Melese et al., 2017). However, these solutions tend to be rigid and do not perform well under conditions of uncertainty (Goel et al., 2006). This is a shortcoming in relation to the problem of this thesis and illustrates the need for a method that helps to design pipelines that can deal with these uncertainties.

Research regarding uncertainty and pipeline design focuses on either minimizing the effects of uncertainty by directly intervening at the source or designing a pipeline that has the capability to handle uncertainty with a certain range - also referred to as robust designs (Mudchanatongsuk et al., 2008). The approach to minimize the effects of uncertainty is useful during the operation of the pipeline, but less in the design phase (Neufville, 2003). In order to design robust pipelines, stochastic scenarios for the demand and production have been applied to test the pipeline designs (Baufumé et al., 2013; Lou et al., 2014). Melese et al. (2014) extended this approach by combining it with a graph theory method by Heijnen et al. (2014) that generates fast results of network topology. With the robust design approach it is possible to evaluate the different design possibilities easily under different future scenarios.

Although the designs generated with these methods might be robust, they often still under-perform in conditions of a high degree of uncertainty. An analogy can clarify this: one might be dressed to walk through a thunder-storm or in 30 degrees. Although this outfit is robust as it allows someone to walk wherever he wants to go, it does not include swimming trunks and therefore does not provide the option to go swimming. Furthermore, these designs tend to be fixed, they do not have the ability to downsize in response (de Neufville and Scholtes, 2011; Neufville, 2003). This aspects reduces the relevance of these designs for this thesis. For example, a pipeline design with a large capacity does not have the ability to decrease when the demand is not as high as expected.

Another approach to deal with uncertainty is the flexible design approach. In the engineering field, flexibility provides the possibility to change the system after the intervention has been implemented (Saleh et al., 2004). This approach centres on beiling able to adapt the system to unexpected future circumstances. The general idea of flexible design is explained by Cardin et al. (2015) as a design that can avoid the worst risks, and take advantage of fortunate opportunities. The concept of flexibility is often related to the concept of real options (Melese et al., 2017). The real option concept is explained by Neufville (2003) as "the right, but not the obligation, to change a project in the face of uncertainty". With respect to these real options four categories have been established that can be included in the design: the option to abandon, to expand, to switch or the option to defer (Martins et al., 2015). Real options were originally used in the financial sector to value the option of flexibility in the context of large, expensive projects. In the engineering field, real options can be explained through the example of integrating an extra structural strength in a suspension bridge which enables its owners to double- check it in case of need. Cardin et al. (2015) state that the approach does not suggest the most optimal design, but it provides a convincing argument for the reason why the flexible design is appropriate and how it should be implemented, and thus why decision-makers should consider flexible designs. As for the infrastructure engineering, Martins et al. (2015) provide an overview of the current literature on real options in infrastructure design and state that this concept gained more importance and should be applied predominantly in the initial phase of infrastructure design. Now one comes close to what is needed in the context of this thesis. Melese et al. (2017) and Nie et al. (2017) have applied the flexible design approach in the context of the design of pipeline infrastructure. Nie et al. (2017) applied the real option method and included storage possibilities in the network. It is the work of particulary Melese et al. (2017) that shows the strongest link to this study and offers several leads. Melese et al. (2017) used the flexible design approach and developed a flexible design generation and evaluation method for the energy and industrial infrastructure networks. Therefore, Melese et al. (2017) offer a method to analyse flexible pipeline designs for the connection between Rotterdam, Chemelot and North-Rhine Westphalia. The next section elaborates on this analysis method in more detail.

2.1.2 A method to analyse flexible pipeline designs

The flexible design approach of Melese et al. (2017) is based upon a practical four-step process by de Neufville and Scholtes, 2011: (1) recognize the major uncertainty, (2) identify a flexibility options to deal with these uncertainties (3) evaluate the flexibility options and (4) implement the best option. The first two steps identify the options to include flexibility. Melese et al. (2017) uses real options as a way to define the basic elements of flexibility. To identify the valuable real options, large sets of potential design configurations are evaluated. A method developed by Heijnen et al. (2014) is used to do an easy and fast assessment of the various configurations and the low-regret options. In the last two steps, the flexibility options are analysed with respect to their performance. The Net Present Value (NPV) metric is used to compare the performance of the flexibility options. This NPV is calculated with the following equation:

$$NPV = Revenue - Costs$$

of which the revenue and costs are calculated with the following equations:

$$Revenue = \sum_{t=1}^{n} \frac{\sum q_i}{(1+r)^t}$$

$$Costs = \sum l_e * q_e^{\beta}$$

The NPV is then calculated under various future demand scenarios, which are determined using Monte Carlo simulation. Lastly, after analysing the performance of the flexibility options under different future scenarios, a sensitivity analysis is executed to determine the sensitivity to the main assumptions.

The flexibility analysis method by Melese et al. (2017) is a clear and easy way to analyse different flexible pipeline designs with respect to their performance. Therefore, this method is selected to analyse the flexible pipelines to connect Rotterdam, Chemelot and North-Rhine Westphalia. However, this method is focused on analysing the flexibility regarding two key uncertainties: flow rate changes of the existing participants of the network and uncertainty about new participants that join the network in the future. These uncertainties affect the path and the capacity of the network and therefore the analysis of the flexible pipeline is focused on cost minimization with regard to the path and the capacity.

However, the uncertainties regarding the pipeline connection between Rotterdam, Chemelot and North-Rhine Westphalia differ from the ones in the study of Melese et al. (2017). They are not only targeted at the capacity of the pipeline and they are not affecting the path of the network. Therefore, a deeper analysis of the extra costs and revenues of the suitable flexibility options of this case study is required. The analysis model of Melese et al. (2017) is focused on the minimization of the length and capacity and the cost component of the proposed NPV model by Melese et al. (2017) does not provide a comprehensive cost evaluation for flexibility options that are not affecting the length of the network but other aspects such as the compression costs. Therefore, the NPV model of Melese et al. (2017) has to be expanded with the ability to perform a more detailed cost analysis of the flexibility options of this research.

2.1.3 Knowledge gap

Summarizing the consulted literature, it can be concluded that a so-called comparative assessment of pipeline designs is available. It enables the selection of the best design from a range of designs, focusing on minimum cost optimization and including various demand scenarios to test the performance of a design over time. The work of Melese et al. (2017) is particularly helpful in approaching the problem of this thesis. It introduces the flexible design approach, which is targeted at analysing options that create flexibility with respect to participants and flow uncertainty. It encompasses concepts and notions, procedures and calculations that are useful in the context of this thesis.

However, in certain respects, this thesis cannot follow into the footsteps of Melese et al. (2017). First, the uncertainties in the context of the connection between the Port of Rotterdam, Chemelot and North-Rhine Westphalia differ from the ones that Melese et al. (2017) took into account. The uncertainties of Melese et al. (2017) concern participants and length of the pipeline path. In the context of this thesis, the path and length of the pipeline are given factors, while the key uncertainties are the type of fuel, its amount and its purity (as treated into more detail in chapter 3 and 4). Second, the costs model of Melese et al. (2017) does not fit to the costs of the pipeline in the context of this study. In Meleses study, the costs were determined mainly by the length of the pipeline, while, in the context of this thesis, compression costs play an important role.

The conclusion here is that the existing literature shows a twofold gap:

1. the uncertainty factors of the context of the Port of Rotterdam, Chemelot and North-Rhine Westphalia – type of fuel, amount of fuel and purity - have not been covered before (See chapter 3 and 4);

2. the the cost model that is used is limited in relation to what is needed here.

This study tries to fill these gaps. From a methodological perspective, its aim is to adapt the model of Melese et al. (2017) to the context of the pipeline connection of the Port of Rotterdam, Chemelot and North-Rhine Westphalia by including other uncertainty factors than Melese et al. (2017) did and by developing a relatively more complex costs model.

The next section 2.2 presents the adaptation of the method of Melese et al. (2017) to the problem of this thesis.

2.2 METHOD DESCRIPTION

The research method of this study is based on the flexible design approach of Melese et al. (2017). This approach varies the flexibility of the design of the pipeline and uses the NPV to determine the performance of the flexible pipeline designs under various future scenarios. This approach is illustrated in the research flow of this study, which is presented in figure 2.1. Next, the separate steps in this flow are shortly described.

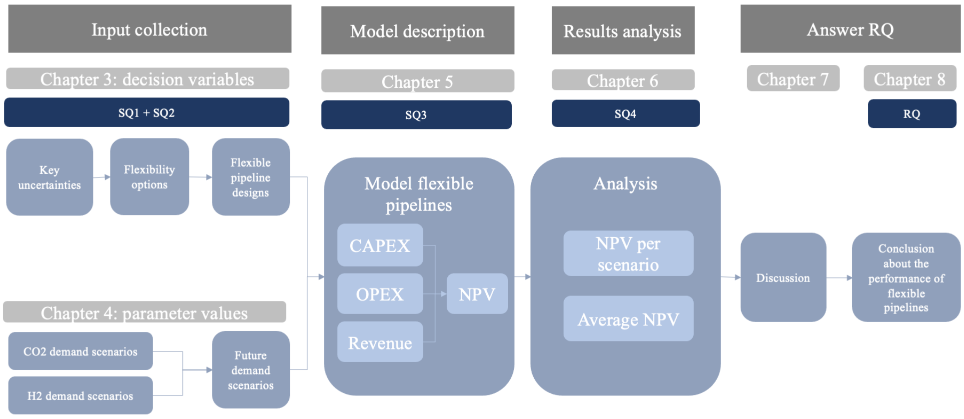

Figure 2.1: Research flow diagram

1 Input collection

The first step of this research is to collect the input for the model. The input can be separated into the decision variables and the parameter values, which are described separately.

1a) *The decision variables: characterization of the main uncertainties and the identification of the flexibility options.*

This step answers the first two sub-questions:

SQ1: What are the key uncertainties regarding the pipeline connection between Rotterdam, Chemelot and North-Rhine Westphalia?

To answer the first sub-question, information needs to be gathered about the requirements of the actors that are involved in this infrastructure. Therefore, an actor analysis is executed. From this analysis, the key uncertainties regarding the pipeline connection between Rotterdam, Chemelot and North-Rhine Westphalia are derived.

SQ2: what are possible flexibility options to reduce the risk of these uncertainties?

In order to answer the second sub-question, the literature is analysed to search for options that can be included into the design to decrease the effect of the key uncertainties. These flexibility options are the decision variables of the designs and varying the flexibility options results in a total of almost 2500 pipeline designs. In step 3, these designs are used as the input for the model.

1b) *Parameter values: future demand scenarios*

In order to get a good indication of the performance of the designs, the designs have to be tested under different demand scenarios. A scenario is the development of the demand over time. This step will generate eight future demand scenarios. The demand data of the Port of Rotterdam is used to determine a low, reference and high hydrogen and carbon dioxide demand scenario. First, the literature regarding the hydrogen and carbon dioxide use in industrial sectors is presented in order to give the reasoning behind the demand estimations of the Port of Rotterdam. Next, the low, reference and high hydrogen and carbon dioxide demand scenarios are combined into eight final demand scenarios that are used to determine the parameter values.

2 Modeling flexible pipelines: a Net Present Value (NPV) model

This step answers the third sub-question:

SQ3. How can the performance of the flexible pipeline designs be measured?

The review of the literature about flexible pipeline design analysis illustrated a gap with respect to the NPV model that is used to evaluate the performance of the pipeline designs. Therefore, this step aims to develop a NPV model that is able to analyse the performance of the flexibility designs established in step 1a. First, the literature regarding hydrogen pipeline, natural gas reassignment, carbon-dioxide pipeline and multi-purpose pipeline is analysed. The findings in the literature are then synthesized into a NPV optimization model that is able to generate the NPV of the flexible pipeline designs that are proposed in step 1 under the different future demand scenarios derived in step 2.

3 The analysis of the results

In order to analyse the 2500 pipeline designs under the eight future demand scenarios, the mathematical model is then translated to Spyder Integrated Development Environment (IDE). This is an open-source cross-platform integrated development environment for scientific programming in the Python language. The python language is an object-oriented programming language that is commonly used to streamline large complex data sets. Analysing the designs in Spyder IDE answers the fourth sub-question:

SQ4: How do the flexible pipeline designs perform on the established criteria?

In order to get a clear insight into the costs and revenues of the flexible pipeline designs, the analyses of the results is separated into two analysis: an analysis per scenario and an analysis of the average performance over all scenarios.

3a) *Performance per scenario*

At this stage, the pipeline designs are analysed per future scenario. In this analysis, first, the capacity is optimized per design. Next, the design with the highest NPV is selected per scenario. This step analyses the CAPEX and the revenue to determine whether one design performs better or worse in a certain future scenario.

3b) *Average performance over all scenarios*

In this analysis the average NPV over all future scenarios is calculated. Based on the average NPV, the design with the best performance is selected. This step provides insight into whether a design is able to withstand various future scenarios.

4 Answering the research question

In the last step, the main research question is answered:

RQ: How do flexible pipeline designs perform for the transportation of sustainable fuels between the Port of Rotterdam, Chemelot and North-Rhine Westphalia from 2025 until 2050?

This step aims to synthesize the outcomes of the model and to discuss their relation to the main assumptions and model limitations. Next, a recommendation regarding including flexibility in the pipeline connection between Rotterdam, Chemelot and North-Rhine Westphalia is given.

3 DECISION VARIABLES: FLEXIBLE PIPELINE DESIGNS

This chapter covers the development of the different pipeline designs to transport renewable fuels between Rotterdam, Chemelot and North-Rhine Westphalia. This chapter answers the first two sub-questions:

SQ1: What are the key uncertainties regarding the pipeline connection between Rotterdam, Chemelot and North-Rhine Westphalia?"

SQ2: what are possible flexibility options to reduce the risk of these uncertainties?

In order to answer the first sub-question, an actor analysis is executed. In this actor analysis, the requirements and objectives of the actors involved with the pipeline connection are defined. The different requirements per actor will define what the key uncertainties are regarding the pipeline connection.

In the next section, the literature regarding these uncertainties is consulted in order to derive options that can be included into the design of the pipeline in order to increase the flexibility regarding the uncertainties. These options are referred to as flexibility options. These flexibility options are the decision variables of this study.

The last section gives the values of the decision variables and an overview of the flexible pipeline designs that are evaluated in this study.

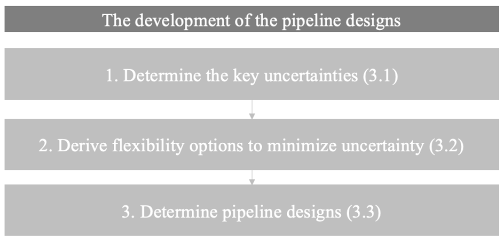

Figure 3.1: Outline of chapter 3

3.1 DETERMINING THE KEY UNCERTAINTIES

The development of a renewable fuel transportation network is subject to various uncertainties. These uncertainties can be derived from the requirements of the involved actors. Therefore, a case-specific actor analysis, guided by the approach of Enserink et al. (2010), was conducted.

In order to identify the actors that are involved with the construction of the hydrogen transportation network between Rotterdam and North Rhine-Westphalia, one could ask the question; 'Who is interested in the transportation link between Rotterdam and North Rhine-Westphalia?'. However, starting with this question, a wide range of actors can be identified. It is a difficult task to determine exactly which actors from this wide range fall within the scope of the problem and which do not. To determine this, it is important to ensure that the actor network is in line with the chosen level of the problem analysis (Enserink et al., 2010). This study was narrowed down to the actors that have initiated the construction of the pipeline, meaning the Port of Rotterdam, Chemelot, North-Rhine Westphalia and GasUnie. Figure 3.2 represents an overview of the actors involved in this case study. The objectives and requirements by the various actors are identified and discussed below. Next, the overlapping and contradicting objectives and requirements are identified in order to define the key uncertainties.

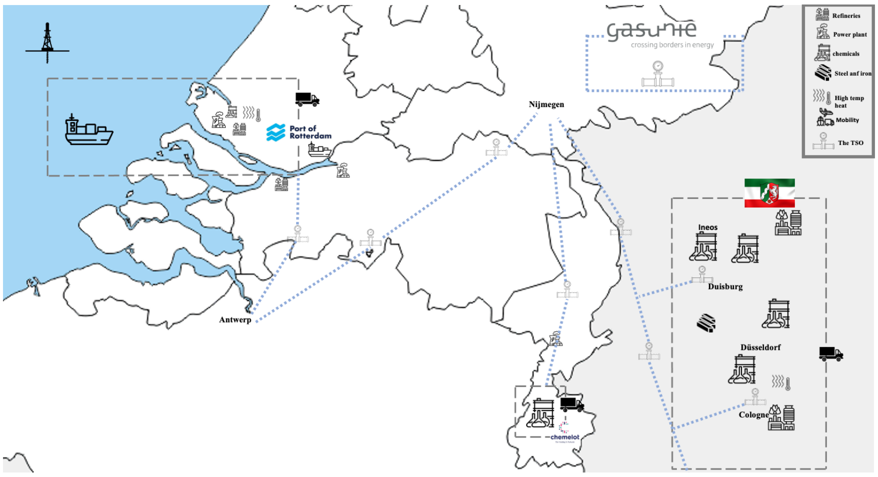

Figure 3.2: An overview of the actors involved in the pipeline connection between the industrial clusters the Port of Rotterdam, Chemelot and North-Rhine Westphalia

3.1.1 Chemelot and North-Rhine Westphalia

For Chemelot and North-Rhine Westphalia the objectives and the requirements of the pipeline are defined by the industries that are located in their clusters [1]. All the industries have the same objective regarding the pipeline connection: they want support to decarbonize their processes. However, the requirements differ per industry as they depend on the way they want to decarbonize their processes. Therefore, the requirements per industrial sectors are discussed separately.

- Chemical industry: The chemical industry produces a complex array of outputs such as plastics and fertilisers (IEA, 2019). For the chemical industry, there are three ways to decrease greenhouse gas emissions: blue hydrogen, green hydrogen and biomass. However, biomass is shown to be significantly less cost effective than green and blue hydrogen, giving hydrogen the greatest potential in this sector (IEA, 2019). Grey hydrogen is already used in large volumes for the production of ammonia (NH_4OH) and methanol (CH_3OH) (IEA, 2019). These processes can be decarbonized by replacing grey hydrogen by green and blue hydrogen. The equipment required for the greener path-ways is already installed and only a hydrogen purity of 99.9 per cent is required. For the use of blue hydrogen in the global chemical industry, a total global CO_2 storage capacity of 450 Mton per year is necessary (IEA, 2019). As one storage facility has an average capacity of 1Mton per year, 450 new storage capacities would have to be installed (IEA, 2019). For the use of green hydrogen in the global chemical sector, the electricity demand will increase by 11 percent of the current world wide electricity demand (IEA, 2019). However, at locations that produce cheap green electricity such as Oman and Portugal, the use of green hydrogen is in competition with the use of natural gas or coal,

1 This research places the power sector and the mobility sector under the category "industry" because their production plants and refueling stations are located in industrial clusters.

even with carbon capture use and storage. Therefore, in order to make this industry more sustainable, a significant investment in green hydrogen production has to be made. This all indicates that the chemical industries who rely on green hydrogen will become more sustainable and therefore are important users of a hydrogen infrastructure.

- Refineries: Oil refineries are one of the largest hydrogen users today. In this industry, hydrogen is used for hydrotreatment and hydrocracking. However, the hydrogen used in these processes is currently grey hydrogen, resulting in a CO2 emission of 230 Mton/year (IEA, 2019). It is a relatively easy step to switch from grey hydrogen to blue or green hydrogen as it requires no changes in their processes (IEA, 2019). However, as the hydrogen is mostly produced as a by-product or on-side, the refinery has to invest in CCUS-technologies or has to have access to green hydrogen. It depends on the development of the technology and costs of green hydrogen whether or not the refinery industry will opt for a carbon-dioxide or hydrogen transportation network (IEA, 2019). Aside from the easy implementation in their current processes, the refinery industry only requires 99,90 per cent hydrogen purity for its processes and therefore does not have purity limitations to its usage and the transportation network.

- Iron and steel industry: In the iron and steel industry, there are two production processes: the primary production method and the secondary production method. The primary steel production process can use two methods: (1)Blast furnace - basic oxygen furnace (BF-BOF), which accounts for 90 percent of the steel production and produces hydrogen as a by-product and (2) direct-reduction of iron-electric arc furnace (DRI-EAF), which uses hydrogen, but only accounts for 7 percent of the steel production (IEA, 2019). The secondary production method uses recycled scrap steel. There are three green pathways for the iron and steel industry:(1) increase the share of the DRI-EAF process in the steel production, (2) increase the secondary produced steel, (3) implement CCUS technologies in the current processes (IEA, 2019). The share of recycled steel is estimated to rise in the future but is limited by the availability of steel scrap. Therefore, the use of DRI-EAF and CCUS will have to rise accordingly in order to reach the emission targets. If the DRI-EAF technology uses green, externally produced, hydrogen, major changes are required, which incur significant costs (IEA, 2019). Furthermore, the BF-BOF technology is now used in 90 percent of the steel industry and with the already existing overcapacity, the change to use of green H2 would be too expensive (IEA, 2019). On the other hand, CCUS technologies are at a more advanced stage of development and more economically efficient (Bellona Europe, 2018). Therefore, the steel and iron industry is likely to first invest in CCUS and thus requires a carbon dioxide transportation infrastructure. However, in the long run, the switch to hydrogen is also promising if contracts between the network operator and the iron and steel industry include a gradual rise in the share of green hydrogen. This would help these industries to incorporate sustainable hydrogen in their current processes.

- High temperature heat: The industry uses high temperature heat for different processes, such as melting, drying and gasifying. Currently, fossil fuels are used to generate high temperature heat. Apart from the chemical and steel industry, this heat is mostly used in the cement industry. Hydrogen is an expensive alternative for the generation of high temperature heat compared to fossil fuels (IEA, 2019). An alternative that seems more cost-competitive is the use of biomass based energy supply in combination with CCUS, referred to as bio-energy (IEA, 2019). Hydrogen would only be attractive for remote industries which do not have access to CCUS or in a situation where the bio energy supply is limited. However, one advantage of using hydrogen for high temperature heat is that it only requires hydrogen with 95 percent purity, making it possible to transport the hydrogen in the old natural gas pipelines to the industries (PWC, 2021).

- The power sector: for the power sector, decarbonising their processes is very expensive. One potential is co-firing ammonia (with biomass) or installing additional new hydrogen turbines and connecting these to existing plants (IEA, 2019). This will significantly reduce the carbon intensity of coal power plants. The use of hydrogen does not require a high purity level but the technology to easily implement it in current systems is still developing, resulting in high capital costs (IEA, 2019). Another potential for hydrogen in the power sector is investing in large capacity fuel cells or hydrogen storage facilities. The decision to invest in hydrogen is dependent on the price of natural gas, the carbon dioxide tax and the price and supply of ammonia (IEA, 2019). The other sustainable alternatives, natural gas power generation with CCUS and a biogas power plant, also require high capital costs as the implementation of CCUS technology is very expensive and biogas power plants typically operate on a smaller scale (IEA, 2019).

- Mobility sector: Hydrogen gas has long been heralded as a potential renewable fuel for the mobility industry. It is also possible to use hydrogen to produce hydrogen-based transportation fuels such as ammonia, methane and methanol. Hydrogen-based fuels have the advantage that they are relatively easy to implement in the existing infrastructure because of their short refuelling time and the great range they offer. However, comparing hydrogen based fuel to other alternatives, shows that the advantages go at the expense of efficiency. In the light transport sector, which does not require long distance traveling, this disadvantage resulted in other sustainable alternatives dominating the market. The heavy transport sector is characterised by the demand for a wide range, short refuelling time and easy access, which could be delivered by hydrogen and hydrogen based fuels (IEA, 2019). The requirements for a hydrogen transportation infrastructure would then be 99.999 purity level and an extensive international refuelling network (PWC, 2021; U.S. Department of Energy et al., 2016). Especially this last requirement is essential in the heavy transport sector as the decision to choose a sustainable fuel depends on the availability of the fuel at the maritime ports or airports (IEA, 2019). Currently, hydrogen is in the lead in the race for more sustainable energy use in this sector because it offers some clear advantages, but if other ports switch to, for example LNG, hydrogen will most likely lose it competitive advantage (IEA, 2019).

3.1.2 The Port of Rotterdam

The Port of Rotterdam is a different cluster in this case study than Chemelot and North-Rhine Westphalia. The PoR not only has the role of a decarbonizing cluster, but also of an energy transportation hub. Therefore, they are concerned about obtaining a strong position with regard to the transportation of renewable energy. Being a first mover is very important for the strategic position of the Port of Rotterdam and a pro-active role is required (Drift, 2020). The Port of Rotterdam sees a high potential for hydrogen, but also has the ability to store carbon dioxide in the depleted gas fields in the North sea (Port of Rotterdam, 2020a). For the port of Rotterdam, the transportation pipelines have to supply a capacity that allows for the wide transportation of renewable fuels.

