Distilling the Perspectives On Blue Hydrogen

A Social Cost Benefit Analysis of Using Blue Hydrogen for Decarbonising High Temperature Heat Demand within Refineries in the Port of Rotterdam

Master Thesis - Management of Technology

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Delft University of Technology

TU Delft

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A Social Cost Benefit Analysis of Using Blue Hydrogen for Decarbonising High Temperature Heat Demand within Refineries in the Port of Rotterdam

by

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Cover: Global Warming Warning Stripes by Professor Hawkins, 2018

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Preface

This thesis, titled ' Distilling the Perspectives On Blue Hydrogen ', marks the end of my Masters Program in Management of Technology at the TU Delft. It sums up the work that I have conducted from February 2024 until July 2024. I feel grateful to have had the opportunity to work together with a supportive and inspiring group of people during this period.

The overall academic journey at the TU Delft over the past two years has provided me with wide spread knowledge and gave me a lot of inspiration. These experiences not only improved my understanding but also deepened my interest and commitment to the field of technology.

I would like to extend my gratitude to my first supervisor, Mar Perez-Fortes, whose critical mind and inspiring discussion have challenged me to think critically. The conversations we had made my rethink my research from different angles. Her energy in guiding me through the learning experience of this thesis was amazing. I would like to express my gratitude to my thesis committee for their support throughout the research journey. I want to thank committee-chair Niek Mouter for the help during this thesis, socio-economic research opened new perspectives for me regarding the importance of public value. The feedback and insightful lectures of my second supervisor, Servaas Storm provided me with a new way of thinking that significantly contributed to this academic journey. I want to thank the PhD group for their inspiration and for letting me take part in the bi-weekly meetings. I also want to thank my fellow master student Marnix de Koning, for helping me in reviewing and discussing my work and for being a great study buddy during the Masters program.

Finally, I would also like to express my gratitude to my family, friends, and partner Floor, who have supported me throughout every breakthrough and breakdown during my study period.

Now that I have finished my technician degree, bachelor's degree, and master's degree, this accomplishment marks the end of this chapter in my academic career. But as time has taught me, one should never rule out the possibility of starting another academic project in the future.

I hope you find this thesis both informative and engaging.

Sincerely,

S.W.J. van Dongen
Delft, July 2024

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Executive Summary

The refineries in the Port of Rotterdam are significant contributors to CO_2 emissions. They account for 20% of the Dutch industrial CO_2 emissions and 6% of the national CO_2 emissions. These significant emission contributions present a challenge in aligning refineries in the Port of Rotterdam with the EU and Dutch decarbonisation targets. Within these refineries, high temperature heat emissions represent a significant share, accounting for +/- 70% of the total emissions.

Blue hydrogen is seen as an emerging and promising solution for the decarbonisation of high temperature heat demands in industrial processes of refineries. It can serve as a direct replacement for fossil fuels, significantly reducing carbon emissions. Existing studies have primarily focused on the technical and commercial feasibility from a corporate perspective, often overlooking a more comprehensive and holistic perspective that considers the public viewpoint.

The goal of this thesis is to determine the net social and economic impact of using blue hydrogen for decarbonising high temperature heat generation in refineries within the Port of Rotterdam (PoR) (NL), from the perspective of the corporate and public. This thesis answers the following main research question:

"What are the costs and benefits of using blue hydrogen for the decarbonization of high temperature heat generation within refineries in the Port of Rotterdam considering the Dutch/EU net zero targets in 2050, from the perspective of the corporate versus the public?"

To answer this question, a Social Cost Benefit Analysis (SCBA) is performed according to EU guidelines. This involves projecting a business as usual scenario (BAU) based on EU guidelines, which include a reference scenario forecasting future refinery emissions and high temperature energy demand based on 2020 policies and assumptions. This original EU BAU scenario is not set-up to reach the climate targets. The assessed blue hydrogen intervention scenario, is configured to reach the 2030, 2040, and 2050 climate targets. The costs and benefits that occur from implementing the intervention scenario will be identified from the corporate and public perspective. This in order to determine an overall value for each perspective and to identify any potential differences between them.

The BAU reference scenario projects a decline in energy demand and CO_2 emission from refineries. High temperature heat demand from refineries located in PoR is expected to decrease from 96.6 PJ in 2020 to 34 PJ by 2050. CO_2 emissions resulting from high temperature heat within PoR refineries are forecasted to decline from 6.4 Mtpa in 2015, to 2 Mtpa by 2050 under the BAU scenario. This projected decline is mainly driven by current policy measures decreasing fuel needed for mobility and the general decrease in demand for refinery products.

The difference between the CO_2 emissions in the BAU scenario and the emission reduction targets of the EU/Netherlands determines the amount of CO_2 reduction that is needed. Based on this, the size and scope of the intervention scenario is configured, aiming to reach the CO_2 reduction targets through the implementation of blue hydrogen for combustion purposes.

The intervention scenario involves the centralized production of blue hydrogen using a Auto Thermal Reformer (ATR) combined with Carbon Capture & Storage (CCS). The input of the ATR consists of refinery fuel gas, a byproduct of the refinery which is normally used for heat generation, supplemented with natural gas. The hydrogen capacity that is needed to reach the CO_2 reduction targets compared to the BAU scenario, consists of an installed capacity of 1400 MW which is capable of delivering 289 kt of blue hydrogen per year. This results in a total CO_2 emission reduction of 44.4 Mt in the time period between 2024 and 2050 compared to the BAU scenario. This reduction is necessary to meet the Dutch and EU decarbonisation targets.

For the intervention scenario, the direct, indirect, and external effects are identified for both perspectives. The most significant direct effects are the CAPEX costs for hydrogen production, CO_2 transport

and storage and the benefits of avoided EU ETS costs. The most significant indirect effects are the investments in hydrogen infrastructure and potential subsidies to support the intervention scenario. The most significant external effects are the societal benefits due to CO_2 reduction and the improved public health.

This study finds that blue hydrogen offers a potential solution for decarbonizing high temperature heat generation in refineries but that there is a significant valuation difference between corporate and public value. The NPV from a corporate perspective is 172 MEUR this is based on a cost of 4,009 MEUR and a benefit of 4,181 MEUR. The NPV of the public perspective is 8,834 MEUR this is based on a cost of 6,057 MEUR and a benefit of 14,891 MEUR. This difference highlights the broader societal and environmental benefits that are not fully captured in corporate financial metrics. The main factor in the discrepancy between the two perspectives is the difference in valuation of CO_2 emissions. The CO_2 EU ETS price does not fully incorporate the external cost of carbon, this is due to currently undervalued pricing.

Addressing the significant difference in the valuation of the blue hydrogen intervention could involve implementing targeted policy measures. This can be achieved by studying the impact of raising the EU ETS price to narrow the difference in the valuation of CO_2 prices between the corporate and public perspective. The results from this thesis highlight that the EU ETS Price seems to not fully internalize external effects. A localised policy measure that could be used is the increase of the Dutch CO_2 Levy. The recommendation is to assess the appropriate Dutch CO_2 Levy to correctly value external effects that the EU ETS does not take into account.

Further research could provide insight in the potential mechanisms between the increased Dutch CO_2 levy and a corresponding increase in a subsidy such as the SDE++ subsidy. This research can assess the effectiveness of creating a mechanism where emitters fund the subsidies for those willing to decarbonize via the increased Dutch CO_2 Levy revenues.

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Nomenclature

Abbreviations

Abbreviation	Definition
ATR	Auto Thermal Reformer
BAU	Business as Usual
BH_2	Blue Hydrogen
CAPEX	Capital Expenditure
CBA	Cost Benefit Analysis
CEA	Cost Effectiveness Analysis
CH_4	Methane
CCS	Carbon Capture and Storage
CFD	Contract for Difference
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
ETS	Emissions Trading System
EU	European Union
GDP	Gross Domestic Product
GHG	Greenhouse Gas
H_2	Hydrogen
HTH	High Temperature Heat
IRR	Internal Rate of Return
LCOH	Levelized Cost of Hydrogen
LNG	Liquefied Natural Gas
MCA	Multi-Criteria Analysis
NG	Natural Gas
NOx	Nitrous oxides
NPV	Net Present Value
OPEX	Operational Expenditure
PJ	Petajoule
PSA	Pressure Swing Absorber
RFG	Refinery Fuel Gas
ROI	Return on Investment
SDE++	Stimulation of Sustainable Energy Production and Climate Transition
SCBA	Social Cost Benefit Analysis
TAR	Turn Around (Maintenance Period Refinery)
WLO	Welvaart en Leefomgeving (Welfare and Environment)
Units of Measure	
€/MWth	Euros per Megawatt Thermal
€/kg	Euros per Kilogram
€/MWh	Euros per Megawatt Hour
MEUR	Million Euros
Mtpa	Mega Tonnes Per Annum
%	Percent
, (comma)	Thousand separator
. (point)	Decimal separator

1 Introduction

In the pursuit of sustainable energy solutions, industries with high energy demands face a major challenge: the need to decarbonise. Refineries are in particular a significant contributor to carbon emissions, this is due to the high temperature demanding processes such as crude oil distillation and cracking. This challenge is especially pronounced in the Port of Rotterdam, due to the presence of 4 of the 10 largest emitters in the Dutch industrial sector (NOS, 2024). Reflecting against the ambitious net zero targets set by both the European Union and the Netherlands for 2050, the need to explore alternative energy sources has never been greater.

Within the broader energy transition, multiple decarbonisation options are being studied and are strategically planned. The energy transition is mainly driven by technology readiness and economic feasibility and reduction targets, leading to scheduling and research of various options accordingly. One of these options that is gaining attention is blue hydrogen, known for its potential as a low carbon energy carrier (AlHumaidan et al., 2023). Blue hydrogen has the potential to be technically and economically feasible in the short term as a decarbonisation option. This is due to the proposed use of known technology, partial utilization of existing infrastructure and significant CO_2 emission reduction it can achieve. Blue hydrogen is considered as a transitional solution towards green hydrogen within the energy transition (Lagioia et al., 2023). The combination of blue and green hydrogen has strategical benefits by allowing shared infrastructure and modification investments.

Blue hydrogen is produced from natural gas or refinery fuel gas through Auto Thermal Reforming (ATR) or Steam Methane Reforming (SMR) combined with carbon capture and storage (CCS). While both ATR and SMR can produce hydrogen, ATR is preferred for its exothermic process and input stream flexibility (Muhammed & O., 2023). The low carbon properties of blue hydrogen make it a promising solution for reducing emissions in energy intensive industries like refining. The concept of blue hydrogen is still quite novel in the sense that no large scale operation with the combination of a ATR + CCS including subsurface CO_2 storage is been performed. This novelty means that the feasibility and implications of the adoption of blue hydrogen needs further examination (Ueckerdt et al., 2024).

The goal of this master thesis is to assess the value and feasibility of using blue hydrogen for the decarbonisation of high temperature heat generation within the refineries located in the Port of Rotterdam, from both the public and corporate perspective.

This introductory chapter describes the significance of the decarbonisation efforts within the refinery sector of the Port of Rotterdam. Hereafter the concept of blue hydrogen will be introduced along with its role of reducing carbon emissions. Finally, the research objectives and structure of thesis will be outlined.

1.1. Context

Addressing climate change is currently a main priority for governments, businesses, and society as a whole. This urgency is especially seen in energy intensive industries like refineries. Refineries face a complex situation, navigating the balance between government ambitions and corporate responsibility, often facing challenges (Sovacool et al., 2019).

Legal actions against governments, for example Shell's role in climate change, underscore the public's growing demand for environmental accountability (Domans & Preston, 2021). Decarbonisation is not only necessary for tackling climate change but can also be of value in terms of economic benefits, due to new market opportunities (Zenghelis, 2019).

For industries that are very depended on fossil fuels, transitioning to low carbon energy sources presents both challenges and opportunities. Understanding the relationship between society and these industries can be helpful, this because of their impact on daily life and the economy.

The Port of Rotterdam demonstrates this dynamic of society and industry. With the ambitious decarbonisation targets set, exploring alternatives like blue hydrogen is essential. The significance of blue hydrogen mainly arises from its capacity to directly substitute traditional fuels like natural gas on a 1 to 1 basis, while also having the potential for transport and storage via existing infrastructure (Zapantis et al., 2021). This becomes especially relevant when considering the challenges associated with electrification, including technological shifts and the need for base load high temperature heat generation in continuous 24/7 operating processes, this against the intermittent nature of renewable power sources (Wei et al., 2019).

This thesis examines the potential of blue hydrogen in reducing carbon emissions resulting from high temperature heat generation, this in line with EU and Dutch decarbonisation targets. The focus is on Scope 1 emissions, which are direct emissions from owned or controlled sources, and Scope 2 emissions, which are indirect emissions from the generation of purchased electricity, steam, and heating (Anquetin et al., 2022). By studying the economic, environmental and social aspects, the aim is to create a overview of the value from the public and corporate perspectives.

1.2. Problem Statement

The refineries in the Port of Rotterdam are significant contributors to CO_2 emissions. They account for 20% of the Dutch industrial CO_2 emissions and 6% of the national CO_2 emissions (Centraal Bureau voor de Statistiek, 2024). This presents challenges in aligning the refinery operations with the European Union and Dutch targets of 55% reduction in emission by 2030, 90% reduction by 2040 and finally achieving net zero (100%) by 2050. Decarbonising high temperature heat processes within refineries have a significant impact on the overall CO_2 footprint of a refinery, as around 70% of refinery emissions results from high temperature heat demand (Fatih et al., 2020). Decarbonising high temperature heat within refineries is challenging due to their dependence on fossil fuels for heat generation through combustion.

Blue hydrogen produced through Auto Thermal Reforming with Carbon Capture & Storage, is emerging as a strategic solution for the energy transition. It aligns with the broader energy transition strategy of shifting from blue to green hydrogen, offering high temperature heat (850+ degree Celsius) with CO_2 captured and stored in subsurface fields. However, the transition to blue hydrogen requires various technical, economic, and social considerations. Technically, it requires technologies which are not proven at this scale and with the adaption of existing infrastructure (AlHumaidan et al., 2023). Economically, it demands significant investments and creates financial risks regarding the unpredictability of CO_2 pricing and energy transition outlook (Tetteh & Salehi, 2023). And socially, it impacts public health and sustainability.

Given these complexities, it is essential to explore how the adoption of blue hydrogen can be evaluated from a comprehensive perspective that includes both technical and socio-economic factors. While blue hydrogen presents a promising option, understanding the full impact requires evaluation beyond just technical and commercial feasibility.

The main focus of this research is to evaluate the social cost and benefits of using blue hydrogen for high temperature heat decarbonisation in refineries located in the Port of Rotterdam. This involves analyzing the overall cost and benefits from both corporate and public perspectives, and identifying gaps between these perspectives. The goal is to gain insight into the potential discrepancies between the perspectives, with a main focus on how societal benefits compare to the economic investments required from both perspectives.

Previous studies have addressed the feasibility of blue hydrogen to serve as a decarbonisation option from the perspective of the corporate, the main focus of these research studies consider the corporate technical and commercial feasibility. What these research studies show is that commercial feasibility is quite low (Dokso, 2024), this creates inertia in decarbonisation. What lacks is the knowledge and insight in to the corporate versus the public perspective on blue hydrogen usage in PoR refineries. The insights of the public perspective can give overall context and motive on the importance of the decarbonisation for society.

The knowledge gap addressed in this research is significant because understanding both corporate and public perspective on decarbonisation is crucial for successfully reaching climate targets. Decarbonisation emphasizes the collaboration between the corporate actions, and public policies. A social cost benefit analysis can provide insights into the positions of both perspectives, leading to better understanding of their perspectives and identifying cost and benefit drivers. These insights can provide information to policymakers about the current position of the perspectives on blue hydrogen within refining.

The importance of a holistic view that incorporates both perspectives through an social cost benefit analysis is also motivated by the decarbonisation obligation that countries face. Decarbonisation targets are legally binding targets for nations, but not for the companies that operate within them (TNO, 2021; Zachary Byrum & Wilcox, 2023). If a decarbonisation option is not economically viable for a corporate, they may choose to not invest. However, for a nation, the targets are binding. This underscores the need to assess blue hydrogen from two perspectives, as the public sets the policy framework that incentivize the corporates to take action, which facilitates collaborative efforts to reach the targets. Without such a dual perspective insight, there is a risk of decarbonisation slowing down or reaching inertia due to the lack of understanding of each others position.

1.3. Research Questions

The overall objective of this research is to explore the perspectives on the use of blue hydrogen for high temperature heat generation within PoR refineries. The following main research question will serve as a guideline for this research.

Main research question

- What are the costs and benefits of using blue hydrogen for the decarbonisation of high temperature heat generation within refineries in the Port of Rotterdam considering the Dutch/EU net zero targets in 2050, from the perspective of the corporate versus the public?

Five sub-research questions have been formulated to provide structure and guidance in addressing the main research question.

Sub research questions

1. What is the business as usual high temperature heat energy demand and CO_2 reference case for refineries in the Port of Rotterdam?
2. What is the projected emission reduction from using blue hydrogen for heat generation in Port of Rotterdam refineries compared to the business-as-usual reference case in the time period between 2024 - 2050?
3. What are the costs and benefits effects of the blue hydrogen intervention scenario from a corporate perspective?
4. What are the costs and benefits effects of the blue hydrogen intervention scenario from a public perspective?
5. How do the perspectives of the corporate compare to those of public regarding the costs and benefits effects of the intervention scenario?

1.4. Study Scope

This section describes the scope of the study. This consists of geographical boundaries, technologies, timelines and inter dependencies.

- **Temporal Framework:** The study focus on the period of 2020 to 2050, aligning with the climate targets set by the Dutch government and the European Union
- **Geographical Focus**: The analysis is performed on the refineries in the Port of Rotterdam
- **Emission Scope**: The study considers both Scope 1 (direct emissions from owned or controlled sources) and Scope 2 (indirect emissions from generation of purchased energy) emissions related to high temperature heat processes within refineries.
- **Decarbonisation Options:**The focus within this report is on blue hydrogen and its production technologies. Blue hydrogen is only utilized within a refinery for heat generation not for feedstock purposes. This study assumes the technological feasibility of blue hydrogen production and implementation and the availability of the required infrastructures.
- **Infrastructure Interdependencies**: The study considers the interdependence's between the refineries and the CO_2 and Hydrogen infrastructures. These are integrated in the refinery infrastructure network which consists of all infrastructure within the refineries plot location.

The study also outlines exclusions to maintain a focused scope:

- **External Impact:** The analysis does not account for impacts outside the boundaries of the refineries except for the necessary consideration of interconnected infrastructures that connect industries such as H_2 and CO_2 transport.
- **Other Industry:** Although the study acknowledges the potential hydrogen off-take and interdependence with other heavy industrial sectors, it does not go into a detailed analysis of these sectors. These are considered as a high level assumptions.

1.5. Link to Management of Technology

The Management of Technology (MOT) program educates students to become and think as technology managers, analysts, and entrepreneurs, focusing on a technology-based orientation within competitive environments across various industrial sectors (TU Delft, 2024). The curriculum covers the impact of technology on companies and the synergies between companies, government, and the public. The aim of this thesis is to obtain both corporate and public perspectives on a new potential technology aimed at decarbonising the refinery sector. This goal aligns with the Master program objectives consisting of researching innovative processes that are used as a corporate resources. Also the strategical alignment between the public and corporate stakeholders is addressed. The following courses have been relevant in writing this thesis:

The Financial Management courses has helped me with skills & knowledge in financial modeling for business cases and projects. This consists of translating technical inputs into financial and economic outputs together with modeling cash flows. The Technology Dynamics course provided insights into the industrial ecosystem and its connection to government, which is in this case relevant for addressing the research questions. The Emerging and Breakthrough Technologies course focused on identifying opportunities within the industrial technology space. Finally, the MOT specialization course on Cost Benefit Analysis (CBA) provided the foundational principles and guidance necessary for conducting a CBA throughout the thesis.

1.6. Report Outline

This thesis is divided into nine chapters. Chapter 1 is the introduction chapters which sets the context by highlighting the importance and need of decarbonising the refining industry in the Port of Rotterdam. It introduces the research problem, objectives, questions, and scope. Chapter 2 is the Background which provides an overview of climate targets and their potential impact for refineries in PoR. It shows the current energy usage and carbon emissions within the refining sector and explores decarbonisation options available. Within chapter 3 the methodology is outlined by showing the analytical framework used for the cost benefit and social cost benefit analysis. It describes the development of both the reference and intervention scenarios, the evaluation of the perspectives and the overall analysis.

In chapter 4, Reference Scenario, the baseline scenario is constructed using existing European and Dutch energy emission data and forecasts. The goal is to isolate the high temperature heat demand within refineries to establish a reference scenario for evaluating the impacts of the intervention scenario. Chapter 5 intervention scenario, details the configuration of the intervention scenario, which involves the use of blue hydrogen to replace traditional fossil fuels for high temperature heat generation. It covers the production setup, ramp-up process, and the required modifications to accommodate the hydrogen fuel to the burners.

Chapter 6, Effects, identifies the effects resulting from the intervention scenario from both corporate and public perspectives. It evaluates the direct, indirect, and external effects, providing the input for the cost benefit analysis. In chapter 7, the results are presented. This consists of the outcomes of the scenarios including a sensitivity analysis.

The discussion takes place in chapter 8. Within this chapter the results are discussed along with their implications, strengths, and limitations. It contextualizes the results within the broader framework of decarbonising refineries. Finally in chapter 9 the conclusion will be provided by, summarizes the key findings of the study, highlighting its contributions to the field. It offers concluding remarks and suggests directions for future research.

2
Background

In this background chapter, the essential terms, technologies, and contextual factors will be explained to establish the knowledge base for this report. This chapter contains background information regarding the overarching climate targets and their implications for the Dutch refining sector. It goes into the background of the refineries in the Port of Rotterdam, identifying its contributions regarding CO_2 emissions and energy usage. It delves into the background of hydrogen as a potential option. Furthermore it provides an overview of the main decarbonisation options available to refineries, as well as an overview of the policies and regulations governing the sector in the Netherlands. Finally the underpinning of socio-economic and socio-technical aspects are explained.

2.1. Climate Targets

The climate targets established and agreed upon in the Paris Agreement of 2015 together with the European Green Deal have significant effects on the sustainability needs and emission reductions ("United Nations Framework Convention on Climate Change", 2015). The Paris Agreement aims to limit global warming to well below 2 degrees Celsius, with further efforts to limit it at 1.5 degrees Celsius. The European Green Deal sets objectives for achieving climate net zero by 2050, with sub targets of a 55% reduction in greenhouse gas emissions by 2030, a 90% reduction by 2040, and 100% reduction by 2050, this based on 1990 emission levels ("European Commission", 2024). These targets apply to all EU member states.

While these decarbonisation targets are legally binding at the European level, individual member states maintain flexibility in how they achieve them. Member states are tasked with implementing policies and regulations to meet these targets (Government of the Netherlands, 2019). At a national level Dutch targets must align with EU targets but can be even more ambitious if local governments choose to do so. The international companies within the refining sector sets their own decarbonisation goals (Rijnmond, 2021). Interestingly, while there may be industry-wide initiatives or voluntary agreements to reduce emissions, targets set by individual refining companies are not legally binding. Refineries can face regulatory pressure or market incentives such as levies to align with national and/or EU targets, but there is no legal obligation binding individual refineries to decarbonise (Immink et al., 2022). It is the responsibility of member states to decarbonise their territories through policy implementation. These policies can incentivize or motivate the corporates to invest in decarbonisation projects.

Figure 2.1 shows that achieving the 1.5 to 2-degree Celsius warming scenario demands substantial decarbonisation efforts. Currently we are on a path towards a +/- 3 degree temperature increase. This potential outcome can cause significant risks to health, the environment, and the climate (European Environment Agency, 2024).

2.1.1. Targets in the Dutch Refining Sector

Even though, Dutch government aligns closely with European policies and targets, it faced a unique challenge known as the Urgenda case (Leijten, 2019). This legal action was started by the Urgenda

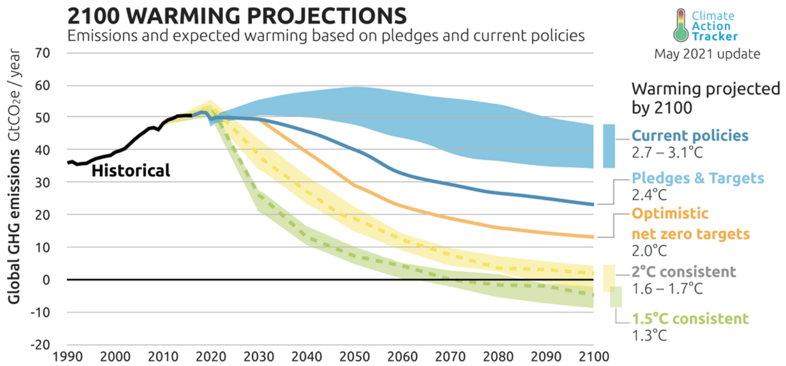

Figure 2.1: Projected Global Warming (Climate Action Tracker, 2022)

Foundation and citizens in 2013 declaring that the government had a legal obligation to protect its citizens from climate change, this by adopting more ambitious emissions reduction targets. The District Court of The Hague ruled in favor of Urgenda, demanding the government to achieve a minimum 25% reduction in emissions by 2020. This case has served as an accelerator for the Dutch government to chase more ambitious climate targets. In addition to the EU policies, the government has implemented localized emission reduction plans. These will be explained in section 2.5.