3.1.3 The TSO

In the Netherlands and the northern part of Germany, GasUnie is in charge of building and maintaining the infrastructure for the large-scale transport of gas. Currently, the main duty of TSO is the maintenance of the natural gas network. However, in a renewable energy future, the TSO will be responsible for the construction of renewable transportation networks. As the TSO is state owned, its objective is to have the lowest societal costs. However, societal costs can be viewed from different perspectives. From an economical perspective, low societal costs are translated into a low CAPEX and financial risk, while from an environmental perspective it is translated to low green house gas emissions. These perspectives result in contradicting outcomes, since low green house gas emissions require a great pipeline capacity, leading to high investment costs. Moreover, a small capacity avoids risk, but does not support the reduction of green house gas emissions. Therefore, both requirements have to be balanced.

3.1.4 Synthesis of the requirements

The actor analysis shows that the TSO is the one that carries the risk of investment. This risk can be decreased by high revenue perspectives. Therefore, the TSO is concerned about the requirements of the users of the pipeline: the various industries. The Port of Rotterdam is very pro-active regarding the construction of a pipeline. Their main requirement is a great capacity that allows to transport large volumes of renewable fuels in the future. This capacity is dependent on the future demand by the industries in North-West Europe. This illustrates that the requirements of the TSO and the Port of Rotterdam are both dependent on the requirements of the industries located in Chemelot and North-Rhine Westphalia.

Focusing on these industries, what is clear is that they all have the same objective: decreasing the carbon gas emissions. However, the requirements differ per industry because the requirements are dependent on the actions that will be taken to decrease the greenhouse gas emissions. The analysis shows that these actions are dependent on the technological development of sustainable fuels and the measures that might be taken by the government such as the carbon-tax. Therefore, at this moment, it is still very uncertain what the requirements of the industries will be in the future.

It is difficult to include this general uncertainty in the model that is put to the test in this thesis. Various actors were consulted in this respect and it was a collective decision to include three key uncertainties in the study, which are considered to be of major relevance to the general notion of uncertainty:

1. What should be the purpose of the pipeline: to transport carbon-dioxide or hydrogen?
2. What will be the demand of the fuel transported through the pipeline?
3. What purity level is required for the transportation of hydrogen?

This study analyses the performance of pipeline designs in relation to these three key uncertainties.

3.2 OPTIONS TO INCLUDE FLEXIBILITY

The previous section established three key uncertainties for the pipeline connection between Rotterdam, Chemelot and North-Rhine Westphalia. This section identifies options that can be included in the design that gives the pipeline the ability to be flexible regarding these uncertainties. These options are identified by consulting the academic literature as well as by actors in the Port of Rotterdam.

3.2.1 Flexibility with respect to uncertainty about the purpose of the pipeline

It is uncertain which fuel is transported in the pipeline between Rotterdam, Chemelot and North-Rhine Westphalia: carbon dioxide or hydrogen. Therefore, the purpose of the pipeline is uncertain. A pipeline that is able to first transport carbon dioxide that can subsequently be reassigned to the transportation of hydrogen decreases the impact of the uncertainty about the purpose of the pipeline. Such a pipeline is referred to as a multi-purpose pipeline. A multi-purpose pipeline is a pipeline of which the design is not limited to the transportation of one fuel, but is intended to transport other fuels as well. Until today, no multi-purpose pipelines have been installed in practice. There are multi-production pipelines which are used to transport different hydrocarbon liquid products in batches in a single pipeline such as Diesel, Petrol, Kerosene and Jet Fuel (Zhou et al., 2020). However, hydrogen and carbon-dioxide require a different operating pressure (Baufumé et al., 2013; Knoope, 2015). Therefore, they do not allow for the transportation of one shortly after another. Furthermore, there are pipelines that are currently reassigned for a new purpose, such as the natural gas pipelines. However, their design was not initially intended for the transportation of multiple fuels. Therefore, the design is not optimized for a multi-purpose. Buck Consultants International (2021) confirmed that it is possible to install a pipeline that is able to first transport carbon dioxide and later hydrogen. This research will investigate the costs and benefits of such a multi-purpose pipeline that transport carbon dioxide until 2040 and is then reassigned to transport hydrogen between Rotterdam, Chemelot and North-Rhine Westphalia.

3.2.2 Flexibility with respect to uncertainty about the capacity of the pipeline

There is great uncertainty about which industries want to import hydrogen and which industries want to export carbon dioxide (IEA, 2019). This goes together with a great uncertainty about the capacity of the pipeline. A pipeline that has the flexibility to increase its capacity with the increase of the future demand would adapt to this uncertainty.

The literature has established three options to expand the capacity of the pipeline (Cerniauskas et al., 2020; Knoope et al., 2013; Melese et al., 2017). The first option is to install a larger diameter than the diameter calculated on the initial demand (Melese et al., 2017). This allows for the option to expand the pipeline when the demand unexpectedly increases in the future. The second option would be to increase the maximum allowed pressure by increasing the capacity of the compressors and the wall thickness (Knoope, 2015). The last option to increase the capacity of the connection is to reassign the natural gas pipelines for the transportation of hydrogen. Although it has been established that this capacity is not sufficient for the future hydrogen demand, the costs of this reassignment are relatively low (Cerniauskas et al., 2020). Therefore, combining a new pipeline with the option to reassign the natural gas pipelines provides a relatively cheap option to expand the capacity in the future.

3.2.3 Flexibility with respect to the purity of hydrogen in the pipeline

The requirements of the industries involved differ regarding the purity of hydrogen. The purity, or also called quality, of hydrogen is determined by the percentage of contaminants. When hydrogen is mixed with other dusts, the purity of the hydrogen decreases. The purity is dependent on the method of production, transportation or storage. Green hydrogen almost has no contaminants and therefore is 100% pure (Stedin, 2020). Blue hydrogen has a lower purity, 99.9%, but enough for the chemical, refinery and steel industry (Stedin, 2020). The transportation method also influences the purity of hydrogen. When hydrogen is transported in pipelines that have transported other gasses in the past, the steel of the pipeline still contains contaminants and the purity of hydrogen decreases (PWC, 2021). Therefore, a multi-purpose pipeline or the natural gas pipelines are not able to deliver 99.999% hydrogen. An option to deliver high purity hydrogen is a single-purpose hydrogen pipeline. A pipeline that is solely constructed for the transportation of hydrogen, has no contaminants in the pipeline and therefore does not decrease the purity of hydrogen. Another option to be flexible regarding the purity of hydrogen is the so-called quality treatment of hydrogen. However, Cerniauskas et al. (2020) established that quality treatment is very expensive and a model to determine the specific costs of quality treatment is not available (Knoope, 2015). Therefore, the option to deliver 99.999 % hydrogen is only analysed by installing a single-purpose hydrogen pipeline.

3.3 THE PIPELINE DESIGNS

The previous section described the flexibility options that can be included into the designs of the pipelines. These are the variables of this research. Figure 3.3 summarizes the findings of this chapter and illustrates how the decision variables are combined into the pipeline designs.

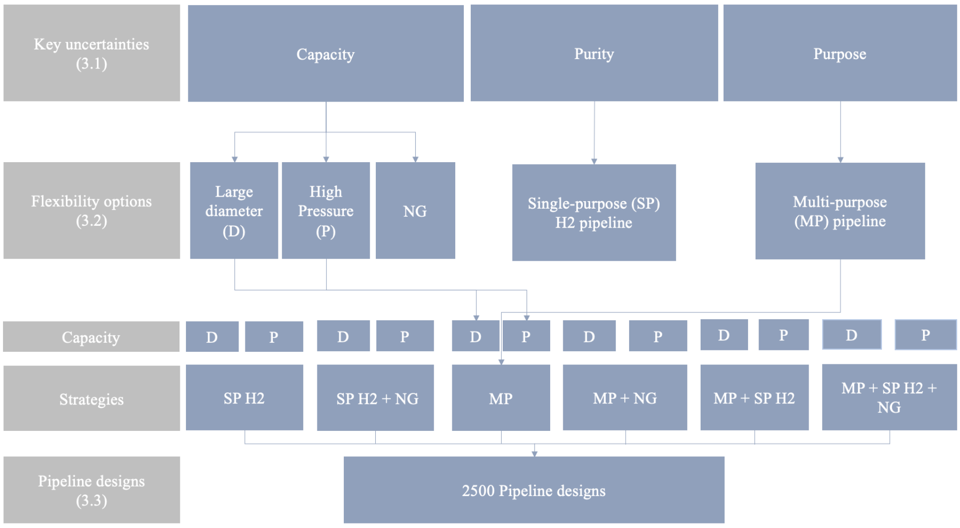

Figure 3.3: An overview of the key uncertainties, the flexibility options and the generation of the pipeline designs

In total, there are five variables (see line 2 in figure 3.3). The value of the diameter (D) and pressure (P) vary over a range. The value of the diameter is based on the Nominal Pipe Size (NPS). As this research is focused on a transmission pipeline,the four largest sizes are selected (Knoope, 2015). The value of the pressure is based on the pressure range used by Knoope (2015). The decision to install a multi-purpose (MP), a single purpose hydrogen (SP) pipeline and reassign the natural gas pipelines(NG) just have a yes or no value. Therefore, the variables can be divided in continuous variables (the diameter and the pressure) and binary variables (a multi-purpose pipeline, a single purpose hydrogen pipeline and/or reassignment of the natural gas pipelines).The binary variables are referred to as the flexibility strategy. An overview of the variables and their values is presented in the table below. The flexibility options do not mutually exclude each other. Indeed, sometimes they even depend on each other. Therefore, the flexibility options are combined in this research.

A combination of flexibility options forms a pipeline design. In total, almost 2,500 combinations can be formed. These 2,500 pipeline designs are used as input for the model.

Decision variable	Values	Units
Diameter	[0.6, 0.9, 1.05, 1.2]	meter
Pressure hydrogen	[4, 10, 15, 20, 25]	MPa
Pressure Carbon dioxide	[3, 8-16]	MPa
Multi-purpose pipeline	Yes / No	-
Single-purpose pipeline	Yes / No	-
Natural gas pipeline reassignment	Yes / No	-

Table 3.1: The decision variables.

4 PARAMETER VALUES: DEMAND SCENARIOS

This chapter covers the description of the demand scenarios that are used to set the parameter values of the model and evaluate the performance of the designs. The demand scenarios are formed based on the low, reference and high hydrogen and carbon dioxide demand estimations by the Port of Rotterdam (Appendix A). In order to give the context of the demand scenarios of the Port of Rotterdam, first the reasoning behind the hydrogen and carbon dioxide demands is described. Next, the hydrogen and carbon dioxide demands are combined into the eight scenarios that are used in this study, which are explained in the last section.

4.1 CONTEXT OF THE HYDROGEN AND CARBON DIOXIDE DEMAND

There is significant uncertainty regarding future hydrogen and carbon dioxide demand. This uncertainty is the result of unknown factors relating to speed of development of the relevant technology and its cost-effectiveness. It will determine industries' willingness to invest in hydrogen or carbon dioxide in the future. Therefore, the Port of Rotterdam has derived a reference, low and high hydrogen and carbon dioxide demand from the potential technological developments determined by IEA (2019) and Dena et al. (2021)[1]. These demands are clustered into various scenarios, which are used as input for the model in this study. This section describes the potential technological developments of hydrogen (4.1.1) and carbon dioxide (4.1.2) by IEA (2019) to give a context to the scenarios that are used in this study.

4.1.1 Hydrogen demand

Figure 4.1 presents the low, reference and high hydrogen demand scenario of the Port of Rotterdam in Mton per year. The following sections describe the reasoning behind these scenarios per industry. This information is summarized in table 4.1.

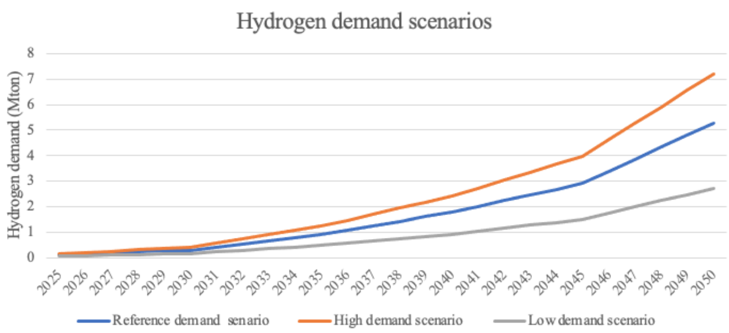

Figure 4.1: The low, reference and high hydrogen demand scenarios (Mton/year)

1 A Lower Heating Value of 120 MJ/kg is used to convert TWh hydrogen / year to Mton hydrogen /year (Granovskii et al., 2007)

Refineries

The refinery industry currently has a significant hydrogen demand. This demand will possibly increase in the future when the use of hydrogen in its current processes is increased or when the organizations involved start producing new products that require hydrogen. Therefore, the reference scenario consists of today's hydrogen demand in the oil industry and its increasing trend. It is not bound by restrictions. Because the demand for oil still shows an upward trend today, it is reasonable to assume that demand for hydrogen will do the same. In the high demand scenario, the hydrogen demands of the oil industry would increase because it starts producing new sustainable fuels that would require hydrogen.

As the oil produced by the refinery industry contains significant sulphur emissions, the ever-increasing emission regulations can negatively affect oil demand. Therefore, in the low demand scenario, today's hydrogen demand will not expand due to production quality requirements. Furthermore, electrification and efficiency improvements will result in a further decrease of the oil demand.

The chemical industry

The production of ammonia and methanol in the chemical industry puts the greatest demand on hydrogen currently (IEA (2019)). Therefore, in the low demand scenario, hydrogen will be used to lower the carbon emissions in the current production of ammonia and methanol in the chemical industry. However, due to recycling and reuse in this sector, this demand is likely to show slow, if any, growth compared to today's hydrogen demand. In the reference scenario, the future demand for methanol and ammonia has increased. Therefore, the demand for hydrogen in these processes is increased and thus the need for hydrogen to be imported. In the high demand scenario, ammonia and methanol have developed to have the potential to function as energy carriers for the transmission, distribution and storage of H2. Therefore, the ammonia and methanol demand can increase significantly in the chemical industry.

The iron and steel industry

As described in chapter 3, the demand for hydrogen in the steel industry is influenced by two main factors: the share of secondary steel production in the overall steel production and the share of DRI-EAF method in the primary steel production. From these factors, the likely developments and the low, reference and high demand have been predicted. The low demand scenario presents business as usual where the hydrogen demand is equal to the current hydrogen demand. The share of secondary steel remains 23 per cent and the share of the DRI-EAF method in the primary steel production process remains 7 per cent (IEA, 2019). In the reference scenario, the share of secondary steel continues on its current trajectory and increases from 23 to 25 per cent. As the DRI-EAF method requires less capital-intensive equipment, an increase in the share of scrap steel production also results in an increase in the use of the DRI-EAF method. Therefore, the share of the DRI-EAF method is predicted to increase to 14 per cent. Together this results in a potential doubling of hydrogen demand in the iron and steel industry (IEA, 2019). In a high hydrogen demand scenario, the share of secondary steel continues to increases to 29 per cent and the share of DRI-EAF increases to 100 per cent. This results in a hydrogen demand that could be 8 times higher than the current hydrogen demand (IEA, 2019).

The industrial sector: high temperature heat

As today no hydrogen is used to generate high temperature heat and it remains an expensive alternative compared to fossil fuels, biomass and CCUS, the demand for hydrogen in high temperature heat production is not included in the low and reference demand scenarios. Only in the high demand scenario, hydrogen for high temperature heat is included.

The power sector

In the power sector, hydrogen has three potential usages:

1. Supplying additional heat input in co-fired power plants: when biomass fuel replaces coal in coal-fired power plants, the energy input feeding the boilers is reduced due to the lower heating value of biomass. Therefore, additional low-carbon heat is required (H-Vision, 2019).

2. Fuelling gas turbines

3. Flexible electricity generation

When the installation of new gas turbines is relatively expensive and in-efficient, coal fired power plants will only integrate the use of hydrogen gas turbines in the Boiler Feed Water (BFW) preheating sections of the power plant (H-Vision, 2019). Gas-fired power plants will use gas that consists of 25 per cent hydrogen and hydrogen is not used for flexible electricity generation. These developments describe the low demand scenario. In the reference scenario, the hydrogen gas turbines develop to be very efficient and therefore are not only used for BFW cycle but also for steam generation of co-fired power plants in the reference scenario (H-Vision, 2019). Gas-fired power plants will use gas that consists of 50 per cent hydrogen. In addition, flexible electricity generation with hydrogen is included in the demand, due to the increase in variable renewable electricity sources.

Currently, the impact of hydrogen firing on the existing boilers is unknown. However, when this impact turns out to be low, no investment in new turbines will have to be made, resulting in a low barrier to switch to hydrogen which would consequently result in a higher hydrogen demand. Furthermore, in a high hydrogen demand future, the technology of gas fired power plants will succeed in the use of 100 per cent hydrogen which lowers the greenhouse gasses significantly as well as increases the hydrogen demand. Beside the efficient and economical technological developments, the share of variable renewable electricity will have increased further and the demand for flexible electricity generation with hydrogen will be high.

The mobility sector

There is a significant potential for the mobility industry to benefit from the use of hydrogen as any vehicle can technically be powered by hydrogen (IEA, 2019). The fluctuation in demand in this sector is dependent on the percentage of vehicles that eventually ends up using hydrogen instead of another transport fuel.

In the low demand scenario, hydrogen has not reached its significant potential due to the advantages of other fuels. Therefore, there is no extensive hydrogen refuelling infrastructure and the share of hydrogen in the transport sector is limited to the vehicles that are not heavily dependent on this infrastructure and that invested in hydrogen as an early adopter.

In the reference scenario, hydrogen is the most efficient fuel for long distance traveling but cannot compete in price and infrastructure for short distance transport. Therefore, the hydrogen is used in this sector for trucks and inland shipping. The energy efficiency of hydrogen is however not high enough for international shipping and flights.

In the high demand scenario, the hydrogen demand reaches its full potential. Not only does the heavy transport sector use hydrogen, but the light transport sector also switches to hydrogen due to low prices and a widely available infrastructure.

Industry	Low demand	Reference demand	High demand
Oil refineries	Oil production decreases due to sulphur restrictions and electrification.	Oil demand increases with current trend oil.	Oil sector also produces new sustainable fuels.
Chemical industry	Current methanol and ammonia production.	The production of ammonia and methanol increases.	Methanol and ammonia are used as energy carriers.
Steel and cement industry	Share secondary steel is 23 % and the DRI-EAF is 7%.	Share secondary steel is 25 % and the DRI-EAF is 14%.	Share secondary steel is 29 % and the DRI-EAF is 100%.
High temperature heat	-	-	Hydrogen is used to generate high temperature heat.
Power sector	Hydrogen used in BWF preheating and 25% of the gas is hydrogen.	Hydrogen is used for BWF preheating and for steam generation and 50% of the gas is hydrogen.	100% hydrogen is used and no new turbines are necessary.
Mobility sector	Only early adopters.	Trucks and inland shipping.	Light and heavy transport.

Table 4.1: An overview of the use of hydrogen per industry in different future scenarios.

4.1.2 CO2 demand

Similarly to hydrogen demand, the CO2 demand cannot be calculated precisely yet, but the CO2 demand from industrial clusters is likely to remain stable over time and will already have a significant volume in the near future (Bellona Europe, 2018). The Port of Rotterdam estimated a low, reference and high the carbon dioxide demand in Mton/year. These demand scenarios are illustrated in figure 4.2 (Buck Consultants International, 2021; Dena et al., 2021). The next section describes the reasoning behind these scenarios.

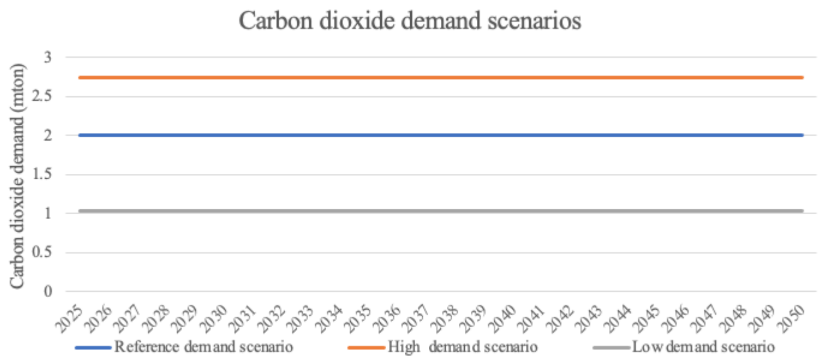

Figure 4.2: The low, reference and high carbon dioxide demand scenarios (Mton/year)

The iron and steel industry, as well as industries that generate high temperature heat are very likely to invest in technologies to capture carbon-dioxide emissions (IEA, 2019). The chemical and the refinery industry are in doubt whether to invest in hydrogen or in carbon dioxide technologies (IEA, 2019). These sectors use grey hydrogen, but also produce grey hydrogen as a by-product. Therefore, they can decide to invest in the capture of carbon dioxide or to import green hydrogen. This illustrates that their decision is dependent on the development of green hydrogen production. In the mobility and the power sector, the capture of carbon dioxide is not possible or requires too many high-risk investments (IEA, 2019). This illustrates that carbon dioxide demand is dependent on which industries will invest in hydrogen and which in carbon dioxide. Therefore, a low, reference and high demand scenario can be derived. In the low demand scenario only the iron and steel industry invest in the capture of carbon dioxide and carbon dioxide is captured by the production of high temperature heat. In the reference scenario, the chemical and the refinery sector also decide to invest in the capture of carbon dioxide. However, there also is significant production of green hydrogen, reducing the costs of green hydrogen. Therefore, these industries use a combination of green and blue hydrogen. In the high scenario, the green hydrogen is not economically efficient and the chemical and refinery industries only use blue hydrogen to decarbonize their processes.

4.2 DEMAND SCENARIOS

In this study, the above described industrial demand is combined to form the demand scenarios which will be used to test the performance of the various pipeline designs. Combining the low, reference and high hydrogen and carbon dioxide demand results in 9 scenarios. However, one scenario is not realistic. Therefore, in total 8 demand scenarios are used to analyse the flexible pipelines. These scenarios are listed and shortly described below.

Scenario 1: Green hydrogen future

In this scenario, green hydrogen technology will develop fast. Therefore, it is likely for all industries to invest in hydrogen, even the ones for which Carbon Capture Storage (CCS) currently seems more profitable. Therefore, a high H2 demand and a low CO2 demand are used in this scenario.

Hydrogen demand	Carbon dioxide demand
High	low

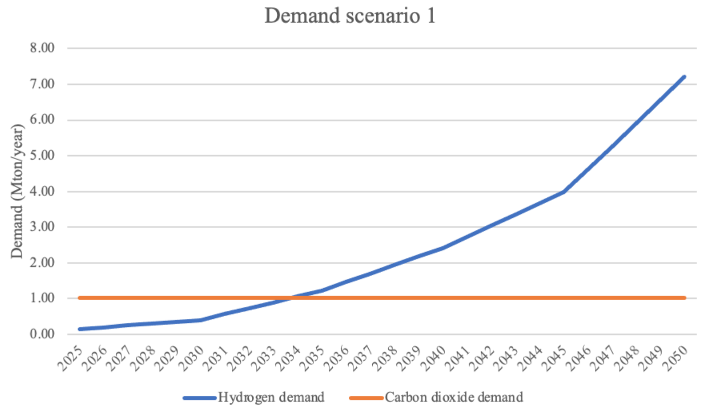

Figure 4.3: Demand scenario 1

Scenario 2: Blue and green Hydrogen future

In the situation where the technology of blue hydrogen becomes very efficient at an early stage, the blue hydrogen demand will increase significantly. Since blue hydrogen still requires carbon dioxide to be stored, the industrial clusters will also require carbon dioxide transportation. In time, the production of green hydrogen increases.

Hydrogen demand	Carbon dioxide demand
High	reference

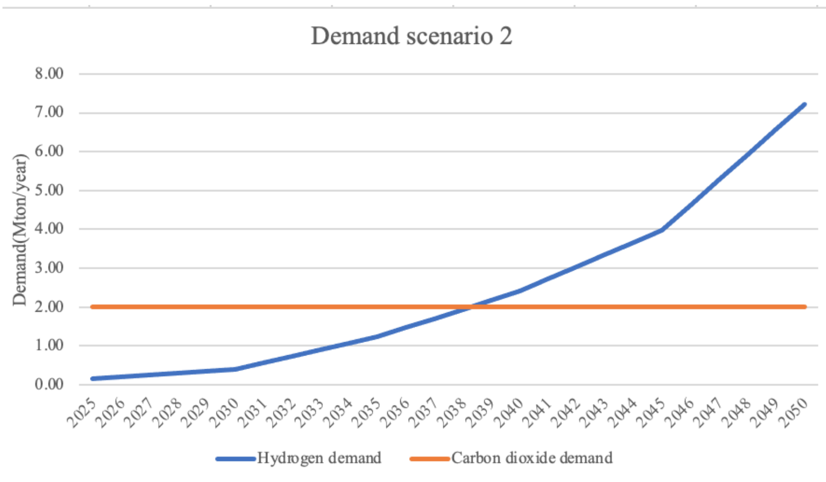

Figure 4.4: Demand scenario 2

Not realistic scenario: too sustainable future

In this scenario there is a high hydrogen demand and a high carbon dioxide demand. However, in the high demand scenario of carbon dioxide, the chemical and refinery industry use blue hydrogen to decrease the carbon emissions while in the high hydrogen scenario, they use green hydrogen. This illustrates that this scenario is not compatible with the hydrogen demand of the chemical and refinery industry. Therefore, this scenario is not realistic.

Scenario 3: Low incentives
The carbon emission targets for the industrial sector, set by the government are not strict in this scenario. Therefore, the industries involved do not have compelling incentives to invest in the new technologies. However, the green hydrogen technology does develop into a profitable source of energy and the industries that can easily switch to (partly) using hydrogen will buy hydrogen.

Hydrogen demand	Carbon dioxide demand
reference	low

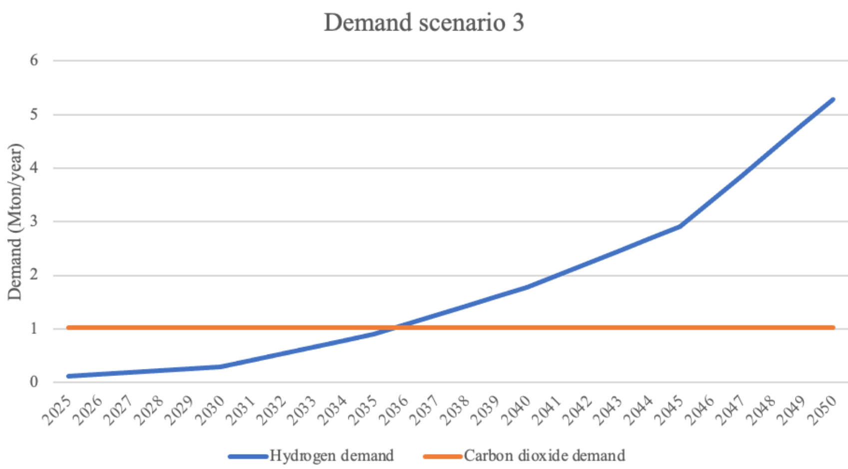

Figure 4.5: Demand scenario 3

Scenario 4: CO2 storage helping to transit to a green hydrogen future
In this scenario, the green hydrogen technology develops into a cheap and efficient source of energy at a later stage. Therefore, the industries for which it is currently more profitable to capture and store their carbon dioxide emissions, will invest in the CCS technology. Other industries which are more reliant on hydrogen, invest in the hydrogen technology.

Hydrogen demand	Carbon dioxide demand
reference	reference

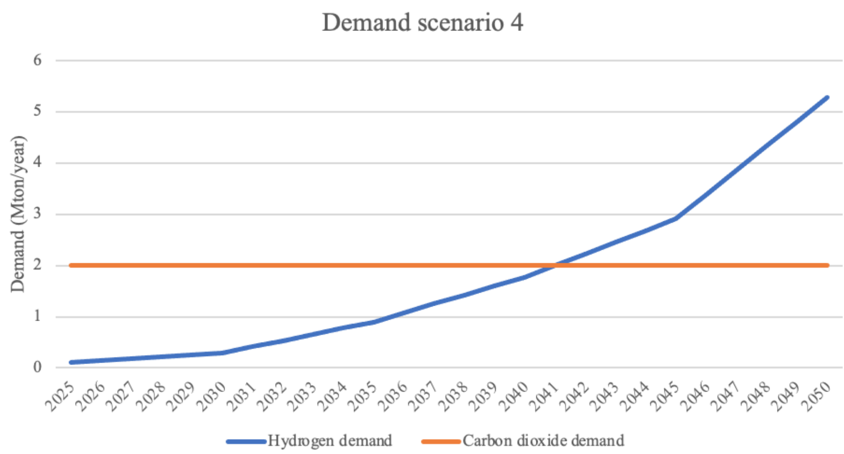

Figure 4.6: Demand scenario 4

Scenario 5: Late blue hydrogen
In this scenario, the blue hydrogen becomes the most profitable option to decrease greenhouse gasses in the industrial sector. However, as this development takes time, some industries will invest in the CCS technology along the way. As both hydrogen producers and the industries who invested in CCS require a carbon dioxide network, the demand for CO2 remains high.

Hydrogen demand	Carbon dioxide demand
reference	high

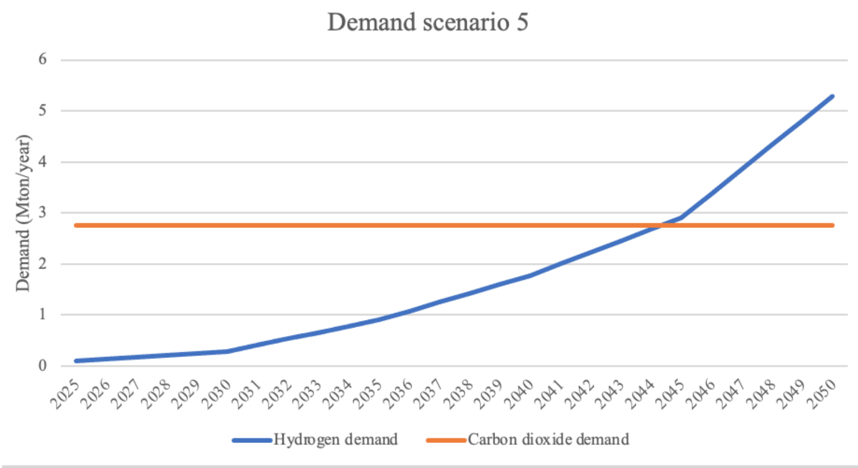

Figure 4.7: Demand scenario 5

Scenario 6: Alternative future
The actions taken by the government to decrease the carbon emissions in the industrial sector are limited in this scenario. Alternatively, another technology, not CCS or H2, will dominate the market in the renewable industry. Therefore, industries do not have the incentives to invest in these technologies and the hydrogen and carbon dioxide demand is low.

Hydrogen demand	Carbon dioxide demand
low	low

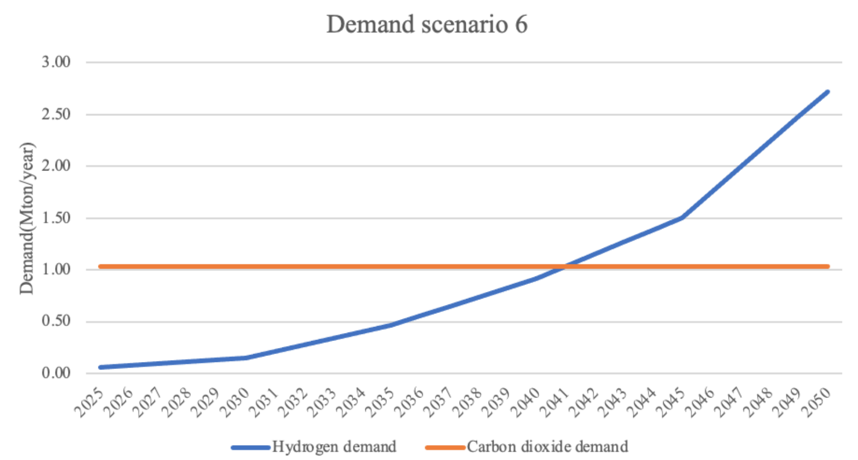

Figure 4.8: Demand scenario 6

Scenario 7: CO2 storage helping to transition to the use of other sustainable technologies

The industries for which CO2 storage currently has an advantage over hydrogen, invest in CCS technologies. In this scenario, hydrogen does not develop to be the most efficient technology to decrease the industrial carbon emissions and only the industries for which little to no extra investment was required will buy hydrogen.

Hydrogen demand	Carbon dioxide demand
low	reference

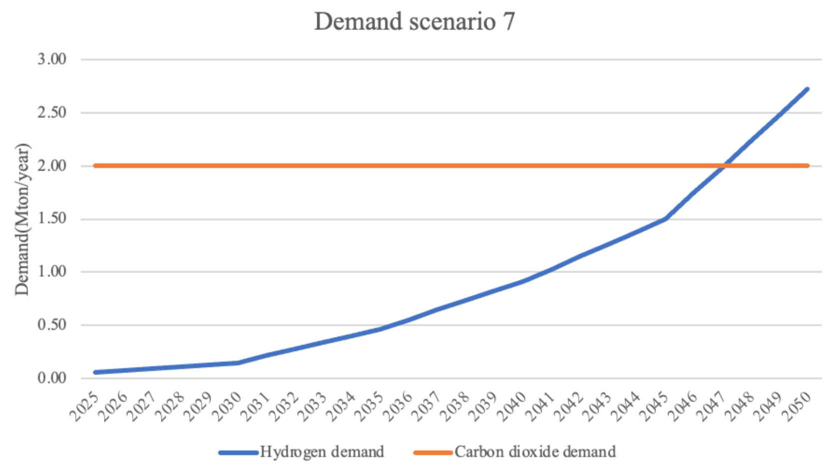

Figure 4.9: Demand scenario 7

Scenario 8: CCS dominance

In this scenario, the government has strict targets set for the industrial emissions and the CCS technology is already easy to implement. Therefore, almost all industries are forced to invest in the CCS technology to store their CO2 emissions resulting in carbon dioxide storage dominating the market.

Hydrogen demand	Carbon dioxide demand
low	high

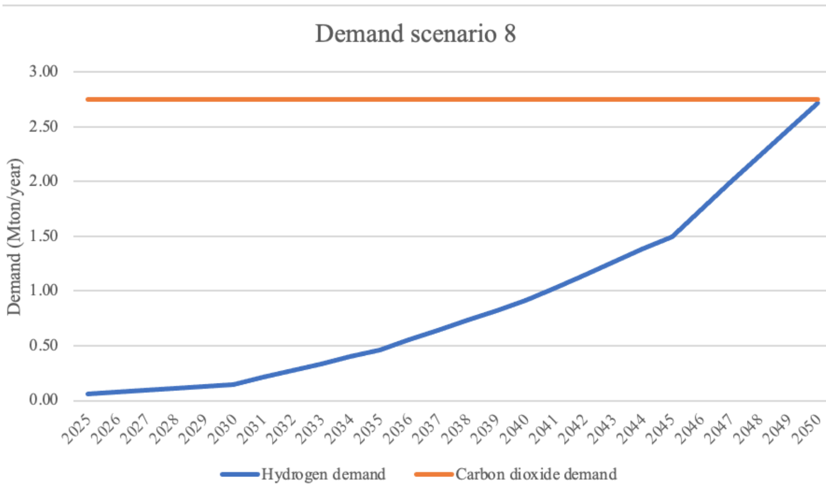

Figure 4.10: Demand scenario 8

5 MODEL DESCRIPTION

This chapter covers the description of the flexible pipeline evaluation model. Therefore, this chapter answers the third sub-question:

SQ3: How can the performance of the flexible pipeline designs be measured?

The literature review regarding flexible pipeline analysis established that the flexible pipeline analysis model of Melese et al. (2017) was not suitable for the analysis of the flexible pipelines that can connect Rotterdam, Chemelot and North-Rhine Westphalia. The cost equation of their NPV model was not suited to the critical cost components in the context of this study. Therefore, this chapter first reviews the literature regarding the costs models of flexible pipelines that fit into this research. Next, the literature is synthesized and the flexible pipeline NPV model of this research is presented in section 4.2. The last section concerns the validation of the outcome of this model.

5.1 LITERATURE REVIEW REGARDING PIPELINE COST MODELS

This section reviews the literature regarding hydrogen pipelines, the reassignment of natural gas pipelines, carbon dioxide pipelines and multi-purpose pipeline in order to determine a cost model that relates to the characteristics of the context of this study.

5.1.1 Hydrogen pipelines

The characteristics of existing hydrogen pipelines have been described in several studies. First of all, it is clear that the hydrogen energy density is three times lower than the natural gas energy density. Therefore, the hydrogen pipeline is assumed to be operated at pressure levels higher than natural gas, increasing the wall thickness of the pipe (Baufumé et al., 2013). Furthermore, the steel that is used for a hydrogen pipeline differs from the steel that is normally used because conventional steel causes hydrogen permeation into the crystalline steel structure, diminishing the mechanical properties of the material (Cerniauskas et al., 2020). Apart from hydrogen permeation, also hydrogen embrittlement occurs, which leads to accelerated crack growth (Baufumé et al., 2013; Cerniauskas et al., 2020; Ogden, 1999).

The specific characteristics of hydrogen imply that the overall cost of hydrogen transmission is about 1.5- to 3-fold that for natural gas over a range of pipeline sizes (Ogden, 1999). In order to get a deeper understanding of the costs of hydrogen pipelines, Baufumé et al. (2013) and André et al. (2014) developed cost models to determine the hydrogen pipeline investment costs. These studies vary the diameter and the length of the pipeline and assume a constant operating pressure. Baufumé et al. (2013) assume the transportation pressure to be 10 MPa and calculated the investment costs of a 0.9 m diameter pipeline to be 2200 euro per meter, whereas André et al. (2014) assume an average pressure of 5 MPa, which results in

2500 euro per meter for a 0.9 diameter pipeline.

5.1.2 Reassignment of the natural gas pipelines

Because of the high capital costs involved in designing a new hydrogen pipeline, many studies analyse the costs of using the existing natural gas network to transport hydrogen. These studies show that, although additional costs such as investigations of possible risks, safety measures, purification, blending, and extraction of hydrogen have to be made, using the existing infrastructure still requires significantly lower investment compared to the construction of new hydrogen pipelines (Kovač et al., 2021). In order to get a more detailed picture of the exact costs of reassignment, Cerniauskas et al. (2020) performed a detailed study on the costs of reassigning the natural gas pipelines in Germany. Two approaches were identified that avoid material failure: reassignment without modification or reassignment with inhibitor admixture (Cerniauskas et al., 2020). The reassignment without modification alternative requires an additional maintenance and repair procedure to avoid hydrogen embrittlement. In the case of applying inhibitor mixtures, the inhibitors undermine the reaction between the pipeline material and hydrogen. The study of Cerniauskas et al. (2020) developed a reassignment cost model for both methods which varies the diameter and the length. An analysis of the natural gas network in Germany revealed that, reassignment of large diameter pipelines (250 mm or larger) only creates a substantial cost reduction when the method to reassign without modification is applied (Cerniauskas et al., 2020). Applying inhibitors for large diameter pipelines prove to be more cost-intensive than constructing a new pipeline because of the capital expenditures for inhibitors and purification costs (Cerniauskas et al., 2020).

The majority of recent studies also analyse the effect of using a mixture of hydrogen and natural gas because they assume that an immediate changeover from natural gas to hydrogen is not a realistic scenario. A 5-10 per cent hydrogen volume added to natural gas is potentially optimal for the natural gas system, as it does not require modification of the current infrastructure or the equipment of domestic and industrial end-users (Kovač et al., 2021). However, the blend concentration should be assessed in detail as it may vary depending on the pipeline network system and natural gas composition (Kovač et al., 2021). Furthermore, recent studies indicate substantial limitations regarding the reduction of carbon emissions, mainly caused by technical blending limitations and difficulties in the hydrogen separation process (Cerniauskas et al., 2020).

5.1.3 Carbon dioxide pipelines

The costs of a carbon dioxide network is determined by the construction, compression and pumping costs. In the literature, several models describe the investment in CO2 pipelines. Knoope et al. (2013) divides the models in:

- Linear cost models
- Models based on the weight of the pipeline
- Quadratic equations
- Models based on flow rates

However, none of these models develop a comprehensive economic minimization method for CO2 pipeline transport with respect to diameter, steel grade, wall thickness, number of pumping stations, and inlet pressure, incorporating both gaseous and liquid CO_2 transport (Knoope et al., 2013). Therefore, Knoope (2015) developed a model including these parameters. When using this model, the costs (excluding initial compression) for transporting 3 Mt/y over 100 km are between 1.8 and 3.3 €/ton for liquid and 4.0-6.4 €/ton for gaseous CO_2 transport (Knoope, 2015).

Regulating the operating pressure has been indicated as an important element of carbon dioxide pipelines (Knoope et al., 2013; Peletiri et al., 2018). Currently, there is a total of over 8000 km of carbon dioxide pipelines around the world (Peletiri et al., 2018). For these pipelines, the minimum pressure is determined by the flow requirement and the need to avoid CO_2 phase changes. The maximum pipeline pressure is set by economic concerns. The maximum and minimum pressure are then used to calculate pressure-boosting distances (Peletiri et al., 2018). Within the calculated distance, the CO_2 remains in the desired phase. Figure 3.1 shows the required pressure in order to transport carbon dioxide in a certain phase. Carbon dioxide can be transported in the gaseous, super-fluid, liquid and two-phased form.

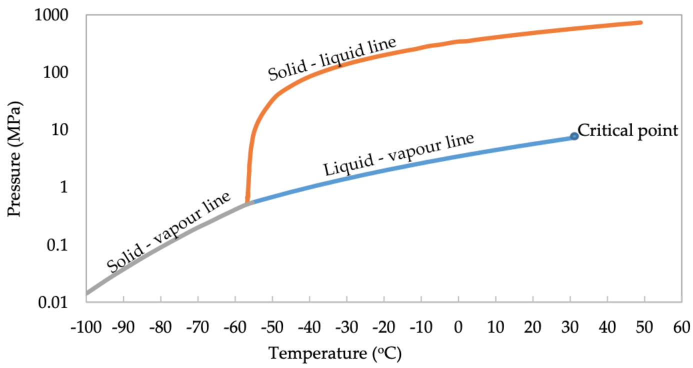

Figure 5.1: Phase diagram of pure CO_2 (Peletiri et al., 2018)

Generally, transporting gaseous CO_2 in pipelines is not economical due to the high volume of the gas, low density and high-pressure losses (Peletiri et al., 2018). However, for short distances and a small gas flow, transporting CO_2 in the gaseous state might be more cost-effective than in the liquid state (Knoope et al., 2013).

Most of the literature prefers transporting CO_2 as a super-critical fluid since the energy density is high and the viscosity low (Peletiri et al., 2018). Consequently, a large amount of CO_2 can be transported in a pipeline with minimal friction losses. Knoope (2015) determines that for onshore pipelines transporting liquid CO_2, the optimal inlet pressure is between 9 and 13 MPa with pumping stations installed roughly every 50 - 100 km. For offshore pipelines, pumping stations are not an option and the inlet pressure is determined by the length of the pipeline, therefore the operating pressure could increase up to 25 MPa (Knoope, 2015).

Two-phased flow is not recommended due to the fact that vapor bubbles are formed which will implode under increasing pressure, leading to very high local velocities and pressure peaks, eroding the material in the molecular structure of the pipeline (Knoope, 2015). Moreover, the vapor bubbles, as well as other operational difficulties arise because a two-phase flow is more difficult to handle by compressors and pumps (Knoope, 2015).

On top of regulating the operating pressure, security and safety measures to manage problems with possible leakage are necessary. Assuming there is enough understanding about leakage, design codes should be set to mitigate the risks. Furthermore, crack propagation can be a serious problem for pipelines transporting CO_2 in the dense or super-critical phase. Whether cracks initiated by for instance corrosion due the presence of water in carbon dioxide or earth quakes occur, depends on the characteristics of the fluid transported and the material of the pipeline (Knoope et al., 2013). Alternative steels, such as stainless steel are resistant to corrosion and are much more expensive than carbon steel.

5.1.4 Multi-purpose pipelines

A multi-purpose pipeline that is able to first transport carbon dioxide and later in time hydrogen has never been constructed so far. Therefore, the characteristics of an optimal operating pipeline and the investment costs have also not yet been determined. Nevertheless, the reassignment of natural gas pipelines shows that it is physically possible to have a multi-purpose pipeline by changing the operating pressure to the optimal pressure of the other gas with compressors or pumping stations (Cerniauskas et al., 2020). However, the initial pipeline design should consider the safety and pressure requirements of all gasses that might be transported in the future in order to avoid high operation and maintenance costs. Therefore, a multi -purpose pipeline cost function needs to be developed to determine the optimal characteristics and the initial pipeline design. Using this cost function, the benefits of such a multi-purpose pipeline can be evaluated and compared to the benefits and investment costs of "single purpose pipelines".

5.1.5 Synthesis of the literature

The literature provides insight into the characteristics of hydrogen transport, carbon dioxide transport and hydrogen transported in natural gas pipelines. It also relates those characteristics to the design of the pipeline. Based on these designs, the associated costs can be determined. However, no model exists that determines the design and the associated costs of a multi-purpose pipeline and this model is necessary to analyse the performance of the flexible pipeline designs to connect Rotterdam, Chemelot and North-Rhine Westphalia. Therefore, this research synthesizes the findings in the literature and uses the characteristics of hydrogen, carbon dioxide and natural gas reassignment to develop a model that is able to determine the design and the associated costs of a pipeline based on the gas that flows through the pipeline. The next section elaborates on this model in detail.

5.2 MODEL DESCRIPTION

5.2.1 General model description

This section proposes a NPV optimization model that is able to calculate the NPV of the flexible pipeline designs to connect Rotterdam, Chemelot and North-Rhine Westphalia (figure 6.2). The model has the following assumptions:

- The scope: the model is limited to transmission pipelines with a fixed path. The pipelines that connect the transmission pipeline to the specific industries are not included in the scope of this model. Therefore, the scope of this model can be illustrated as designing a railway connection between three big cities of which the path is already established and the way the customers get to the train station is not included in the scope.
- Time resolution: a yearly flow without fluctuations is assumed
- Time horizon: In order to take impact of the yearly growing demand into account, a time horizon from 2025 until 2050 has been set.

- Input: The input is defined by the diameter, the operating pressure, the design strategy and the demand scenarios
- Output: The output includes the CAPEX, the OPEX and the revenue of a pipeline design which are in turn used to calculate the NPV

The mathematical model is translated into Spyder. This is an open-source cross-platform integrated development environment for scientific programming in the Python language and allows for the fast NPV optimization of multiple pipeline designs under various demand scenarios. How the model should be used is described in more detail in appendix B.

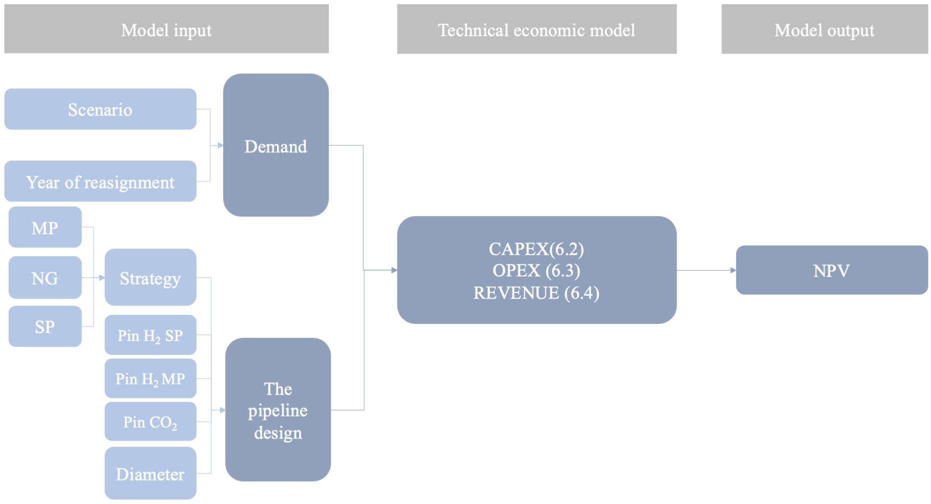

Figure 5.2: The model that was used to evaluate the performance of flexible pipeline designs that connect the PoR, Chemelot and NRW

This model is applied to measure the performance of the flexible transmission pipeline designs that can connect the Port of Rotterdam, Chemelot and North-Rhine Westphalia. In this case study, it is assumed that hydrogen is transported from the Port of Rotterdam to the Chemelot and North-Rhine Westphalia and carbon dioxide is transported from Chemelot and North-Rhine Westphalia to the Port of Rotterdam. The figure below presents a global picture of the path of the pipeline of which the length has been determined to be 200 km (Buck Consultants International, 2021). The figure also illustrates the natural gas network. The length of the natural gas network is 250 km and the pipeline is designed for an operating pressure of 4 MPa (PWC, 2021).