The Dutch government agrees that the process of decarbonising refineries is complex and requires significant time, investment, and support. This recognition of the decarbonisation challenge has maintained flexibility and cooperation between the government and the refineries (Minister EZK, 2023). Also the ambition of the the Netherlands to be one of the top performers and role models in the energy transition is a important motive (van Zinderen Bakker, 2023). This has led to so called 'tailored agreements' (Maatwerk) with refineries aimed at supporting their decarbonisation efforts (Rijksoverheid, 2023). These agreements have potentially impact on the decision to adopt blue hydrogen within refineries. More insights into this subsidy form can be found in section 2.5.3.

Individual refineries are also framing decarbonisation targets for themselves in anticipation of the future (Reuters, 2023) (BP, 2024)(Shell, 2024a). This initiative begins with the rebranding of their organizations, shifting from being a pure oil companies to transitioning to a broader identity as energy companies. Companies like BP and Shell have transitioned from being a 'Integrated Oil Companies' (IOCs) to 'Integrated Energy Companies' (IECs). This shift allows them to open up their portfolios with future commodities like (green/blue) hydrogen, green ammonia, bio alternatives & a wind/solar portfolio. The motivation behind these targets primarily comes from (Suwailem, 2022):

- **Corporate Responsibility**
  IECs recognize their role in contributing to decreasing their GHG and commit to their corporate responsibillity
- **Risk Management**
  Proactively managing risk such as regulatory changes & shifts in consumer preference
- **Investor and Stakeholder decisions**
  Setting climate targets can enhance a companies reputation, attract socially responsible investors and maintain trust.
- **Competitive Advantage**
  Ability to differentiate from competitors, when future markets are introduced.

The crucial point to note is that refineries follow world-wide decarbonisation objectives, rather than localized climate targets. This means that IOCs & IECs are not restricted to achieving its decarbonisation goals within a specific country. If there is greater potential for better economic outcomes somewhere else, they may choose for the option to relocate their operation (Wood Mackenzie, 2024a).

2.2. Hydrogen Use and Potential within Refineries

In figure 2.2 the widespread potential of hydrogen is shown for its end users. On the left the production methods and labels of hydrogen are displayed, next the transport/logistical elements and to the right the potential end usage.

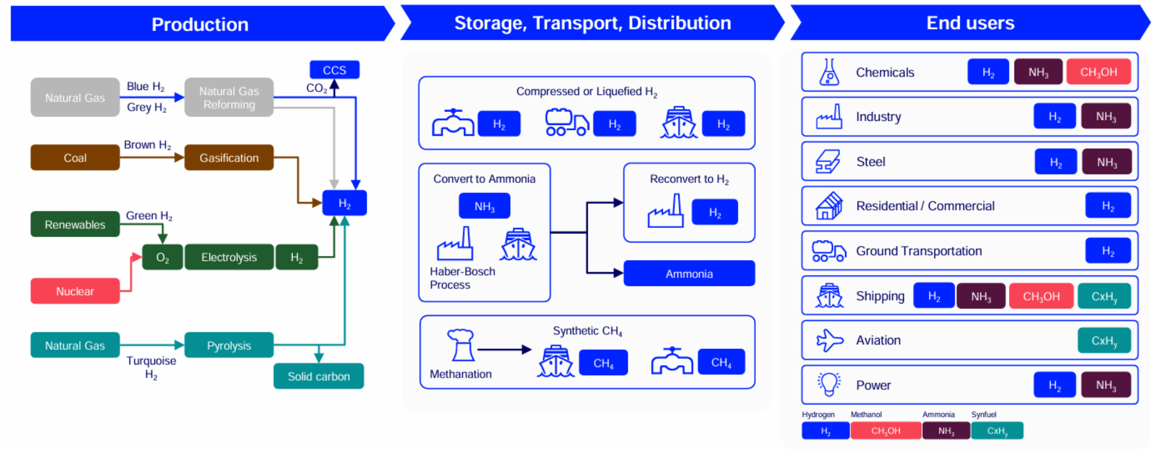

Figure 2.2: Hydrogen and its Derivatives (Wood Mackenzie, 2024b)

Hydrogen is widely used within the refining process. One of the main roles of hydrogen in refineries is in the usage within hydroprocessing. Here it serves as a product for removing impurities and upgrading hydrocarbon feedstocks (Parkash, 2003). Hydrogen is currently considered a feedstock within the refineries and not used as a fuel since alternatives like natural gas and refinery fuel gas are more technically and economically attractive (Abdin et al., 2020).

Hydrogen can be categorized in multiple colour labels, the colour identifies the production process and their associated environmental impact (Nikolaidis & Poullikkas, 2017). The main categorizations that are discussed and related to refining, are grey, blue and green.

1. **Grey Hydrogen**: Grey hydrogen is produced from natural gas using SMR or ATR without carbon capture, resulting in emissions of CO_2. Currently this is the most common form of hydrogen production but has significant environmental drawbacks due to its carbon emissions.
2. **Blue Hydrogen**: Blue hydrogen is produced from natural gas through SMR or ATR, with carbon capture and storage (CCS) used to capture and store the resulting CO_2 emissions. While it reduces CO_2 emissions compared to traditional natural gas usage, it still involves fossil fuels.
3. **Green Hydrogen**: Green hydrogen is produced through electrolysis, using renewable energy sources such as wind or solar power to split water molecules into hydrogen and oxygen. No CO_2 emissions are emitteded due to the renewabe energy source. Seen as final hydrogen solution in transition.

2.3. Overview Dutch Refining Sector

Refineries are positioned in the downstream segment of the oil & gas value chain. Upstream activities involve the exploration and exploitation of oil & gas resources. Upsteam exploited oil is then transported through trading channels to the downstream sector for refining (Stauff, 2021). After the refining step, the refined products are distributed to shipping, aviation, and retail markets. Refineries worldwide emit approximately 1,300 million tonnes of CO_2 annually, making them significant contributors to global CO_2 emissions (Sunny et al., 2022). To put this in perspective, the global electricity and heat generation sector emits 13,000 million tonnes of CO_2 annually (Ritchie & Roser, 2020). The Dutch position within in the oil & gas value chain is mainly in transport & storage, downstream activity and retail.

There are five refineries located in the Port of Rotterdam which collectively emit 10 million tonnes of CO_2-equivalent per year and having a total capacity of 67,000 kilo tonnes of crude oil per year (in 2018) (Emissieautoriteit, 2022). These refineries process crude oil into products such as gas oil, fuel oils, gasoline, kerosene, and others for both the Dutch market and export. The refining of crude oil

Figure 2.3: Overview Refineries in the Port of Rotterdam (Port of Rotterdam, 2022)

is a process which requires high levels of energy that results in the emission of greenhouse gases (GHGs), primarily CO_2. The majority of scope 1 and 2 CO_2 emissions[1] from refineries originates from the combustion of fuels like natural gas and residual refinery gases to generate heat for distillation processes (Parkash, 2003) which is shown in section 2.3.2.

Table 2.1: Overview Capacity and Direct Emission Port of Rotterdam Refineries (Netherlands Environmental Assessment Agency (PBL), 2020)

Refinery site	Crude Oil Capacity [kt/yr]	Direct CO_2 Emission 2018 [kt/yr]
BP Refinery Rotterdam	20,000	2,254
Esso Refinery Rotterdam	9,100	1,583
Gunvor Rotterdam	4,500	397
Shell Refinery Rotterdam	21,000	4,211
Vitol Rotterdam	3,500	102
Total	67,007	10,180

The refineries located in the PoR collectively employ between 5,000-6,500 workers and contributed 36 billion euros to net turnover in 2018, contribution 0.38% to the Dutch GDP. It is worth noting that this low GDP contribution may be misleading due to the close integration of the refining sector within the broader industry sector, which contributes 11.6%. The value of a refinery to a country also includes several spillover effects, such as the innovation ecosystem that promotes growth and new developments (van der Sleen et al., 2019). It also provides certainty for other companies that depend on refineries which stabilizes the broader industrial partnerships. Additionally, having a competitive refinery sector ensures that the Netherlands remains a strong competitor in the energy and refinery market, which in turn boosts the economy and enhances its trading position.

2.3.1. Energy Usage in Refineries located in the PoR

As highlighted in figure 2.4, a refinery is a high energy demanding plant. In 2018 the total energy intake of Port of Rotterdam refineries was around 134 PJ. This energy was mainly used for high temperature processes such as the generation of steam, energy for heating crude oil and other processes (Netherlands Environmental Assessment Agency (PBL), 2020). The figure shows the total energy consumption of refineries in the Port of Rotterdam. The fuel gas section represents residual refinery gas extracted during the distillation process, which is then used for combustion purposes. This refinery fuel gas can be valued as equivalent to natural gas. High temperature processes within refineries primarily involve heating product streams through combustion, typically in furnaces or boilers.

[1] Scope 1 emissions are those directly emitted by a company's operations, while Scope 2 emissions are indirectly produced through the consumption of purchased energy.

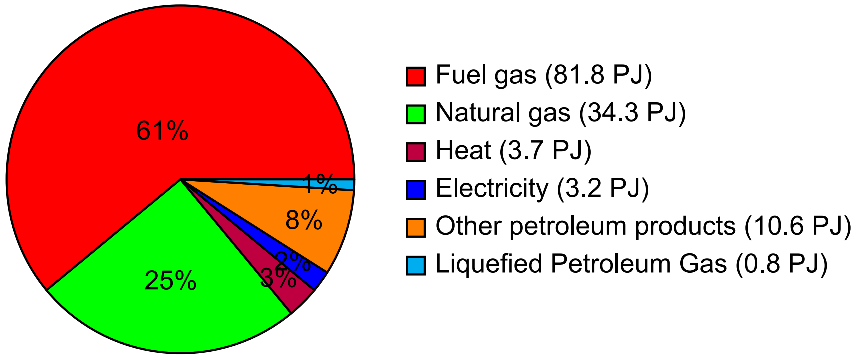

Figure 2.4: Energy Consumption Distribution in PJ (This includes NG & RFG Feedstock and Export) (Netherlands Environmental Assessment Agency (PBL), 2020)

Implementing blue hydrogen for high temperature heat generation will not significantly change the overall energy consumption of a refinery since it directly replaces current fuel sources (AlHumaidan et al., 2023). The production of blue hydrogen within the ATR process generates steam as a byproduct. This steam is utilized within the refinery, reducing the need for additional fuel in steam boilers. This will be further explained in chapter 5. Blue hydrogen will primarily substitute fuel gas and natural gas, targeting specific processes for decarbonisation, this is detailed in the next section. Fuel gas is a byproduct of the distillation process and is currently used as fuel for combustion within the refinery. Fuel gas is comparable to Natural gas in terms of composition, it is more volatile to changes due to process conditions, fuel gas can serve as input stream for the blue hydrogen plant. Explained in section 2.6.

2.3.2. Carbon Dioxide Emissions from Refineries

Figure 2.5 presents the breakdown of emission sources within a refinery, this can be divided in 4 categories. Furnaces and boilers contribute to CO_2 emissions due to the heat delivered for refining processes. Utilities ensure the supply of electricity and steam. The fluid catalytic cracker upgrades low H_2 feedstock into more valuable products. Finally, hydrogen manufacturing addresses the hydrogen demand in processes, with many refineries having on-site hydrogen production plants. What can be seen is that around 70% of CO_2 emissions originate from combustion processes for heat generation, while the remaining 30% are related to chemical reactions during catalyst regeneration in catalytic cracking units (Güleç et al., 2020). Blue hydrogen can reduce CO_2 emissions from the combustion processes within furnaces, boilers, heat-utilities, and hydrogen production. However, the fluid catalytic cracker requires different decarbonisation options since its CO_2 emissions result from the regeneration of the catalyst (AlHumaidan et al., 2023). This indicates that blue hydrogen has the potential to decarbonise approximately 70% of refinery emissions.

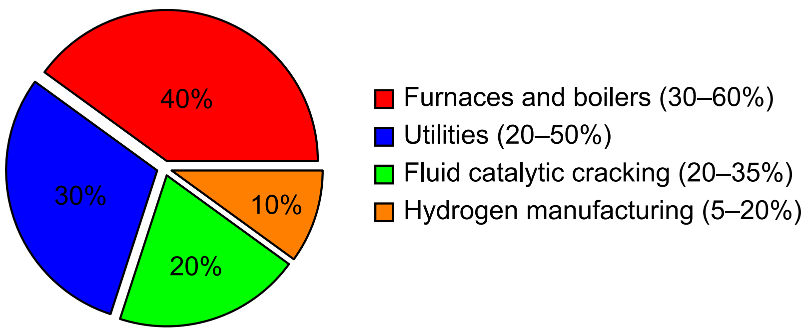

Figure 2.5: Energy Consumption Distribution in Refining Processes (Fatih et al., 2020)

2.3.3. Decarbonisation Options for Dutch Refineries

Multiple governmental and private studies have been performed to research the energy transition of refineries within the Port of Rotterdam (PBL, 2022; Van Wee, 2012; Wong & Van Dril, 2020). Plan Bureau Leefomgeving (PBL), an independent research institution advising the government, has conducted research into the energy transition of refineries in the Netherlands. What these studies highlight, is the absence of a singular optimal pathway for the refinery energy transition. This because no single option can solve all refinery decarbonisation objectives. Instead, they emphasize the multitude of viable directions towards achieving climate goals (Netherlands Environmental Assessment Agency (PBL), 2020). PBL identifies primary CO_2 reduction categories for refineries, which can be summarized as follows:

Table 2.2: Options for Decarbonising the refining sector in the Netherlands (Netherlands Environmental Assessment Agency (PBL), 2020) [FCC = Fluid Catalytic Cracker]

Category	Technology	Relevant to process
Carbon capture	Carbon capture and storage	Applicable mainly for hydrogen production, FCC and for gasification units
		Possibly applicable to all current stacks, but limited by space requirements
Fuel substitution	Electric furnaces	Possibly applicable to all processes that present gas-fired equipment (e.g. atmospheric distillation, cracking processes, reforming)
	Electric boilers	Steam boilers
	Electric shaft equipment	Steam turbines replacement
	Blue/green hydrogen as fuel	Possibly applicable to all processes that present gas-fired equipment (e.g. atmospheric distillation, cracking processes, reforming)
Feedstock substitution	Co-processing (5-10%) pyrolysis bio-oil from biomass in FCC unit	Co-feed for FCC
	Blue/green hydrogen as feedstock for processes	All hydrotreating and hydrocracking processes
Process design	Stand-alone plant for biofuels production via pyrolysis bio-oil upgrading and Fischer Tropsch fuels production	Process alternative for production of LPG, gasoline, kerosene and gasoil/diesel
Residual heat usage	Use of process heat, internally or externally	Possibly applicable to all processes with excess heat

Trade association VEMOBIN has identified primary pathways indicating a transitional phase where blue hydrogen will temporarily decarbonise refineries. Subsequently, electrification and the adoption of green hydrogen will replace blue hydrogen, establishing a fully renewable energy form (Commission, 2019; Römgens & Dams, 2018). This raises question from the corporate side on if a investment in blue hydrogen makes sense if their is a successor awaiting closely. This is critical since these project are capital intensive.

2.4. Pre Combustion Capture of Carbon Dioxide

For this research pre combustion capture is chosen over post combustion capture which will be explained in more detail in section 2.4.1. The main argument is that blue hydrogen is viewed as a transitional phase to the final destination of green hydrogen, within the hydrogen energy transition. Blue and green hydrogen share infrastructure and overall modifications and investments, this creates potential for re-using investments and knowledge to proceed to green. Additionally, pre combustion capture offers opportunities such as hydrogen usage as a externality to different industries. Post combustion does not align with the hydrogen pathway in the energy transition. Below the pre combustion capture process will be detailed, followed by a comparison with post combustion capture.

Pre combustion capture refers to the process where CO_2 is captured from fossil fuels before combustion occurs (Jansen et al., 2015). The fuel is converted to a mixture of CO_2 and hydrogen. The CO_2 is separated and captured before hydrogen is used for feedstock or fuel purposes (Zapantis et al., 2021).

For this research a Auto Thermal Reformer (ATR) is chosen over a Steam Methane Reformer (SMR), this is because a ATR has a wider range of input streams which it can process. A ATR can process Refinery Fuel Gas as input stream whereas a SMR is less flexible and more restricted to Natural Gas (North Sea Transition Authority, 2021). ATR technology is also favourable due to the exothermic byproduct steam which can be utilized in the refinery. ATR is a process for producing hydrogen from hydrocarbon feedstocks like natural gas and RFG. ATR combines oxygen and steam within the reformer to initiate simultaneous partial oxidation and steam reforming reactions. This self-sustaining process generates hydrogen-rich synthesis gas (syngas) while minimizing byproducts consisting of CO and unreacted CH_4 (Rowshanzamir, Eikani, et al., 2009). A drawback from the ATR process is the 20% efficiency loss when converting natural gas into hydrogen. This means that transforming one fuel in to another, loses 20% of energy capacity ((NREL), 2002).

In ATR, a downstream carbon capture units captures the CO_2-rich syngas stream. Once captured, CO_2 can be stored or utilized creating a low-carbon hydrogen product (Jamieson, 2023).

The remaining gas stream is at a quality of +/- 97.5% hydrogen purity. This 97.5% is classified as fuel spec hydrogen that is suitable for replacing natural gas or RFG. A additional step towards bringing blue hydrogen towards a feedstock specification is to process the hydrogen through a purification unit called a pressure swing absorbed unit (PSA). Here the hydrogen gets enhanced to a purity of +/- 99.5% pure hydrogen.

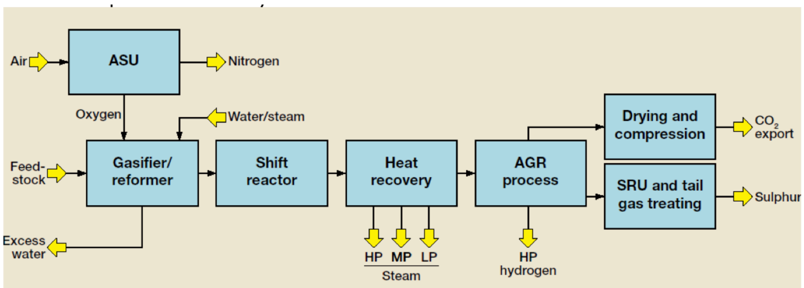

Figure 2.6: Pre Combustion Capture Process (ATR) (Jamieson, 2023)

2.4.1. Comparison against Post Combustion Capture

Post-combustion capture, captures CO_2 emissions after the combustion of fossil fuels. This takes place at the stack(s) of a refinery (Chao et al., 2021). This method can be used in processes such as the Fluid Catalytic Cracker (FCC) at a refinery, where CO_2 is emitted through the regeneration of catalysts and released via the stack (Güleç et al., 2020). The CO_2 emitted by the regeneration of catalysts cannot be avoided by implementing hydrogen or any other pre-combustion capture option.

Post-combustion capture comes with drawbacks; a high amount of energy is required for conditioning the captured CO_2 and regenerating the absorbent creating a overall efficiency of +/- 75% (P. H. Feron et al., 2020). This method is limited to the specific location of application, with no scope for further externalities. Therefore, every refinery and each of its stacks would need to be equipped with a post-combustion capture plant to achieve emission reduction goals.

The efficiency of pre-combustion capture is slightly higher because the energy required for CO_2 capture is smaller. Pre-combustion plants generally have lower total investment costs when existing pipeline infrastructure can be used. A drawback of pre-combustion plants is their limitation to capture only fuel-emitted CO_2, excluding CO_2 from chemical reactions.

2.4.2. Carbon Capture & Storage in the Netherlands (CCS)

The Netherlands is currently developing the infrastructure for carbon storage. This infrastructure will be part of the pre- and post-combustion capture systems which involves storing the captured CO_2. This is achieved by using empty gas fields within the Dutch North Sea as storage. A compressor station on land feeds the transport pipeline to the offshore platform, where CO_2 is injected into the empty reservoir. Once the reservoir reaches capacity, it is sealed. The capacity of CCS in the Netherlands is around 1,600 million tonnes (EBN & Gasunie, 2018). When this is put in to context against the total CO_2 emissions in the Netherlands in 2020 were 164.5 million tonnes, it can be concluded that there is sufficient storage capacity for industrial purposes (Rijksinstituut voor Volksgezondheid en Milieu (RIVM), 2021). The primary projects which will start up first include the Porthos project with a capacity of 37 million tonnes, and the Aramis project, with a combined capacity of 437 million tonnes of CO_2 (Porthos, 2023).

The CO_2 backbone is the connecting pipeline facilitating CO_2 transport for stakeholders willing to store CO_2 in empty gas fields. This backbone is shown in figure 2.7. All Dutch refineries have the capability to connect to this infrastructure.

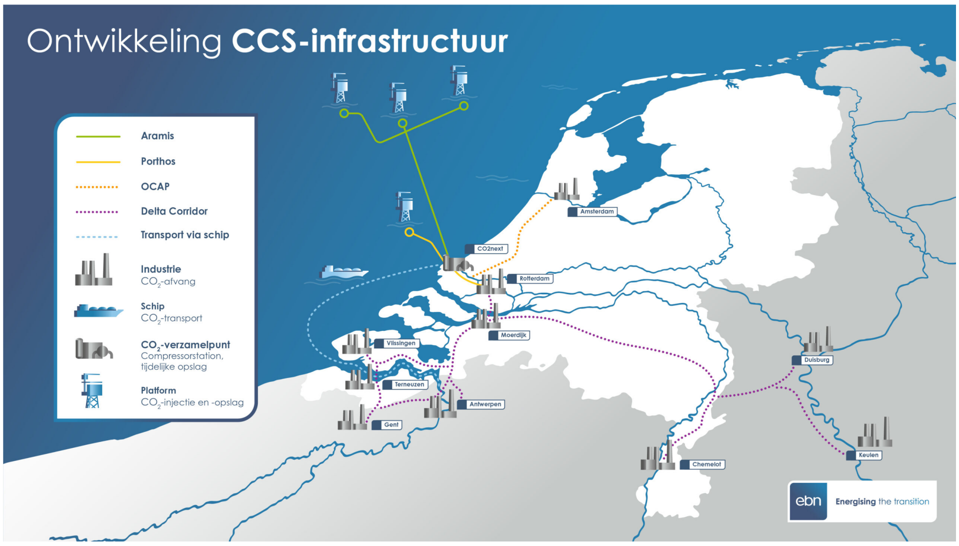

Figure 2.7: CCS Infrastructure in the Netherlands (EBN & Gasunie, 2018)

The projected timeline for the projects aims for start up between 2027 and 2028. This aligns with the timeline of the climate targets and provides the industry with a solution for storing captured CO_2 (Porthos, 2023).

The CCS value chain involves multiple stakeholders such as the government, joint ventures, and fully commercial partners. This creates a hybrid set up where government supports a project with commercial interests. Currently regulations are being developed to ensure reasonable CO_2 storage tariffs for customers. These regulations need to address potential conflicts of interest among the stakeholders. The main support mechanism/subsidy for CCS customers is the SDE++ subsidy further explained in 2.5.3 (Algemene Rekenkamer, 2024).

2.5. Policy & Regulation

Dutch refineries face several policy and regulatory challenges related to incentives and support aimed at achieving decarbonisation targets. A policy is designed to provide a framework for guiding and incentivizing refineries towards adopting carbon reducing measures. EU ETS and Carbon Levy are identified as main policies instruments impacting refineries.

2.5.1. EU ETS

The EU ETS system exist of a cap and trade system for carbon credits. The cap is lowered every year to incetivize refineries to decarbonise (Convery, 2009). Refineries are given or are required to purchase these credit allowances. These allowances represent emission rights. As figure 2.8 illustrates: If a refinery emits less than its allocated allowances, it can sell the residual allowances to other participants which can be seen as a benefit (assuming market demand from others to buy rights). If a refinery exceeds its allowances, it needs to purchase additional allowances or face a penalty, which can be seen as a cost. This market-based approach motivates investments in low carbon improvement to reduce emissions cost-effectively. The EU ETS is used in all EU member states, creating a equal frame work for addressing climate change (European Commission, 2022).

The EU ETS is considered as a major cost to refineries in general. Literature suggests that this hold similair effect and importance in a cost benefit analysis (Roberts & White, 2011). However, the perception of the cost or benefit of the EU ETS may differ between corporate and public perspectives.

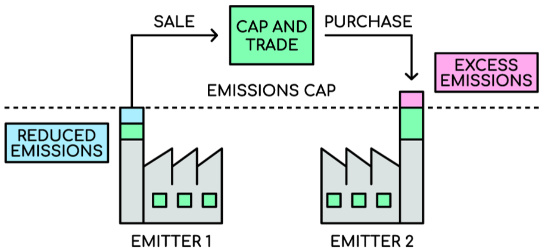

Figure 2.8: EU ETS Cap and Trade System (European Commission, 2022)

2.5.2. Dutch Levy

The Dutch Levy consists of an instrument for the Netherlands to pursue more ambitious localised targets in achieving national climate objectives. The government can adjust the height of the levy themselves, which can results in an additional impact on top of the EU ETS (Rijksoverheid, 2022). When the market mechanism of the EU ETS falls short due to price volatility, over allocation of allowances and carbon leakage, the levy can be put in place to function as a Carbon Floor Price (CFP). The difference between the Levy and the EU ETS is paid to the Dutch government as a tax. Dutch levy trajectories are established until 2030 and are currently undergoing governmental discussions, with plans to raise the levy to further incentivize industrial EU ETS companies to reduce their CO_2 emissions (PBL, 2024).

2.5.3. Subsidies

In addition to policies which incentivize refinery to decarbonise, the Dutch government also implemented subsidies as a means of supporting companies to take action. Subsidies which are focused on the main decarbonisation options in industry, and specifically in refining have been introduced. These subsidies focus on options such as blue and green hydrogen which are currently considered. Refineries are can apply for multiple subsidies at different phases of the project. The various subsidies are shown in 2.9.

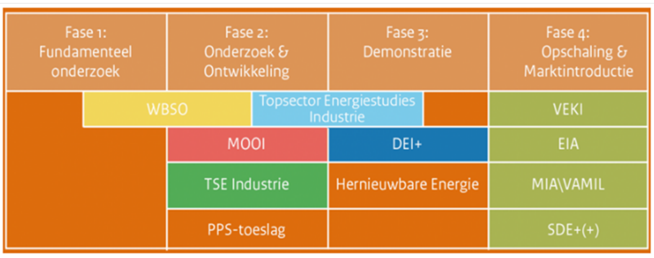

Figure 2.9: Overview Subsidies Industry (Energie, 2024)

The technologies used in the production of blue hydrogen are not completely new, but the combination of technologies and their scale are. It is for these reasons that the primary subsidies for such projects include the SDE++ Subsidy, EIA, and VAMIL (Rijksfinanciën, 2024). The EIA and VAMIL are financial incentives that allow for tax deductions on investment costs. The SDE++ Subsidy serves as the primary operational subsidy which is more focussed on the operational cost of a project. This section will give an insight in the SDE++ subsidy and the ”Maatwerk” subsidies since these are most suitable for blue hydrogen projects for refineries.

SDE++

The SDE++ subsidy functions as a Contract for Difference (CFD) subsidy by providing financial assistance or acting as insurance against a low EU ETS price (Ministry of EZK, 2023). In this scheme, the CFD covers the gap between a predetermined strike price and the actual price paid for CO_2 EU ETS allowances. If the strike price falls below the CO_2 EU ETS price, the subsidy steps in to bridge this difference, supporting decarbonisation projects. The strike price is set by the government through market research to determine a realistic EU ETS price in which a certain decarbonisation option ,such as blue hydrogen, is viable on its own without any further support. The SDE++ is not connected to the Dutch CO_2 Levy. Each technology category applying for SDE++ operates with its own specific strike price. In other words, when the EU ETS price exceeds the strike price, a decarbonisation project becomes economically viable. The SDE++ subsidy is proven to be effective for public application such as solar panel incentives and heat pumps. The SDE++ is likely to have a significant impact on pre-combustion projects, as CO_2 EU ETS is a fundamental aspects of these initiatives.

$$SDE++ = Strikeprice - (EUETS * Inflation) * \mathrm{CO_2}\ Stored \tag{2.1}$$

Maatwerk - ”Tailor-Made Agreements”

The government acknowledges that major industries such as refining, face decarbonisation challenges due to their operation and scale. The government approaches companies that are in the list of top 10 biggest emitters in the country, 4 of these 10 emitters are refineries. The government opens up the conversation to discuss the needs for these companies to decarbonise. Aspects such as financing, timing and level playing field are mostly discussed. The Tailor Made Agreements start with the siging of an expression of principle and progress to a binding stage with a joint agreement. This subsidy can result in forms of financial support such as CAPEX and OPEX subsidies, or speeding up permit processes (PwC, 2022; Rijksoverheid, 2023; VNCI, 2024).

2.6. Socioeconomic Analysis for a Decarbonisation Project

The primary goal of conducting a socioeconomic analysis within the area of decarbonisation is to assess the balance of advantages and disadvantages associated with a particular action on society as a whole (Brent, 2006). This becomes particularly relevant when the project aims to influence a topic as critical as decarbonisation, which affects individuals across the nation/globe. Socioeconomic analysis can inform on the social potential of a decarbonisation option, and highlight any need to intervene (Annema, 2013). Moreover, socioeconomic analysis serves as a valuable tool for evaluating various policies, investments, and other measures within sectors that impact society.

2.6.1. Quantifying Effects From a Corporate & Public Perspective

When analysing a project from a social standpoint or from a purely economical/financial standpoint some fundamental assumptions and principles are different (Boardman et al., 2018). In terms of quantifying effects, technical parameters such as energy, mass and heat will not be interpreted differently among stakeholders since these are non negotiable parameters. However, the importance varies: for a commercial entity selling hydrogen, the focus is on the mass of hydrogen sold, whereas for the government, the emphasis is on the reduction or avoidance of CO_2 emissions within Dutch borders.

From a corporate perspective, the primary goal is profitability and financial sustainability. Corporate focus on direct financial returns, assessing whether the project will increase shareholder value through outputs such as Net Present Value and Internal Rate of Return (D. D. Kim et al., 2020). This perspective involves stakeholders like shareholders, investors, employees, and customers. These stakeholders prefer valuation of a project in terms of monetary values based on market prices. Non market effects are often excluded unless they have direct financial implications. The corporate perspective prefers a shorter time horizon and a higher discount rate this reflects the need for quicker returns and the company's risk preferences (Rowell, 2014). Risk is assessed in terms of financial uncertainty, market volatility, and competitive position (Schopp & Neuhoff, 2013).

The public perspective aims to maximize social welfare, considering a broader range of impacts. This includes non monetary and indirect effects on society. This perspective includes stakeholders like taxpayers, residents, local communities, and future generations, necessitating an analysis that considers diverse interests and the distributional effects across different societal groups (D. D. Kim et al., 2020). Valuation includes both market and non-market effects, assigning monetary values to externalities such as environmental damage, public health impacts and other more qualitative effects. This by using techniques like shadow pricing. A longer time horizon and a lower discount rate are often used, reflecting social preferences for future benefits and inter generational equity (Lorenzoni & Pidgeon, 2006).

Shadow Pricing

Shadow pricing is a technique that internalizes externalities by assigning monetary values to effects that do not have a market price. These effects can exist of environmental, health and reputational costs and benefits. This method is mainly used from a public perspective. By reflecting the 'true' economic cost of these externalities, shadow pricing helps ensure that otherwise overlooked or ignored costs or benefits are accounted for (Starrett, 2000).

Shadow prices can be determined through guidelines and calculations provided by organizations like CE Delft (Delft, 2021b). Government agencies have calculated shadow pricing variables for a variety of environmental effects, such as CO_2, NOx emissions, and other effects.

Shadow pricing may also be necessary to evaluate other effects on corporate or public perspectives, such as reputation, competitive position, and energy dependency. These are sometimes hard to monetize with shadow pricing, in this case these parameters are better suited for multi criteria analysis (Mariotti et al., 2012).

Literature often concludes that market prices or mechanisms fail to accurately value benefits or damages from a broader perspective (Färe & Grosskopf, 1998). This discrepancy is why the public perspective can significantly diverge from the corporate perspective on certain parameters (Brink et al., 2016).

2.6.2. Cost Benefit Analysis

The principles of a socioeconomic analysis describe that Cost-Benefit Analysis (CBA) should evaluate all the positive and negative impacts of a measure in terms of money as much as possible. The main principle of CBA is that the value of an outcome is what people are willing to pay to achieve or avoid it (Boardman et al., 2018).

Two types of CBA can be categorized and used simultaneously, these two types consist of: 1) Financial CBA (FCBA) and 2) Social CBA (SCBA). A FCBA analyzes the potential financial return of a project over its lifetime to justify the costs or benefit incurred by the company, providing a corporate perspective. In contrast, SCBA focuses on the projects contribution to overall social welfare (Van Wee, 2012).

A Social CBA captures all positive and negative effects of an intervention from the perspective of society as a whole. It includes financial effects from the corporate perspective, making the Financial CBA a part of the SCBA. Furthermore the SCBA goes beyond direct effects by incorporating additional effects with socio-economic value, such as environmental impact, health, and safety (Drèze & Stern, 1987).

The outcome of a CBA results in a discounted cost and benefit cash flow over the project's lifetime. The results are presented using one or more measures of financial or social value. These measures mainly consist: 1) Net Present Value (NPV) provides the absolute value of project and is directly comparable between perspectives, 2) Internal Rate of Return (IRR) is the discount rate when the NPV is zero, this is a measure that can be compared to minimal investment thresholds that companies set, 3) benefit-cost ratio (B/C) displays the ratio between benefits and cost. 4) abatement cost, refers to the cost of reducing CO2 emissions. Displays the cost of the project compared to the emission reduction potential (Boardman et al., 2018). In SCBA mainly the NPV is favoured due to the direct and absolute comparison between perspectives, takes into account the time value of money, gives a measures which is easy to interpreted. Regarding the corporate perspective next to the NPV, the IRR is a commonly used measure since it can be compared to the investment threshold (hurdle rate) independent of the scale of investments (Brigham, 1975).

In a Financial CBA, an NPV greater than zero indicates that a project is expected to be financially profitable. In a Social CBA, an NPV greater than zero generally means that the project will contribute positively to overall social welfare (Luminița et al., 2022). The outcomes of FCBA and SCBA can be contradictory.

CBA follows multiple guidelines, these guideline provide a standardized framework for the valuation of effetcs, scope, time horizon and discount factors. The guidelines are specified towards a sector specific projects and a geographical bound area. These guidelines create transparency and comparability among projects (Mistry & Freudenburg, 2023). Literature indicates that the EU has established specific guidelines for energy and decarbonisation projects (European Commission, 2021) (European Commission & Policy, 2015). These guidelines specifically address economic feasibility, adherence to climate targets, and efficiency measures regarding decarbonisation projects. Dutch guidelines outline principles for energy and environmental projects but do not explicitly address decarbonisation projects (CPB, 2015).

In Table 2.3, 4 socio-economic methods for analyzing projects are displayed. For projects such as national decarbonisation initiatives two main perspectives are particularly relevant. The corporate perspective valuates the business case as key model, with the primary question being the profitability of the investment. From a public perspective SCBA is more suitable since decarbonisation has social impacts and can improve overall social welfare. Cost-Effectiveness Analysis (CEA) and Multi-Criteria Analysis (MCA) are not taken into account for this study since multiple alternatives will not be compared. Also MCA depends on the analyst judgment regarding the value of each criteria, this introduces subjectivity. A trade-off scheme between CBA and MCA is provided in Appendix A.

Table 2.3: Overview Socio-economic analysis methods (Boardman et al., 2018) || SCBA = Social Cost Benefit Analysis CEA = Cost Effectiveness Analysis | MCA = Multi Criteria Analysis

Technique	Situation	Answers
Business case	Private actor that wants to invest	Is there profitability in this investment?
SCBA	Social effects and desires of policy or intervention are not clear	Does intervention lead to bigger social welfare?
CEA	Alternatives known, only cost needs to be determined	Which alternative is most effective?
MCA	Hard to monetize effects	Which alternative is most effective given weight of various objectives?

What can be concluded is that Cost-Benefit Analysis (CBA) is chosen as the most suitable method for evaluating the blue hydrogen decarbonisation option. The limitations of a CBA are not expected to hinder its use in this study, since most of the projects impacts can be monetized in a transparent way. The research objective is to assess the existence and size of the gap between two perspectives, making CBA accurate enough for this task. A downside of the CBA analysis for this project is the valuation of qualitative effects, which need to be assessed high level or excluded from the research. Literature suggest high level evaluation of qualitative impacts, whether they represent a cost or a benefit, and their potential significance (CPB, 2015). This will be further explained in the methodology.

3 Methodology

This chapter provides an overview of the main methodology which is used for this research. It includes an overview of how the SCBA is structured and performed, along with the guidelines that are considered. The corporate and public perspectives are described together with their key values and assumptions. Finally, the chapter provides insights in the anticipated scenarios and outcomes along with overall limitations.

3.1. Analytical Framework for CBA & SCBA

A structured and sequential cost benefit analysis will be performed, as outlined in figure 3.1. Initially, a problem-setting exercise is undertaken, detailed in the proposal and introduction chapter 1. Next, the reference scenario is established which is elaborated in section 4, representing the existing policies and assumption in a specified base year. This serves as a BAU reference scenario against which the impact of the intervention scenario effects is evaluated. The intervention scenario is then described in section 5. When the intervention scenario is configured, the cost and benefits for both perspectives can be identified which are discussed further in section 6. With all information gathered, the cost and benefits can be conceptualized and modeled. Results, case scenarios and sensitivity analysis are shown in 7.

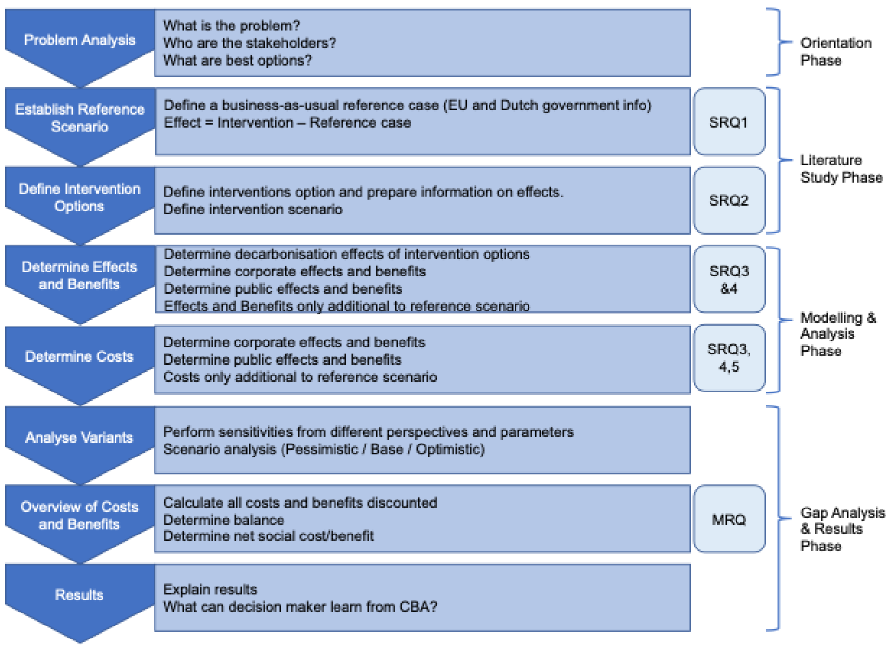

Figure 3.1: Workflow of the Structured Cost Benefit Analysis Process based on CPB, 2015

For this research a project specific SCBA structure is formulated, shown in figure 3.2. All detailed steps shown in the figure will be explained in this chapter.

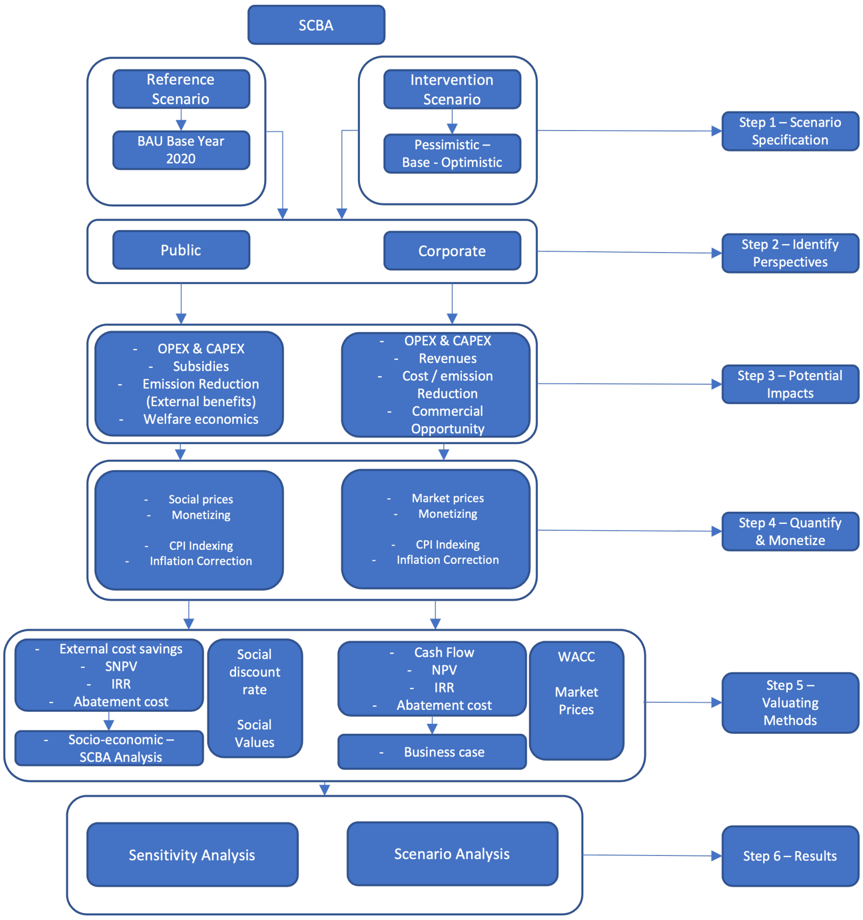

Figure 3.2: Schematic Diagram SCBA Steps

3.1.1. Guidelines and Principles

Since the general CBA methodology spreads across a multiple of sectors, branches, and worldwide regions, guidelines are made to tailor the CBA analysis towards specific projects and policies. For this research, specific guidelines are maintained to ensure that the CBA is representative and transparent. The specific usage of these guidelines will be mentioned in the report.

The main guidelines used within this research are:

- **MKBA Energie (Draft Paper):** This is a Dutch proposal report introducing a guideline on energy projects. Although not an official guideline, assumptions can be drawn from this proposal (Koopmans et al., 2018). This guideline is suitable since it covers a proposal for Dutch Energy SCBA although its not official, it gives guidance.
- **Methodologies for assessing projects in the field of renewable energy:** This is a European Commission guideline on projects in the field of renewable energy. It emphasizes the cross-border aspects but can also be used for general renewable energy projects (European Commission, 2021). This is appropriate since reference scenarios are based on EU and Dutch forecasts.
- **Guide to CBA of investment projects:** This guideline by the European Commission has a specific focus Energy projects. Can be seen in Chapter 5 Energy (European Commission & Policy, 2015).
- **General guideline CBA:** This is a high-level overview of the general guidelines of (Social) Cost-Benefit Analysis published by Dutch bureau of economic policy analysis (CPB, 2015). This guideline guides overall CBA process, also giving guidance on displaying and discussing results.

3.1.2. Perspectives

The perspective which is assumed in the cost benefit analysis determines which costs and benefits can be included in the analysis (D. D. Kim et al., 2020). In the problem statement, two perspectives are identified: the public perspective and the corporate perspective. These perspectives value the outcomes of the analysis differently. When combining these perspectives the following potential outcomes can be concluded, see figure 3.3. This figure shows that when there is a positive outcome from the corporate perspective, the project is likely profitable and does not require subsidies. A positive NPV from the public perspective indicates that the positive direct, indirect, and external effects outweigh the negative ones, generating positive social value. If the corporate perspective shows a low or negative NPV, there may be a need for support in the form of subsidies. When the public NPV is negative, the negative effects surpass the positive ones, potentially necessitating measures such as increased levies or for example higher carbon taxes to mitigate these negative impacts. Further in this section the perspectives will be explained with their key values and valuations in terms of discounting rate. The Net Present Value (NPV) will serve as the main outcome measure, this is explained together with other measures in section 3.1.6.

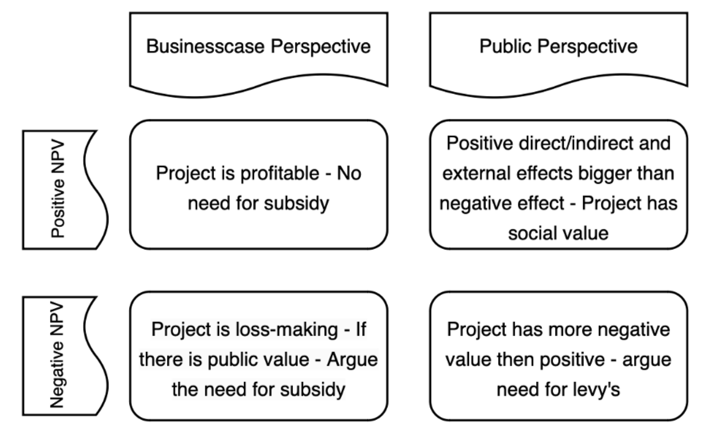

Figure 3.3: Businesscase & Public Perspective

Corporate Perspective

The corporate perspective identifies the direct costs and benefits resulting from investment decisions at the level of an individual project, explained in section 3.1.4. An important reason to incorporate the corporate perspective in a SCBA is that they have the assets (which produce emissions), knowledge and capital to invest in decarbonisation options (Manley & Heller, 2021). The goals that are key for the corporate consist of competitive position both national as internationally and making sure that profitability is in line with shareholders expectations (Marschinski et al., 2020). A more refinery specific goal is that reliable and safe operations is key for sustainable business operations (Joly, 2012). The corporate perspectives values projects with a business case approach aimed for profitability.

The main metrics used to evaluate the corporate perspective are the NPV and the Internal Rate of Return (IRR), relevance and use of outcome measures can be found section 3.1.6.

The corporate perspective on decarbonisation is nuanced in this context. IOCs are transitioning towards becoming IECs, this by expanding their energy portfolios to include renewable and low-carbon alternatives (Reuters, 2024). The corporate perspective values decarbonisation not as a legally binding aspect, for the corporate profitability is assumed as the main driver in this research (Constable, 2020). Since the corporate is moving from being a IOC to a IEC, the commercial opportunity of a strategic position in low carbon technology is valued to be relevant for the corporate perspective.

The net benefit for the corporate perspective will be determined with equation 3.1.

$$NB_p = \Delta B_p - \Delta C_p \tag{3.1}$$

Where

NB_p = Net Benefit Intervention Scenario

ΔB_p = Change in Private Benefits compared to Reference Scenario

ΔC_p = Change in Private Costs compared to Reference Scenario

Corporate Discount Rate - Weighted Average Cost of Capital

The discount rate from the corporate perspective is based on the companies capital structure. This includes the amount of debt and equity that is used to finance projects. The discount rate is based on the weighted average cost of capital (WACC). The cost of debt reflects the borrowing cost and risk associated. The amount of debt mainly influences the discount rate used in the CBA.

$$WACC = \left(\frac{E}{V} \times Re\right) + \left(\frac{D}{V} \times Rd \times (1 - Tc)\right) \tag{3.2}$$

where:

$E =$ Market value of the firm's equity

$D =$ Market value of the firm's debt

$V = E + D$

$Re =$ Cost of equity

$Rd =$ Cost of debt

$Tc =$ Corporate tax rate

The WACC of refineries operating in the Netherlands vary between 7.5% and 8.5% ("AlphaSpread", 2023) (Finbox, 2024). For this analysis a WACC of 8% will be used for the corporate perspective. The cost benefit calculation will be performed on a nominal basis.

Scope

The corporate perspective in this report contains all cash flows related to the intervention scenario, impacting the profitability of refineries operating in the Netherlands. The investments within the refinery sites boundaries, and costs incurred for services extending beyond those boundaries will be taken into account. Boundaries are illustrated in figure 3.2 and later in figure 6.2.

Public Perspective

The public perspective considers the direct, indirect, and external costs and benefits of the intervention scenario, effects are explained further in section 3.1.4. This perspective assesses the value for the society as a whole (Bonner, 2018). In the public perspective, market prices are not always relevant, in this case social prices and assumptions will be incorporated. These social prices account for externalities that market prices do not capture, such as the effects of CO_2 emissions. In the public perspective, there is a focus on assessing how effectively a project or policy can reach the climate targets (CPB, 2015). The public perspective incorporates the corporate perspective, as they can influence overall public welfare.