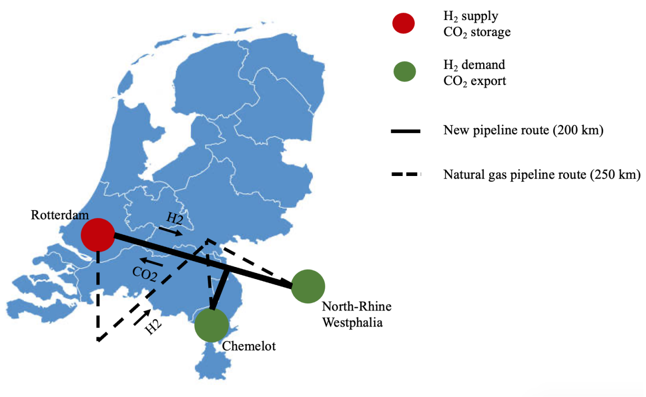

Figure 5.3: Illustration of the network of the case study

5.2.2 Mathematical model description

This section covers the mathematical description of the model. In total almost 30 mathematical equations are used in this model. An overview of the equations and their relations is presented in table 5.1[1]

Number	Concept	Underlying calculations	Second layer of underlying calculations	Third layer of underlying calculations
Eq. [1]	Net Present Value (NPV)	[25];[28];[30]	[28] is determined by [27], [30] is determined by [29]	
Eq. [2]	Total construction costs	[4];[5];[6];[7]	[7] is determined by [8]	
Eq. [9] and [10]	Compressor costs	[11];[15]	[11] is determined by [12];[13]. [15] is determined by [16];[17];[18].	[13] is determined by [14]. [18] is determined by [19];[20];[21].
Eq. [22]	Total compression costs	[9];[10]		
Eq. [23]	Total Pumping costs	[[11];[15]	[11] is determined by [12];[13]. [15] is determined by [16];[17];[18].	[13] is determined by [14]. [18] is determined by [19];[20];[21].
Eq. [24]	Total reassignment costs			
Eq. [25]	CAPEX	[2]; [22]; [23]; [24]		
Eq. [28]	$OPEX_{total}$	[27]	[2]; [22]; [23]; [26]	
Eq. [30]	$Revenue_{total}$	[29]		

Table 5.1: Overview of the mathematical equations and the relationships between them.

Equation [1] represents the general equation to calculate NPV. It shows that in order to determine the NPV, the capital costs (CAPEX), the yearly operation and maintenance costs (OPEX) and the yearly revenue of a pipeline design have to be determined. These concepts are described separately in the next sections.

$$NPV = \sum_{t=1}^{n} \frac{Revenue(t)}{((1+r)^t} - (CAPEX + \sum_{t=1}^{n} \frac{OPEX(t)}{(1+r)^t}) \quad [1]$$

1 Eq. [1];[29] Melese et al., 2017
Eq. [4];[5];[6];[8];[12];[14];[15];[16];[17][23] Knoope, 2015
Eq. [9] Chandel et al., 2010
Eq [10] Reuß et al., 2017
Eq [11] IEA, 2010
Eq [18];[19];[20];[21] IEA, 2010
Eq [24];[27] Cerniauskas et al., 2020

where, revenue (t) is the revenue of the pipeline in year t, n is the lifetime of the project (=25), r is the discount factor (=8%), CAPEX are the capital costs(€) and OPEX(t) are the yearly operation and maintenance costs(€).

Capital Expenditures

In this study, the CAPEX and OPEX are based on the carbon dioxide pipeline cost minimization model by Knoope, 2015. Although this model was developed for the transportation of carbon dioxide, the model can relatively easily be adapted to analyse the costs of pipelines that transport other fuels. The main cost elements of a pipeline system are the construction costs, the compressor costs and pumping costs. If a natural gas pipeline is adjusted to transporting hydrogen, no pipeline construction costs are involved, only compression costs. The next sections describe how to determine the construction costs, compression/pumping costs and reassignment costs.

Pipeline construction costs

Looking at the historical experience of natural gas pipeline construction, the costs can be divided into four categories (figure 5.4):

1. Material costs: the costs of the pipe itself, the coating and, if applied, cathodic protection.
2. Labor costs: Labor costs include costs of installation and transportation.
3. Right of Way costs (RoW): acquisition, repair and compensation costs of damage
4. Miscellaneous costs: surveying, engineering, supervision etc.

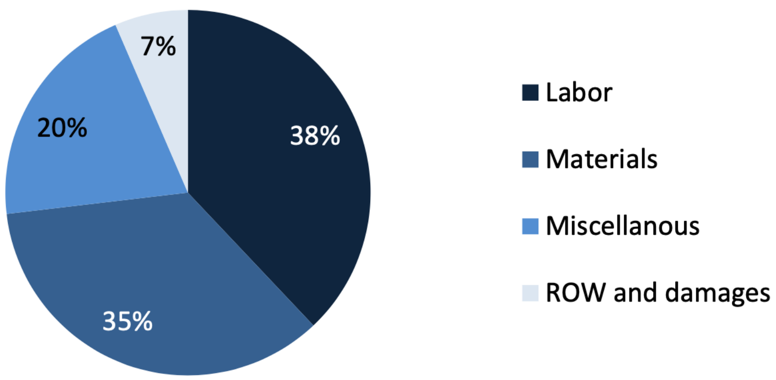

Figure 5.4: Cost division for onshore natural gas pipelines in the USA (Knoope, 2015)

The mathematical functions developed by Knoope (2015) to determine the construction costs [2] exists of four separate functions for the material [3], labor [4], RoW [5] and miscellaneous [6] costs for CO2 transportation pipelines are presented below.

$$C_{construction} = C_{material} + C_{Labor} + C_{RoW} + C_{miscellaneous} \quad [2]$$

$$C_{material} = t * \pi * (D - t) * L * \rho_{steel} * C_{steel} \quad [3]$$

$$C_{labor} = 825 * D * L \quad [4]$$

$$C_{RoW} = 83 * L \quad [5]$$

$$C_{miscellaneous} = (C_{material} + C_{Labor}) * 0.05 \quad [6]$$

where, $C_{material}$ are the material costs (€); C_{labor} are the labor costs (€); C_{RoW} are the right of way costs(€); $C_{miscellaneous}$ are the miscellaneous costs(€) ; t is the wall thickness (m); D is the diameter (m); L is the length (=200.000m); ρ_{steel} is the density of steel, (=7900 kg/m3 for all steel grades); and C_{steel} are the steel cost (€/kg)(=1.49 for X70 steel)

The functions of labor, RoW and miscellaneous do not change when hydrogen instead of CO2 flows through the pipeline. However, the material that is used for a hydrogen pipeline differs because under load conditions, hydrogen embrittlement can occur (Baufumé et al., 2013). Hydrogen embrittlement restricts the use of authentic steel for the transport of hydrogen under pressure. The resistance of steel to hydrogen embrittlement depends on its micro structure and on hydrogen pressure. Therefore, conventional steel has to be used, which has improved hardness properties. The use of conventional steel increases the steel costs by 25 per cent (Baufumé et al., 2013). Therefore, equation [3] is replaced by equation [7]. No further adjustments are necessary to determine the costs of a hydrogen or multi-purpose pipeline.

$$C_{material} = t * \pi * (D - t) * L * \rho_{steel} * (C_{steel} * 1,25) \quad [7]$$

These equations show that the key variables that play a role in pipeline construction costs are the diameter, the wall thickness and the length.

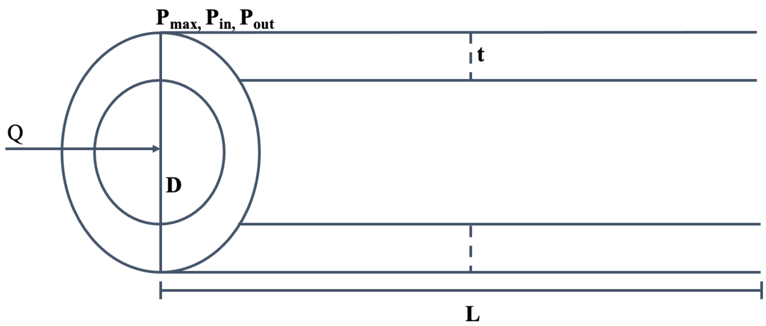

Figure 5.5: Variables in pipeline construction

For the diameter of a pipeline, nominal pipeline sizes (NPS) are available. In this research, a 30, 36, 42 and 48 inch pipeline have been selected and tested on their performance. The diameter has a significant impact on the costs of the pipeline. However, a large diameter also allows for a larger flow, which in turn increases the revenue. Therefore, a balance has to be struck between the costs and the revenue of a certain diameter.

In addition to the diameter and the length of the pipeline, the wall thickness also determines the costs of construction. Pipelines require certain wall thicknesses in order to avoid the risk of cracks appearing in the steel. To calculate this required wall thickness, equation [8] is used (Knoope, 2015). This equation shows that the thickness is dependent on the diameter, the maximum pressure and the stress intensity characteristics of the steel. As the energy density of hydrogen is three times smaller than that of natural gas, the operating pressure has to be increased in order to deliver the same amount of energy. However, this requires an increase in the wall thickness. Therefore, different options of maximum allowed pressure will be reviewed and compared.

$$t = (D * Pmax)/(2 * S * E * F) + CA \qquad [8]$$

Where t is the wall thickness (m), D is the diameter (m), Pmax is the maximum pressure (=Pin MPa), S is the minimum yield stress (=500), E is the longitudinal joint factor (=1), F is the design factor related to the terrain(=0.5) and CA is corrosion allowance (=0.001)

Chapter 1 established that the path of the pipeline is a given factor in the context of the Port of Rotterdam, Chemelot and North-Rhine Westphalia. Therefore, the length of the pipeline is not varied in this research and is assumed to be constant at a value of 200 km.

Compression costs

Compressor stations are included in the pipeline design to compress the gas to the required transportation pressure. In this research, two types of compressors are used, initial and intermediate compressors. Initial compressors, compress the gas from the pressure level at which it leaves its source to the required transportation pressure at the inlet of the pipeline. Intermediate compressors, are placed along the pipeline to compensate for the pressure drop that occurs when gas is transported over long distances.

Currently, the compression of CO2 is often included in the capture rather than in the transportation step. However, in order to optimise the transportation network, it is crucial to include the costs of compression (Knoope, 2015). Knoope et al. (2013) reviewed the various cost estimation models for carbon-dioxide compressors and concluded that it should include a link between the capital cost and the installed capacity. However, the available data is limited and the literature in which it is referred to shows a significant range in assumed installation factors. This causes a significant difference between the cost estimations and makes it difficult to determine an accurate correlation between capacity and costs. Therefore, the various cost models are compared to the cost estimations by EBN and Gasunie (2017) and the compression cost model of Chandel et al. (2010). [9] was selected to be used in this study.

$$C_{compCO2} = (2.3 * W + 0.15) * 10^6 \qquad [9]$$

Where IcompCO2 are the CO2 compressor costs (€) and W is the installed capacity of the compressor (MW).

Little reference is made to the costs of the compression of hydrogen in the professional literature. Reuß et al. (2017) included the compression of hydrogen in its hydrogen supply chain model and determined a cost equation model [10]. The outcomes of this model are used by Cerniauskas et al. (2020) to estimate the costs of hydrogen compression. They are in line with the cost estimation used by Baufumé et al. (2013). Therefore, this model is selected to be used in this research.

$$C_{compH2} = 3900 * (W/0.001)^{0.8335} \qquad [10]$$

Where IcompH2 are the H2 compressor costs (€) and W is the installed capacity of the compressor (MW).

Both equations require the installed capacity to determine the costs. The installed capacity is determined using equation [11].

$$W = P1 - P2/\eta * (Q/\rho) \quad [11]$$

where, P1 is the output pressure (MPa), P2 is the input pressure (MPa), Q is the capacity of the pipeline (kg/s) and ρ is the density(kg/m3)

For initial compressors, P1 is the requested transportation pressure(Pin) which is varied for the different pipeline designs. P2 is the pressure at which the gas leaves its source, which is 3 MPa for hydrogen (Enagás et al., 2020) and 0.1 MPa for carbon dioxide EBN and Gasunie, 2017. The capacity (Q) and the density (ρ) are determined with equations [12], [13] and [14], which are also varied for the various pipeline options since they depend on the diameter and the inlet pressure.

$$Q(kg/s) = v * \rho * \pi * D/4 \quad [12]$$

$$\rho(kg/m^3) = Pave * M/(T * R) \quad [13]$$

$$Pave = 2/3(Pin + Pout - Pout * Pin/(Pout + Pin)) \quad [14]$$

where, Q is the flow (kg/s), v is the velocity of the gas (m/s), ρ is the density of the gas(kg/m^3), D is the diameter (m), Pave is the average pressure (MPa), M is the molar mass, T is the temperature, R is the gas constant, Pin is the inlet pressure (MPa) and Pout is the outlet pressure (MPa)

Intermediate compressors are placed along the pipeline to assure that the pressure does not drop below the minimum transportation pressure (P2) and remains at the requested pressure level (P1). The minimum pressure for hydrogen and gaseous CO2 (P2) is 1.5, as a pressure below 1.5 MPa stops the flow (Knoope, 2015). For liquid CO2 a minimum pressure of 8 MPa is required because below 8 MPa, the CO2 transforms to gaseous CO2 or two-phases CO2 (Knoope, 2015). P1 is the requested transportation (Pin). From the minimum pressure (Pmin), the initial pressure (Pin) and the pressure drop (ΔP) [15], the number of compressors and P2 are determined (IEA, 2010; Knoope, 2015; Mokhatab et al., 2019). The practical model description in Appendix B discusses the calculation of the number of compressors and P2 in more detail.

$$\Delta P = \frac{32 * ff * Q^2}{\pi^2 * \rho * D^5)} \quad [15]$$

$$ff = \frac{1.325}{ln((\frac{\epsilon}{3.7*D}) + (\frac{5.74}{Re^0.9})^2} \quad [16]$$

$$Re = \frac{\rho * D * v}{\mu} \quad [17]$$

$$\mu = 10^{-4} * K * exp((X * \frac{\rho}{62.4})^Y)/1000 \quad [18]$$

$$K = \frac{9.4 + 0.2 * M) * T^{1.5}}{209 + 19M + T} \quad [19]$$

$$X = 3.5\frac{986}{T} + 0.001M \quad [20]$$

$$Y = 2.4 - 0.2X \quad [21]$$

*Where, Δ P is the total pressure drop (MPa), ff is the friction factor, ρ is the density (kg/m^3), ϵ is the pipe absolute roughness (= 50*10$^-$6 m), D is the diameter (m), Re is Reynolds number, v is the average velocity (m/s), μ is the absolute viscosity (kg/msec), M is the molar mass and T is temperature (R).*

The determined capacity is then used in equation [9] for CO2 and [10] for H2 to determine the cost of compression. The total compression costs [22] are the sum of all compressor costs.

$$C_{comp} = I_{compH2\_Initial} + I_{compH2\_Intermediate} + I_{compCO2\_Initial} + I_{compCO2\_Intermediate} \quad [22]$$

Where, C_{comp} are the total compression costs (€), $I_{compH2\_Initial}$ are the initial hydrogen compression costs(€), $I_{compH2\_intermediate}$ are the intermediate hydrogen compression costs(€), $I_{CompCO2\_Initial}$ are the initial carbon dioxide compression costs (€) and $I_{CompCO2\_Intermediate}$ are the intermediate carbon dioxide compression costs(€)

Pumping costs

When liquid fuels are transported, pumping stations instead of compressors are placed along the pipeline to compensate for pressures. Therefore, in this study pumping stations instead of compressors are used when CO2 is transported in its liquid phase. Since water and CO2 pumping station do not differ significantly, the costs of water pumps are used to estimate the costs of CO2 pumps. The costs for water pumps are given for multiple capacities in Iterliance LLC for California Energy (2002). Based on this study, Knoope (2015) determined the relation between capacity and investment costs which resulted in the following cost function:

$$C_{pump} = 74.3 * W_{pump}^{0.58} * n^{0.9} \quad [23]$$

Where, C_{pump} are the total pumping costs (€) and W_{pump} is the capacity of the pump (MW)

The maximum capacity of a pump is 2 MW (IEA, 2002). Therefore, larger capacities require multiple pump units (n) to be installed in parallel. Installing them in this way enables them to better handle the variations in mass flow (Knoope, 2015). Therefore, a train advantage via a multiplication factor of 0.9 is applied (Meerman et al., 2012).

The capacity of pumping stations is determined with the same equation which is used to calculate the capacity of compressor stations (equation [11]). However, the economic velocity for liquid CO2 transport is different from the velocity of gaseous CO2 transport. For liquid CO2 transport, the velocity has to be below a certain value to avoid erosion, vibrations and damaging of the pipeline (Knoope, 2015). Therefore, a maximum velocity of 6 m/s is specified in carbon steel pipelines (Knoope et al., 2013). Based on these requirements, GasUnie (n.d.) determined a velocity of 2.5 m/s for liquid CO2 (Knoope, 2015). Therefore, in this study, a transportation velocity of 2.5 m/s is used for liquid CO2. In order to determine the number of pumping station and P2 equations [15],[16],[17],[18],[19],[20] and [21] are used.

Reassignment costs

Cerniauskas et al. (2020) established a cost function for the reassignment of the natural gas pipelines without modification [24]. They assumed that no capital costs for the pipeline itself are required, only new compressor and gas pressure regulation stations that are compatible with the hydrogen environment are installed (Cerniauskas et al., 2020). The associated costs of the compressor station are estimated according to the hydrogen compressor cost data presented by Reuß et al. (2017).

$$C_{reassignment} = ((1.67 * 10^{-4}) * D_{NG}^2 + (-2 * 10^{-13}) * D_{NG} + (-7.8 * 10^{-10})) * L_{NG} \quad [24]$$

Where, $C_{reassigment}$ are the total reassignment costs (€), D_{NG} is the diameter of the natural gas pipeline (=0.9m) and L_{NG} is the length of the natural gas pipeline (=250.000 m)

The total capital expenditures

The total capital expenditures of a pipeline are the sum of the construction, compression, pumping and reassignment costs. In summary, the total capital expenditures are calculated using the following functions:

$$CAPEX = C_{construction} + C_{comp} + C_{pump} + C_{reassignment} \quad [25]$$

Operational Expenditures

The operation and maintenance of pipelines cover aspects such as pipeline monitoring, emergency response, repair and analysis of pipeline accidents. The general equation to calculate the total operation and maintenance costs are the sum of the yearly costs and are discounted over time (t) with discount factor (r), using the equation below:

$$OPEX_{total} = \sum_{t=1}^{n} \frac{OPEX(t)}{(1+r)^t}$$

Where, OPEXtotal are the operational costs over the total project lifetime n (=25) (€), OPEX(t) are the operational costs of the pipeline in year t and r is the discount factor (=8%)

In the literature on this issue, the yearly operational and maintenance costs of new pipelines are determined as a percentage of the capital expenditures. The literature review by Knoope (2015) determined that this percentage ranges from 1.5 percent to 4.0 per cent for the pipeline OM costs and from 1.5 to 5 per cent for pumping and compressor stations.

In this study, the operation and maintenance assumptions of Knoope (2015) are used: the pipeline OM costs are 1.5 per cent of the construction costs and the compressor and pumping OM costs are 4 per cent of the compression and pumping capital costs. The energy consumption of compressors and pumping stations are not included here.

For pipelines that are reassigned, the operational costs comprise only of the pipeline degradation costs, not the energy costs of the compressors. The effect of the pipeline degradation on the operation costs is determined based on the stress intensity range. This is the damage to the material due to an increase in the number of cracks. The operation and maintenance costs function determined by Cerniauskas et al. (2020) is used in this research to calculate the reassignment OM costs and is presented in equation [27].

$$OPEX_{reassignment} = (1.1 * 10^{-4} * D_{NG}^2 + -1.6 * 10^{-2} * D_{NG} + 2) * L_{NG} \quad [26]$$

Where, $OPEX_{reassignment}$ are the total operational costs of the natural gas pipeline (€), D_{NG} is the diameter of the natural gas pipeline (=0.9m) and L_{NG} is the length of the natural gas pipeline (=250.000m)

In summary, the total operation and maintenance cost are determined using the following equation:

$$OPEX(t) = C_{construction} * 0.015 + C_{comp} * 0.04 + C_{pump} * 0.04 + OPEX_{reassignment} \quad [27]$$

$$OPEX_{total} = \sum_{t=1}^{n} \frac{C_{construction} * 0.015 + C_{comp} * 0.04 + C_{pump} * 0.04 + OPEX_{reassignment}}{(1+r)^t} \quad [28]$$

Where, OPEX(t) are the operation and maintenance costs in year t, $C_{construction}$ are the total construction costs of the pipeline (€), C_{comp} are the total compressor costs of the pipeline (€), C_{pumpp} are the total pumping costs of the pipeline (€), $OPEX_{reassignment}$ are the yearly operational costs of the natural gas pipeline (€), $OPEX_{total}$are the operational costs over the total project lifetime n (=25) (€) and r is the discount factor (=8%)

Revenue stream

In addition to the costs, it is also necessary to calculate the income of the pipeline. However, this study is not aimed at determining the precise revenue model of a pipeline, and therefore, a simplified revenue model by Melese et al. (2014) is used [28]. This model calculates the yearly revenue as the expected income with a linear function of the yearly flow Qt (kg/year). In this study, it is assumed that the network developer generates income by charging a certain rate per unit capacity. The expected income is determined using the following function:

$$revenue(t) = EI(t) = \alpha * Qt \quad [29]$$

Where, EIt is the Expected Income of year t (€), α is the connection fee (=0.1 €/kg) and Qt is the yearly flow (kg/year)

The rate per unit (alpha) is assumed to be 0.1 euro per kg. It can be changed to get a more realistic revenue or varied for different scenarios. The yearly flow (Qt) is determined by the demand for hydrogen or carbon dioxide and the pipeline capacity.

The total revenue of the pipeline in its lifetime is calculated as a summation of the discounted expected yearly incomes with a discount rate (r) of 8 percent. The sum of the discounted cash flows of the pipelines is the revenue of a pipeline design:

$$Revenue_{total} = \sum_{t=1}^{n} \frac{revenue(t)}{(1+r)^t} = \sum_{t=1}^{n} \frac{EI(t)}{(1+r)^t} \quad [30]$$

Where, Revenue is the revenue of the pipeline over the total project liftime n(=25) (€), EIt is Expected Income of year t(€) and r is the discount factor (=8%)

Net Present Value

The performance of a pipeline design option is evaluated using the Net Present Value (NPV). Combining the above described cost and revenue functions the following NPV functions can be determined:

$$NPV = \sum_{t=1}^{n} \frac{revenue(t)}{(1+r)^t} - (CAPEX + \sum_{t=1}^{n} \frac{OPEX(t)}{(1+r)^t}) \qquad [1]$$

of which

$$Revenue(t) = EI(t) = \alpha * Qt \qquad [29]$$

$$CAPEX = C_{construction} + C_{comp} + C_{pump} + C_{reassignment} \qquad [25]$$

$$OPEX(t) = C_{construction} * 0.015 + C_{comp} * 0.04 + C_{pump} * 0.04 + OPEX_{reassignment} \qquad [27]$$

5.3 VALIDATION OF THE MODEL

Several assumptions have been made to construct the NPV model. These assumptions are presented in appendix A. Furthermore, the model has several limitations, which are discussed in chapter 7. However, these assumptions and limitations should not decrease the accuracy of the outcome of the model. Therefore, in order to validate the model, the outcome of the model should be compared with the findings in the real-world that it presents. However, this model is constructed to analyse the performance of hydrogen and multipurpose pipelines, of which very few, if any, exist in real life. Nevertheless, as this NPV model is built up of different equations that represent separate parts of carbon-dioxide and hydrogen pipeline characteristics and costs, the model can be validated by validating these parts separately. As the model should represent the situation of the chosen case-study, the outcomes are preferably validated by the CCS and hydrogen cost estimations by GasUnie, the network operator involved in this case study (EBN and Gasunie, 2017; Enagás et al., 2020). However, not all elements are included in these studies.

5.3.1 A new pipeline

The construction costs equations by Knoope (2015) were initially developed for a carbon-dioxide network, but are in this research adjusted for a hydrogen network. They can be validated by comparing the outcomes to models that determine the costs of a hydrogen pipeline. Using the construction cost equation by Baufumé et al. (2013), the construction cost of a 900 mm diameter and 200 km pipeline with a maximum pressure of 10 MPa is about 447 million euro, whereas the model in this research is calculated at 444 million euro. Furthermore, Tzimas et al. (2007) and Enagás et al. (2020) determined that the average pipeline construction costs are 2005 euro per m, which is in line with both this model and the model of Cerniauskas et al. (2020).

As described above, the cost of compressors, for both hydrogen and CO2, vary significantly. In this research it is decided to select the costs that are compatible with the case study. Therefore, the costs of CO2 compressors in this study are validated by comparing them to the costs given in an overview of CCS costs by the Dutch network operator GasUnie EBN and Gasunie (2017). In this overview the cost of a 5 MW compressor are estimated between 12,5 and 16 million euros. This is in line with the compressor costs determined in this research by independent variables which is 13 million euro. The hydrogen compressor costs are validated by the fact that the cost model by Reuß et al. (2017) resembles the reassignment CAPEX by Cerniauskas et al. (2020), which also represents the compressor investment costs.

As CO2 in the Netherlands is currently transported in the gaseous state, GasUnie has not published any pumping cost estimations. Therefore, it is not possible to validate the model by Knoope (2015) for the Dutch situation.

5.3.2 A reassigned pipeline

As mentioned above, Tzimas et al. (2007) estimate a new pipeline to cost 2005 euro per meter. Enagás et al. (2020) and Wijk van and Hellinga (2018) establish the costs of reassignment to be within 10 percent of the construction costs. Using the reassignment CAPEX model by Cerniauskas et al. (2020), which is applied in this research, the cost of reassignment is calculated at 200 euro per meter which is about 10 per cent of the construction costs.

5.3.3 Operation and maintenance

The operation and maintenance are always estimated at an percentage of the capital costs. Therefore, the estimated capital costs determine the validity of the operation and maintenance costs. However, what percentage of the capital costs is chosen differs per case. Enagás et al. (2020) establish the operation and maintenance costs of the pipeline between 0.8 and 1.7 per cent, which is in line with the chosen 1.5 per cent in this research. The separate operation and maintenance costs of compressors and pumping stations are not estimated by GasUnie. However, most of studies estimate CO2 pipelines costs at four per cent (Knoope et al., 2013).

5.3.4 Revenue

As described above, the revenue model is a very simplified model of the real-world revenue, but serves its purpose for analysing the risks and benefits of including flexibility in pipeline design. However, when a deeper understanding of the possible revenue stream of a pipeline design is required, the revenue model should be improved with more specific details on the income model of the network operator. This model is only valid when various design options are compared to each other.

6 RESULTS

In this chapter, the results will be covered. This chapter answers the fourth sub-question:

SQ4: How do the flexible pipeline designs perform on the established criteria?

The analysis exists of three parts. First, a scenario analysis is executed. In this section, the NPV of the pipeline designs are calculated under the different future demand scenarios and the NPVs of the separate strategies and the flexibility options are compared per scenario. In section 6.2, the average NPV over all future scenarios is determined in order to analyse the average performance of the pipeline designs. Lastly, in section 6.3, the results will be analysed on their sensitivity to some of the critical assumptions in the model.

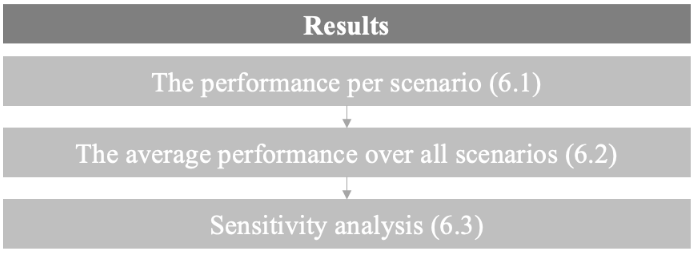

Figure 6.1: Outline of the results chapter

6.1 PERFORMANCE PER SCENARIO

This section analyses which pipeline design scores best under which future demand scenario. In total, almost 2500 pipeline designs are analysed. The NPV of these designs is calculated under 8 future scenarios. Therefore, the results of this study contain 20.000 NPVs.

It is not relevant and too encompassing to discuss all the 20.000 NPVs. For example, if a single-purpose pipeline of a 0.6 diameter performs best, all single-purpose pipeline options with other diameters than 0.6 can be excluded from the analysis. Therefore, the 20.000 NPVs are reduced to a selection of the relevant NPVs by applying a framework that is presented in figure 6.2.

Figure 6.2 on the next page concerns one of the eight scenarios, namely scenario 1. This scenario includes 2500 pipeline designs. The next row in Figure 6.2 categorizes these 2500 pipeline designs with respect to strategy, i.e., single purpose (SP), single purpose + natural gas (SP+NG), multi-purpose (MP), and etcetera. The third row concerns the optimization of the pipeline capacity. For example, if from the 20 single-purpose pipeline designs, the design with a 0.6 diameter 25 MPa pressure has the highest NPV in scenario 1, this design is selected as the best performing single-purpose design in scenario 1.

In this way, with respect to each strategy, the optimal pipeline condition was determined. Next (fourth row), the six strategy options, each with its optimal pipeline conditions, were analysed with respect to their performance.

This procedure is repeated in every scenario. The results are presented in table 6.1 and 6.2.

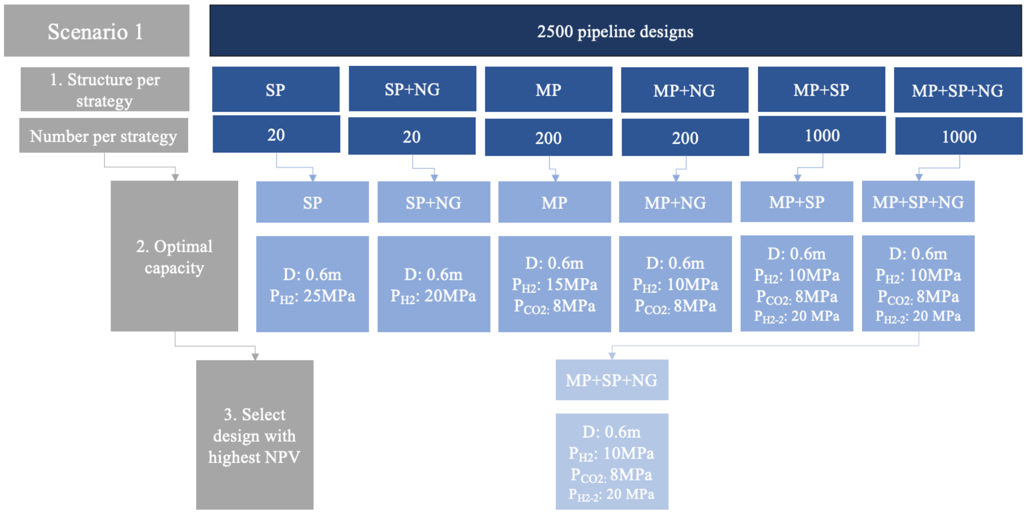

Figure 6.2: Outline of the process to structure the results with respect to scenario 1

Scenario	Strategy	Capacity Diameter (m)	Design Pressure (MPa)	H2	Pressure (MPa)	CO2	Pressure (MPa)	H2-2	NPV (million €)	Results CAPEX (million €)	Revenue (million €)
Scenario 1	SP	0.6	25						€1,106	€553	€1,801
	SP+NG	0.6	20						€1,262	€541	€1,948
	MP	0.6	15		8				€959	€416	€1,482
	MP + NG	0.6	10		8				€1092	€416	€1,559
	MP + SP	0.6	10		8		20		€1,366	€795	€2,871
	MP + SP + NG	0.6	10		8		20		€1,968	€751	€2,925
Scenario 2	SP	0.6	25						€1,106	€553	€1,801
	SP+NG	0.6	20						€1,262	€541	€1,948
	MP	0.6	15		8				€1,856	€416	€2,378
	MP + NG	0.6	10		8				€1,989	€369	€1,245
	MP + SP	0.6	10		8		20		€2,772	€795	€3,768
	MP + SP + NG	0.6	10		8		20		€2,865	€751	€3,822
Scenario 3	SP	0.6	20						€617	€492	€1,235
	SP+NG	0.6	10						€752	€368	€1,214
	MP	0.6	10		8				€897	€335	€1,315
	MP + NG	0.6	4		8				€1,003	€304	€1,382
	MP + SP	0.6	10		8		20		€1,366	€635	€2,157
	MP + SP + NG	0.6	4		8		20		€1,461	€605	€2,212
Scenario 4	SP	0.6	20						€617	€492	€1,235
	SP+NG	0.6	10						€752	€368	€1,214
	MP	0.6	10		8				€1,794	€335	€2,211
	MP + NG	0.6	4		8				€1,900	€304	€2,278
	MP + SP	0.6	10		8		20		€2,263	€635	€3,054
	MP + SP + NG	0.6	4		8		20		€2,358	€605	€3,109

Table 6.1: Scenario 1,2,3 and 4 and design of the pipeline in relation to the NPV, CAPEX and revenue.

Scenario	Strategy	Capacity Diameter (m)	Design Pressure (MPa)	H2	Pressure (MPa)	CO2	Pressure (MPa)	H2-2	NPV (million €)	Results CAPEX (million €)	Revenue (million €)
Scenario 5	SP	0.6	20						€617	€492	€1,235
	SP+NG	0.6	10						€752	€368	€1,214
	MP	0.6	10		10				€2,481	€339	€2,905
	MP + NG	0.6	10		10				€2,573	€371	€3,046
	MP + SP	0.6	10		10		10		€2,950	€640	€3,747
	MP + SP + NG	0.6	4		9		10		€3,030	€617	€3,796
Scenario 6	SP	0.6	10						€175	€284	€524
	SP+NG	0.6	4						€289	€246	€594
	MP	0.6	10		8				€796	€335	€1,214
	MP + NG	0.6	4		8				€854	€304	€1,232
	MP + SP	0.6	4		8		4		€897	€467	€1,464
	MP + SP + NG	0.6	4		8		4		€939	€500	€1,555
Scenario 7	SP	0.6	10						€175	€284	€524
	SP+NG	0.6	4						€289	€246	€594
	MP	0.6	10		8				€1,693	€335	€2,111
	MP + NG	0.6	4		8				€1,750	€304	€2,129
	MP + SP	0.6	4		8		4		€1,794	€467	€2,360
	MP + SP + NG	0.6	4		8		4		€1,836	€500	€2,451
Scenario 8	SP	0.6	10						€175	€284	€524
	SP+NG	0.6	4						€289	€246	€594
	MP	0.6	10		10				€2,380	€339	€2,804
	MP + NG	0.6	4		9				€2,240	€317	€2,815
	MP + SP	0.6	4		10		10		€2,470	€535	€3,131
	MP + SP + NG	0.6	4		9		4		€2,508	€513	€3,138

Table 6.2: Scenario 5,6,7 and 8 and design of the pipeline in relation to the NPV, CAPEX and revenue.

6.1.1 Performance of the strategies

Table 6.1 and 6.2 illustrate that in every scenario the MP+SP+NG strategy has the highest NPV. Comparing the optimal designs per scenario shows that the optimal designs only have minuscule differences in the operating pressure of hydrogen and carbon dioxide:

- The hydrogen pressure in the single-purpose pipeline decreases in scenarios with low hydrogen demand.
- The carbon-dioxide demand increases from 8 to 9 MPa in the high CO2 scenarios.

In order to determine why this design performs best, first the NPV is separated into the revenue (column 9) and the CAPEX (column 8) which are discussed respectively. Next, the performance of flexibility options per scenario are discussed separately.

The MP+SP+NG pipeline designs have the highest revenue in every demand scenario. To determine the benefits of the extra revenue generated by including the option to deliver 100% pure hydrogen, the MP+SP+NG design is compared to the MP+NG design. The table shows that in scenario 1 and 2 (the high hydrogen demand scenarios) the revenue doubles and in the other scenarios the revenue increases by a factor of 1.2. To determine the benefits of the extra revenue generated by including the option to export carbon dioxide, the revenue of the MP+SP+NG pipeline is compared to the SP+NG revenue. The results show that the revenue is almost doubled in scenario 1, 2, 3 and 6 whereas the revenue can become even four times as big in scenario 5, 7 and 8. This shows that including both options, and especially the option to export carbon-dioxide, shows significant revenue increases in every scenario.

Although MP+SP+NG design has the highest NPV, this design also has the highest CAPEX due to the extra pipeline that is constructed. This increases the costs by about 35%. The option to transport carbon dioxide does not add extra costs. Moreover, the CAPEX decreases slightly when the CAPEX of a single purpose pipeline is compared to the CAPEX of a multi-purpose pipeline. The fact that the best designs have the highest CAPEX leads to the conclusion that this design scores best due to the extra revenue. This illustrates that even in the low hydrogen and low carbon dioxide scenarios, the extra costs that are included with flexibility, do not outweigh the benefits of the potential revenue.

6.1.2 Performance of the flexibility options

Option to switch

Table 6.3 presents the average NPV of the designs that have the option to switch (column 1) and the average NPV of the designs that do not have this option (column 2) per scenario. This table illustrates that in every scenario, having the option to switch creates a higher NPV, predominantly because the revenue increases significantly in scenarios 3 tm 8 (reference and low hydrogen demand). Only in scenario 2, where a high hydrogen demand is combined with a low carbon dioxide demand, a single purpose pipeline performs better than a multi-purpose pipeline. The increasing revenue is explained by the fact that carbon dioxide and hydrogen demand complement each other. As explained in chapter 4, the hydrogen demand is very low in the first operating years of the pipeline due to lack of renewable electricity (IEA, 2002). However, carbon dioxide has no scaling and costs barriers. Therefore, there is a significant carbon dioxide demand in the first operating year, increasing the revenue (Bellona Europe, 2018). Secondly, having the option to switch does not increase the CAPEX. Moreover, having this option even decreases the CAPEX. This is explained by the fact that transporting carbon dioxide requires a lower operating pressure. Therefore, the optimal operating pressure is decreased as well as the compression costs. Although a lower operating pressure results in a smaller capacity, the extra revenue generated from the transport of carbon dioxide outweighs this limitation. It can thus be concluded that no specific scenario influences the performance of a multi-purpose pipeline compared to a single purpose pipeline. Only if it is very likely that the futures turns out to have a low carbon dioxide and high hydrogen demand, is the installation of a multi-purpose pipeline not beneficial.

	Average NPV with MP (million €)	Average NPV without MP (million €)
Scenario 1	€1,346	€1,184
Scenario 2	€2,962	€1,184
Scenario 3	€1,182	€685
Scenario 4	€2,079	€685
Scenario 5	€2,207	€685
Scenario 6	€872	€232
Scenario 7	€1,768	€232
Scenario 8	€2,444	€232

Table 6.3: The average NPV of the designs with the option to switch versus the designs without this option.

Option to expand

In chapter 3, three options that include the flexibility to expand the capacity of the pipeline have been discussed: installing a larger diameter, increasing the operating pressure and reassigning the natural gas pipelines. Focusing on the increase of the diameter and the pressure, the optimization of the capacity shows that the optimal design has a 0.6 m diameter in every strategy and in every scenario. This illustrates that installing a larger diameter does not generate a higher NPV. Rather, the operating pressure is increased to increase the capacity in different scenarios. To get a better understanding of the relationship between the operating pressure, the diameter and the NPV per scenario, the results of the optimization of the capacity are further discussed in appendix D. With regard to the reassignment of the natural gas pipelines, table 6.4 illustrates that including the capacity of the natural gas pipelines in the pipeline design generates a higher NPV in every scenario. The costs of reassignment, about 34 million, are significantly low, considering the additional capacity. Creating this capacity by increasing the operating pressure would result in 45 million extra compression costs and increasing the diameter would cost 155 million. This illustrates the relatively low costs when one decides to expand the capacity significantly.

	Average NPV with NG (million €)	Average NPV without NG (million €)
Scenario 1	€1,441	€588
Scenario 2	€2,039	€588
Scenario 3	€1,072	€487
Scenario 4	€1,670	€487
Scenario 5	€2,118	€490
Scenario 6	€694	€362
Scenario 7	€1,292	€362
Scenario 8	€1,739	€368

Table 6.4: The average NPV of the designs with the option to expand the capacity with the natural gas pipeline capacity versus the designs without this option.

Option to deliver 100% pure hydrogen

Table 6.5 presents the performance of the option to deliver 100 % pure hydrogen per scenario. This table shows that only scenario 1, 2 and 3 leads to increases in the NPV when including this flexibility. This illustrates that only in scenarios with high hydrogen demand, having the option to deliver 100 % pure hydrogen performs well. A good performance is thus not guaranteed. However, when it is combined with a multi-purpose pipeline, the pipeline design reaches the highest NPV. This shows that the carbon dioxide demand is significantly higher than the hydrogen demand of the mobility industry. However, these two options are not mutually exclusive. Therefore, a combination of a multi-purpose and single-purpose pipeline can be applied.

	Average NPV with SP (million €)	Average NPV without SP (million €)
Scenario 1	€1,426	€1,026
Scenario 2	€2,001	€1,922
Scenario 3	€1,049	€950
Scenario 4	€1,497	€1,847
Scenario 5	€1,837	€2,527
Scenario 6	€575	€825
Scenario 7	€1,024	€1,722
Scenario 8	€1,361	€2,400

Table 6.5: The average NPV of the designs with the option to deliver 100% pure hydrogen versus the designs without this option.

6.2 THE AVERAGE PERFORMANCE OVER ALL SCENARIOS

This section covers the analysis of the average performance of the pipeline designs by comparing the average NPV in all demand scenarios. For this analysis, again, the average NPV of 2500 designs are calculated. To structure the results, the same steps as illustrated in the scenario analysis are executed (see figure 6.2). The results are presented in table 6.6.

	Design				Results	
Strategy	Capacity Diameter (m)	Pressure H2 (MPa)	Pressure CO2 (MPa)	Pressure H2-2 (MPa)	NPV (million €)	CAPEX (million €)
SP	0.6	20			€552	€507
SP+NG	0.6	10			€686	€368
MP	0.6	10	9		€1,591	€337
MP+NG	0.6	4	9		€1,676	€316
MP+SP+NG	0.6	10	9	15	€1,928	€719
MP+SP	0.6	4	9	10	€1,990	€617

Table 6.6: The design of the pipeline in relation to the average NPV and CAPEX.

The scenario analysis already showed that the SP+MP+NG designs performed best in every scenario. Therefore, it is not surprising that SP+MP+NG design also scores best on average.

Table 6.7 compares the average NPV of the design when flexibility options are included with the ones where they are not. This table concludes that the flexibility options to switch increase the average performance of the design. The ability to deliver 100% pure hydrogen only shows to increase the average NPV of the design when it is combined with the option to switch.

	Average NPV with (million €)	Average NPV without (million €)
Option to switch	€1,793	€601
Option to expand (with NG reassignment)	€1,451	€1,341
Option to deliver 100% pure H2	€1,276	€1,634

Table 6.7: The average NPV of the designs with a flexibility compared to average NPV without a flexibility option.

Overall, it can be concluded that the option to switch from carbon-dioxide to hydrogen has a low average CAPEX and a high average revenue and therefore is a flexible and low-risk option to include in the design. The option to expand with the capacity of the natural gas pipelines increases the NPV of the designs and has relatively low added extra costs. On the contrary, the option to have the ability to include all industries does carry a high financial risk since an extra pipeline and a hydrogen-only pipeline with a large capacity both require high investment costs. However, when all options are combined in one design, the highest NPV can be reached.

6.3 SENSITIVITY ANALYSIS

In this section two sensitivities will be analyzed. Specifically, the sensitivity of the performance of the design strategies to the connection fee and the compression costs are considered.

6.3.1 Sensitivity to connection fee

The connection fee value is varied to check its effect on the performance of the NPV of the flexible designs. The connection fee is the amount paid by sources per unit capacity. In the original model, the connection fee was set at 0.1 euro per kg. In this analysis the connection fee is halved to 0.05 euro per kg to analyse its influence.

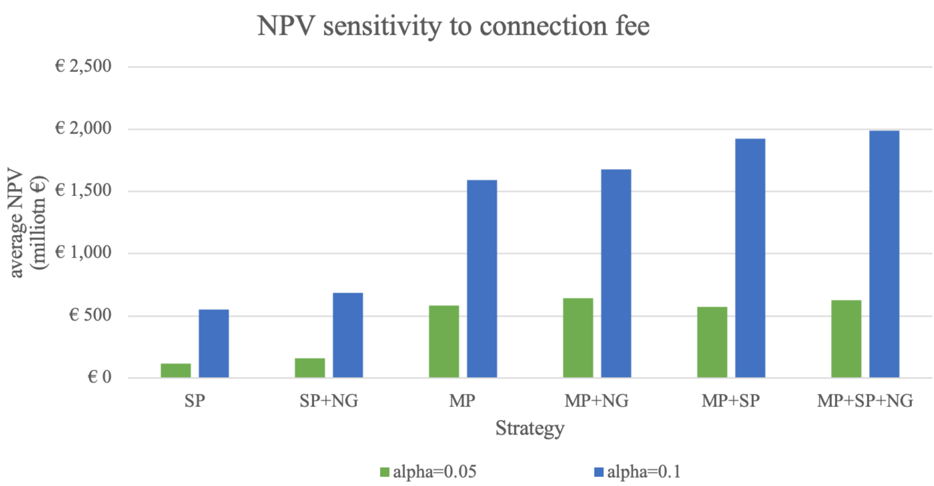

Figure 6.3: Illustration of the sensitivity to the connection fee

Evaluating the influence of the connection fee, it can be concluded that the best performing strategy has changed. Where first the best strategy was the MP+SP+NG strategy, when the connection fee is halved, the MP, MP+NG, MP+SP and the MP+SP+NG designs have about the same NPV. This illustrates that the performance of the MP+SP+NG design is dependent on the generated revenue. The analysis of the connection fee shows that when the connection fee is decreased, the extra costs for this pipeline outweigh the extra benefits of delivering 100 % pure hydrogen. As the mobility industry is the only industry requiring this purity, further research on the actual demand by the mobility industry is necessary to determine whether the costs of the extra pipeline are worth the effort.

6.3.2 Sensitivity to the compression costs

The carbon dioxide compressor costs function is varied to check its effect on the NPV. The carbon dioxide compressor cost model determines the cost of the intermediate and inlet compressors by a function that shows the relation between the installed capacity and the investment costs (see section 5.2.2). As explained in the model description, the cost functions for carbon dioxide compressors vary significantly. In this study, it was decided to use the cost model of Chandel et al. (2010) as this matches with the estimate costs by GasUnie (n.d.)). Since the cost function by IEA (2002) gives a significant difference in the compressor costs, the results of using the function by IEA (2002) are compared to the results of this study, that used Chandel et al. (2010).

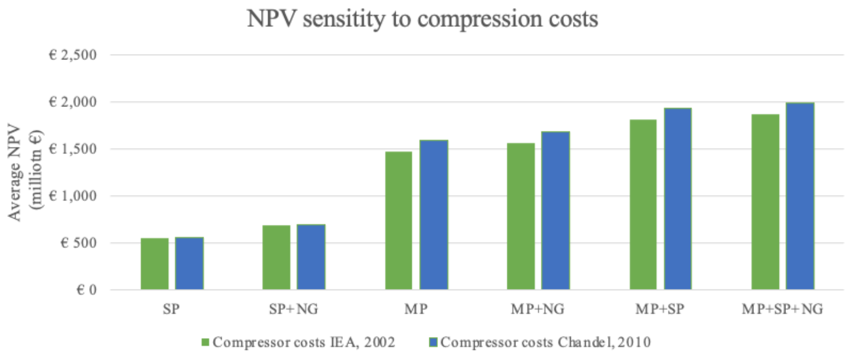

Figure 6.4: Illustration of the sensitivity to the compressor costs

The comparison of the NPVs when IEA (2002) is used versus when the study of Chandel et al. (2010)) is used shows no significant differences. It can thus be concluded that, when compressor costs are assumed to be high, the CAPEX does not significantly increase.

6.4 SUMMARY OF THE RESULTS

The findings can be summarized in the following statements:

1. The MP+SP+NG strategy has the highest NPV in every scenario.
2. The option to switch creates a higher NPV in every scenario.
3. Including the capacity of the natural gas pipelines in the pipeline design generates a higher NPV in every scenario.
4. Including the option to deliver 100% pure hydrogen increases the NPV in the three high-hydrogen demand scenarios 1, 2 en 3.