NPV is a more appropriate metric than IRR for the public perspective, since it expresses net present value for society as a whole making it a absolute value. Further explanation and motives regarding outcome measures is explained in 3.1.6.

The net benefit for the public perspective is expressed in equation 3.3.

$$NB_s = \Delta B_s - \Delta C_s \tag{3.3}$$

NB_s = Net Social Benefit Intervention Scenario

ΔB_s = Change in Social Benefits compared to Reference Scenario

ΔC_s = Change in Social Costs compared to Reference Scenario

Public Discount Rate

The nominal social discount rate is used in CBA to discount costs and benefits. This social discount rate reflects the social view of how future benefits and costs are to be valued against current benefits and cost (Boardman et al., 2018).

The social discount rate is calculated by the social time preference formula named the Ramsey formula (Caplin & Leahy, 2004). For this research the social discount rate appropriate to decarbonisation / investment / energy projects will used provided by the specific guidelines.

- Guideline EU: 5%
- Guideline NL Finance: 2.25%
- Guideline EU Energy projects: **4%**

For this research the nominal social discount rate of 4% will be used which is described by the EU Energy/Industry guideline (European Commission, 2021). This rate is appropriate because the refineries are located in the Netherlands and are influenced by European factors such as natural gas prices, the EU ETS and other widespread costs and benefits across the EU. The higher social discount rate provided by the EU Energy guidelines also accounts for a greater uncertainty and risk associated with long-term decarbonisation projects, making it suitable for this studies purposes. A sensitivity on the social discount rate will be performed in the analysis.

Overlap/Shared Perspectives

Although it may appear that the perspectives are opposed in terms of goals, objectives, and valuation, there are potentially common goals and overlapping ambitions. This will be considered in collecting effects and in the final analysis. Subsidies can be seen as a transfer cost in the overlap of the perspectives, however in this report, subsidies are account for as a benefit for the corporate and a cost for the public perspective. This because subsidies are not a 100% transfer costs in this study, due to the difference in discount rates (CPB, 2015) (European Commission, 2021).

3.1.3. Anticipated Scenarios

The basis of this Social Cost Benefit Analysis (SCBA) consists of two scenarios: a reference scenario, referred to as the Business as Usual (BAU) scenario and the intervention scenario, where an investment or technology is implemented.

Reference Scenario

The reference scenario, known as the Business as Usual (BAU), serves as the baseline where current practices, policies, and technologies as of 2020 continue without significant changes. This also includes geographical, demographically, and economic forecasts. No direct actions or investments are taken place in this scenario. The BAU scenario is used in climate models to be examined in the fields of climate politics, policy, social behavior, technological progress, and the results of inaction (Boardman et al., 2018; European Commission & Policy, 2015). It provides a baseline against which the impacts of intervention scenarios are assessed. Reference scenario will be based on CO_2 emission basis and energy (PJ) basis, specifically for high temperature heat demand of refineries located in the PoR. The European Union publicly provides BAU scenarios for research purposes (Commission et al., 2021). These general scenarios will be adapted and isolated to fit the problem statement to create a specific reference scenario for this research.

In the EU Guideline BAU scenario, climate goals will not be achieved, since its based on supply and demand forecasts and no direct actions are considered. This is crucial because only one intervention option, blue hydrogen in this study, will be tested against the reference scenario to eventually reach the decarbonisation targets. Including multiple decarbonisation options or a preset decarbonisation pathway in the BAU scenario could lead to double counting of effects, which would compromise the findings (Commission et al., 2021).

Intervention Scenario: Blue Hydrogen

The intervention scenario will present a deviation from the BAU baseline, incorporating specific changes to reach the targeted CO_2 reduction goals. For this study, the intervention scenario evaluates the impact of using blue hydrogen for high temperature heat demand in refineries located in the Port of Rotterdam.

This scenario is configured to close the difference between the BAU scenario, which is not reaching the decarbonisation targets, to using hydrogen and reaching the targets set in 2030, 2040 and 2050. By comparing the intervention scenario against the BAU scenario, impacts such as emission reduction, and costs & benefits effects can be evaluated from two different perspectives. This comparison enables a assessment of the total benefits, and forms the basis for a comparison of perspectives (CPB, 2015).

The intervention scenario will be configured based on literature information and existing blue hydrogen initiatives (Deltalinqs, 2019). The decarbonisation demand necessary will be determined by assessing the difference between the BAU scenario and the climate targets, which will then serve as the basis for the intervention scenario.

3.1.4. Categorization of Effects

In a SCBA from the corporate and public perspective, the effects resulting from the intervention scenario, can be divided into three categories: direct effects, indirect effects, and external effects (Bonner, 2018). The relevance of these effects depends on the perspective being considered, which will be displayed next (Mishan & Quah, 2020) .

- **Direct effects**

  Direct effects in a cost-benefit analysis are the effects that can be directly linked to the project. Users, owners, and operators directly experience the consequences. For the determination of the direct effects, government price sets such as PBL SDE++ (PBL, 2022) have been used as the main input, along with values found in literature. If there is a deviation from PBL (Final Advice SDE++, 2022 (Ministry of EZK, 2023)) in the direct effects, it is indicated and explained. Direct effects are used in the corporate and public perspective.

- **Indirect effects**

  Indirect effects arise when direct effects influence other areas. They can be both positive and negative. Examples include costs for infrastructure adjustments, employment. Indirect effects are only counted towards the public perspective.

- **External effects**

  To fully assess the societal perspective, the external effects must be considered. These are the unpriced impacts (both costs and benefits) a project has on third parties. Third parties are not compensated for these effects (or, if beneficial, do not contribute to the projects realization). For example, external effects of changes in public health, land use and CO_2 reduction. External effects are only counted toward the public perspective.

To gain a better understanding of the effects, a variation in assumptions will be applied. This involves using low, base, and high scenarios, where the low and high scenarios is depended on the variations set in table 3.1. This creates a bandwidth of results to account for uncertainty. Some effects can be difficult or impossible to monetize. These effects will be identified and qualitatively analyzed at a high level. This approach aims to provide context on the potential impact of these non-monetizable effects.

3.1.5. Anticipated Outcomes

Within the intervention scenario, 3 cases are described. A pessimistic, base , and optimistic case towards this blue hydrogen project. The cases are determined by the maturity of the technology using the Technology Readiness Level (TRL), and price variations used in CAPEX-related projects and government price sets (Hansen et al., 2009; Netherlands Environmental Assessment Agency (PBL), 2020), see table 3.1. These cases are designed to account for uncertainty of H_2 and CCS technology and market scenarios. Cases are set up under the same base year. Table 3.1 displays case descriptions.

Parameter	Pessimistic	Base	Optimistic	Note
CO_2 EU ETS Price	80%	100%	120%	KEV Variation
CO_2 Levy Price	80%	100%	120%	KEV Variation
CO_2 Transport/Storage Tariff	120%	100%	80%	TRL 7-8
CAPEX	115%	100%	85%	TRL 8-9
Subsidy	80%	100%	120%	SDE Variation

Table 3.1: Intervention Scenario Cases & Parameter Variation

Optimistic Case

- **CO_2 Transport and Storage Tariff:** CCS developers can offer favorable tariffs for Transport & Storage of CO_2.
- **Carbon Pricing:** Anticipate high carbon prices or strong carbon pricing mechanisms, incentivizing industries to invest in low-carbon alternatives like blue hydrogen.
- **CAPEX:** Expect relatively low capital expenditure (CAPEX) for blue hydrogen production facilities due to technological advancements, economies of scale, and favorable financing conditions.
- **Regulatory Environment:** Envision a regulatory environment that strongly supports and accelerates the deployment of hydrogen infrastructure, including subsidies.

Base Case

- **CO_2 Transport and Storage Tariff:** CCS developers can offer average tariffs for Transport & Storage of CO_2.
- **Carbon Pricing:** Foresee moderate carbon prices or a mixed regulatory landscape with varying levels of carbon pricing across regions, providing some incentive but not driving widespread adoption of blue hydrogen.
- **CAPEX:** Expect average CAPEX for blue hydrogen production facilities, with costs influenced by market conditions, technological maturity, and project-specific factors.
- **Regulatory Environment:** Anticipate a mixed regulatory environment with some support for hydrogen initiatives but also regulatory hurdles, and competing priorities.

Pessimistic Case

- **CO_2 Tansport and Storage Tariff** CCS developers can offer unfavorable tariffs for Transport & Storage of CO_2.
- **Carbon Pricing:** Expect low carbon prices or weak carbon pricing mechanisms, providing little incentive for industries to transition to low-carbon alternatives like blue hydrogen.
- **CAPEX:** Expect high CAPEX for blue hydrogen production facilities due to technological uncertainties, lack of economies of scale, and limited access to affordable financing.
- **Regulatory Environment:** Anticipate a challenging regulatory landscape with stringent permitting requirements, and limited government support for hydrogen initiatives.

Sensitivity Analysis

To evaluate the impact of individual parameters on the outcome. A sensitivity analysis will be performed to provide insight into the range of variation of the NPV. This analysis will help test the potential impact of uncertainties associated with these parameters. Sensitivity analysis will only be performed on the base case.

- Commercial price of blue hydrogen
- CO_2 Price Sets (Corporate and Public)
- CO_2 Transport and Storage Tariff's
- Discount rates
- CAPEX Variations

- Regulatory changes / Subsidy intensity

Varying these parameters within a specified range of + 20% and - 20% will enable the identification of uncertainties and risks associated with different practical scenarios. A 20% variation is chosen since it captures the majority of market and policy fluctuations, and it belongs to industries best practices, based on published techno-economic analysis.

3.1.6. Main Outcome Measures

In this section the relevance and explanation of the main outcome measures is provided. The economic outcomes of a SCBA can be expressed in various measures. The main, leading, and common outcome measure within this analysis is the Net Present Value (NPV).

Net Present Value (NPV)

The NPV reflects the net present value of the intervention scenario its lifetime. The sum of all cost and benefits are discounted to account for the time value of money. This is performed by discounting the corporate perspective using the WACC and for the public perspective the social discount rate. A positive NPV indicates that the sum of all discounted benefits outweigh the sum of all discounted costs.

The main argument for using the NPV as leading measure is the ability to directly compare a absolute number of wealth against a different perspective or project. This can be done since the discount factor from a specific perspective or project is already incorporated in the calculation of the NPV. The NPV can be seen as a measures which tangible for the reader to understand since its an absolute value. The NPV formula can be seen in equation 3.4.

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \tag{3.4}$$

$NPV = Net\ Present\ Value$

$C_t = Cashflow\ Period\ t$

$r = Discount\ rate$

$n = Periods$

Internal Rate of Return (IRR)

The Internal Rate of Return (IRR) is the discount rate that makes the NPV of all cash flows equal to zero. It represents a projects expected rate of return. IRR is a useful measure for the corporate perspective to compare the return of the project compared to the minimal corporate threshold (Hurdle Rate). The IRR is a measure that indicates the performance of a project independent on the scale of the size or investment of the project. The IRR will be used in the report to contextualize results compared to hurdle rates which are provided by the corporate. It will not be the leading metric since the IRR needs to be compared to the WACC or the social discount rate which can be different in various projects and perspectives. The IRR formula is provided in equation 3.5.

$$0 = \sum_{t=0}^{n} \frac{C_t}{(1+IRR)^t} \tag{3.5}$$

Abatement Cost

Carbon abatement cost measures the cost per unit of CO_2 reduced by the intervention scenario. This measure is aimed at emission reducing project to provide insight into the cost effectiveness of different decarbonisation options. The abatement cost which will be calculated is specific to a project or perspective since the total cost will be discounted with a project/perspective specific discount rate. This measure will be used for discussion purposes to evaluate the cost of the intervention scenario compared to the forecasted CO_2 price, but not as a leading measure.

$$\text{Abatement Cost} = \frac{\text{Present Value Total Cost of Abatement}}{\text{Quantity of Emissions Reduced}} \tag{3.6}$$

Benefit Cost Ratio (BCR)

The Benefit-Cost Ratio (BCR) will be presented when performing the case analysis to provide an overview of the ratio between the cases. BCR is a commonly used measure in SCBA which demonstrates the relative costs and benefits of the proposed cases. This measure gives simple overview when comparing cases. This measure will also be used for high level discussion.

$$BCR = \frac{\sum_{t=0}^{T} \frac{B_t}{(1+r)^t}}{\sum_{t=0}^{T} \frac{C_t}{(1+r)^t}} \tag{3.7}$$

where:

- B_t = benefits in year t
- C_t = costs in year t
- r = discount rate
- T = total number of years

3.2. Price Level - Base year

The assumptions within the model will have a base year depended on the publication of the information. To be able to compare price sets and assumption, these input data require indexing. Indexing involves the adjustment for inflation of economic and financial parameters. CAPEX numbers are next to being indexed, also corrected towards the cost engineering index. This index factors in CAPEX values from plants, labor rates, material costs, market conditions, and more.

Indexing will be applied by using the CPI index (Centraal Bureau voor de Statistiek, 2024), see Appendix B for CPI index. If indexing is needed based only on inflation, a PBL guideline of 1.5% increase per year is used (PBL, 2022). All price levels will be based on year: 2023

See Appendix B for CPI index. The CPI indexing formula is given by:

$$\text{Adjusted Value} = \left(\frac{\text{CPI}_{\text{Current Year}}}{\text{CPI}_{\text{Base Year}}}\right) \times \text{Original Value} \tag{3.8}$$

3.3. Time Horizon

The SCBA and CBA do not share the same preference in terms of time horizon. SCBA prefers long time horizons since this provides the possibility to consider long term effects of environmental and decarbonisation effects. A higher discount rate favors projects that yield benefits relatively early in their lifetime. In contrast, a lower discount rate assigns a more similar value to benefits over time. A low discount rate for a SCBA means that impacts on future generations are given a greater significance. In other words, future generations will be considered more equally valued in the effect of the cost and benefits (de Bruyn et al., 2017).

In a corporate CBA or business case the time frame is depended on the operational lifespan of the plant that is invested in. In this study the ATR + CCS combination is studied. The lifetime of this plant is 25 years (Muhammed & O., 2023). To meet the first decarbonisation target in 2030, the ATR+CCS combination will start operating in this year. This means that the ATR+CCS operation lifetime spans until 2055. This encompasses all decarbonisation targets. For modelling efficiency ,the time frame in which the SCBA will be performed is from 2020 to 2050. This is also inline with the EU reference case time frame, which will be used for the Reference Scenario in section 4.

3.4. Validation

Scenarios and results will be validated to ensure they match the expectations and requirement for their intended use. Validation will be conducted on the reference scenario, intervention scenario, and effects and results collectively. This involves cross-matching forecast of supply and demand scenarios that closely align or correlate with PoR refinery operations. To get a better insight in the validation of the whole report, a expert meting will be organized with a public consultancy company to review the SCBA Methodology, scenario determination, and completeness and correctness of effects and results. Furthermore each individual validation will include recommendations for further research to improve validation and to improve the outcomes. Validation of reference scenario can be found in section 4.2 and for the intervention, effects, results thus full report in appendix C.

3.5. Model limitations

The SCBA will be conducted in a Microsoft Excel model. This model faces internal and external uncertainties in the form of: forecasting uncertainties, data limitations, assumptions and simplifications and external factors. If in retrospect, solutions to these limitations become apparent, they will be addressed in the discussion section. For now these are the main limitations being accounted for:

Forecasting Uncertainties

The reference scenario is based on theoretical forecasts, introducing variability compared to real life conditions. Data is based on historical datasets which will be the basis for future forecasts. This causes uncertainty of extrapolating historical data plus the uncertainty of the forecasted EU reference case.

To be able to model the decarbonisation targets effectively, targets will be set up in a linear way. This instead of a step wise target in 2030, 2040 and 2050. The practical implication of linear decarbonisation approach is not further researched.

Data Limitations

CAPEX and OPEX specific to blue hydrogen plants can be difficult to identify due to confidentiality. Mainly public price sets will be used for CAPEX and OPEX values. If there is any deviation regarding assumptions being made from consultancy & engineering reports will be mentioned.

Pricesets provided by governmental bodies and consultant may differ from current market prices. This is due to rapidly changing market and economy conditions. These variations will not be used in the model. Long term, established price outlooks will be used throughout.

Assumptions and Simplifications

To be able to effectively set up the model to achieve the objective of this study, simplifications need to be performed. Especially on public expenditures that cover multiple industries, such as in infrastructure. Cost that are allocated for refineries are based on the utilization rate that refineries have in this public expenditure. If refineries would use for example 20%, then 20% of cost is allocated to the refineries.

Also in terms of economic externalities and value leakage across the borders. These are not considered in the model of the project. The assumptions are bound to Dutch territory.

Qualitative parameters are mainly based on literature research. No interviews are conducted. Qualitative parameter which are not monetizable are excluded from the SCBA.

Since there are many inter dependencies within the refinery sector delays are likely. For this model Project and investment timing are assumed to be accurate. No delays are expected or accounted for.

External Factors

External effects such as changes in the economic environment are not accounted for in the project. This includes, inflation rates, currency rates etc. Sensitivity analysis can give insight in these aspects.

Additionally, no regulatory changes are assumed in this research. Existing regulations can affect the project, new regulations are not account for.

Changes in technology and innovation can effect the cost and benefits of the model. Changes in terms of technology improvements outside the scope of this research are not accounted for.

4 Reference Scenario

The reference business as usual (BAU) scenario is used to establish a baseline against which the changes and impacts of the intervention scenario can be measured. This chapter outlines the foundation of the BAU scenario and explains how it is specifically isolated towards high temperature heat demand within refineries in the PoR. This chapter will address the first sub-research question:

RQ1: What is the business as usual high temperature heat energy demand and CO_2 reference case for refineries in the Port of Rotterdam?

In order to form the basis of this SCBA, a baseline in the form of a BAU scenario needs to be identified. This scenario will consist of a Port of Rotterdam High Temperature Heat BAU scenario. In order to isolate this final scenario, this study will use a official European Commissions Reference Case as foundation (Commission et al., 2021). This reference case consists of specific reference scenarios per country and per industry specific sector. The EU base their policy targets on these reference scenarios.

The EU reference scenarios are established with a baseline year set in 2020. Subsequent projections are formulated based on the commitments made as of 2020. These scenarios are categorized according to industry types and classifications, making a clear differentiation between non-ETS and ETS entities. Refineries are categorised within the ETS category, as explained in section 2. These scenarios do not take into account any direct action or investment to reach climate targets, only natural technological improvements and policy as of 2020, and projected supply and demand projections are considered.

4.1. Determining the Reference Scenario

In this report the BAU scenario is set up on the basis of the Dutch EU ETS Sector scenario provided by the EU. From the Dutch EU ETS sector scenario, the Dutch PoR refinery emissions scenario is isolated based on the emission split within the Dutch EU ETS sector (+/- 13% of Dutch ETS emissions stems from PoR refineries) (Centraal Bureau voor de Statistiek, 2024). Subsequently, the high temperature heat demand is isolated based on energy usage within PoR refineries (Netherlands Environmental Assessment Agency (PBL), 2020) seen in table 4.1, this to develop a specific scenario for this SCBA. This involves reviewing literature and historical data on refinery emissions and energy usage. The energy demand of high temperature heat is illustrated in table 4.1. This table excludes NG and RFG exports which is shown in figure 2.4, only consumption for heat generation is considered.

Extrapolating this division over time creates a BAU scenario specific to high temperature heat energy demand and emissions in PoR refineries. For modeling purposes, and given the significant contribution of high temperature heat demand to the total energy demand within refineries, the division of high temperature energy demand within refineries (energy share of +/-70%) described in 2.3.1 is assumed to remain constant over time.

Table 4.1: High Temperature Heat Demand in PoR Refineries (PJ) 2020 (Netherlands Environmental Assessment Agency (PBL), 2020) || CHP = Combined Heat & Power | RFG = Refinery Fuel Gas | NG = Natural Gas

Category	**Demand (PJ)**
CHP from RFG	6.8
CHP from NG	13.7
Boiler usage from RFG + NG	9.8
RFG Combustion	66.3
Total	96.6
Total minus CHP from NG	**82.9**

This results in a total demand for high temperature heat energy of 96.6 PJ, which is supplied by natural gas and refinery fuel gas. Combined heat and power (CHP) from natural gas is excluded from fossil fuel replacement, as converting gas turbines to hydrogen requires technology outside the scope of this study (D. Kim, 2019). CHP from refinery fuel gas is included since it involves co-firing after the gas turbine, by using a standard burner.

The identified split in high temperature heat demand is extrapolated based on the 2020 base figures, this in alignment with the trajectory of the original Dutch EU ETS Refining reference scenario. This extrapolation creates a BAU reference scenario specifically targeting high temperature heat energy demand of PoR refineries. These figures are validated through historical energy usage, ensuring consistency. Detailed calculations and validation are outlined in appendix D. In figure 4.1 the BAU reference scenario for high temperature heat demand for refineries in the PoR is shown.

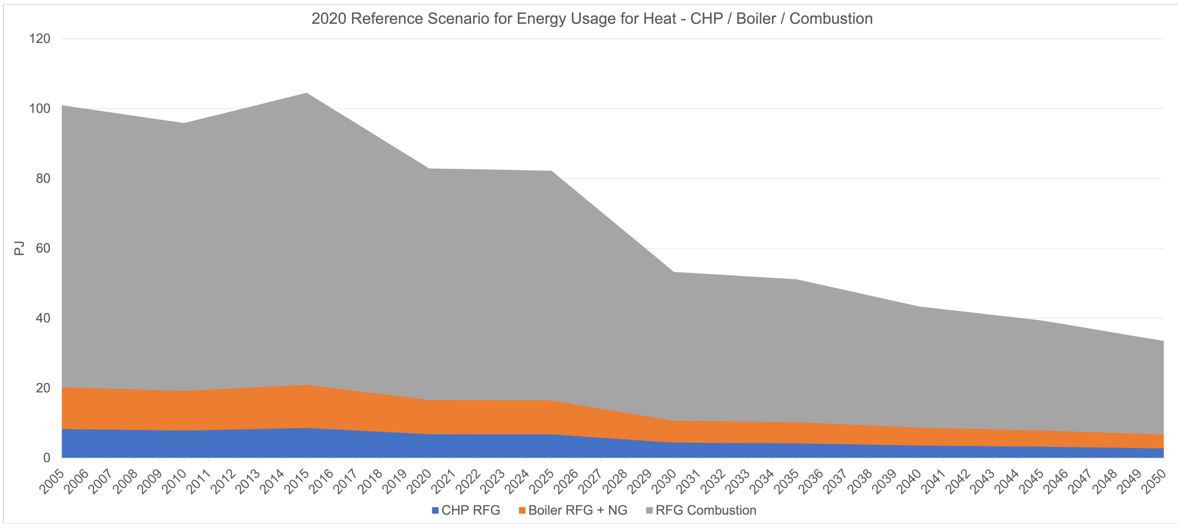

Figure 4.1: Reference Scenario - Energy Demand High Temperature Heat of PoR Refineries

With the reference scenario established in terms of energy demand, the next step is to calculate the associated CO_2 emissions. This is performed by using the emission factor for natural gas and refinery fuel gas. The emission factor for natural gas is 0.20 tonne/MWh and for refinery fuel gas 0.22 tonne/MWh (NEA, 2022). Figure 4.1 illustrates the split between RFG and NG. The emissions are calculated using the emission factors based on the amounts of RFG and NG. The reference scenario based on CO_2 emissions can be seen in figure 4.2.

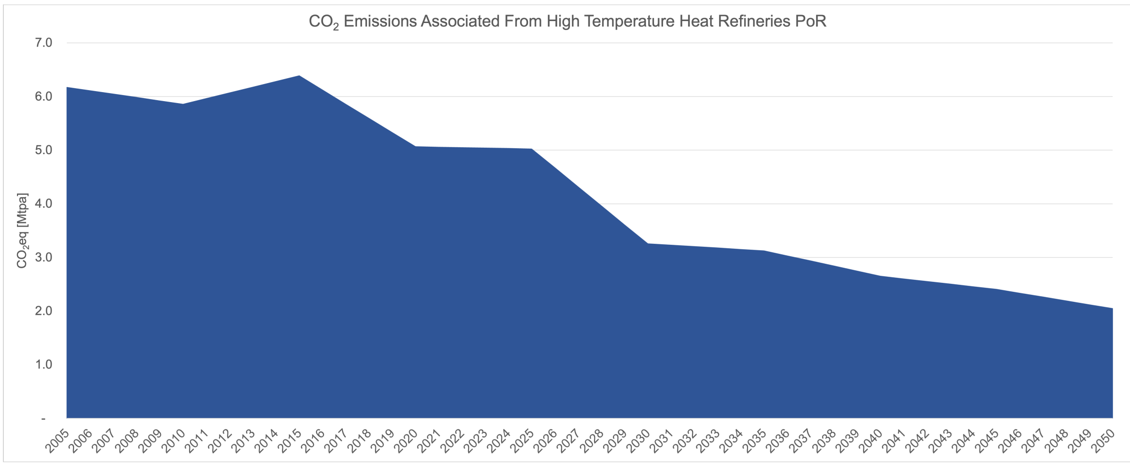

Figure 4.2: Reference Scenario: CO_2 emissions associated from PoR Refinery High Temperature Heat Usage

The BAU scenario shows a significant decline in both energy demand and emissions resulting from the refining process over time. The main driver behind this reduction in energy consumption and emissions is the ongoing electrification of the current mobility fleet, which currently relies heavily on fossil fuel products coming from refineries (Commission et al., 2021). Additionally, forecasts predict a shift in truck mobility towards hydrogen and shipping moving towards gasoline and LNG (CONCAWE, 2013). The main driver for the overall decline in energy usage within the refinery is the decrease in demand for refinery products. This results in the high temperature energy demand from refineries to decrease from around 110 PJ in 2015 to around 40 PJ in 2050 & CO_2 emission from 6.4 Mtpa in 2015 to approximately 2.05 Mtpa in 2050.