5. The MP+SP+NG has the highest NPV, regardless of scenario.
6. The main result – as formulated in statement 1 - is sensitive to the assumed connection fee. When the connection fee is half of what was assumed in this study, the differences between four of the six strategies are leveled.
7. The main result – as formulated in statement 1 - is not sensitive to compression costs: even when the compression costs are assumed to be high, the NPVs do not increase.

7 DISCUSSION

On reflection, the most exciting aspect of this study is that the model worked. It resulted in an outcome that makes sense and can be interpreted, while it is also relevant for the industrial clusters involved. If the validity of a study could be determined by the old adage that "the proof is in the pudding", this study would pass the proof. However, this type of validity is called 'face validity' (Runkel and McGrath, 1973), and, although highly esteemed by experts who work in practical settings, this type of validity is not sufficient from a scientific perspective.

In modelling studies, making assumptions and proposing calculations is unavoidable. This general statement is applicable to this study too. A complete list of all assumptions made in this thesis can be found in appendix C. The calculations can be found in chapter 5. It is argued here that various assumptions and calculations of the current study need to be scrutinized critically, and, if needed, they should be varied tentatively, before the outcome of this study leads to practical decision-making and implementation of concrete measures. One should be aware of the fact that this thesis presents a snapshot of a model that can be regarded as a work-in-progress and that is still open to improvements.

Below, some of the assumptions and calculations of this model are further homed in on and reflected upon. 7.1 concerns limitations of the model as it is; 7.2 discusses the results in relation to the limitations of the cost model and the assumed demand scenarios.

7.1 LIMITATIONS OF THE MODEL

7.1.1 Critical assumptions

First and foremost, key assumptions are made with respect to the degree of the demand and production of hydrogen. As there is a lack of information about the development of the production and demand, this study presupposes that the demand will develop as is predicted by the Port of Rotterdam. However, as explained in chapter 6, the investments that have to be made in order for different industries to request the estimated volume of hydrogen are high and even in the low demand scenario, extensive efforts are required by the industry to implement hydrogen in their processes. Furthermore, it is assumed that there already is a demand to export carbon dioxide in 2025, while this also requires expensive adaptations to the processes of industry.

Furthermore, as the demand is a leading factor in this study, the assumption is made that there will always be enough supply to meet this demand. However, the current hydrogen production is limited to 52 PJ of which 50 PJ is used in the Port of Rotterdam itself (Dena et al., 2021). For the Port of Rotterdam to deliver the demand that is used in this study, the hydrogen production has to increases threefold. This increase in production is very dependent on the import of hydrogen from other countries and this requires the establishment of new partnerships.

Furthermore, the generation and use of hydrogen is assumed to be constant over the year while in reality there are daily fluctuations involved. Therefore, this study assumed enough storage capacity to deal with these fluctuations. However, in reality, storage is still a critical component of the hydrogen value chain.

If this study was based on the actual hydrogen demand and production trend, the CAPEX of the pipeline would have had a higher weight in the NPV of the pipeline. Consequently, the financial risks of the options would increase and it would be less attractive to invest in options with a large capacity or that have the flexibility to expand. Furthermore, it is possible that none of the options that are tested in this research turn out to be profitable and the investment in a hydrogen pipeline will have to be postponed until the demand increases.

However, this study is aimed at analysing infrastructure designs that are not only able to meet the demand of the different industries involved, but also those of an infrastructure that functions as a stepping stone for industry in the transition to hydrogen. In the current hydrogen transition, one of the main barriers is the absence of a transportation infrastructure (Accenture, 2021). Therefore, if industries had access to a hydrogen infrastructure, it is likely that the current hydrogen demand increases.

The second set of assumptions that needs to be considered here concerns the velocity, temperature and purity of the fuels. The actual flow and corresponding optimal conditions in a pipeline are determined by complex relationships between various factors such as the pressure, the velocity and the diameter. However, within the time frame that was set for this research, it was not possible to evaluate the impact of all the factors involved. Therefore, one velocity was assumed as well as a constant temperature and the effect of impurities are not taken into account.

In reality, as with pressure, the velocity decreases with the transportation distance. This decrease is determined by the inlet pressure, the diameter and the number of pumping or compressor stations. Other studies that evaluated the impact of the operating conditions on the pipeline design, initially determined a maximum and a minimum speed to which the velocity could fall. If a design option uses a combination of pressure, distance and pumping stations that results in a velocity that falls outside this range, the design is excluded from the analysis. Including a varying velocity in this research could have resulted in the exclusion of some of the analysed options. However, this study includes the analysis of the pressure drop and a minimum pressure level. Therefore, it is likely to assume that the velocity in the included designs would not drop below the minimum velocity if a range would have been applied. Furthermore, the velocities used in this study are primarily determined as the optimal transportation velocities for hydrogen and carbon dioxide by GasUnie (n.d.) and the Port of Rotterdam. This decreases the potentially negative impact of the constant velocity on the pipeline design.

Apart from the velocity, the temperature is also set at a constant value of 285 Kelvin. However, delving deeper into pipeline design, the temperature influences the density of the gas and therefore the capacity of the pipeline and consequently the required capacity of the compressors and pumping stations. Furthermore, the inlet and surrounding temperature also have an effect on the pressure drop. Lower input and ambient temperatures result in lower pressure losses and are more favourable to CO_2 pipeline transportation. Therefore, if temperature had been included as a variable and a range was determined to which the temperature could fall, the number of compressors and pumping stations and their costs might have changed. Consequently, the benefits of a multi-purpose pipeline could have changed. However, the temperature used in this study is determined as the likely operating temperature by Knoope (2015) and therefore the effects of the temperature might be negligible.

Focusing on the effect of impurities, it has been determined that they affect the physical and thermodynamic properties of the flowing fluid and therefore the capacity, the minimum pressure and the material requirements of the pipeline (Peletiri et al., 2018). For carbon dioxide in particular, the concentration of impurities can be very large, depending on the capture process and the purity of the feed fuel. However, most studies have not included the effect of impurities and although modelling to represent practical situations is necessary, this was not included in this research due to time limitations.

The third set of key assumptions involves steel and the corresponding price and yield stress. The steel used in this study is determined by the price and yield stress of X70 steel but increased by 25 per cent to take the required steel improvements corresponding with the transportation of hydrogen into account. However, the used X70 steel price dates back to 2017 and therefore ignores possible price developments. Furthermore, 25 per cent is a rough estimation and new steel that is considerably more expensive, but perhaps shows significant other benefits, may be developed by the time the model can be applied. The assumed steel price and yield stress has an impact on the wall thickness and the construction costs. Knoope (2015) determines that if, for example, X80 steel is used instead of X70 steel, the wall thickness should be increased by 2.5 and therefore the transportation costs are reduced. Consequently, the lower construction costs and lower amount of steel used can compensate for the higher steel price, resulting in an overall cost reduction. Implementing higher steel grades could improve the performance of the pipeline designs that are evaluated since it could increase the maximum operating pressure and decrease the construction costs. However, varying the steel used would have the same impact on all designs and therefore it is not likely that it would have influenced the comparative results of this study.

Lastly, no variation for the topographical conditions of the pipeline route are taken into consideration in this study and the factor that corrects for the terrain type is assumed to be constant. However, in reality, a pipeline can cross different types of terrain, for example sparsely populated or mountainous areas. The terrain the pipeline has to cross can cause significant changes to the costs of the pipeline. First of all, if failure occurs, gas can be released from the pipeline. In the case of carbon dioxide transport, if it is released in areas with topographical depressions, carbon dioxide clouds can occur. In order to avoid this, block valves can be installed or rerouting might be necessary. Furthermore, the construction costs of a pipeline also depend on the terrain of the pipeline, as populated areas involve more obstacles, whereas the construction of a pipeline in an established corridor is easier by comparison. The model developed in this study was not linked to topographical maps and different types of terrain. Even though a preliminary determined path is used, the cost saving that this results in is not incorporated. Furthermore, for other cases, other terrain types might be present and a corresponding terrain factor would influence the construction costs of the pipeline. Nevertheless, the terrain type would only influence the results when different flexibility designs would take a different route. Furthermore, the correcting factors for ranges in terrain type are quite large, making it difficult to determine what the exact financial consequences are of the topographical conditions.

7.1.2 Limitations of the model itself

The first limitation of the model relates to the assumption that the reassignment of the natural gas pipelines contains the same steps as reassigning a carbon dioxide pipeline. Currently, no pipelines that are aimed to first transport carbon-dioxide and later switch to the transportation of hydrogen have been installed, neither have they been analysed in the existing literature. It was very difficult to determine what the difference would be between a single purpose and a multi-purpose pipeline. However, many studies analysed the possibility of using the old natural gas pipelines to transport hydrogen. As these pipelines are already used for the transportation of different gasses, they can be considered multi-purpose pipelines. However, these pipelines did not first transport carbon dioxide and the relation between carbon dioxide and hydrogen might result in different changes than between hydrogen and natural gas. For instance, it is conceivable that the transportation of hydrogen after carbon dioxide requires very expensive cleaning techniques as the hydrogen might react with the carbon dioxide leftovers in the pipe. Furthermore, the initial design of the pipeline was not aimed at delivering various fuels. If it had been aimed at delivering various fuels, the initial design of the pipeline might have been different. For example, with future transportation of hydrogen in mind, the initial wall thickness might have to be increased to account for the higher pressure level, or the use of different steel might have to be considered that would mitigate the hydrogen embrittlement, decreasing the total costs. Nevertheless, as the reassignment of the natural gas pipelines is the only example of pipeline reassignment, the same process was used to determine the reassignment costs of a carbon dioxide pipeline. Therefore, the assumption was made that only the compressor and the corresponding operation and maintenance costs differ compared to a single purpose pipeline and it should be stressed that this assumption might have to be reconsidered on the basis of practical experience or a detailed study on multi-purpose pipelines.

The second limitation of the model is the way the compressor costs are determined. It was decided to include the cost function determined by Chandel et al. (2010). However, verifying its validity is very difficult due to limited available information about the exact compressor costs and the relation to the installed capacity. In total, only five compressor station estimations are found of which 3 determine the costs based on the capacity of the compressor and 2 give a fixed price. In addition, the estimated costs differ significantly, for instance, the costs for a booster station of 1.25 MWe are reported in the range 3.1 - 36 million euros (Knoope et al., 2013). Moreover, although the literature determines different compressor cost functions for hydrogen and carbon dioxide, the reasoning behind this difference is not discussed. Therefore, two separate cost functions are included in this research, but without the explanation behind this decision. One can assume that due to the low energy density of hydrogen more capacity is required to compress the same amount of hydrogen compared to carbon dioxide. However, since the cost functions are based on the relation between the capacity and the costs, one joint cost function would readily incorporate this difference. Furthermore, the literature also does not discuss the re-use of compressor stations which could lead to extensive cost savings.

Apart from the arbitrariness of the cost functions, the compressor costs also did not include the electricity costs that come with compression. The energy costs are related to the electricity costs, the operation hours and the capacity of the compressor. Furthermore, the exact energy consumption is determined by the temperature, the pressure difference, the number of compression stages, the compressibility factor and the specific heat ratio. Focusing attention on the energy consumption of a compressor is a complex issue in itself and would benefit from a standalone study on this topic.

Because of the reasons described above, the compression costs are often left out of the research. However, in this research the compressor costs determine the difference in CAPEX of a multi-purpose and a hydrogen pipeline. Therefore, the compressor costs play a significant role in the results of this research. In order to improve the functionality of the model, the compression costs model has to be validated by practical experience or improved with new insights.

The third limitation is the oversimplified revenue model that is used in this study. Based on the flexibility design approach by Melese et al. (2017), a revenue model that calculates the expected income as a linear function of capacity is used. This model assumes that the network developer generates income by charging a certain fee per unit capacity and this charging fee is set at 1 euro per kg transported fuel. In reality, the network operator draws up a contract with the user as to the capacity required, the time frame and from which entry to which exit point the gas needs to be transported and the users are charged accordingly. Therefore, the actual income is not determined by the exact flow through the pipeline but by preliminary signed contracts. Consequently, the network operator is less dependent on daily fluctuations and the role of the industries that will actually create contracts with the network becomes more significant. Furthermore, the tariff is determined by dividing the income cap of GasUnie by the estimated registered capacity. The allowed income is calculated based on the CAPEX, OPEX and a market-based return. This shows that the fee is determined in relation to the investment costs, but also limited to a certain value. Although the model of this study provides sufficient insights into the performance of the different flexibility options, the impact of who is contracted with the network and with what capacity as well as how the CAPEX impacts on the transportation fee could improve the performance of the model.

7.2 DISCUSSION OF THE RESULTS

In this section, the conclusions about the performance of the flexibility options are analysed in relation to the limitations of the cost model (7.2.1) and the assumed demand scenarios (7.2.2)

7.2.1 Relation to the limitations of the cost model

In this section, the results are related to the limitations of the cost model. The analysis of the flexible pipelines concluded that a multi-purpose pipeline that has the option to switch between carbon dioxide transport and hydrogen transport is a flexible and low cost option for the pipeline connection between Rotterdam, Chemelot and North-Rhine Westphalia. However, as stressed earlier, no multi-purpose pipeline has been constructed in practice before. Therefore, the cost of a multi-purpose pipeline has not been validated. Furthermore, the model assumed that the additional costs of a multi-purpose pipeline only include compression costs. However, there might also be other costs involved with the construction and operation of a multi-purpose pipeline such as quality treatment of the pipeline. Therefore, the cost estimations might be too low. However, the results also illustrated that a pipeline that has the option to switch between carbon dioxide and hydrogen has a significantly higher revenue. Therefore, although the costs of a multi-purpose pipeline increase, the increase in revenue is a significant benefit compared to the other flexibility options.

Analysing the options to expand led to the conclusion that installing the ability to increase the pressure results in a higher NPV than an increase of the diameter. However, this conclusion is based on the estimated compressor costs, which are very uncertain. Nevertheless, the sensitivity to the compression costs illustrated no significant differences in the results. Furthermore, it was concluded that the reassignment of the natural gas pipelines is a relatively low cost option to expand the capacity of the pipeline connection between Rotterdam, Chemelot and North-Rhine Westphalia. This conclusion was validated by the estimations that the reassignment of the natural gas pipelines would cost 10% of the construction of a new pipeline (Enagás et al., 2020; Wijk van and Hellinga, 2018). However, a new and more detailed report about the specific reassignment of the natural gas pipelines in the Netherlands was published after the analysis of this study and this report increased this percentage to 25%. Therefore, the new reassignment cost estimations should be analysed and the option to reassign the natural gas pipelines to increase the capacity of the pipeline should be reconsidered.

Lastly, it was concluded that a pipeline that combines all the flexibility options and installs one multi-purpose and one single-purpose hydrogen pipeline results in the best performance. However, this study assumed that the construction costs of a second pipeline only includes material costs. In reality there might also be labor costs involved in the construction of the second pipeline. Therefore, the costs of a pipeline design with a combination of a multi-purpose and a single-purpose pipeline might have higher costs than calculated in this research and the designs with just one pipeline might have a higher NPV.

7.2.2 Relation to the assumed demand scenarios

The model developed in this study is aimed to be used for the analysis of the performance of flexible pipeline designs to connect the Port of Rotterdam, Chemelot and North-Rhine Westphalia. Although different demand scenarios already have been applied in this study, only 8 scenarios have subsequently been used and they all show the same trend. Therefore, this section will discuss the results of chapter 6 by evaluating whether the results depend on the demand scenarios of Rotterdam, Chemelot and North-Rhine Westphalia alone or if they are more widely applicable.

Evaluating the results of the designs that included the option to switch between carbon dioxide and hydrogen, were found to have a significantly better NPV than the designs that did not include this option. This is explained by the additional flow and the relatively low costs that the option to transport carbon dioxide involves. At first sight, the benefits of this option are connected to the added demand of carbon dioxide. However, the actual demand will not change this result due to the fact that hydrogen and carbon dioxide complement each other (Bellona Europe, 2018). It has been established that there is a high possibility that carbon capture will serve as a stepping stone to implementation of hydrogen (Bellona Europe, 2018; H-Vision, 2019). Furthermore, if industry decides not to use hydrogen, the pipeline still has the potential to transport carbon dioxide. Equally, when industry will not invest in carbon dioxide, the pipeline is still able to serve as a hydrogen transportation pipeline. Therefore, it is likely that, whatever demand is used for the analysis of the flexibility of multi-purpose pipelines, it is highly likely to show that the NPV will increase when it is compared to a hydrogen pipeline.

Analysing the option to expand, the results illustrated that pipeline designs that installed the ability to increase pressure to expand the capacity of the pipeline scored better than the options that installed a larger diameter. This can be explained by the fact that the compression costs are lower by comparison than the construction of a larger diameter. However, the compression costs are determined by the compressor capacity, which in turn are determined by the flow through the pipeline. Therefore, an increase in demand increases the required compressor capacity and consequently the compressor costs. This illustrates that there might be a turning point when the high demands results in the compressor costs exceeding the costs of installing a greater pipeline. Therefore, it can be concluded that the optimum break-even point between pressure and the diameter is dependent on the applied demand of this study and might not apply in other cases.

Furthermore, it can be concluded that the reassignment of the natural gas pipeline is a relatively low cost option to expand the capacity of the designs and therefore improves the NPV. The cost of installing a greater diameter or increasing the operation pressure to a level that generates the same capacity, is always more expensive than reassigning natural gas pipelines, of which demand scenario is used. However, as this study is limited to the NPV of the new pipeline and does not take the possible demand of natural gas into account, the added value might be less than determined in this study.

Lastly, the sensitivity analysis concluded that the option that provides the ability to deliver 100% pure hydrogen is dependent on the demand of the mobility sector and other sectors that require 99.999 per cent hydrogen purity. This conclusion already indicates the dependence on the demand. In this study, the estimated demand scenarios of the Port of Rotterdam were used and these scenarios were based on the assumption that the hydrogen demand of the mobility sector is solely transported by pipeline. However, in reality, fuel for the mobility sector is also transported by truck. Therefore, further research is required about the demand of the mobility sector: whether a pipeline design that includes all the flexibility options generates the highest NPV here, or not, requires more specific consideration.

This chapter focused on the limitations of this thesis and reflected on the assumptions in the model and in the calculation procedures. By homing in various assumptions, it became clear that the specific character of the assumptions did not affect the outcome that a combination pipeline of all the flexibility options results in the best performance in comparison to the other options.The essential characteristics of the model do not seem to be invalidated by the assumptions that were made.

However, there are two assumptions that works differently: (1) the assumption that the hydrogen demand of the mobility sector is completely covered by pipeline transport and (2) the assumption that compression costs are the only difference between a multi-purpose pipeline and a second purpose pipeline. These assumptions might be a flaw in our study. Therefore, they need further investigation.

The conclusion of this reflection on the limitations of this study is that although the model that was developed and presented here is a snapshot and has not yet been perfected, it works and there is no reason to believe that it cannot become perfected with some extra effort.

8 CONCLUSION AND RECOMMENDATIONS

This chapter concludes this research. First, in section 8.1, the main research question is repeated and the conclusion to the main research question is presented. Next, the conclusions with respect to the sub-questions follow. Section 8.2 and 8.3 present the scientific and societal contributions of this research. Lastly, section 8.4 presents the recommendations for further research and practical recommendations for the Port of Rotterdam, Chemelot and North-Rhine Westphalia.

8.1 CONCLUSION

This thesis had the following research question:

"How do flexible pipeline designs perform for the transportation of sustainable fuels between the Port of Rotterdam, Chemelot and North-Rhine Westphalia from 2025 until 2050?"

A flexible pipeline design that exists of a multi-purpose pipeline and a single-purpose hydrogen pipeline, as well as reassigns the existing natural gas pipelines for the transportation of hydrogen, proved to have the best performance. This design has the flexibility to switch: a multi-purpose pipeline is able to first transport carbon dioxide and can later switch to the transport of hydrogen. This design also has the option to deliver 100% pure hydrogen because a single-purpose hydrogen pipeline that is part of it does not decrease the purity of hydrogen. Furthermore, this design has the flexibility to expand the capacity when the natural gas pipelines are reassigned for the transportation of hydrogen.

Analysing the performance of the flexibility options separately showed that when the option to switch and the option to expand the capacity by reassigning the natural gas pipelines are included in the pipeline design, the NPV increases compared to designs which did not include these options. The option to deliver 100% pure hydrogen only has a high NPV when it is combined with the option to switch. The option to expand the capacity is more economical when a pipeline has the ability to increase the pressure than when a pipeline has a larger diameter.

In order to be able to answer the main research question, first the key uncertainties with regard to the pipeline connection between Rotterdam, Chemelot and North-Rhine Westphalia had to be identified. An analysis of the requirements and objectives of the actors involved established three key uncertainties:

- Should the pipeline transport hydrogen or carbon dioxide?
- What should the capacity of the pipeline be?
- What hydrogen purity level should it deliver?

Secondly, the possible flexibility options that can reduce the effect of the uncertainties on the performance of the pipeline have been defined. The following flexibility options have been established, which form the decision variables of this research: a multi-purpose pipeline that has the option to first transport carbon dioxide and later switch to the transport of hydrogen, a single purpose hydrogen pipeline that is able to deliver 100 % pure hydrogen, reassigning the natural gas pipeline to transport hydrogen and expanding the pipeline capacity by increasing the pressure or the diameter. These flexibility options are then combined to form the flexible pipeline designs which are tested on their performance.

Thirdly, a model was developed to investigate the performance of the flexible pipelines. The flexible design approach by Melese et al. (2017) established that the Net Present Value is a suitable metric to analyse the performance of the flexible pipeline designs. This thesis has presented a more comprehensive NPV model that is able to calculate the costs of a pipeline design based on the characteristics of the gas that flows through the pipeline, which could be hydrogen, carbon dioxide or both after one another. These costs are used to optimize the NPV and determine the performance of flexible pipeline designs that can be used to transport renewable fuels between the Port of Rotterdam, Chemelot and North-Rhine Westphalia.

Lastly, the flexible pipeline designs are analysed with respect to the NPV. The flexible pipeline designs that include all flexibility options have the highest NPV. When analysing the flexibility options separately, the option to switch between carbon dioxide and hydrogen in the design significantly increase the NPV of the pipeline. The option to expand the capacity by reassigning the natural gas pipelines for the transportation of hydrogen also increases the NPV, but less significantly. Having the option to expand the capacity of the new pipeline is more economical when the pressure can be increased than when a larger diameter is installed. The designs that include the option to deliver 100% pure hydrogen only have a high NPV when they are combined with the option to switch.

8.2 SCIENTIFIC CONTRIBUTION

This thesis identifies two gaps in research regarding pipeline design and addresses these gaps. Firstly, it contributes to the emerging research on the flexible design of pipelines by expanding uncertainties that can be analysed. Currently, the main focus of research on flexible pipelines relates to uncertainty about the location of the participants and the quantity of the demand, while there is also uncertainty about what fuel, what amount and what purity level would be requested. These uncertainties do not affect the pipeline length, but rather the pressure, diameter and purity level. This thesis provides an expansion of the flexibility analysis of pipelines. While until now, optimization of the path of the pipeline was included, from now on optimization of the design of the pipeline with regard to the pressure, the diameter and the purity of the gas can also be taken into account.

Secondly, this research filled a research gap with regard to a model that is able to define the characteristics and the design of a *multi-purpose* pipeline and to calculate the associated costs. This was done on the basis of consulting the literature regarding the hydrogen and carbon dioxide pipelines. Most literature establishes a cost model for hydrogen or carbon dioxide, where only the diameter and the length of the pipeline are varied (André et al., 2014; Baufumé et al., 2013; Cerniauskas et al., 2020). Knoope et al. (2013) have expanded these models by including variations in the operating pressure, steel and the terrain of the pipeline. However, this approach was only focused on carbon-dioxide pipelines. It is a merit of this thesis that it combines the findings of these studies into one model that can compare pipeline designs that are suited for the transportation of both hydrogen and carbon dioxide and its associated costs. This means that the cost calculations of the model that is presented in this thesis is the first attempt to compare this kind of multi-purpose pipeline designs with the single-purpose pipeline and is in that respect unique.

8.3 SOCIETAL CONTRIBUTION

The introduction of this thesis stresses the need for a renewable fuel transportation pipeline between Rotterdam, Chemelot and North-Rhine Westphalia to support decarbonization of industrial clusters. However, there is lots of uncertainty about the design of the pipeline, due to many uncertainties about the future technology and policy developments. This thesis analyses flexible pipeline designs based on scientific research. As a result, this research will contribute to a more structured and more scientifically-based debate on the optimal pipeline construction, facilitating more informed decision-making. This reduces the chances of post-decision regret and is likely to reduce the risk on sunk investments.