This established BAU reference scenario provides the basis for the SCBA. The next phase consists of designing a blue hydrogen intervention scenario that aligns with the decarbonisation targets. When the intervention scenario and subsequently the effects are identified, these can be measured against the BAU reference scenario to create a outcome which can be assessed.

4.2. Validation

All energy and emission data are sourced from government agencies that monitor energy usage and CO_2 emissions from industrial companies. These emissions are accurately measured since emission limits and EU ETS trading systems rely on this data (Centraal Bureau voor de Statistiek, 2024).

The original reference scenario provided by the EU ETS represents a snapshot of the projected reference situation at a specific point in time. These scenarios always include a range of uncertainty because the BAU case for the future depends on many variables, making precise future predictions difficult. To explore variations, the BAU can be adjusted in terms of timing and trajectory. The current level of accuracy is sufficient for this report to test a delta value compared to an intervention scenario. Figure 4.3 displays the multitude of inputs in to the EU Reference model.

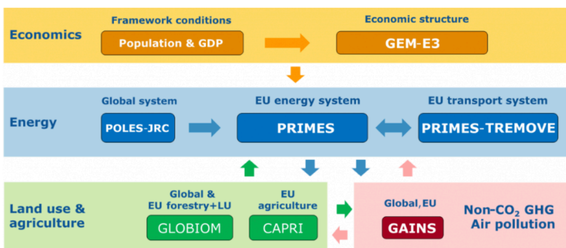

Figure 4.3: European Reference Case Model Method (Commission et al., 2021)

According to the projections by the Research Institute Quintel, the total energy demand from refineries is anticipated to decrease from 156 PJ in 2013 to 47 PJ by the year 2050 (Kerkhoven & Terwel, 2016).

This aligns closely with the reference case calculated in this report. Quintel's analysis encompasses the entirety of energy demand, and when scaled specifically to high-temperature heat demand, the figures are closely to the calculated values in this study.

The research of Voogt and Estrada, 2023 & Platform Investico, 2023 estimates that the Dutch refineries will produce around 30-50 % of todays oil products in 2050. This sits close to the high temperature heat demand reference scenario that is been configured for this report. In percentage wise the BAU scenario will reduce around 60% of todays high temperature heat demand in 2050. This sits just above the expected decline range in oil products. A decrease in oil throughput is in line with a decrease in energy demand to heat this oil throughput.

Figure 4.4 shows a forecast from WoodMackenzie on refinery products in the Netherlands. These show a decline of roughly 40 - 60%. This decline matches the calculated BAU in this report.

The validation and comparisons in this section are considering all Dutch refineries. This research specifically focuses on PoR refineries. The PoR refineries consist of 5 out of a total of 6 refineries in the Netherlands, these 5 refineries account for +/- 90% of the countries total refining capacity. This dominant position of PoR refineries in the Netherlands makes it feasible to validate and compare against country specific refining forecasts and information.

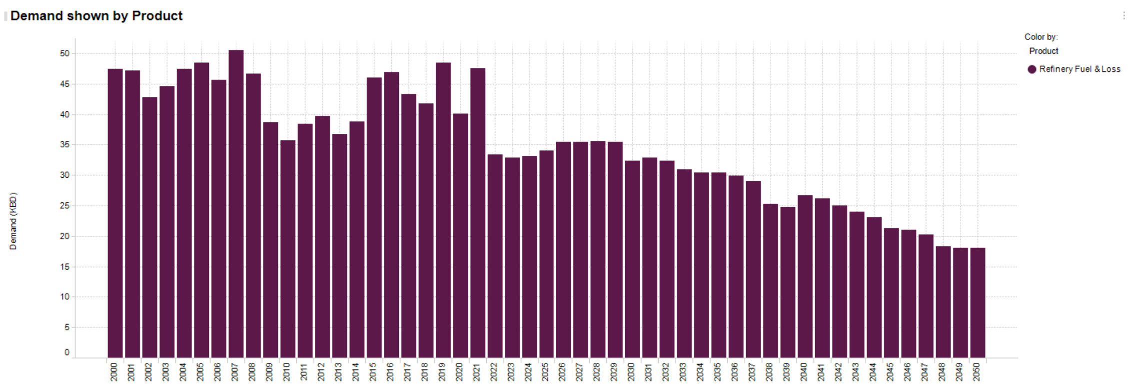

Figure 4.4: Wood Mackenzie forecast of Refinery Products (Jenkins, 2024)

5 Intervention Scenario

This chapter outlines the setup and configuration of the blue hydrogen intervention scenario. The intervention scenario is designed and configured to transition from the BAU reference scenarios towards achieving the defined climate targets. The impact of the intervention scenario in reaching the climate targets compared to the BAU scenario will be analyzed through the SCBA. This chapter addresses the second research question:

RQ2: What is the projected emission reduction from using blue hydrogen for heat generation in Port of Rotterdam refineries compared to the business-as-usual reference case in the time period between 2024 - 2050

5.1. Hydrogen Production Setup

The hydrogen production setup is based on initiatives and literature studies that suggest the optimal configurations. Additionally, characteristic of the hydrogen transport backbone and CO_2 Backbone are used to configure an optimal hydrogen production setup.

Blue hydrogen will be produced using the ATR + CCS processes explained in section 2.6. For this study blue hydrogen production and carbon capture is set up centralized. This means that a single hydrogen production source is located in the PoR. This is realistic since not every refinery will build its own blue hydrogen plant and there are limited options to connect to the CCS network (de Laat, 2020). Initiatives are being carried out consisting of hydrogen backbones which are purposed for transporting blue hydrogen to industrial clusters. In figure 5.1 the set up of hydrogen production can be seen. The inner circle is the hydrogen production plant, the outer circle shows the backbone on which the five refineries are connected. This blue hydrogen production set-up follows the same principles as similar blue hydrogen projects such as H-Vision (Deltalinqs, 2019).

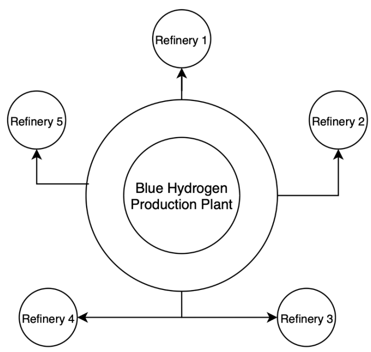

Figure 5.1: Hydrogen Production & Distribution Setup

The hydrogen backbone, displayed by the outer circle, extends beyond refinery infrastructure. This backbone is planned to interconnect with other industrial clusters. See appendix E for more information.

Figure 5.2 details the blue hydrogen production set-up in a schematic way. What can be seen is that RFG & NG is used as input to be reformed, resulting in output stream of blue hydrogen with the CO_2 being captured and transported to storage.

Given that RFG is a residual product from the refining process with no direct alternative use besides combustion, it will function as primary input source for the ATR, reducing CO_2 directly. Additional input demand of the ATR is met by natural gas. RFG has comparable specification as NG which makes it suitable for ATR input (NPL, 2020). Appendix F displays the RFG Composition. The figure also shows that the lower quality hydrogen (97.6%) is used within refineries and the higher quality hydrogen (99.6%) is sold commercially to the backbone, which is explained in section 5.3.

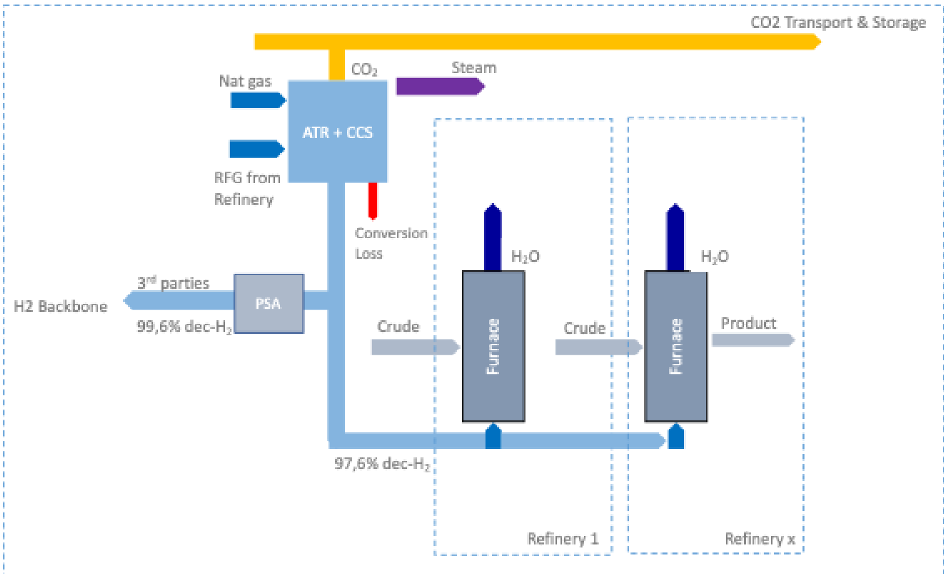

Figure 5.2: Schematic Display of Blue Hydrogen Production Set-up

The main assumptions for modeling the blue hydrogen production setup are detailed in table 5.1:

Table 5.1: Table of Main Parameters for Intervention Scenario Modelling

Parameter	Value	Source
ATR Efficiency	80%	(Cubeiro & Figueredo, 2007)
ATR Steam generation	0.078 MWh_steam/MWh_outputH2	(Muhammed & O., 2023)
ATR Electricity Demand	0.09 MWh_e/MWh_outputH2	(Muhammed & O., 2023)
Carbon Capture Rate	97%	(Hydrogen UK, 2023)
PSA Mass Split	80%	Appendix H
Boiler Efficiency	70%	(Energy.NL, 2021)
Hydrogen Fuel Spec	97.50%	(Gasunie, 2023)
Hydrogen Feedstock Spec	99.50%	(Gasunie, 2023)
Hydrogen Fuel Energy	39.76 kg/MWh	Appendix H
Hydrogen Feedstock Energy	29.5 kg/MWh	Appendix H
Natural Gas Emission Factor	0.20 tonne CO_2/MWh	(CO2 Emissiefactoren, 2024)
Refinery Gas Emission Factor	0.22 tonne CO_2/MWh	(CO2 Emissiefactoren, 2024)
Yearly running hours	8760	
LHV Hydrogen	120 MJ/kg	

5.2. Hydrogen Production Ramp Up

To be able to determine the trajectory of the introduction of blue hydrogen as fuel for refineries, a ramp up rate needs to be defined. This trajectory is set-up according to the decarbonisation goals set by the EU & Dutch government ("European Commission", 2024) (CE Delft, 2018). This scenario focuses purely on the intervention of blue hydrogen to decarbonise high temperature heat within refineries, green hydrogen phasing in will not taken in to account. Only blue hydrogen will be implemented over time to replace current fossil fuels within PoR refineries.

In the scenario shown in figure 5.3, refineries align with the Dutch and EU climate targets outlined in table 5.2. Achieving these targets involves bridging the gap between the emissions projected by the reference scenario for high-temperature heat in refineries and the targeted levels. While the climate targets are initially established as stepwise objectives, they will be linearly interconnected for modeling purposes and to better reflect real-life scenarios. This adjustment makes for a smoother and more realistic ramp-up rate in the adoption of blue hydrogen. Table 5.3 shows the amount of hydrogen that is needed compared to the BAU case for refineries to be able to achieve the percentage in reduction compared to 1990 values. 1990 emissions values are determined on 5.9 Mtpa (RIVM, 2020).

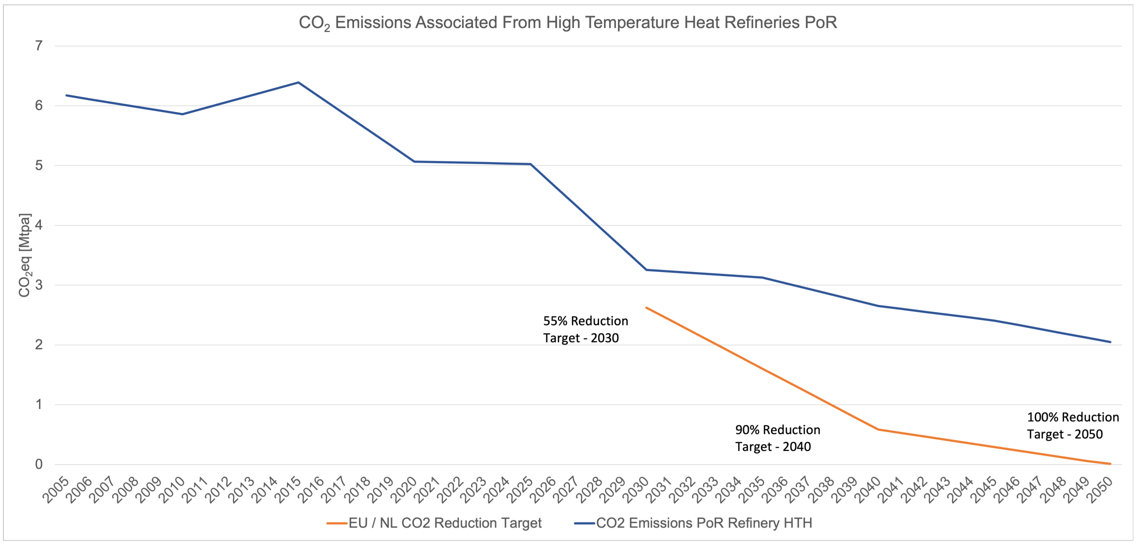

Figure 5.3: BAU CO_2 emission versus the Dutch/EU Paris Agreement CO_2 Reduction targets based on 5.9 Mtpa CO_2 HTH Refinery Emissions in 1990

Table 5.2: CO_2 Emission Reduction Targets [%]; BAU Reference Scenario Emission in a specific year [Mtpa] and Reduction Needed in a specific year [Mtpa]

Year	Reduction target [%]	BAU Emissions [Mtpa]	Reduction Needed [Mtpa]
1990	-	5.9	-
2030	55%	3.3	0.63
2040	90%	2.6	2.1
2050	100%	2.1	2.1

Table 5.3: Blue Hydrogen Needed in Intervention Case to Reach Decarbonisation Targets

Year	Reduction target [%]	Blue Hydrogen Needed [PJ]	Blue Hydrogen Needed [ktpa]
2030	55%	15.6	130
2040	90%	33.5	275
2050	100%	34	280

Table 5.2 & 5.3 conclude the required amount of reduction necessary to reach the CO_2 reduction targets for each specified year. These requirements are converted into the corresponding amount of blue hydrogen needed. This is based on the energy content that blue hydrogen will replace of the currently used natural gas and refinery fuel gas.

5.3. Hydrogen Production Scale

The hydrogen production scale is based on the determined decarbonisation demand needed to meet the decarbonisation goals, shown in table 5.3. In order to meet these targeted decarbonisation goals within specified time-frames, a total and maximum capacity of 1133 MWth of hydrogen equivalent is needed. This translates to an installed capacity of 1400 MW which delivers +/- 289 ktpa of blue hydrogen. 1400 MW of installed capacity aligns with the ability to build a singular blue hydrogen ATR + CCS plant (Air Liquide Engineering, 2024). Constructing a smaller blue hydrogen plant multiple times is not desirable due to economies of scale, investment costs, land usage and infrastructure. Figure 5.4 illustrates the ramp-up of blue hydrogen usage alongside the decline of burning fossil-based sources. The residual RFG and NG which is replaced thus not burned anymore, will serve as input for the ATR.

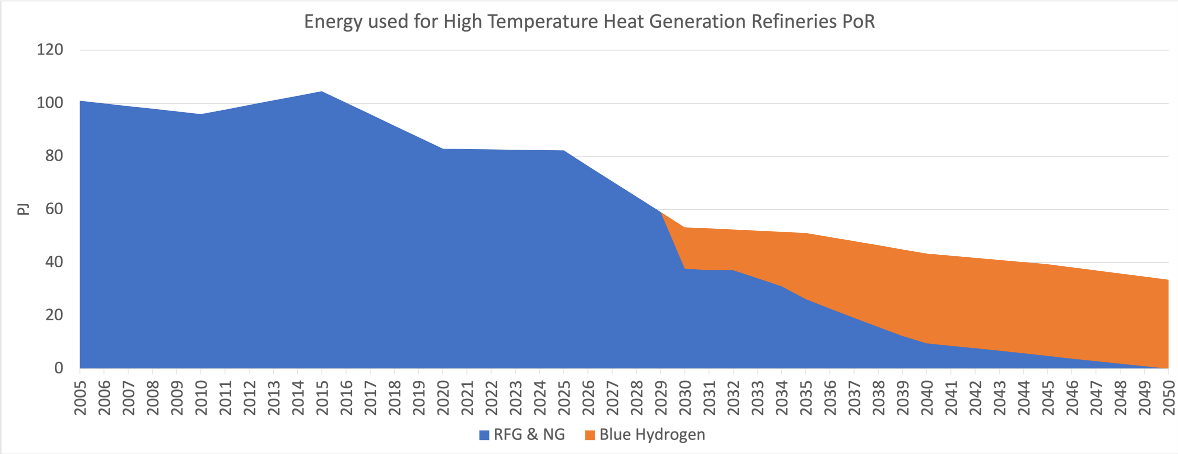

Figure 5.4: Intervention Scenario Displaying Ramp-up in Blue Hydrogen and the Phase Out of RFG & NG

Residual Hydrogen

As figure 5.4 shows, is that less hydrogen is needed to bridge the gap to the 2030 targets, due to the natural decline in the BAU scenario. What can be seen is that the gap between the reference case and the targets for 2040 and 2050 is more significant. In Figure 5.5, the split of blue hydrogen for refinery and commercial usage is shown. Given the surplus of blue hydrogen in the initial years, which the refinery cannot fully utilize, it will be sold to meet demand on the hydrogen backbone. In the initial years up to 20 PJ of blue hydrogen will be available for the backbone. When compared to the projected (high temperature heat) blue hydrogen demand from other sectors such as chemical, steel and fertilizer on the backbone consisting of +/- 50PJ, this amount of hydrogen is assumed to be fully absorbed by the market, see appendix G for the hydrogen demand in the Netherlands (den Ouden et al., 2020).

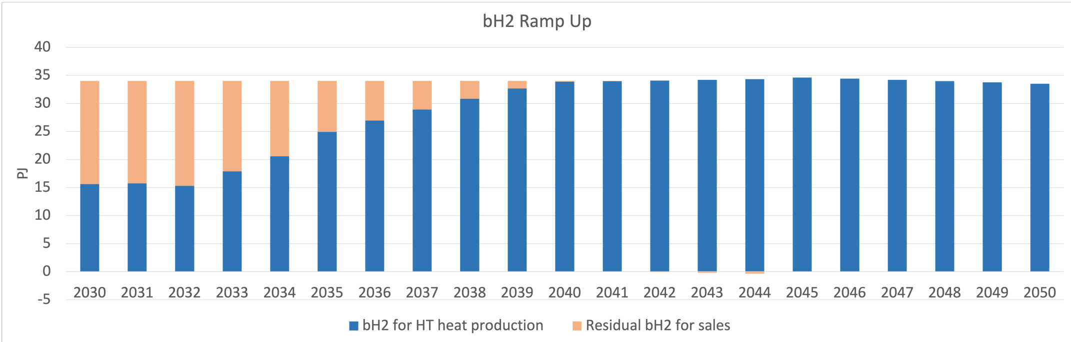

Figure 5.5: Blue Hydrogen for Commercial Sales versus Blue Hydrogen for PoR Refineries over Project Lifetime

5.4. Hydrogen Quality

Hydrogen produced from the ATR process has a purity of 97.5% hydrogen. This quality is directly suitable for combustion purposes (Gasunie, 2023). To achieve the correct purify to be able to sell hydrogen to the backbone a purity of 99.6% hydrogen needs to be achieved (HyNetwork, 2021). This is performed by a Pressure Swing Absorber (PSA). This purification steps causes extra cost and inefficiency. By purifying the stream from 97.5% to 99.6%, 20 mass% of the 97.5% input stream will be lost as a residual stream (Sircar & Golden, 2000). This results in a 20 mass% loss of marketable hydrogen.

In this analysis a fuel-grade hydrogen (97.5%) will be used for burning within the refineries and feedstock grade hydrogen (99.5%) for residual sales. This due to the restriction of the hydrogen backbone specification. PSA calculation is shown in appendix H.

5.5. Refinery Modifications

In order to burn blue hydrogen in refinery boilers and furnaces, modifications to the burners are necessary. Burners designed for burning refinery fuel gas and natural gas cannot simply switch to blue hydrogen without adjustments. This due to differences in factors like the Wobbe Index and NOx emissions and overall heat management and distribution within a furnace (Prasad, 2020). Burner manufactures are developing and producing future-proof burners which are able to burn 99.5% hydrogen (Lowe et al., 2011). For this research it is assumed that there is availability to this technology.

The burner modifications need to be performed in the so called refinery Turn Arounds (TAR). These are maintenance sessions where the process units go out of service and receive modifications. These maintenance cycles occur every +/- 5 years. During these periods traditional NG and RFG burners in equipment such as boilers and furnaces are switched out for hydrogen burners. These modifications are assumed to be in line with the timing of burning hydrogen.

5.6. PoR Refinery and Third-Party Decarbonisation Potential

In conclusion, this chapter describes the intervention scenario's potential to decarbonise PoR refineries and third-party customers connected to the hydrogen backbone. Table 5.4 displays the reference scenario emissions for 2024-2050, alongside the CO_2 emissions when the intervention option is implemented. The last column shows the reduction compared to the reference scenario. Additionally, the table highlights the CO_2 reduction for third-party customers achieved through commercial hydrogen sales. To be able to reduce this CO_2 potential, a 1400 MW blue hydrogen plant is needed which is fully utilized to be able to sell blue hydrogen to the backbone and eventually be in full use for reaching refineries decarbonisation targets. A snap shot of the energy and emission reduction values of the intervention scenario can be seen in appendix I.

This intervention scenario serves a deviation from the BAU reference scenario in order to reach the decarbonisation targets, in the next section the effects of the intervention scenario will be identified.

Table 5.4: CO_2 Emissions and Emission Reduction by Implementing Intervention Scenario Between 2024 - 2050

CO_2eq. [Mt]	**BAU Emissions**	**Intervention Scenario Emissions**	**Reduction**
PoR Refineries	162.3	125.9	36.4
Third Party	-	-	8
Total	-	-	**44.4**

6 Effects

To assess the impact of the intervention scenarios from both corporate and public perspectives, all cost and benefit effects of the intervention scenario need to be identified. Each perspective values costs and benefits differently. This chapter will gather and analyze the effects from both perspectives, providing a overview of these impacts. The categorization of the direct, indirect and external effects are described in the methodology chapter 3.1.4. The collected effects will enable the calculation of an overall NPV which is shown in the result section. This chapter aims to answer the third, fourth, and the fifth sub-research questions.

RQ3: What are the costs and benefits effects of the intervention scenario from a corporate perspective?

RQ4: What are the costs and benefits effects of the intervention scenario form a public perspective?

RQ5: How do the perspectives of the corporate compare to those of public regarding the costs and benefits effects of the intervention scenario?

6.1. Corporate Cost and Benefits

When discussing corporate cost and benefits this means that cost and benefits are valued against making a monetary profit for a refinery. Corporate believes are that financial performance are the main priority to keep the business healthy and running. These are primarily direct effects.

6.1.1. Costs

Capital Expenditure (CAPEX) & Operational Expenditure (OPEX)

The capital expenditure required to build a blue hydrogen production plant consist of the ATR plant & CCS plant. The additional CAPEX that adds up on to the blue hydrogen plant is, the refinery piping infrastructure, retrofitting of burners and the PSA unit. All these CAPEX cost are incurred upfront of the project, resulting in a major cost. The refinery infrastructure CAPEX is difficult to estimate costs due to the potential reuse of existing infrastructure, discussed in literature (Tsiklios et al., 2022).