Furthermore, this research provides valuable insights on how to strategically deploy infrastructure by carrying out an analysis on the value of various flexible designs. This information is relevant for the investing organization TSO, while public actors also benefit from insights into flexible design strategies when they utilize vital infrastructure in the construction of public-private partnerships.

Lastly, although this thesis focuses on the renewable fuel pipeline connection between Rotterdam, Chemelot and North-Rhine Westphalia, the pipeline cost model of this research can be used for the design evaluation of a pipeline connection between other industrial clusters as well.

8.4 RECOMMENDATIONS

8.4.1 Recommendations for further research

Taking the described limitations and assumptions in chapter 7 into consideration, several future research directions can be indicated, such as a detailed study on the difference between a multi-purpose and a hydrogen pipeline design, the actual costs of compression, varying the temperature, velocity and purity of the gas and applying different demand scenarios. A further investigation of these limitations will improve the level of accuracy of the model. In this section, three other options for further research will be discussed. These options are not focused on improving the model, but rather on expanding the use of the model on a broader level.

First of all, further research could be oriented to expanding the scope of this research by including an analysis of the distribution pipelines. Distribution pipelines form the connection between the transmission pipelines and the industries involved and therefore have shorter distances and lower pressure requirements. By including distribution pipelines in the design, the optimal pressure in the transmission pipeline might change and the location of the inlet compressor can be optimized. In addition, as distribution pipelines do not have a specific corridor that they have to follow and the location of the specific industries is uncertain, a complex problem emerges about the route of the distribution pipelines. Therefore, the model of this research can be expanded with the use of graph theory in order to find the optimal topology for the local network at the different industrial settings.

Furthermore, the sensitivity analysis of this research revealed that risks and benefits of the constructions of a combination of a multi-purpose and a hydrogen-only pipeline are sensitive to changes in industrial demand, specifically the demand of the industries that require 100% pure hydrogen. Section 8.5 elaborates on this issue with respect to the mobility sector.

Moreover, there are also limitations in the revenue model of this research. Therefore, another further research direction that is suggested is the expansion of this technical-economical analysis with an institutional analysis. By determining possible contracts in the form of capacity, entry-exit points and time-frame per industry and expanding the revenue model with the ability to analyse the impact of these contracts, the analysis of different pipeline designs will be taken to another level. Consequently, the model will give a more holistic view on the pipeline design between industrial clusters.

Lastly, another interesting direction for further research would be to use the model to analyse other options for hydrogen transport such as methanol or ammonia. As outlined above, hydrogen has a very low energy density, therefore requiring high pressure or large pipelines to transport the same amount of gas compared to natural gas. Furthermore, directly implementing hydrogen in the mobility industry is challenging since engines have to be adjusted to the use of gas instead of fuel. Therefore, when hydrogen is used in a liquid form, such as methanol, the energy density increases, which in turn decreases the costs of the pipeline and eases the implementation of sustainable fuels in the mobility sector. As this research concludes that the added benefit of installing a pipeline that delivers high purity hydrogen for the mobility industry is dependent on the demand of this sector, further analysis could determine if a methanol pipeline instead of a hydrogen pipeline would increase the performance here. By expanding the pipeline cost model with the option to transport methanol and developing new demand scenarios for the use of methanol, it would be possible to evaluate the option of installing a multipurpose pipeline together with for example a methanol pipeline. This would provide new insights into the optimal hydrogen pipeline connection between industrial clusters.

8.5 PRACTICAL RECOMMENDATIONS FOR THE PORT OF ROTTERDAM, CHEMELOT, NORTH-RHINE WESTPHALIA AND GASUNIE

This research aimed to provide an academic foundation for decisions on pipeline designs between Rotterdam, Chemelot and North-Rhine Westphalia. The researcher recommends to further investigate the construction of a multi-purpose pipeline. Research with regard to the decarbonization of industrial clusters revealed that the demand of carbon dioxide and hydrogen are complementary, which results in the significant advantage of a multi-purpose pipeline (Bellona Europe, 2018). This research confirmed the findings on the decarbonisation of industrial clusters in the existing literature, namely that: the results showed that the revenue of a multi-purpose pipeline increases twofold compared to a single-purpose pipeline. Furthermore, in the case that the hydrogen demand does not increase in the future, the pipeline would still be able to transport carbon dioxide. This also works the other way around, when carbon capture does not seem profitable, the pipeline is still able to transport hydrogen.

This research made a first attempt to determine the costs of a multi-purpose pipeline and established that at first sight, the costs do not outweigh the benefits of the extra revenue perspectives. Therefore, it is recommended to do further research into the impact of site specific characteristics on the costs. For example, in this research, carbon dioxide is transported at 9 MPa, meaning that it is transported in a liquid form. However, currently, in the Netherlands, carbon dioxide is transported in gaseous form. Therefore, further research should focus on the possibilities of liquid carbon dioxide transport in the Netherlands.

Relevant to the Port of Rotterdam, Chemelot and North-Rhine Westphalia is also that this research was based on the reassignment costs of the natural gas pipelines and therefore only included extra compression costs as the additional costs of a multi-purpose pipeline. However, a pipeline that is able to transport hydrogen and carbon dioxide might have limitations with respect to meeting the purity requirements of the fuel and therefore extra costs with regard to the cleaning of the pipeline might be involved. Therefore, it is recommended to delve deeper into the various costs that are associated with a multi-purpose pipeline.

A recommendation on a different level is to search for active collaboration with the mobility sector. Until now, the mobility sector is the only sector that requires 100% pure hydrogen. However, this sector has one of the greatest potentials for the use of hydrogen (IEA, 2019). This research confirmed this great potential, since the best performing pipeline design includes the construction of a multi-purpose pipeline in combination with a single-purpose high-purity hydrogen pipeline. This construction significantly increases the costs, but it has the ability to deliver hydrogen to the mobility sector. However, the hydrogen demand in this study is based on the assumption that hydrogen is transported through pipelines, while in the case of the mobility sector it is also transported by truck. Additionally, the hydrogen demand of the mobility sector is very complex to estimate because this sector is not only dependent on the pipeline connection between Rotterdam, Chemelot and North-Rhine Westphalia, but also of a European, or even global hydrogen transportation network. Therefore, it is recommended to do further research on the specific demands of hydrogen in the mobility sector and consider risk-sharing contracts in order to decrease the risk of the installation of a single-purpose pipeline. Finally, it is recommended to analyse broader collaborations in Europe to support the hydrogen transition in the mobility sector.

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A INPUT DATA

The next page presents the demand of the pipeline in mega ton hydrogen or carbon dioxide per year, specified per industrial cluster.

Demand scenario (Mton H2)		2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
1. Hydrogen demand																											
1.1 reference demand	Transport included																										
	Chemelot	0.05	0.06	0.07	0.08	0.09	0.1	0.122	0.144	0.166	0.188	0.21	0.24	0.27	0.3	0.33	0.36	0.376	0.392	0.408	0.424	0.44	0.456	0.472	0.488	0.504	0.52
	NRW	0.06	0.09	0.11	0.14	0.16	0.19	0.29	0.39	0.49	0.59	0.69	0.83	0.98	1.12	1.27	1.41	1.62	1.83	2.05	2.26	2.47	2.93	3.39	3.84	4.30	4.76
	Transport excluded																										
	Chemelot	0.05	0.06	0.07	0.08	0.09	0.10	0.12	0.14	0.17	0.19	0.21	0.24	0.27	0.30	0.33	0.36	0.38	0.39	0.41	0.42	0.44	0.46	0.47	0.49	0.50	0.52
	NRW	0.03	0.03	0.03	0.04	0.04	0.04	0.12	0.20	0.29	0.37	0.45	0.54	0.63	0.72	0.81	0.90	1.06	1.22	1.37	1.53	1.69	2.11	2.53	2.96	3.38	3.80
1.2 low demand	Transport included																										
	Chemelot	0.03	0.03	0.04	0.04	0.05	0.05	0.06	0.07	0.09	0.10	0.11	0.12	0.14	0.15	0.17	0.19	0.19	0.20	0.21	0.22	0.23	0.23	0.24	0.25	0.26	0.27
	NRW	0.03	0.04	0.06	0.07	0.08	0.10	0.15	0.20	0.25	0.30	0.36	0.43	0.50	0.58	0.65	0.73	0.84	0.94	1.05	1.16	1.27	1.51	1.74	1.98	2.22	2.45
	Transport excluded																										
	Chemelot	0.03	0.03	0.04	0.04	0.05	0.05	0.06	0.07	0.09	0.10	0.11	0.12	0.14	0.15	0.17	0.19	0.19	0.20	0.21	0.22	0.23	0.23	0.24	0.25	0.26	0.27
	NRW	0.02	0.02	0.02	0.02	0.02	0.02	0.06	0.11	0.15	0.19	0.23	0.28	0.32	0.37	0.42	0.46	0.54	0.63	0.71	0.79	0.87	1.09	1.31	1.52	1.74	1.96
1.3 high demand	Transport included																										
	Chemelot	0.07	0.08	0.10	0.11	0.12	0.14	0.17	0.20	0.23	0.26	0.29	0.33	0.37	0.41	0.45	0.49	0.51	0.54	0.56	0.58	0.60	0.62	0.64	0.67	0.69	0.71
	NRW	0.08	0.12	0.15	0.19	0.22	0.26	0.40	0.53	0.67	0.81	0.94	1.14	1.33	1.53	1.73	1.92	2.21	2.50	2.79	3.08	3.37	4.00	4.62	5.25	5.87	6.50
	Transport excluded																										
	Chemelot	0.07	0.08	0.10	0.11	0.12	0.14	0.17	0.20	0.23	0.26	0.29	0.33	0.37	0.41	0.45	0.50	0.52	0.54	0.56	0.58	0.61	0.63	0.65	0.67	0.69	0.72
	NRW	0.04	0.04	0.05	0.05	0.05	0.06	0.17	0.28	0.39	0.51	0.62	0.74	0.87	0.99	1.11	1.24	1.45	1.67	1.89	2.11	2.32	2.90	3.48	4.06	4.64	5.23
		CO2															**H2**										
2. Green H2 future	Chemelot	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.49	0.51	0.54	0.56	0.58	0.60	0.62	0.64	0.67	0.69	0.71
	NRW	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	1.23	1.44	1.66	1.88	2.09	2.31	2.88	3.46	4.03	4.61	5.19
3. Blue H2 future	Chemelot	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.49	0.49	0.49	0.49	0.49	0.60	0.60	0.60	0.60	0.60	0.71
	NRW	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.23	1.24	1.26	1.28	1.29	2.31	2.22	2.13	2.04	1.95	5.19
4. Low incentives	Chemelot	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.36	0.36	0.36	0.36	0.36	0.44	0.44	0.44	0.44	0.44	0.52
	NRW	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.90	0.92	0.93	0.95	0.96	1.69	1.60	1.51	1.43	1.34	3.80
5. CO2 transition to green H2	Chemelot	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.36	0.36	0.36	0.36	0.36	0.44	0.44	0.44	0.44	0.44	0.52
	NRW	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.90	0.90	0.90	0.90	0.90	1.69	1.69	1.69	1.69	1.69	3.80
6. Late blue H2 future	Chemelot	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.36	0.38	0.39	0.41	0.42	0.44	0.46	0.47	0.49	0.50	0.52
	NRW	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	0.90	1.06	1.22	1.37	1.53	1.69	2.11	2.53	2.96	3.38	3.80
7. Alternative future	Chemelot	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.19	0.19	0.20	0.21	0.22	0.23	0.23	0.24	0.25	0.26	0.27
	NRW	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.46	0.54	0.63	0.71	0.79	0.87	1.09	1.31	1.52	1.74	1.96
8. CO2 transition to other alternatives	Chemelot	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.19	0.19	0.20	0.21	0.22	0.23	0.23	0.24	0.25	0.26	0.27
	NRW	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.46	0.54	0.63	0.71	0.79	0.87	1.09	1.31	1.52	1.74	1.96
9. CCS dominance	Chemelot	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.19	0.19	0.20	0.21	0.22	0.23	0.23	0.24	0.25	0.26	0.27
	NRW	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	0.46	0.54	0.63	0.71	0.79	0.87	1.09	1.31	1.52	1.74	1.96

Figure A.1: Overview of the demand data

B PRACTICAL MODEL DESCRIPTION

This section gives a practical description of the use of the model:

1. The model requires the input data which is delivered in two excel files. One excel file presents the design of the pipeline by specifying the value 8 variables (figure B.1):
    - Type: multi-purpose(=2) or single-purpose(=1)
    - Diameter: the diameter of the pipeline(m)
    - Pin H2: the inlet pressure of hydrogen in the first pipeline(MPa)
    - Pin CO2: the inlet pressure of carbon dioxide in the first pipeline
    - R: reassignment of the natural gas pipelines (=1) or not (=0)
    - Second: the installation of a second single-purpose hydrogen pipeline(=1) or not(=0)
    - diameter2= the diameter of the second single-purpose hydrogen pipeline(0.6 in this research)
    - Pin2: the opearting pressure of hydrogen in the second pipeline

A	B	C	D	E	F	G	H
Type	Diameter	Pin H2	Pin CO2	R	second	diameter2	Pin2
1	0.6	4	0	0	0	0	0
1	0.6	5	0	0	0	0	0

Figure B.1: Example of excel file data pipeline designs

The second Excel file presents the demand scenarios(B.2). The first line presents the demand of hydrogen and carbon dioxide, excluding the demand of the mobility sector. The second line presents the total hydrogen demand, including the mobility sector.

A	B	C	D	E	F	G	H	I	J	K
Scenario 1										
2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03
0.15	0.20	0.25	0.30	0.35	0.40	0.56	0.73	0.90	1.06	2.38
Scenario 2										
2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
0.11	0.15	0.18	0.22	0.25	0.29	0.41	0.53	0.66	0.78	1.07

Figure B.2: Example of excel file data demand scenarios

2. The construction costs are calculated using equation [2],[4],[5],[6],[7] and [8]

3. Thereafter, the compression costs are determined using equation [9] for the compression of hydrogen and [10] for the compression carbon dioxide. To determine the capacity of the initial compressor, requested inlet pressure (Pin_H2 for single-purpose hydrogen pipeline, Pin_Carbon dioxide for a multi-purpose pipeline or Pin_H2_2 for a design with a second single-purpose hydrogen pipeline) is used as the value of P1 and P2 has the value of the pressure of which the gas leaves it source(=3 MPa hydrogen, =0.1MPa carbon dioxide). In order to determine the number of intermediate compressors and their capacity, the following statements are used(hydrogen is used as example but these statements are also used but the characteristics of hydrogen are than replaced

by the transportation characteristics carbon dioxide):

Number of intermediate compressors:

Pout = Pin H2 if Pin H2 - total pressure drop H2 [15] >Pout H2
number of compressors = 0

else:

if Pin H2 - total pressure drop H2[15] >Pmin:

number of compressors = 1

else:

number of compressors = total pressure drop [15] / (Pin H2 - Pmin)

Capacity of the intermediate compressors:

pressure drop per km H2 = total pressure drop H2 /(L/1000)
distance between compressors = L / (number of compressors +1)/1000
P1 H2 = Pin H2
if number of compressors = 0:

P2 H2 = 0

else:

if number of compressors ≤ 1 :

P2 H2 = Pin H2 - total pressure drop H2

else:

P2 H2 = Pin H2 - pressure drop per km H2 * distance between compressors

W H2 = P1 H2 - P2 H2 /efficiency * Q H2' / rho H2

4. The pumping costs[23] and the reassignment costs are determined [24]. The number of pumping stations and their capacity are determined using the same statements as are used for the amount and capacity of the compressors costs. Then, the total CAPEX [25] is calculated by adding up the construction,compression, pumping and reassignment costs.
5. The operation costs are determined from the CAPEX of the pipeline using equation [28]

6. The revenue is determined using equation [29]. The yearly flow of the pipeline(Q) is determined using the following statement:

```
Data scenarios row 1 = demand MP

Data scenarios row 2 = demand SP

Capacity_1_H2 = v_H2 * rho_h2 *( pi *(Diameter /1000)**2 / 4)*365*24*60*60/(10**9)

Capacity_1_H2 = v_CO2 * rho_CO2 *( pi *(Diameter /1000)**2 / 4)*365*24*60*60/(10**9)

Capacity_2 = v_H2 * rho_h2 *( pi *(diameter2 /1000)**2 / 4)*365*24*60*60/(10**9)

Capacity_NG = v_H2 * rho_NG *( pi *(D_NG/1000)**2 / 4)*365*24*60*60/(10**9)

If type = 1:

    If R = 1

        If demand SP - (capacity_1 + capacity_NG) >0

            Q = demand SP - (capacity_1_H2 + capacity_NG)

        Else:

            Q = capacity_1_H2 + capacity_NG

If type = 2:

    If second = 1

        If R = 1

            If year <15

                If demand MP - capacity_1_CO2 >0

                        If demand SP - (capacity_2_H2 + capacity_NG) >0

                            Q = demand MP - capacity_1_CO2 + demand SP - (capacity_2_H2 + capacity_NG)

                        Else:

                            Q = demand MP - capacity_1_CO2 + (capacity_2_H2 + capacity_NG)

                Else:

                    If demand SP - (capacity_2_H2 + capacity_NG) >0
```

```
                    Q = capacity_1_CO2 + demand SP -(capacity_2_H2 + capacity_NG)
                Else:
                    Q = capacity_1_CO2 + (capacity_2_H2 + capacity_NG)
    Else:
        If year <15
            If demand MP - capacity_1_CO2 >0
                If demand SP - (capacity_2_H2) >0
                    Q = demand MP - capacity_1_CO2 + demand SP - (capacity_2_H2)
                Else:
                    Q = demand MP - capacity_1_CO2 + (capacity_2_H2)
            Else:
                If demand SP - (capacity_2_H2) >0
                    Q = capacity_1_CO2 + demand SP -(capacity_2_H2)
                Else:
                    Q = capacity_1_CO2 + (capacity_2_H2)
Else:
    If R = 1
        If year <15
            If demand MP - capacity_1_CO2 >0
                Q = demand MP - capacity_1_CO2
            Else:
                Q = capacity_1_CO2
        Else:
            If demand MP - (capacity_1_H2 + capacity_NG)>0
```

Q = demand MP - (capacity_1_H2+ capacity_NG)

Else:

Q = capacity_1_H2 + capacity_NG

Else:

If year <15

If demand MP - (capacity_1_CO2 >0

Q = demand MP - (capacity_1_CO2

Else:

Q = capacity_1_CO2

Else:

If demand MP - (capacity_1_H2)>0

Q = demand MP - (capacity_1_H2)

Else:

Q = capacity_1_H2

7. The NPV in this scenario is calculated using equation [1]

C LIST OF ASSUMPTIONS

Assumption	Value
Velocity H2 (v_h2)	20 m/s
Velocity CO2 liquid(v_co2liquid)	2.5 m/s
Velocity CO2 gas (v_co2gas)	15 m/s
Temperature (T)	285 K
Connection fee (α)	0.1 €/kg
Molar mass hydrogen	2.02
Molar mass CO2	40.01
Steel price (Csteel)	1.49 €/kg
Density steel (ρsteel)	7900kg/m3
Efficiency compressor (η)	75%
Efficiency pumping station (η)	75%
Gas constant (R)	0.0082
Hydrogen pressure electrolyse	3MPa
Carbon dioxide pressure at source	0.01MPa
Natural gas pipeline pressure	4 MPa
Length pipeline path (L)	200km
Discount rate (r)	8%
The mean height of roughness of the pipe (ϵ)	0.000005 mm
Minimum Yield Stress (S)	500 MPa
Design factor related to the terrain(F)	0.5
Longitudinal joint factor (E)	1
Corrosion allowance (CA)	0.001 meter
Design lifetime of pipeline	50 years
Design lifetime of compressors and pumping stations	25 years
O&M pipeline	1.5%
O&M compressor and pumping stations	4%
Steel price increase	25%
Minimum pressure hydrogen and gaseous carbon dioxide	1.5 MPa
Minimum pressure liquid carbon dioxide	8 MPa

Table C.1: List of assumptions and constants.

D RESULTS: OPTIMAL CAPACITY ANALYSIS

In total, almost 2500 pipeline designs are analysed under 8 future scenarios. It was not relevant and too encompassing to discuss the performance of each of these 2500 pipeline designs. Therefore, the discussion of the results was reduced by applying a framework that is presented in figure 6.2. By this process, the optimal capacity per strategy, per scenario was analysed. However, these results exclude some interesting information about the relation between the diameter, the pressure and the average NPV of the pipeline. Therefore, this section covers a discussion of the optimization of the capacity. This section is divided into 4 experiments, the optimal capacity of (1) a hydrogen pipeline, (2) a multi-purpose pipeline, (3) a hydrogen and multi-purpose pipeline and lastly when the capacity of the natural gas pipelines is added to the capacity of the network.

D.1 A HYDROGEN PIPELINE

This experiment covers the analysis of pipeline designs that transport only hydrogen. The diameter of the pipeline is tested for the value of 0.6, 0.9, 1.05 and 1.2 meters and the average pressure is varied from 4 to 25 MPa in increments of 1 MPa. Figure D.1 shows the relation between the diameter and the pressure and the resulting average NPV.

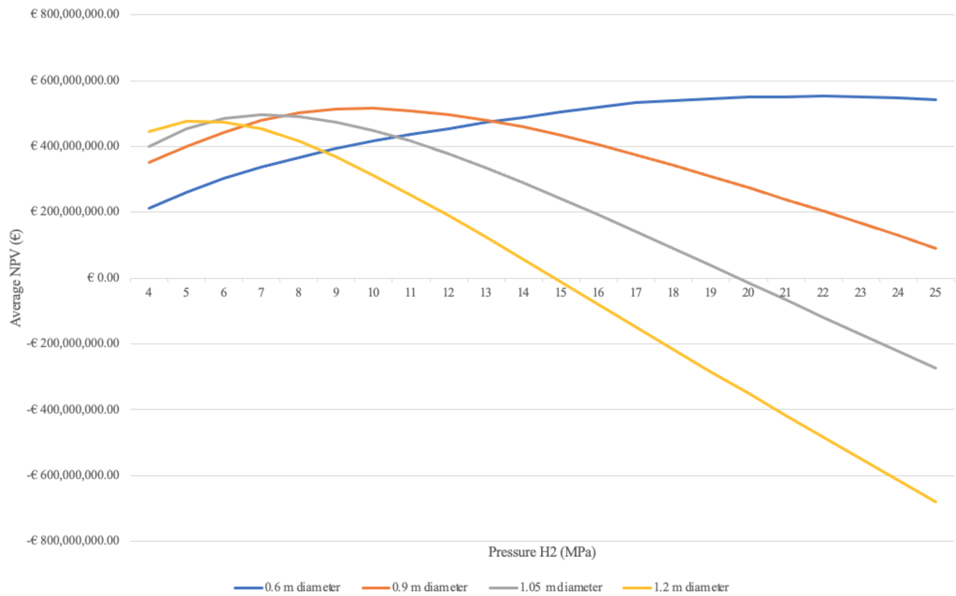

Figure D.1: The average NPV of the hydrogen pipeline designs

From the figure, it can be concluded that the optimal operation pressure increases when the diameter decreases. This can be explained by the fact that a large diameter already meets the demand of hydrogen. Therefore, the pressure does not have to be increased to meet the capacity requirements and this will as a result save on compression costs. Furthermore, the pressure shows to have a greater impact on the NPV when the diameter is increased. This is due to a large diameter already delivering the required capacity when a low operating pressure is installed. Consequently, the compression costs only increase the CAPEX and do not increase the revenue.

Another conclusion that can be drawn from the figure is the fact that the installation of a larger diameter has a significant impact on the costs of the pipeline, greater than the costs of compression. Therefore, it is more efficient to increase the pressure of the pipeline instead of the diameter to increase the capacity.

In this case study, the optimum transportation conditions are a 0.6 m diameter pipeline with an operating pressure set at 20 MPa. Not only does this deliver the highest average NPV, but the effects of setting a higher or lower transportation pressure also, have lesser effect on the costs than in case of installing a greater diameter.

D.2 A MULTI-PURPOSE PIPELINE

This section covers the analysis of pipelines that first transport carbon dioxide but can be reassigned to the transportation of hydrogen. In order to have an indication of the optimal hydrogen transportation pressure in a multipurpose pipeline, the transportation pressure of hydrogen is varied between 4, 10, 15 and 20 MPa. Furthermore, a diameter of 0.6, 0.9, 1.05 and 1.2 meter are tested and the carbon dioxide pressure is set at 3 MPa (for gaseous transport CO2) and from 8 MPa to 15 MPa, in increments of 1 MPa. Beside varying the pressure and the diameter, this experiment is also split into three smaller experiments that differ in the year of reassignment.