The operational expenditure is based on a percentage of the total CAPEX. This is a cost which occurs annually during the lifetime of the project. Maintenance, labour and consumables are factored in the OPEX.

$$CAPEX\ H2\, Production + CCS = CAPEX/MWth{*}TotalMWth{*}CAPEX\ SpendingPattern \quad (6.1)$$

$$CAPEX\ PSA\ = CAPEX/MWth * TotalMWth * CAPEX\ SpendingPattern \quad (6.2)$$

$$CAPEX\ Burner\ Retrofitting = CAPEX/MW * Total\ MW * CAPEX\ Spending\ Pattern \tag{6.3}$$

$$CAPEX\ Refinery\ Infrastructure = CAPEX/MW * Total\ MW * CAPEX\ Spending\ Pattern \tag{6.4}$$

$$OPEX\ H2\ Plant = OPEX\% * Installed\ MW \tag{6.5}$$

Table 6.1: Cost Assumptions CAPEX & OPEX | Price-level: 2019

Item		Low Scenario	Base Scenario	High Scenario	Source
CAPEX bH2 Plant	Euro/MWth	1,020,000	1,200,000	1,380,000	(Energy.nl, 2019)
CAPEX Burner Mods	Euro/MWth	120,000	150,000	180,000	(Navigant, 2019)
CAPEX Refinery Infra	Euro/MWth	68,000	85,000	102,000	(Navigant, 2019)
OPEX bH2 Plant	% of CAPEX	2.4%	3%	3.6%	(Energy.nl, 2019)

In figure 6.2 the CAPEX spending pattern is shown for the blue hydrogen plant and all relevant equipment. The CAPEX spending pattern is based on literature research (Hansen et al., 2009). The general lead & construction of a blue hydrogen plant has a total of +/- 5 years. CAPEX spending pattern is relevant due to the discounting of the significant CAPEX cost.

Table 6.2: Intervention Scenario CAPEX Spending Profile

Years	2024	2025	2026	2027	2028	2029
CAPEX Spend [%]	40	20	20	10	5	5

Electricity Consumption

The ATR requires electricity input to operate its process. Electricity price-sets are displayed in appendix J. CO_2 grid intensity is factored in according to the KEV CO_2 grid intensity (Netherlands Environmental Assessment Agency (PBL), 2020).

$$Electricity\ Cost = Electricity\ Usage\ MWh * Electricity\ Price + CO2\ Grid\ Intensity \tag{6.6}$$

Conversion loss ATR plant

The cost of blue hydrogen is not considered a expense for the refinery as it directly substitutes the existing fuel. Including the cost of blue hydrogen would result in double counting since the individual cost components are already considered in the corporate perspective. The additional costs due to the conversion losses from refroming natural gas to hydrogen in the ATR, are perceived as a cost to the corporate perspective. This is a cost that would not occur in the BAU scenario. These losses are partly due to the exothermic reaction, which can be offset by the value of decarbonised steam produced (included in benefits). Natural gas price sets are detailed in the model and appendix J.

$$Conversion\ Loss = NG\ Price(EU/MWh) * Hydrogen\ Demand(MWh)/ATR\ efficiency \tag{6.7}$$

CO_2 Transport & Storage

The captured CO_2 in the CCS process, is conditioned and then send to storage fields. This transport and storage services is provided by joint ventures consisting of private companies. Against a set transport and storage feem CO_2 is deposited in empty gas fields in the North Sea (Ravi et al., 2017). Transport and storage can be divided in 2 segments. See figure 2.4.2 for more information

- Transport from refinery to centralized hub near shore
  This is offered by the Porthos project, this is government backed project.
- Transport from centralized hub towards storage location + Storage of CO_2
  This is offered by private companies who are involved in oil and gas exploration

$$\mathrm{CO_2}\ Transport\ \&\ Storage = \sum Tariff\ per\ tonne\ of\ \mathrm{CO_2} * tonnes\ of\ \mathrm{CO_2}\ per\ year \tag{6.8}$$

Item		Low Case	Base Case	High Case	Source
CO_2 Transport & Storage	*Euro/tonne* CO_2	64	80	96	(XODUS, 2020)

Table 6.3: CO_2 Transport & Storage Tariffs | Price-level: 2022

Tax on Profit

Corporate income tax is not included in this SCBA. Income tax is valued as a transfer payment that does not reflect actual social cost or benefits. Including this, can lead to double counting and impact the true value of the project to society. Modeling corporate tax for international corporations is complex due to varied tax structures and jurisdictions (Boardman et al., 2018) (NEF Consulting, 2020).

6.1.2. Benefits

From a corporate standpoint benefits are cost mitigating functions or potential profit making effects. This can be direct profits or qualitatively setting the business up for a better strategical position in the future.

CO_2 Cost Avoidance

One of the main benefits is the financial benefit of emission reduction. This mitigates the exposure to the EU ETS and carbon levy which can be seen as a cost in the BAU scenario. For the base case the PBL KEV 2020 EU ETS price sets will be used (PBL, 2022). Full EU ETS price sets can be seen in appendix J. The Dutch levy is published until the year 2032, the assumption is made that levy will be used and maintained after this year to decarbonise the Netherlands. The levy is extrapolated with the same rate as the EU ETS. For this effect it is assumed that avoided CO_2 emission credits can be sold to the market. This is a plausible scenario because, as the allowances in the free EU ETS market phase out, demand for existing EU ETS will likely increase, especially if not all EU ETS sectors decarbonise at the same speed (European Commission, 2022).

$$\mathrm{CO_2}\ avoided\ EU\ ETS = Avoided\ \mathrm{CO_2} * EU\ ETS \tag{6.9}$$

$$\mathrm{CO_2}\ avoided\ Dutch\ Levy = (Dutch\ Levy - EU\ ETS) * Avoided\ \mathrm{CO_2} \tag{6.10}$$

Decarbonised (Blue) Steam

The ATR has a exothermic reaction which generates heat in the form of steam. This is considered as a byproduct. This steam is decarbonised since the CO_2 is captured and stored. The value of decarbonised steam is determined based on the gas price, steam boiler efficiency (70%) and the CO_2 EU ETS & Levy savings. This can be considered as a benefit, as otherwise this steam demand needs to be generated with fossil fuel fired burners in a boiler without CO_2 capture installation.

$$Blue\ Steam = (SteamGenerated\ MWh * Gasprice\ MWh\ )/\ Efficiency \tag{6.11}$$

Commercial Third Party Blue Hydrogen sales

As outlined in the intervention scenario, the blue hydrogen plant will initially be oversized. There is potential demand in the market from other industries. This excess hydrogen can be sold as an alternative to natural gas, thereby avoiding CO_2 ETS costs, or as an alternative to grey hydrogen for feedstock purposes.

There are various commercial structures to valuate the cost of blue hydrogen. Within the analysis of this report the following pricing option is used with a 8% margin (CE Delft, 2022):

$$\text{Cost of Production + 8\% Margin} = \frac{(\text{CAPEX} + \text{OPEX} + \text{Conversion} + \mathrm{CO_2}\ \text{Transport value})}{\text{(Hydrogen Produced - PSA Loss)}} \tag{6.12}$$

(6.13)

EU ETS Free Allowances

EU Free allowances are distributed for decarbonising projects such as investing in a blue hydrogen plant. These allowances are granted to incentivize and support corporate in investing in decarbonising projects (European Commission, n.d.). The total FA allowances received by all individual refineries are considered collectively. These allowances are distributed by the EU and the benchmark is set by at 6.84 tonne CO_2/tonne H_2.

These free allowances will be phased out to make sure to incentivize companies to innovate and create a level playing field. Free allowances phasing can be found in appendix L.

$$Free\ Allowances = Free\ Allowances\ Phasing * FA\ Benchmark * tonne\ H2\ per\ year * EU\ ETS\ Price \tag{6.14}$$

SDE++ Subsidiy (CFD)

The SDE++ subsidy has a category designed for pre combustion & CCS projects, in which blue hydrogen production projects are located. SDE++ is seen as a significant value driver from a corporate standpoint. Its effectiveness is dependent on the EU ETS price, this because the SDE++ operates as a contract for difference scheme. The subsidy intensity is based on the SDE++ strikeprice and the EU ETS price. The SDE++ has the characteristic of a insurance against a low EU ETS Price, to support decarbonisation projects relying on the EU ETS pirce. The equation is shown in 6.12. The SDE++ strike price is valued by the Dutch government at 191 Euro/tonne CO_2 (Ministry of EZK, 2023)

$$SDE++\ Subsidy = (Strike\ Price - EU\ ETS\ Price) * \mathrm{CO_2}\ Stored \tag{6.15}$$

Reputational Impact

Investing in and taking action on decarbonisation initiatives can enhance a corporations reputation. This qualitative, hard-to-monetize parameter is not included in the CBA but can impact several aspects within a corporation. Improved reputation can increase support and acceptance from the country and its citizens, improve employee willingness to work for the company (thereby enhancing innovation and effectiveness of future decarbonisation projects), and strengthen collaborations with academic institutions (Company, 2020) (Baker et al., 2020). Reputational effect can also make corporates invest in less profitable projects. This effects is valued as a benefit.

6.2. Public Cost and Benefits

The public costs and benefits encloses all direct, indirect, and external effects. By valuing all these effects collectively, there can be determine if there is a value gain, or loss for the society as a whole.

6.2.1. Costs

SDE++ Subsidy

The SDE++ subsidy serves as subsidy to protect decarbonisation projects against a low CO_2 price. By providing this subsidy it supports corporates to invest in CO_2 mitigating projects, with the risks of a low CO_2 price. The SDE++ is a contract for difference subsidy which bridges the gap between EU ETS and the strike price set by the Dutch Government at 191 euro/tonne CO_2 (Ministry of EZK, 2023). When the EU ETS is higher than the strike price, subsidy stops.

$$SDE++\ Subsidy = (Strike\ Price - EU\ ETS\ Price) * \mathrm{CO_2}\ Stored \tag{6.16}$$

Maatwerk Subsidies (Tailor-Made Subsidies)

Tailor-made subsidies are negotiated privately between the government and refineries. Consultancy firms have calculated the ”onrendabele top” (inefficient top), referring to the inefficient final portion of financing which is estimated at 1.4 billion euros (PwC, 2022). For this report, it is assumed that tailor-made subsidies will address this inefficient financing gap. Refineries account for approximately 20% of emissions within industrial category. It is assumed that 20% of the 1.4 billion euros will be allocated to refineries participating in tailor-made agreements. This 280 million euro will be divided across the years between 2030 - 2040.

Hydrogen Backbone CAPEX & OPEX

Gasunie a Dutch government backed gas and infrastructure company, has started the construction of the Hydrogen backbone. The government has announced that they will invest 1.5 billion euros in the backbone, with an extra 750 million euro for set backs. This infrastructure has a capacity of +/- 10 GW, in which refineries will claim a +/- 1.2 GW demand. This translates in a government backbone cost of 315 million euros which is allocated for refineries. The first phase of the backbone will be constructed between 2024 and 2030, the CAPEX will be allocated towards these years (Gasunie, 2023).

The OPEX set for this infrastructure investment is 4.5% of the CAPEX, this is inline with other pipeline infrastructure projects. Included is power, maintenance and staffing (Tsiklios et al., 2022).

CO_2 Storage CAPEX

The Dutch government has invested 1.3 billion euros into the Porthos infrastructure (Porthos, 2023). In this study the total emissions that are captured and stored in the intervention scenario are approximately 39 Mtonne. The Porthos capacity is 38 Mtonne. For this study it is assumed that the full capacity of Porthos will be used with a marginal amount of CO_2 being stored in a different field. This means that the total investment in Porthos could theoretically meet the needs of Dutch refineries. A 1.3 billion euros is allocated to fund refinery CO_2 storage CAPEX.

6.2.2. Benefits

Avoided CO_2

A significant benefit of burning blue hydrogen lies in the prevention of CO_2 emissions going into the atmosphere. This is the combined effect from burning blue hydrogen directly in the refinery, residual hydrogen sales to other sectors and the decarbonised steam generated as a byproduct.

The pricing of CO_2 can vary depending on the public assumption that is being made. For this report which is in line with the current decarbonisation targets and the ambition to reach a maximum temperature rise of 2 degrees Celsius, the public price set named WLO 2 Degree price is set as base case (CPB, 2016). This price set corresponds to a carbon budget which limits temperature rise to 2 degrees Celsius between 2016 and 2050.

WLO scenarios are based on European CO_2 budgets and the commitment to meet these budgets within a specified time frame. The WLO price set is considered as an efficient price which indicates that it is set at a level that minimizes the marginal social cost of achieving climate objectives (Ecorys, 2016).

The public CO_2 price is significantly different from the EU ETS market price paid by emitters. This difference exists because the public CO_2 price reflects the marginal social cost emission and is determined by the emission budget required to meet the climate targets. Within this priceset external effects are being valued (Rijkswaterstaat, 2024). The EU ETS price is designed to incorporate external effects and to incetivize companies, but the EU ETS seems to underestimate the CO_2 price compared to the WLO priceset.

The WLO priceset consist of a Low (Laag), High (Hoog) en 2 graden (2 Degree) CO2 price scenarios. The 2016 guidelines recommended using the High and Low cases for analysis, and the 2 degree scenario for sensitivity testing. The 2016 High and Low pricesets are largely outdated in the year 2024, this due to updated climate policies and trajectories. Since a new WLO price set is expected in late 2024/2025, guidelines and consultants advice to use the 2 degree scenario as base case, aligning with current 2024 climate policy (C Vendrik, 2022; CE Delft, 2021; CPB, 2016; Ecorys, 2016).

The WLO Laag & Hoog Priceset are not included in the analysis because it targets above 2 degree scenarios which do not align with the current policy and ambitions (Ecorys, 2016). This would create a misalignment in value due to the fact, that this model calculates CO_2 emissions in percentages and not in degrees Celsius. The percentages of reduction are aligned with the WLO 2 Degree Scenario moving to a net zero scenario by 2050 (Delft, 2023).

CO_2 price-set curves are displayed in Figure 6.1, with detailed prices listed in Appendix J. What can be seen in the figure is that the WLO Hoog scenario is outdated due to its relatively low emission reduction ambition that has been established in 2016. The EU ETS price provided by KEV already surpasses the social value this highlights the outdated nature of the WLO Hoog scenario. Since the avoided cost of CO_2 could have a major effect on the result, this will be taken into the sensitivity analysis to vary the WLO 2 degree scenario by +20% & -20%.

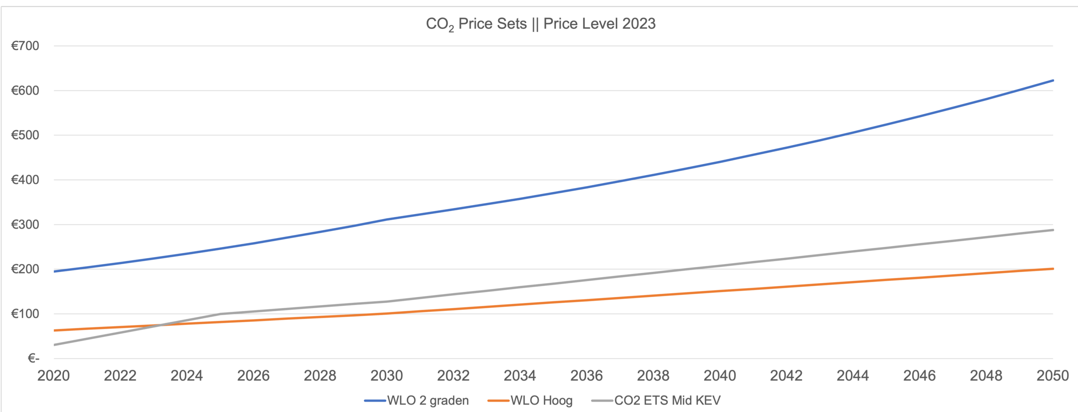

Figure 6.1: Comparison CO_2 Price Sets in euro/tonne: WLO 2 Degree Scenario - WLO Hoog Scenario - CO_2 ETS Middle Scenario KEV

Employment

In the present Dutch economy of 2024, justifying employment benefits is challenging due to the low unemployment rates. This effect is not perceived as a significant direct benefit to the public. For this reason employment benefits will factor into the sensitivity analysis. Assumptions are based on predictions of how many jobs are created within the (blue) hydrogen market. These are scaled back to the needed capacity to operate this project. Salary is based on average Dutch salary and working hours (Randstad, 2024) (Delft, 2021a).

FTE	Rate (Euro/Hour)	Source
100	20	(Randstad, 2024)

Table 6.4: Assumptions Employment Benefits

Corporate income Tax

Corporate income tax is not included in this SCBA. Income tax is valued as a transfer payment that does not reflect actual social cost or benefits. Including this, can lead to double counting and impact the true value of the project to society. Modeling corporate tax for international corporations is complex due to varied tax structures and jurisdictions (Boardman et al., 2018) (NEF Consulting, 2020).

Internationally competitive refining position

Internationally competitive refining position consists of a qualitative effect. This effect emphasizes the benefit of the Netherlands achieving a leading position in the energy transition from a social perspective (Marschinski et al., 2020) (Rotmans et al., 2017). Achieving targets and setting an leading example are valuable effects for the Netherlands. This effect is not monetized or included in the CBA, it holds value in the potential discussion about the trade-offs involving the support of decarbonisation efforts. This parameter is closely linked with innovation, which plays a role in achieving a leading position. This effect is overall valued as a benefit.

6.3. Overview Effects

Table 6.5 on the next page, shows an overview of the effects which are identified. This answers RQ3 and RQ4 by identifying the relevant effects from each perspective for the intervention scenario. Figure 6.2 illustrates these effects within the context of the overall blue hydrogen intervention, highlighting the corresponding boundaries between corporate and public perspectives.

Table 6.5: Overview Effects

Project Effects	Cost / Benefit	Monetizable (Y/N)	Source
Direct effects			
CAPEX H_2 + CCS	Cost	Y - Market Price	(Energy.nl, 2019)
CAPEX Burner Modification	Cost	Y - Market Price	(Keifer & Effenberger, 2021)
CAPEX Infra ISBL	Cost	Y - Market Price	(Keifer & Effenberger, 2021)
CAPEX PSA UNIT	Cost	Y - Market Price	(Thunder Said Energy, 2024)
OPEX	Cost	Y - Market Price	(Energy.nl, 2019)
Electricity Cost	Cost	Y - Market Price	(PBL, 2022)
H_2 Conversion Loss	Cost	Y - Market Price	(PBL, 2022)
CO_2 Transport & Storage H_2 for Fuel	Cost	Y - Market Price	(XODUS, 2020)
CO_2 Transport & Storage H_2 for Commercial Sales	Cost	Y - Market Price	(XODUS, 2020)
Avoided EU ETS Burning	Benefit	Y - Market Price	KEV (PBL, 2022)
Avoided Dutch Levy Burning	Benefit	Y - Market Price	KEV (PBL, 2022)
Avoided EU ETS Steam	Benefit	Y - Market Price	KEV (PBL, 2022)
Blue Steam	Benefit	Y - Market Price	KEV gas-price (PBL, 2022)
H_2 Sales (Commercial)	Benefit	Y - Market Price	Model outcome
Free Allowances	Benefit	Y - Market Price	(European Commission, n.d.)
Subsidies SDE Fuel Only	Benefit	Y - Market Price	(Ministry of EZK, 2023)
Subsidies SDE Commercial	Benefit	Y - Market Price	(Ministry of EZK, 2023)
Maatwerk Subsidy	Benefit	Y - Market Price	(PwC, 2022)
Indirect Effects			
SDE++ Subsidy	Cost	Y - Market Price	(Ministry of EZK, 2023)
Potential Subsidy (Maatwerk - CAPEX)	Cost	Y - Market Price	(PwC, 2022)
Energy Prices	Cost	N	
Hydrogen Backbone	Cost	Y - Market Price	(Gasunie, 2024)
OPEX Backbone	Cost	Y - Market Price	(Muñoz & Ancheyta, 2023)
CO_2 Transport and Storage CAPEX	Cost	Y - Market Price	(Algemene Rekenkamer, 2024)
Innovation	Benefit	N	
Employment	Benefit	Y - Market Price	(Randstad, 2024)
Leading Refinery Position	Benefit	N	
External Effects			
CO_2 Reduction	Benefit	Y - Social Price	(Rijkswaterstaat, 2024)
Safety	Costs	N	

Figure 6.2 on the next page displays all monetizable parameters considered in the SCBA, along with the locations where these effects occur. The boundary is drawn around the blue hydrogen plant and refineries to represent the corporate perspective. Public costs and benefits are illustrated outside this

boundary, encompassing the overall costs and benefits from both the corporate and public perspectives.

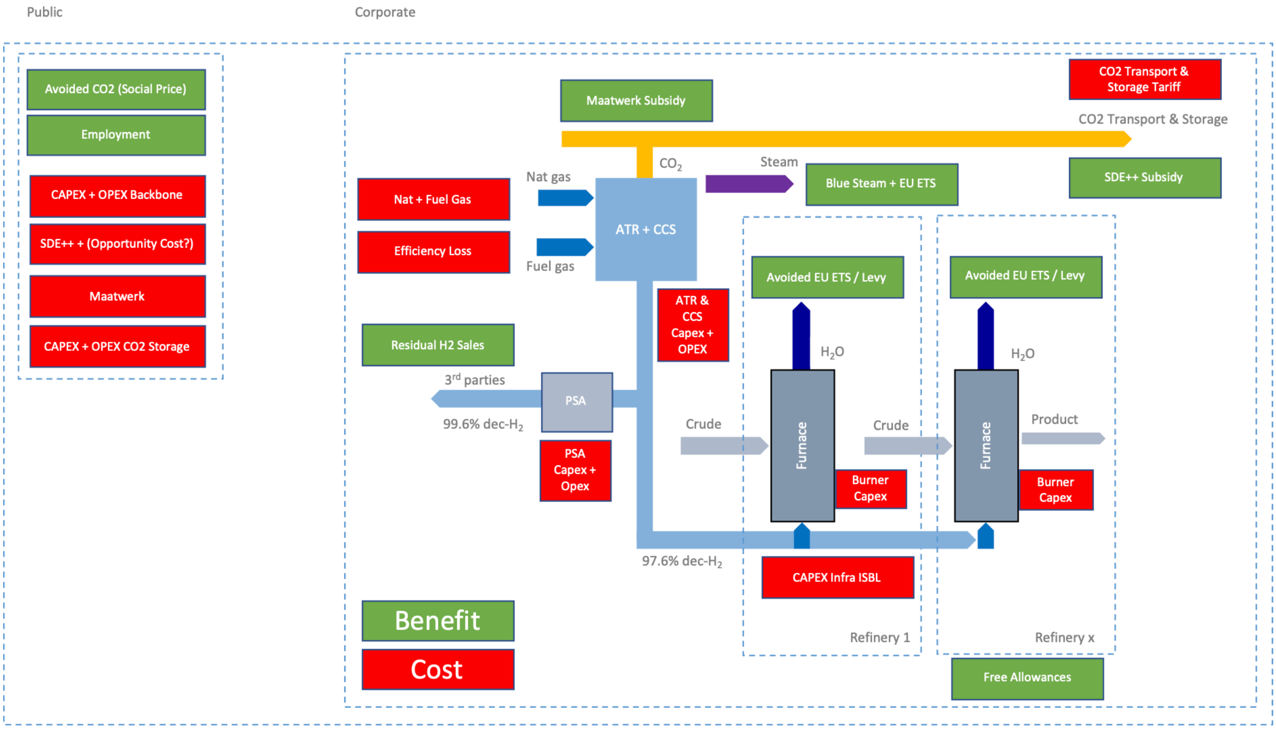

Figure 6.2: Effects of Intervention Scenario for Corporate and Public Perspective

Summing up, the main differences in the cost and benefit effects of the blue hydrogen intervention scenario between corporate and public perspectives address and answer RQ5. Corporates primarily prioritise financial returns and operational efficiency, by doing this they focus on major cost such as CAPEX, OPEX and efficiency losses. In terms of benefits, they focus on the market prices of hydrogen and the cost reduction of EU ETS credits. The public perspective values broader societal impacts, including environmental and health benefits, often not monetized in corporate analyses. The social price of CO_2 reduction and the strategic importance of energy transition are key factors for the public.

A big difference in valuation can be seen considering the market price for CO_2 and the public price. The EU ETS market price is set up to incentivize companies to decarbonise by lowering the cap of the EU ETS trading scheme. Even with this motive behind the EU ETS, the price discrepancy versus the public CO_2 price is major.

Corporates evaluate avoided EU ETS costs as a direct effect affecting their profitability, as the public perspective values it as a external effect effecting climate and ultimately quality of life. The motives are contradictory, because if CO_2 EU ETS would not have an impact on the overall business of the corporate they would attach no value to it, however the value of CO_2 for the public remains the same.

Corporates use market prices to assess costs and benefits which are volatile to economic conditions, whereas public assessments rely on more theoretical social prices. However, some price of the government are market prices, such as the backbone investment, subsidies are subject to theoretically calculated reserved capital.

The corporate and public perspectives on the costs and benefits of the blue hydrogen intervention scenario reveal both common goals and areas of differences. These differences will be quantified in the results section 7, where the values for the perspectives are calculated.

7
Results

In this chapter, the impact of the intervention scenario on the reference scenario is presented by calculating the Net Present Value (NPV). Variations are explored for both pessimistic and optimistic cases, followed by a sensitivity analysis. This chapter addresses the main research question by integrating the findings from all the sub-research questions:

MRQ: What are the costs and benefits of using blue hydrogen for the decarbonisation of high temperature heat generation within refineries in the Port of Rotterdam considering the Dutch/EU net zero targets in 2050, from the perspective of the corporate versus the public?

This chapter is structured as follows: first, the overall costs and benefits of the intervention case are presented. This is followed by a detailed breakdown of costs and benefits from both corporate and public perspectives. Next, in section 7.2 the pessimistic and optimistic scenarios are analyzed. A sensitivity analysis for both perspectives, including additional sensitivities related to price sets and subsidies, is then conducted. The final section provides findings regarding the SDE++ subsidy.

7.1. Overview Cost and Benefits

This section summarizes the results of the overall cost benefit analysis for the intervention scenario, which involves in using blue hydrogen for high temperature heat demand in PoR refineries. The SCBA assumes that blue hydrogen will replace fossil fuels such as NG and RFG in refinery furnaces and other high temperature applications. The ramp up of hydrogen usage is aligned with achieving Dutch climate targets.

Figure 7.1 displays the total emissions and emission reduction resulting from the intervention scenario compared to the reference scenario. What can be seen is that a total of 44.4 Mt is reduced by the intervention scenario of which 36.4 Mt is realized within refineries and a additional 8 Mt is achieved through residual hydrogen sales.

Table 7.1: Emission Comparison Between Reference and Intervention Scenario

	Reference Scenario	Intervention Scenario
CO_2 Emissions 2024-2050 (Mt)	162.3	117.9
CO_2 Reduction Total (Mt)	0.0	44.4

By implementing the intervention scenario to achieve the reductions shown above, the following overview of cost and benefits are calculated. In Figure 7.2, the total costs and benefits from the two perspectives are illustrated.

Table 7.2: Comparison of Reference and Intervention Scenarios from Corporate and Public Perspectives

	Corporate Perspective	Public Perspective
Cost [MEUR]	€ -4,009	€ -6,057
Benefit [MEUR]	€ 4,181	€ 14,891
NPV [MEUR]	€ 172	€ 8,834

The corporate perspective shows an NPV of 172 million euro, build up from a total discounted costs of 4,009 million euro and a discounted benefit of 4,181 million euro. The public perspective presents a NPV of 8,834 million euro, derived from total discounted costs of 6,057 million euro and a discounted benefits of 15,981 million euro. This results in a difference between the perspectives of 8,662 million euro of net present value, this highlights the difference in valuation of cost and value drivers for each perspective.

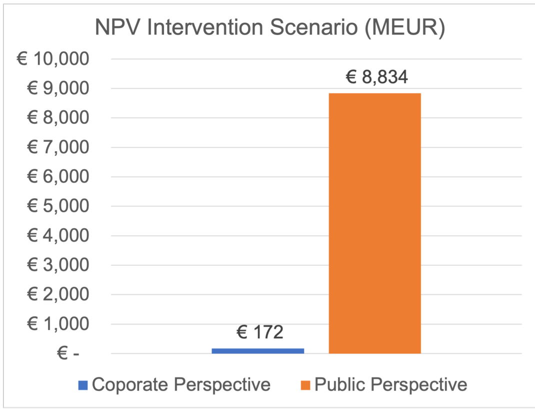

Figure 7.1: Corporate and Public NPV of the Intervention Scenario

Corporate Perspective

Figure 7.2 illustrates the corporate perspective on NPV accumulation, showing the present value of costs and benefits. This figure presents all monetized effects discounted over the projects lifespan.

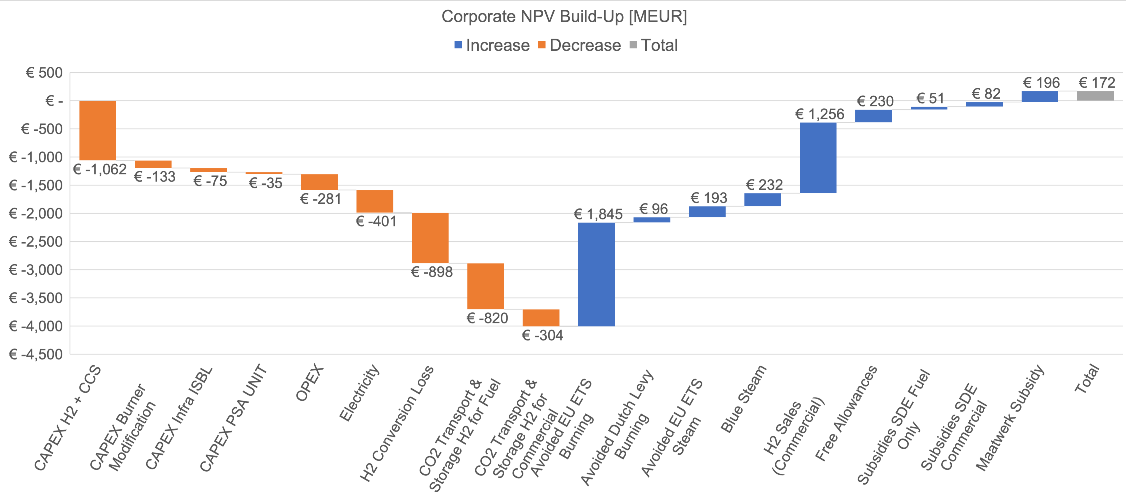

Figure 7.2: Value and Cost Drivers Intervention Scenario from Corporate Perspective

What can be seen is that the primary cost drivers are CAPEX and CO_2 Transport and Storage. The CAPEX has a significant impact due to the investment that is needed long before the (discounted) benefits are received. This misalignment between cost and benefits significantly impacts the overall NPV, since the cost are subject to minimal discounting due to upfront investment, and the benefits are exposed to significantly more discounting due to occurring later in time. What stands out is the influence of CO_2 Transport and Storage on project costs. Over the projects lifetime, the annual storage of CO_2 presents a significant expense, computed as 2,115,960 tonnes of CO_2 multiplied by a tariff of 91 euros per tonne, resulting in an annual cost of 205,248,120 euros. In comparison to the prognosed EU ETS CO_2 price incurring such costs is projected to be in 2034, without factoring in CAPEX investments, solely comparing to the EU ETS pricing multiplied by the reduced CO_2 emissions. The H_2 conversion loss shows a cost of almost 900 million euro, this is lost due to the reforming efficiency from natural gas to hydrogen for the same combustion application.

In terms of positive value drivers, reduced CO_2 emissions & commercial hydrogen sales stands out as major factors. It serves as the primary value driver in a decarbonisation project due to the significant volumes of avoided CO_2 continuing throughout the project duration. While the project tends to be backend-loaded, with the most substantial benefit in CO_2 reduction income occurring in the years after 2040, the discounted cash flow in figure 7.3, displays substantial positive cash flows in the initial years. This is due to the added value of commercial residual hydrogen sales.

Maatwerk subsidies which are paid out in the project early stages, make a significant present value contribution. However, SDE++ subsidies, being contract for difference (CFD) subsidies, do not contribute significantly to value in the base case due to the CFD with the EU ETS price. Hydrogen sales emerge as the second-largest contributor to project value, amounting to 1,256 million euros of present value. These sales contribute to the project commercial viability. This shows that when the hydrogen plant is only partly utilized only for the refineries in the first years, a significant benefit would be missed out on.

The calculated hydrogen price, calculated based on the production costs plus an 8% margin, averages at 3.66 euros per kilogram of blue hydrogen across the project duration. Further details are available in Appendix K. The overall cash flow of the intervention scenario for the corporate perspective results in a 8.4% IRR. This is 0.4% higher than the WACC of 8%, indicating profitability. Additionally the carbon abatement cost is calculated at 110 euro/tonne CO_2, which equals the EU ETS price of 2027, indicating that the intervention is potentially cost-effective from 2027 onwards.

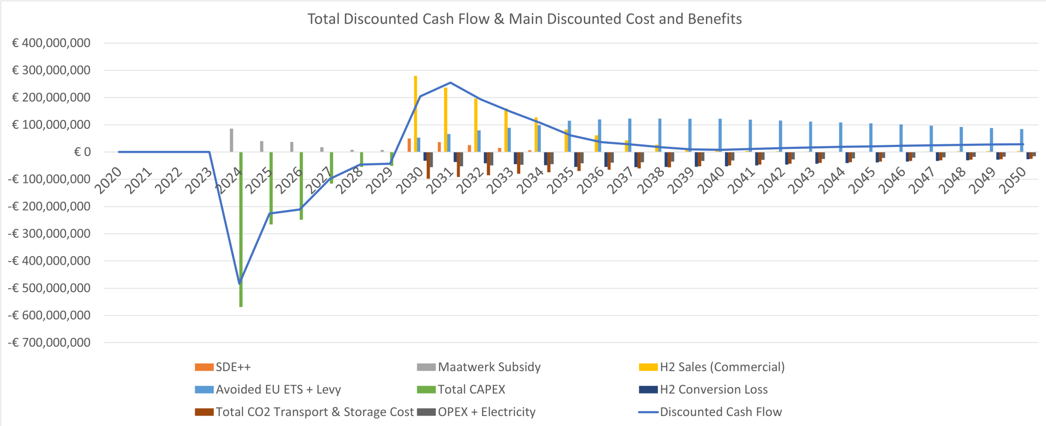

Figure 7.3: Discounted Cash Flow & Main Discounted Cost and Benefit streams

Public Perspective

Figure 7.4 displays the public perspective on NPV accumulation, showing the present value of cost and benefits. This figure presents all monetized effects discounted over the projects life span.

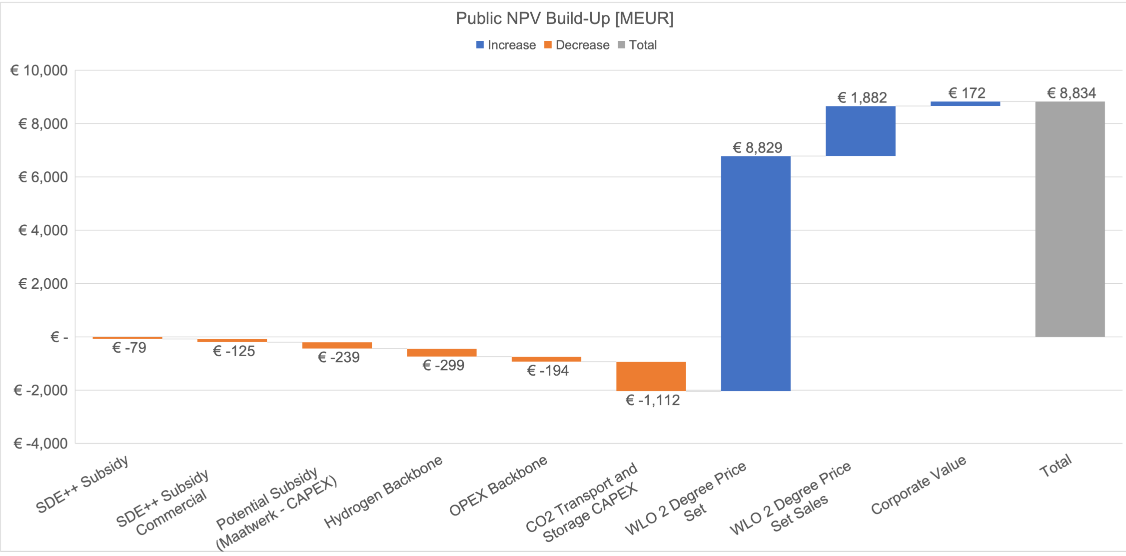

Figure 7.4: Value and Cost Drivers Intervention Scenario from Public Perspective

The primary cost components for the public perspective are shaped by the investments in the hydrogen backbone and carbon capture and storage CAPEX. The SDE++ comes in at a cost of 204 million euros in the base case, this as a results of the CFD between the strike-price and the EU ETS price.

The main value drivers for the public sector stem from the external benefits associated with reducing CO_2 emissions. These social benefits of reducing CO_2 contribute 10,711 million euros to the public perspective under the WLO 2 Degree CO_2 pricing conditions. This external benefit can be subdivided into two components. 1. The CO_2 reduction achieved by refineries, amounting to 8,829 million euro NPV; 2. The CO_2 reduction facilitated by the commercial sale of hydrogen to other sectors within the Netherlands which is in total 1,882 million euros. This results in a total public NPV of 8,834 million euro.

The public perspective also benefits from the performance of the direct effects of the corporate perspective. In the base case that results in a 172 million euro benefit for the public perspective. The overall discounted cash flow from the public perspective results in a IRR of 21%, this is a 17% above the social discount rate of 4% indicating favorable returns.

7.2. Optimistic, Base and Pessimistic Case

In this section an analysis is provided regarding the optimistic and pessimistic scenarios from both corporate and public perspectives. A optimistic scenario represents a blue hydrogen favorable environment and a pessimistic scenario represents a blue hydrogen unsupportive environment. The cases are explained in section 3.1.3, in table 3.1.

Figure 7.5 and table 7.6 show the outcomes for the proposed pessimistic, base and optimistic cases in terms of cost, benefit, NPV, and benefit cost ratio. Benefit Cost ratio is provided to illustrate the ratio between the relative benefits and cost of the cases.

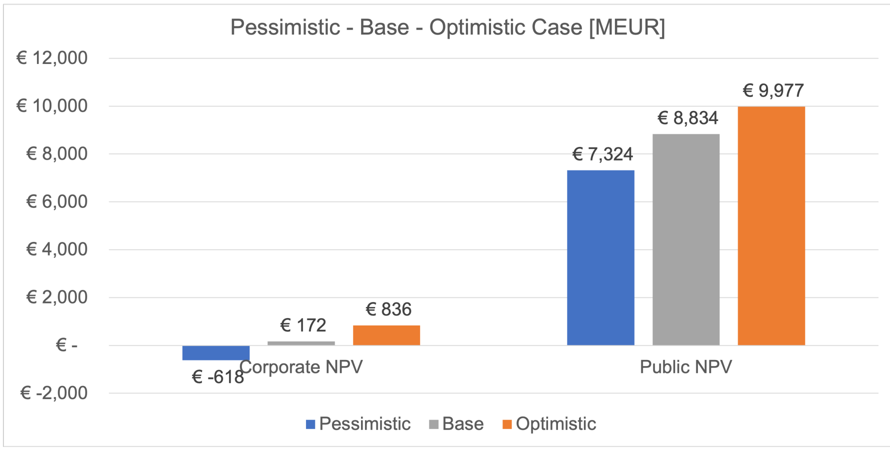

Figure 7.5: Overview NPV Intervention Cases from the Corporate and Public Perspective

	Pessimistic		Base		Optimistic	
	Corporate	*Public*	*Corporate*	*Public*	*Corporate*	*Public*
Cost [MEUR]	€ 4,488	€ 7,256	€ 4,009	€ 6,057	€ 3,554	€ 5,124
Benefit [MEUR]	€ 3,871	€ 14,581	€ 4,181	€ 14,891	€ 4,391	€ 15,101
NPV [MEUR]	€ -618	€ 7,324	€ 172	€ 8,834	€ 836	€ 9,977
B/C	0.86	2.01	1.04	2.46	1.24	2.95

Figure 7.6: Overview Intervention Scenario Pessimistic - Base - Optimistic Case

From the corporate perspective, variations range from a pessimistic negative value of (618) million euros to a positive value of 836 million euros for the optimistic case. This spread represents a downside variation of 21% and an upside variation of 25% compared to the base case. The public perspective shows a pessimistic case of 7,324 million euros and a optimistic case of 9,977 million euros resulting in a 20% downside variation and a 12% upside variation compared to the base case.

Corporate Perspective

In figure 7.7 and 7.8 a NPV bridge is illustrated which displays the change in present value from transitioning from the base case to the optimistic and pessimistic case.

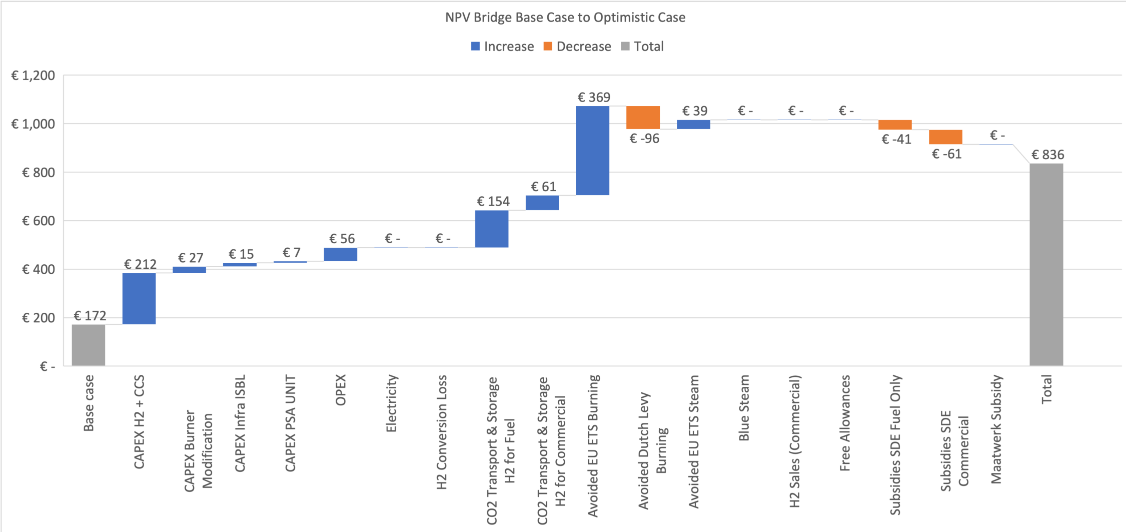

Figure 7.7: NPV Bridge from Base Case to Optimistic Case from Corporate Perspective

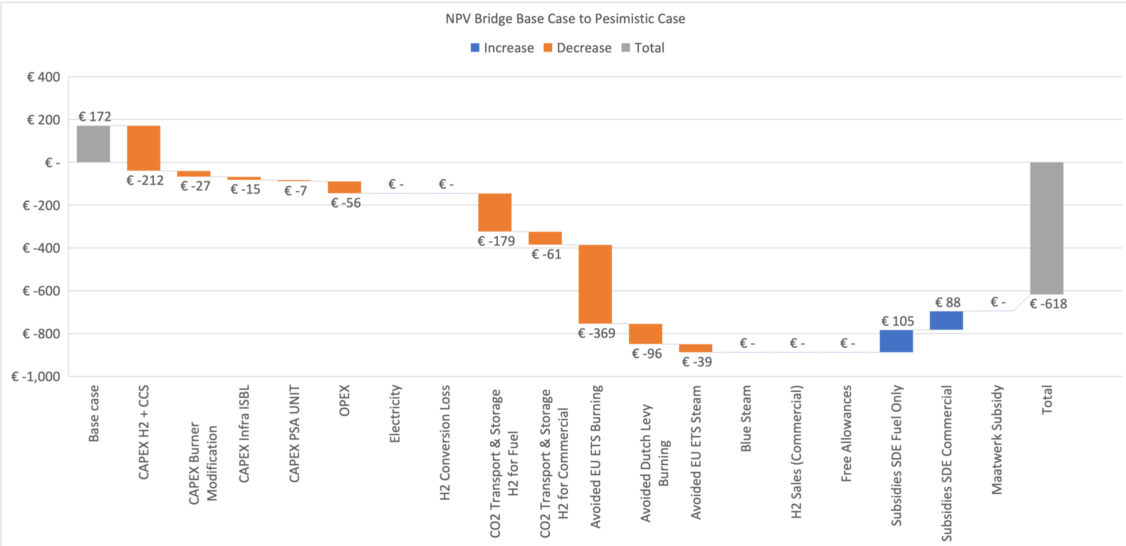

Figure 7.8: NPV Bridge from Base Case to Pessimistic Case from Corporate Perspective

It can be seen that CAPEX and avoided CO_2 EU ETS are primary drivers in this bridge analysis. When optimistic and pessimistic cases are compared against the base case, it can be concluded that the pessimistic scenario has more substantial impact. This mainly due to the CO_2 transport and storage cost and the level of SDE++ subsidy.

Fluctuations in the EU ETS price directly affect the SDE++ subsidy. The SDE++ coverage increases by a total of 193 million euro in the pessimistic case. A difference can be seen compared to the optimistic case in which the SDE++ value decreases by 102 million euro. The impact of the SDE++ is more pronounced in the pessimistic case than in the optimistic case. This displays the insurance mechanism nature of the SDE++ subsidy rather than it being a purely financial incentive. If the SDE++ were to be removed, the pessimistic NPV would drop to -889 million euro.

Public Perspective

In figures 7.9 and 7.10 show the NPV bridge transitioning from the base case to the optimistic and pessimistic case.

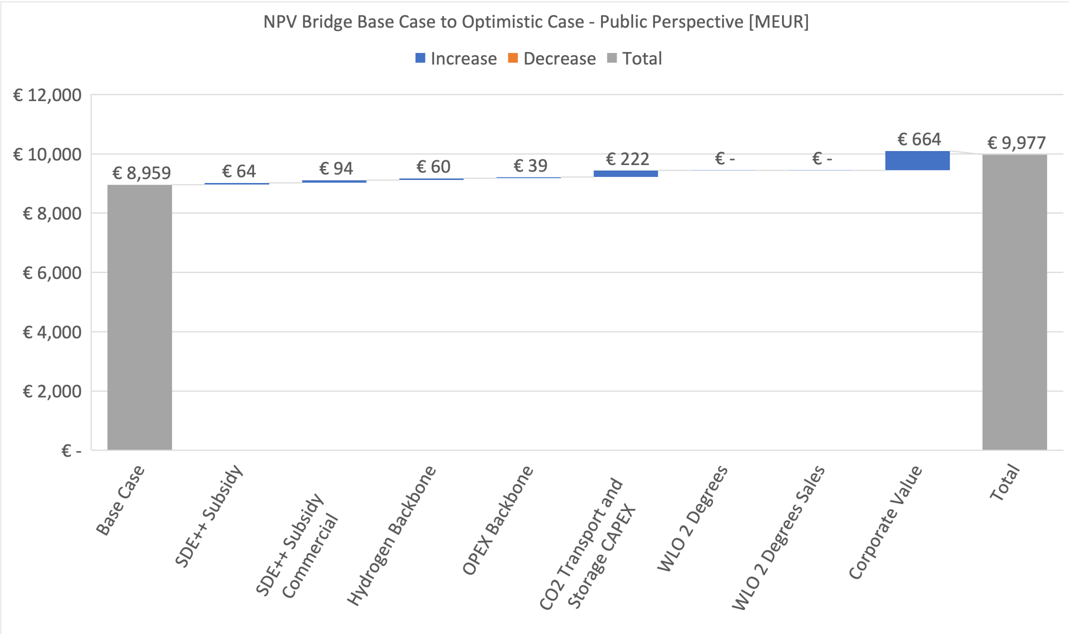

Figure 7.9: NPV Bridge from Base Case to Optimistic Case from Public Perspective

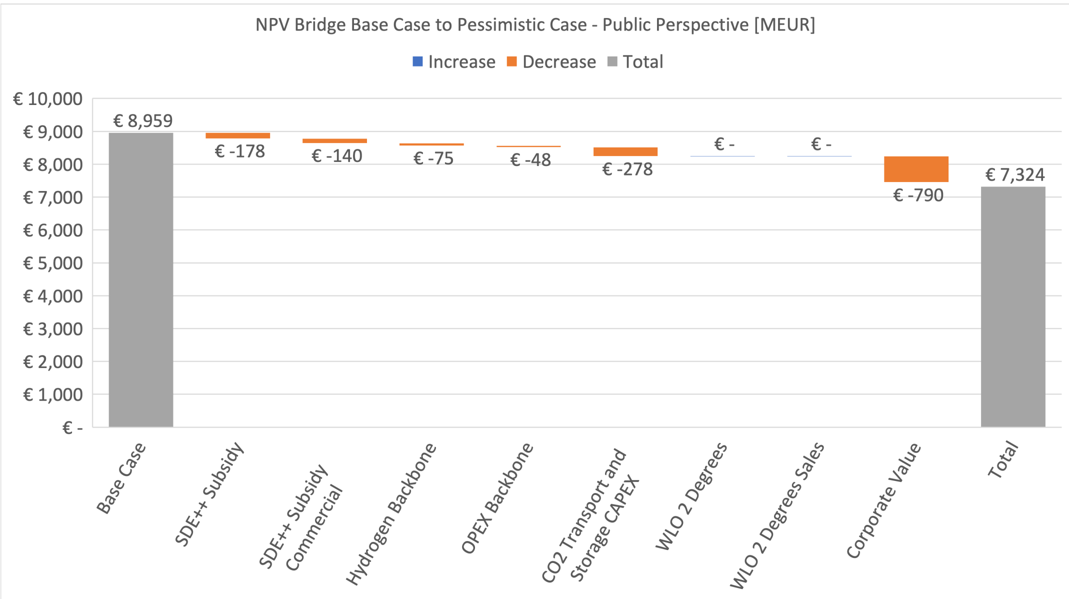

Figure 7.10: NPV Bridge from Base Case to Pessimistic Case from Public Perspective

It can be observed that corporate performance (explained in Corporate Perspective 7.2) significantly influences overall public value, in the optimistic case contributing 664 million euro more than in the base case and in the pessimistic case 790 million euro less than the base case. This is due to the less favorable investment environment for the corporate. In the addition to the increased CAPEX impact from the CCS and backbone, the SDE++ subsidy also affects the public perspective through the CFD mechanism which responds to the lower CO_2 EU ETS price in the pessimistic case.