Figure D.2 presents the average NPV of all options where the blue bars present the NPV when the pipeline is switched between carbon dioxide in 2030, the orange bars in 2035 and the grey bars in 2040. This figure shows a significant increase in the average NPV when the year of reassignment is postponed and no difference in the relation between the diameter and the operating pressure. Therefore, in further analysis, the average NPV of the pipeline designs where the pipeline is reassigned in 2040 are used.

Figure D.3 presents the relation between the average NPV (2040), the diameter and the operating pressure of hydrogen and carbon dioxide. The figure illustrates a negative relation between the diameter and the average NPV. The same trend was seen when analysing a hydrogen pipeline, but is steeper when it contains a multipurpose pipeline because of the relatively stable and high carbon dioxide demand which is already met when a small diameter is installed. Therefore, increasing the diameter does not bring an advantage and significantly increases the costs. Although the hydrogen demand does exceed the capacity, increasing the pressure to 10 or 15 MPa is a more economical solution than increasing the diameter to 1 meter or above.

Comparing the NPV gaseous carbon dioxide transport (pressure = 3MPa) to the NPV of liquid carbon dioxide transport (pressure >5 MPa), it can be concluded that gaseous carbon dioxide transport is not profitable in this case study. Although the low density of carbon dioxide in the gaseous phase means the same amount can be transported in a smaller pipeline, it requires the installation of compressors, which are more expensive than pumping stations used for liquid carbon dioxide. Therefore, the greater capacity offered by gaseous carbon dioxide does not outweigh the extra costs of compression. However, when the demand of carbon dioxide is increasing, gaseous carbon dioxide can possibly create a economical advantage.

Zooming in on liquid carbon dioxide transport, the figure shows that in most cases, increasing CO2 pressure decreases the average NPV and that a pressure of 8-

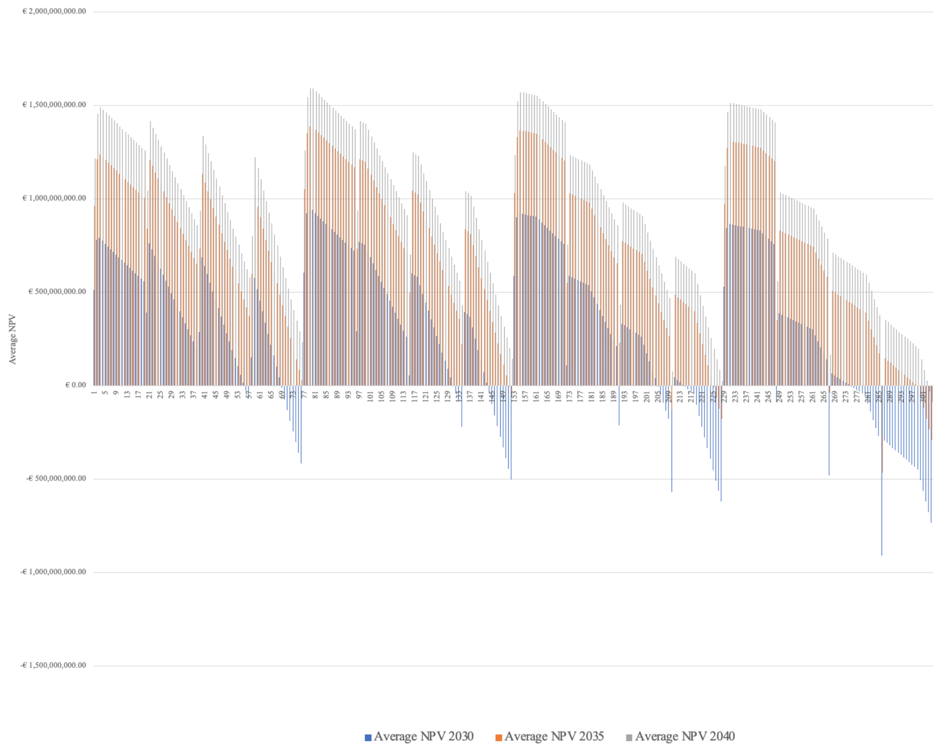

Figure D.2: The average NPV of the multipurpose pipeline options

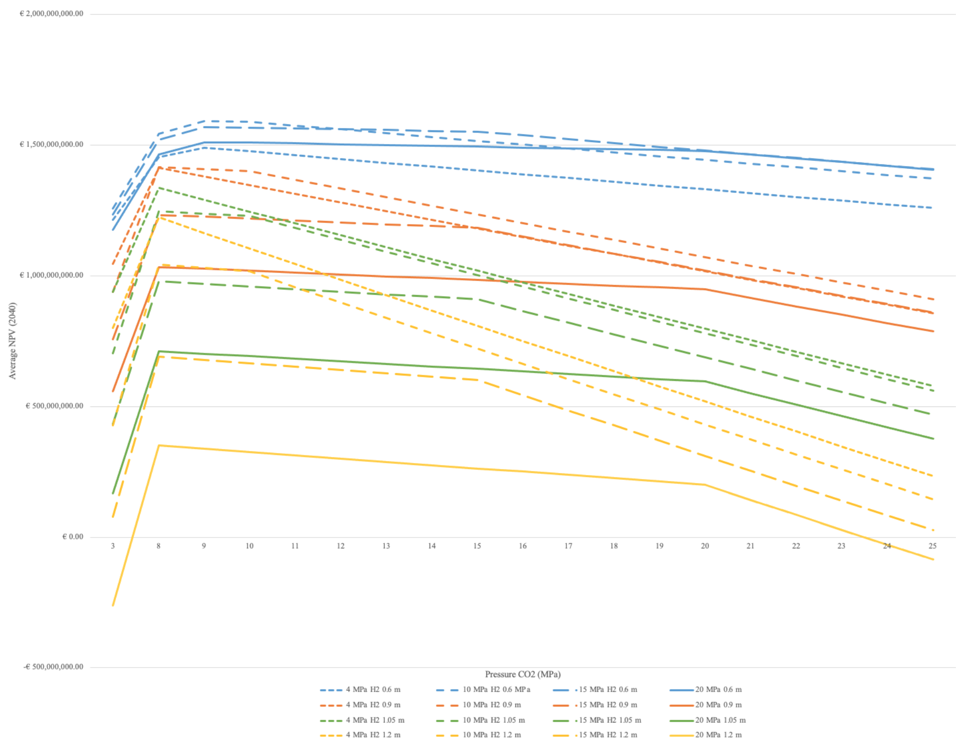

Figure D.3: The average NPV of the multipurpose pipeline options when the pipeline is reassigned in 2040

9 MPa generates the highest NPV. The decrease in NPV due to increasing pressure is greater when a large diameter is installed, however, the decrease is less steep when it is compared to a hydrogen pipeline because of the relatively low pumping

costs and the positive influence of relative stable and high carbon dioxide demand on the revenue. In this case study, a 0.6 m diameter pipeline with 8-10MPa carbon dioxide pressure shows the highest NPV.

Focusing on the effect of the hydrogen pressure, the figure shows, again, that the optimal operating pressure of hydrogen increases when the diameter is decreased. Figure D.4 selected the designs with 0.6 m diameter and 9 MPa in order to get a better understanding of the optimal pressure. This figure illustrates that the optimal pressure is at 10 MPa.

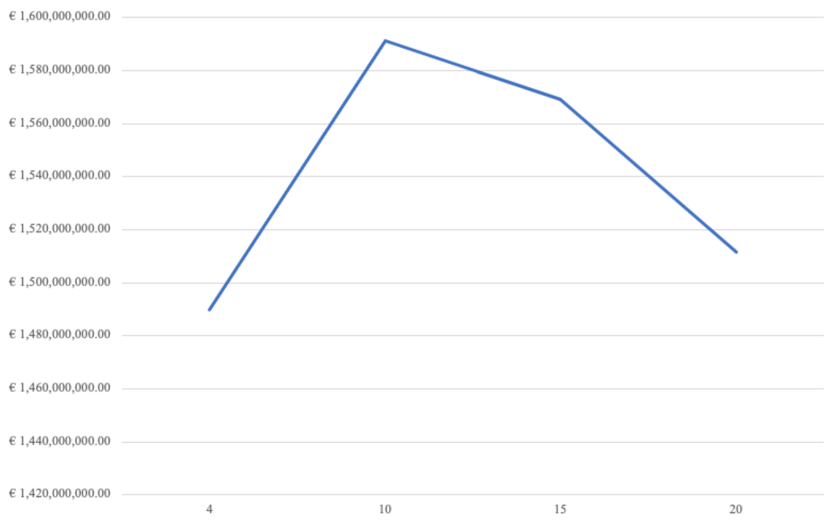

Figure D.4: The relation between the hydrogen pressure and the average NPV(2040)

D.3 A HYDROGEN AND MULTI-PURPOSE PIPELINE

This experiment covers the analysis of a combination of a multi-purpose and hydrogen pipeline. In order to evaluate the possibilities to expand the capacity of the pipeline, the hydrogen pressure in both the multi-purpose and hydrogen pipeline are varied between 4, 10, 15 and 20 MPa. Since experiment 2 showed that carbon dioxide transport at the tested minimum of 3 MPa (gas) and anything tested above 13 MPa is not profitable, these options are excluded in this experiment. Therefore, the carbon dioxide pressure is varied between 8 and 13 MPa. As the capacity of one 0.9 meter pipeline already showed a relative low NPV, in this design only pipelines with a 0.6 m diameter are included. Furthermore, the year of reassignment is also kept constant at 2040 since the construction of an extra hydrogen pipeline would only benefit from late reassignment. Figure D.5 shows the average NPV and the relation to the pressure of carbon dioxide and hydrogen in both pipelines.

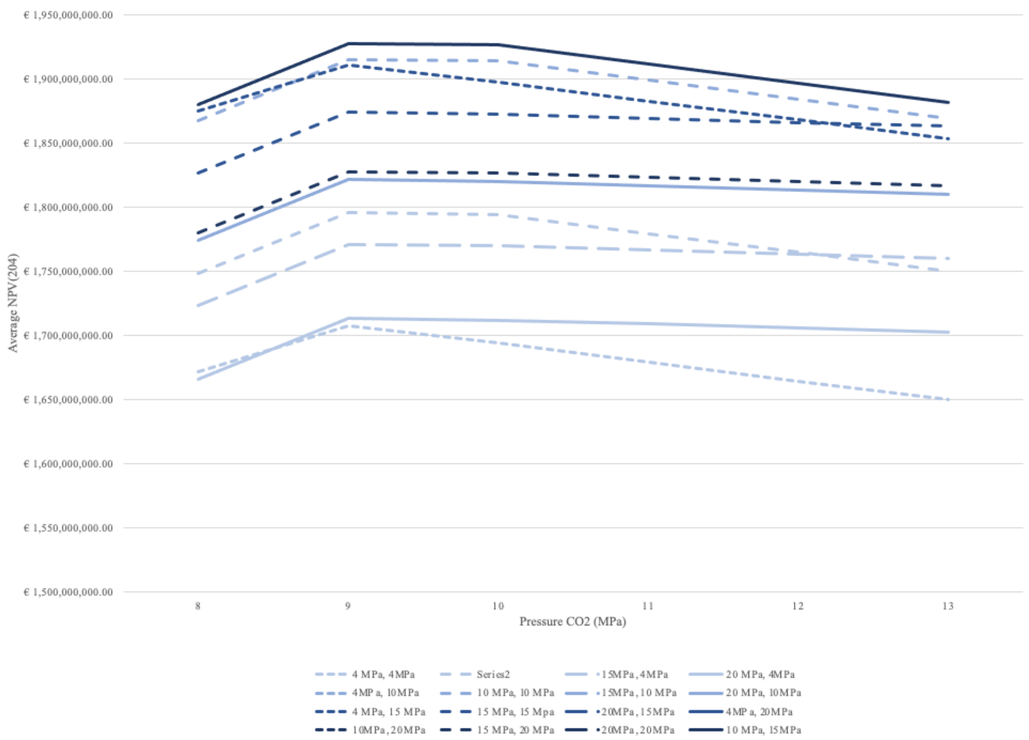

Figure D.5: The average NPV of pipeline designs that combined a hydrogen and multi-purpose pipeline

The figure shows that the carbon dioxide has an overall optimum at 9 MPa. In order to get a better understanding of the relation between the hydrogen pressures in both pipelines, only the options with 9 MPa carbon dioxide pressure are selected and the eight combinations for the transportation pressure of hydrogen are compared on the difference in NPV.

This figure illustrates that the highest NPV is reached by combining a multi-purpose pipeline of 10 MPa with a hydrogen pipeline of 15 MPA. Looking at the relation between the hydrogen pressure in the multi-purpose pipeline and the hydrogen pipeline, what can be seen is that it is not profitable to set a high hydrogen pressure in the multipurpose pipeline or a low hydrogen pressure in the hydrogen pipeline. This can be explained by the fact that the total capacity of the multi-purpose pipeline and hydrogen pipeline with 10 MPa or higher meets industrial de-

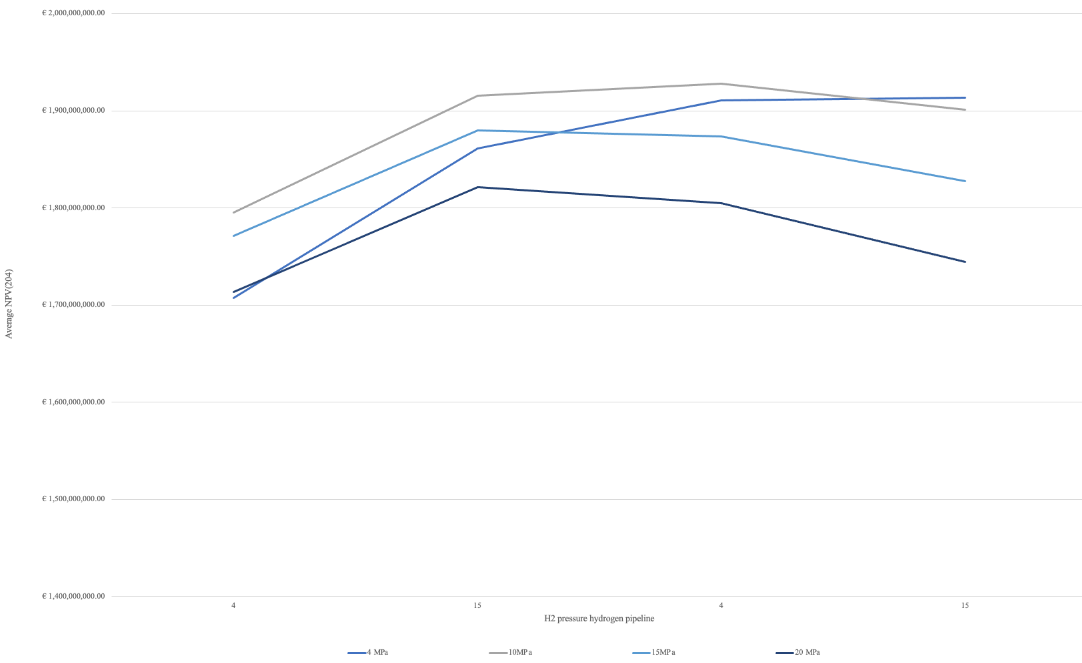

Figure D.6: The relation between the hydrogen pressure and average NPV of a combined multi-purpose and hydrogen pipeline design

mand where low purity is sufficient. Therefore, the pressure in the multi-purpose pipeline does not have to be increased further than 10 MPa. However, the total demand of all industries (including the ones with high purity requirements) is not met with this capacity and since only the hydrogen pipeline can transport this extra demand, the pressure in the hydrogen pipeline has to be increased up to 15 to 20 MPa.

D.4 THE ADDITION OF THE CAPACITY OF THE NATURAL GAS PIPELINES TO THE DESIGN

This experiment covers the analysis of the same pipeline designs as experiment 1, 2 and 3 but in this experiment the capacity can be expanded with capacity of the natural gas pipelines. Figure D.7 presents the relation between the average NPV, the diameter and the operating pressure of a combination with a hydrogen pipeline, figure D.8 presents the same relation with a multipurpose pipeline and figure D.9 looks at a hydrogen and multipurpose pipeline.

The figures show that, in general, the optimal operating pressure decreases when the capacity of the natural gas pipelines is added to the design. This can be explained by applying the same relation that was derived in experiment 1: enforcing a high operating pressure in pipelines with a capacity that already exceeds the demand only increases CAPEX and does not provide revenue to speak of in return. With the extra capacity of the natural gas pipelines, turning point is reached at a lower pressure level.

In addition, it can be concluded that the carbon dioxide pressure has an overall optimum at 9 MPa. In order to get a better understanding of the relation between the hydrogen pressures in a design that combines a hydrogen pipeline with a multipurpose pipeline, only the options with 9 MPa carbon dioxide pressure are selected and the eight combinations for the transportation pressure of hydrogen are com-

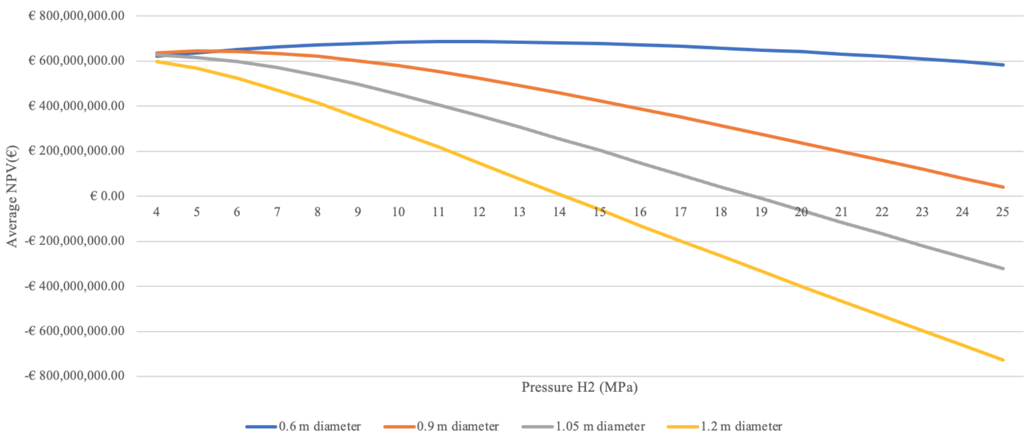

Figure D.7: The average NPV of a hydrogen pipeline design expanded with the capacity of the NG pipeline

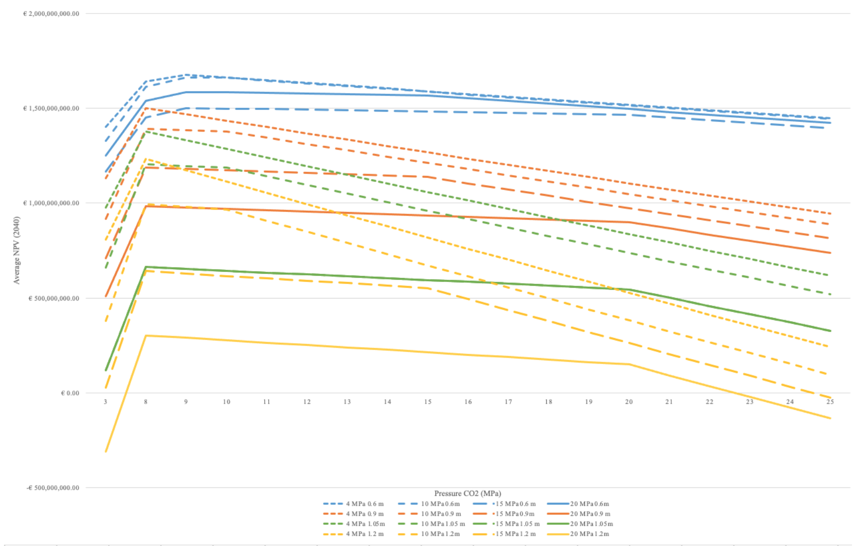

Figure D.8: The average NPV of a multi-purpose pipeline design expanded with the capacity of the NG pipeline

pared on the difference in NPV.

The figure illustrates the same trend as seen in experiment 3 as the pressure of the hydrogen pipeline is dependent on the demand of the industries that require high purity and the hydrogen pressure of the multi-purpose pipeline is dependent on the demand of the industries with low hydrogen purity requirements. However, when the capacity of the natural gas pipeline is included in the design, the overall transport pressure of hydrogen decreases. In this case study, the industrial demand with low purity requirements is already met at a pressure of 4MPa in both pipelines and industries that require a higher purity are provided for when the pressure in the hydrogen pipeline is increases to 10 MPa.

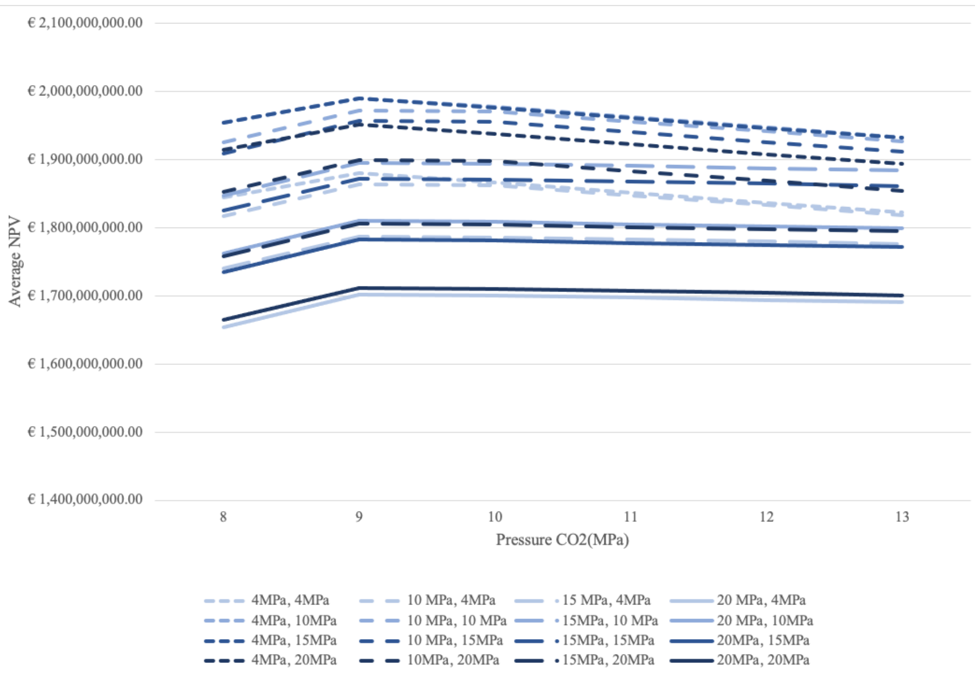

Figure D.9: The average NPV of a combined hydrogen and multi-purpose pipeline design expanded with the capacity of the NG pipeline

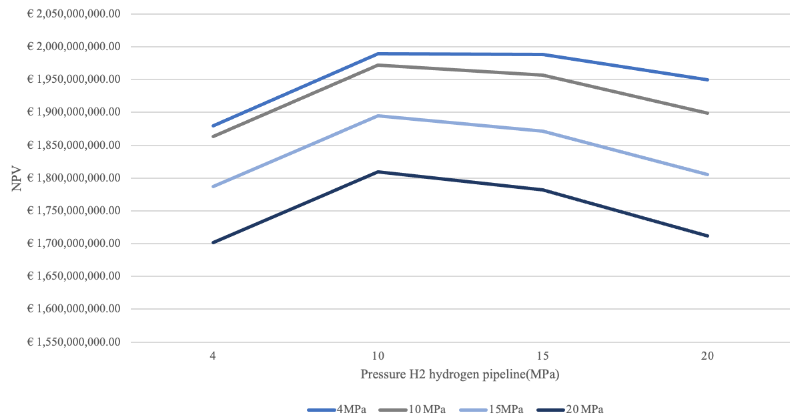

Figure D.10: The relation between the hydrogen pressure and average NPV of a combined multi-purpose and hydrogen pipeline design that is expanded with the NG pipeline capacity

Summarizing, the results of the analysis of the option to expand by either increasing the pressure or increasing the diameter show the following:

- When one wants to have the possibility to expand the capacity of the pipeline, it is more economical to install a pipeline that has the ability to increase the pressure instead of installing a large diameter. Furthermore, when a small diameter is installed, increasing the maximum operating pressure has less impact on the NPV.
- The hydrogen pressure level decreases when the option to first transport carbon dioxide or the capacity of the natural gas pipelines are included to the design. When a single- and multi-purpose pipeline are combined, the pressure of hydrogen is dependent on the demand of the industries that require high purity hydrogen.
- The pressure of carbon dioxide is more or less constant in all designs