Comparison of Corporate and Public Perspective

Within this section the comparison aims to highlight the differences and similarities in the valuations of effects between the corporate and public perspective.

Table 7.3: Comparison of Corporate and Public Perspectives

Perspective	Metric	Pessimistic	Base	Optimistic	Difference Favorable To
Corporate	Cost [MEUR]	€ 4,488	€ 4,009	€ 3,554	Corporate
Public	Cost [MEUR]	€ 7,256	€ 6,057	€ 5,124	
Difference	Cost [MEUR]	**€ 2,768**	**€ 2,048**	€ **1,570**	Corporate
Corporate	Benefit [MEUR]	€ 3,871	€ 4,181	€ 4,391	
Public	Benefit [MEUR]	€ 14,581	€ 14,891	€ 15,101	Public
Difference	Benefit [MEUR]	**€ 10,710**	€ **10,710**	**€ 10,710**	Public
Corporate	NPV [MEUR]	€ -618	€ 172	€ 836	
Public	NPV [MEUR]	€ 7,324	€ 8,834	€ 9,977	Public
Difference	NPV [MEUR]	**€ 7,942**	**€ 8,662**	€ **9,141**	Public
Corporate	B/C	0.86	1.04	1.24	
Public	B/C	2.01	2.46	2.95	Public
Difference	B/C	**1.15**	**1.42**	**1.71**	Public
Corporate	IRR [%]	3.7	8.4	17.1	
Public	IRR [%]	19.6	21	22.1	Public
Difference	IRR [%]	**15.9**	**13.7**	**5.0**	Public

Corporate Perspective:

- **Pessimistic Case:** NPV of € -618 million, B/C ratio of 0.86, indicating higher costs than benefits.
- **Base Case:** NPV of € 172 million, B/C ratio of 1.04, reflecting marginal positive return.
- **Optimistic Case:** NPV of € 836 million, B/C ratio of 1.24, showing favorable outcome.

Public Perspective:

- **Pessimistic Case:** NPV of € 7,324 million, B/C ratio of 2.01, driven by societal benefits from CO_2 reduction.
- **Base Case:** NPV of € 8,834 million, B/C ratio of 2.46, indicating strong public value.
- **Optimistic Case:** NPV of € 9,977 million, B/C ratio of 2.95, reflecting significant societal benefits.

Differences:

- **Cost Difference:** Public incurs higher costs in all scenarios.
- **Benefit Difference:** Public realizes higher benefits consistently.
- **NPV Difference:** Public NPV is significantly higher, favoring the public perspective.
- **B/C Difference:** Public has a higher B/C ratio, reflecting greater valuation of benefits relative to costs.

7.3. Sensitivity Analysis

The major value driver from both perspectives are being tested regarding sensitivity to provide a insight in to potential uncertainty effects. In figure 7.11 & 7.12 the sensitivity analysis can be seen in which individual parameters are adjusted for a +20% and a -20% impact.

7.3.1. Corporate Perspective

In figure 7.11 the corporate sensitivity chart is shown.

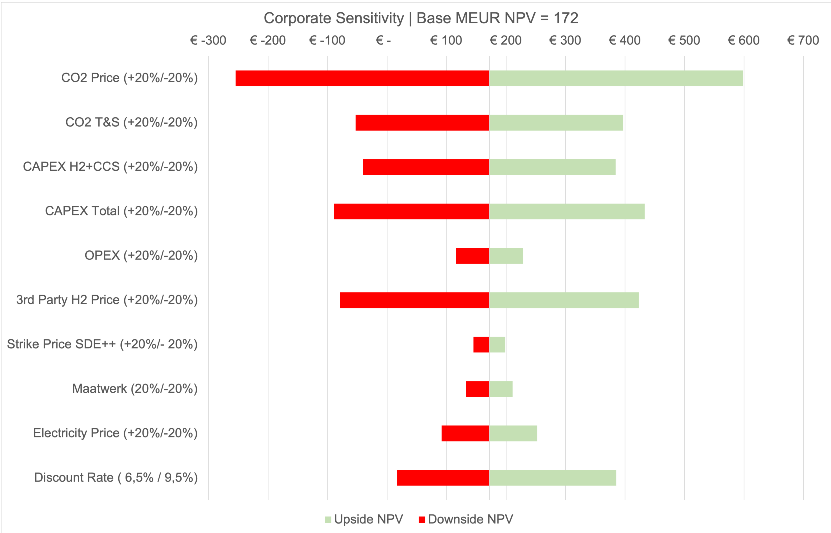

Figure 7.11: Corporate Perspective Sensitivity Analysis

The CO_2 price, CAPEX, transport and storage costs, and the discount rate have a significant impact on the corporate NPV. These parameters are also the main NPV building blocks in terms of cost an benefits. The main reason why these parameters show the biggest effect is due to the timing of when the costs & benefits occur, and the long-term effect they have throughout the projects lifetime. The CO_2 price has a major impact, particularly because it is central to the projects main objective of reducing CO_2. This is due to the fact that CO_2 represents a constant stream valued against a rising EU ETS price. Another impact is done by the discount rate as this directly effects the NPV due to the discounting of the cash flows over the projects lifetime, however this has minimal impact on the projects IRR.

7.3.2. Public Perspective

In figure 7.12 the public sensitivity chart is shown.

The largest effects on the public NPV are driven by variations in the public CO_2 price and the discount rate. The public CO_2 price is particularly impactful since it represents the most value throughout the project lifetime. In terms of the social discount rate, this plays a crucial role due to the projects long time horizon, affecting how future costs and benefits are valued. Especially in this project where public cash flows are significant in size, the discount rate will have a major impact. This gives insight in the importance of determining the correct discount rate since the effects can be significant. The discount rate determines how heavy the cost and benefits are weight against the future generations.

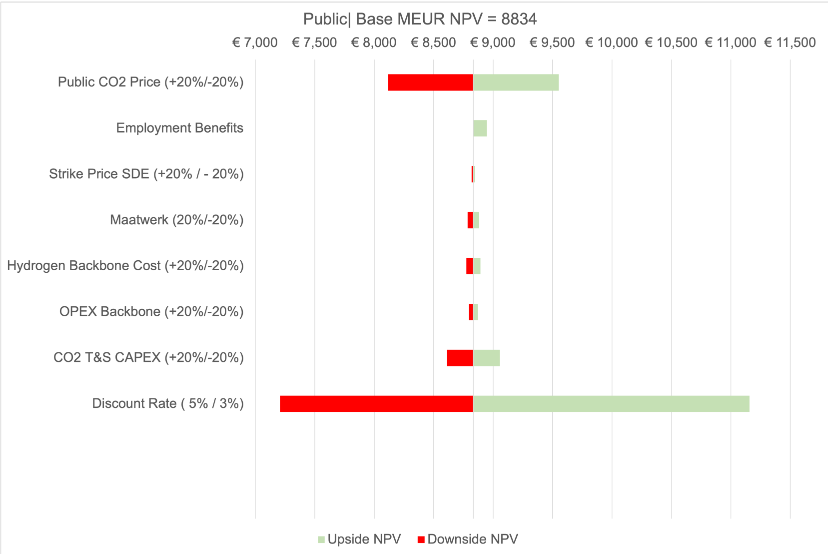

Figure 7.12: Public Perspective Sensitivity Analysis

7.3.3. SDE++ Subsidy

When analyzing the pratical implication of the SDE++ subsidy scheme the following findings were done. Figure 7.13 illustrates the strike price of the SDE++ which is set by the government, alongside the KEV CO_2 price scenario corrected for inflation (Low Mid High).

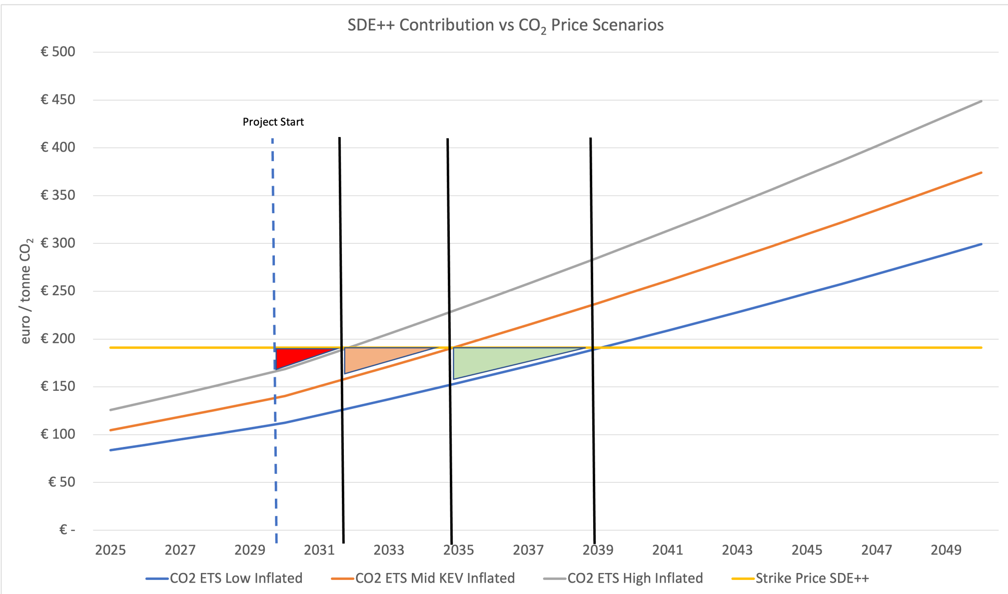

Figure 7.13: The potential value of SDE++ in relation to CO_2 KEV Price-sets

The highlighted area indicates the potential value of the SDE++ subsidy. The SDE++ has a allocated budget for CCS related projects of 6,7 billion euros, in which blue hydrogen plays a significant role (ICIS, 2023). Comparing the total SDE++ contribution in this study to the reserved amount indicates that their is potentially a significant inefficiency that results in opportunity cost. Another finding is that the strike-price of the SDE++ is not corrected for inflation, while the EU ETS price subject to inflation in practice. This results in reduced effectiveness for the corporates.

7.4. Validation

The validation of the overall results consist of the validation of the reference scenario, intervention scenario and effects. The reference scenario validation is performed per section on the basis of cross-verification based on ratio's of increase and decrease of refinery activity. As well as the cross-validation with existing studies and benchmarks these are mentioned in the chapters.

Overall validation consisting of the whole SCBA was conducted by Berenschot Consultancy through a one-hour online Teams meeting. Berenschot Consultancy has extensive experience in socioeconomic studies, including Cost-Benefit Analysis studies. The validation was performed together with Energy Consultant Renze Straatsma, who specializes in (industrial) energy applications. A summary of the validation can be found in Appendix C. The validation had positive outcome, confirming the feasibility of the reference scenario, intervention scenario and SCBA analysis.

The outcomes of the SCBA were compared against renewable energy projects and studies, such as those on solar, wind, and geothermal energy (CE Delft, 2024). The findings indicate that the ratios between public and corporate perspectives align with the conclusions of this study (Berenschot, 2021). A study conducted by Berenschot, 2021 showed that corporately owned solar panel fields have a public value 30 to 60 times higher than their corporate value, primarily due to external benefits. This finding is consistent with the results of this research.

Further validation recommendations consist of determining the reference scenario under multiple scenarios. There is chosen for a single reference scenario based on the assumptions of the EU. Validation can be performed on different scenario which will result in different outcomes. This validation can be performed with experts of of the Ministry of Economic Affairs and Climate Policy (EZK) and the European Climate Foundation. For further validation of the intervention scenario experts of the NLHydrogen branch associated can be consulted, they have a expertise in the specific hydrogen pathway in the energy transition, further more public consultancy companies other than Berenschot, such as CE Delft, Ecorys can be consulted to validate intervention scenarios and technical feasibility and the pricing of effects.

8
Discussion

In this chapter, the results of this study are discussed, providing insights into their implications and evaluating the research limitations. The aim is to contextualize the findings within the framework of decarbonising high temperature heat demand in refineries located in the Port of Rotterdam. The discussion begins with an analysis of the key findings, following the main order of the research. Thereafter, the implications of the full research are put into context, this by discussing the corporate versus public gap itself, and the motives behind the gap.

The primary aim of this study was to research both corporate and public perspectives on the blue hydrogen decarbonisation option of high temperature heat demand within refineries in the Port of Rotterdam, considering the EU & Dutch climate targets. This was achieved by first analyzing the reference situation of refinery heat demand under a business as usual scenario. Following this, an intervention scenario detailing the introduction of blue hydrogen was configured, followed by a cost benefit analysis to evaluate the effects of this intervention on the BAU scenario. The goal was to explore potential discrepancies between the two perspectives and to address the knowledge gap in the cost benefit analysis from these viewpoints on the blue hydrogen decarbonisation option.

8.1. Discussion of key findings

8.1.1. Reference Scenario

The CBA of the intervention scenario is performed on the basis of the BAU reference scenario for high temperature heat demand within refineries in the Port of Rotterdam. The analysis of the BAU scenario is based on the European Commission reference scenario, which is focused towards the Netherlands. Based on the Dutch reference scenario, the refinery high temperature heat demand data could be isolated. This based on the combination of literature research, historical data and the EU/Dutch reference scenario.

The BAU scenario assumes that the distribution of energy demand between the EU ETS sectors remains constant, allowing for the extrapolation of results from 2020 to 2050. However, this assumption may not hold true in reality, since the energy demand and CO_2 emissions within sectors could vary over time. This variation could change the refinery energy split and thereby the BAU scenario. The BAU scenario incorporates major future energy projections based on 2020 policies, natural progress and global forecasts.

The results indicate that the energy demand for high temperature heat decreases from 83 PJ in 2020 to 33 PJ in 2050. This decline in demand may suggest that the number of refineries in the Port of Rotterdam could decrease. It is perceived as unlikely that all refineries will continue to operate at a partial load due to inefficiency in operation. This scenario is plausible considering the existing critical standpoint on the number of refineries in the Netherlands (Estrada & Voogt, 2024). The critical standpoint mentioned, raises questions about the sustainability and necessity of maintaining the current number of refineries, given the shift towards decarbonisation and reducing fossil fuel dependence. The decline in the reference scenario could cause discussions about the potential closure of future redundant refineries in the Port of Rotterdam (Turner, 2021).

The reduction in energy demand and CO_2 emissions in the reference scenario primarily results from the increase in electric mobility and the changing demands of the logistics sector, including aviation and shipping. This is in line with the mainly sold & traded products of the refineries in the Netherlands, which are kerosene, gasoline, and heavy fuel oil (Netherlands Environmental Assessment Agency (PBL), 2020). Moreover, when compared to results from Quintel Intelligence Kerkhoven and Terwel, 2016, the overall decline aligns with their findings. However, the International Energy Agency (IEA) predicts that the highest worldwide energy demand is yet to come, which contradicts the findings of this report and other literature. The prediction of the IEA does not specifically address oil demand for Dutch refineries or the impact on the Dutch reference case (International Energy Agency, 2024). The prediction from the IEA, could indicate a potential increase in the export of products from Dutch refineries to meet the rising worldwide demand.

What can be learned from this theoretical study is that the natural reduction in energy demand and CO_2 emissions in the reference scenario must be taken into account when planning decarbonisation strategies, as it highlights the decarbonisation gap that needs to be addressed. One downside of relying purely on a theoretical approach is that the capacity for decarbonisation may be either underestimated or overestimated for the gap that needs to be addressed. Currently, refineries determine their decarbonisation plans solely against 1990 emissions, ignoring the reference scenario (Burgering, 2022). Future research into more detailed reference scenario paths for all process units within a refinery would offer a basis for determining effective decarbonisation options.

8.1.2. Intervention Scenario

The intervention scenario enables the CO_2 reduction needed to transition from the BAU reference scenario towards the EU and Dutch reduction targets set for 2030 and 2050, based on 1990 emission levels. Blue hydrogen demonstrates technical feasibility for decarbonising refinery heat demand due to the availability of proven and existing individual technologies. However, blue hydrogen has not yet been implemented on such a large scale, particularly with subsurface storage of CO_2. In terms of sizing, a single blue hydrogen plant can be built. This would consist of a 1400 MW ATR + CCS plant, designed to meet the required reduction targets and based on the availability of RFG and NG. The hydrogen plant is oversized in the initial years, creating commercial opportunities due to forecasted domestic and international demand for blue hydrogen. The produced hydrogen can be transported to other refineries and users via the hydrogen backbone. However, any residual hydrogen sold outside the Netherlands does not count towards the Dutch decarbonisation goals (Baker et al., 2020).

An alternative is to scale down the blue hydrogen plant in the initial years, which would significantly reduce the NPV due to partial utilization. If residual blue hydrogen is not sold commercially, a present value of 1.2 billion euros would be lost, as seen in section 7.1. Moreover, economies of scale play a major role in the investment in a blue hydrogen plant. According to ICF International, 2024, comparing a single 1400 MW plant to two 700 MW plants results in 20% savings in CAPEX and 5.5% savings in OPEX. Given the initially high CAPEX and OPEX costs, these savings offer significant advantages.

When comparing blue hydrogen against other decarbonisation options such as: post-combustion capture, multiple smaller hydrogen plants, and importing blue hydrogen, the following comparison can be made;

Post-combustion capture involves retrofitting refineries to capture CO_2 emissions directly from flue gases (Efrosini, 2023). If post-combustion capture would be used, it would result in attaching capture installation to approximately 5-10 stacks per refinery, which results in 25-50 installations overall for the PoR. This option presents practical challenges due to limited installation space and major costs. Each installation requires significant energy to regenerate the catalyst and to condition the captured CO_2. Additionally, each CO_2 capturing installation would need to be independently connected to the CO_2 backbone (P. Feron et al., 2021). Post combustion capture is also not in line with more broader hydrogen plans within the energy transition, since no externalities can be shared with regards to infrastructure and decarbonisation across other industrial sectors.

An alternative option could be the construction of multiple smaller blue hydrogen plants. While this offers flexibility and redundancy, the downsides include increased costs due to lack of scale and increased land use. This approach would also require multiple connections to the hydrogen and CCS backbone. Finally, importing blue hydrogen can be considered a option. This approach positions the refinery as a blue hydrogen customer, potentially leading to higher hydrogen tariffs as modeled in the current scenario for third-party off takers, resulting in higher costs. These options offer different approaches to fulfilling the intervention scenario, and research into the optimal setup and balance between these options could enhance the efficiency of the intervention strategy.

Overall, given that the intervention scenario is designed and scaled based on the reference scenario to achieve the largest CO_2 reduction between 2030 and 2050, which takes place in 2045 with a hydrogen demand of +/- 280ktpa (34.6 PJ), resulting in a CO_2 reduction of 2.1 Mtpa. This means that any uncertainty and deviation from the reference scenario could result in a change in the sizing of the decarbonisation capacity.

Given the uncertainty in the reference scenario, it may be beneficial to set up the intervention scenario in a flexible way. This to accommodate for deviations in decarbonisation demand. This can be achieved by over sizing for third party sales throughout the blue hydrogen plant its lifetime. This approach ensures that if the decarbonisation demand of the refineries are lower then expected, there is potential for off-take of hydrogen by other industries.

8.1.3. Corporate Perspective

From the corporate perspective, the intervention scenario indicates a positive NPV. The net benefit of 172 million euros is relatively small compared to the overall project cost of 4,009 million euro. The risk versus reward ratio is perceived as low due to high uncertainties in future decarbonisation policies, technological advancements, and reliance on partners such as hydrogen offtakers and CO_2 transport and storage developers. The major cost drivers impacting NPV include high upfront CAPEX costs and CO_2 transport and storage expenses. The CAPEX effects are significant due to the necessity for large initial investments and the lack of discounting costs. The optimistic case shows more potential to possible investments in the future with a NPV of 836 million euros of value, this mainly by the decrease in CAPEX and increase in EU ETS price.

When comparing the CO_2 transport and storage tariff from a corporate perspective, it can be compared to the EU ETS price using a simple equation: tariff per tonne of CO_2 versus EU ETS cost per tonne of CO_2. This comparison indicates a break even point in approximately 2034, excluding other costs. This break even point suggests that the investment will take a significant amount of time to become profitable from a corporate perspective for solely decarbonisation. In other words, emitting CO_2 is cheaper than the tariff to store CO_2, when excluding all other costs, creating a corporate dilemma regarding the timing of investing in decarbonisation options.

Selling hydrogen is largely beneficial from a corporate perspective, as seen in the results. When hydrogen is sold at the cost of production plus an 8% margin, the average price over the project lifetime is €3.66/kg. When blue is compared to the current grey hydrogen price of €1.60/kg, blue hydrogen is still expensive (Hoogervorst, 2024). However, as CO_2 EU ETS prices start to rise, blue hydrogen will become competitive against grey hydrogen. A blue hydrogen price of €3.66/kg matches with publicly forecasted blue hydrogen prices performed by consultants (BNEF, 2022). The Dutch government projects blue hydrogen prices to around €5/kg by 2025 (Energy NL, 2024) which contradicts corporate estimates. This higher projected price and earlier availability date (2025) present challenges in economic feasibility, as well as for the availability of CCS, hydrogen infrastructure and burner modifications.

The corporate abatement costs calculated in this report indicates a €110 per tonne of CO_2. This abatement cost closely aligns with research conducted by the corporates themselves, for this instance Shell, 2024b. When blue hydrogen is compared against other decarbonisation options such as green hydrogen, blue hydrogen is relatively affordable. Green hydrogen is projected by the government to cost €5/kg in 2025 and decrease to €4.20/kg in 2030, making it competitive with blue hydrogen (Eblé & Weeda, 2024). However, corporates and consultancy reports forecast the green hydrogen price to be closer to €8 per kg (CE Delft, 2023). Green hydrogen comes in at a abatement cost that ranges from €150 to €250 per tonne of CO_2 (International Renewable Energy Agency (IRENA), 2020).

Blue hydrogen appears to be a more attractive initial step for decarbonisation due to its lower cost. Additionally, blue hydrogen provides base-load production compared to green hydrogen, which is subject to intermittency from renewable sources. Green hydrogen is selected for as the final stage of decarbonisation via hydrogen (CE Delft, 2018), my consideration would be that attention needs to be paid to value blue hydrogen as a longer term solution, instead of a short term (<15year) solution this due to the major investments and commitments from both the corporate and public stakeholders that are shown in this report. This consideration can be addressed by researching the length of the blue transition period and the role of blue hydrogen, when green hydrogen becomes available.

8.1.4. Public Perspective

The social value for the public perspective is significantly positive in every case, this is in contrast with the corporate perspective. This mainly highlights the discrepancy in effects are valued from the corporate perspective compared to society as a whole. The public perspectives values long term environmental and societal cost savings from reduced CO_2 , which is not considered in the corporate perspective. This discrepancy can be seen in figure 6.1 where the market and social CO_2 prices are shown.

These findings align with the current resistance or inertia that corporations often face in developing business cases for decarbonisation projects (Financial Times, 2024; Reuters, 2024). This is in contrast with the public's motivation and perceived value in achieving climate targets. This situation has two aspects: while the public demands and values decarbonisation for its social benefits, the pace of change in public oil (products) consumption does not align with decarbonisation ambitions. Therefore, the government steps in to incentivise companies to decarbonise for the overall welfare.

However, the value of these incentives is minimal compared to the social value of decarbonisation. For instance, the present value of subsidies from the public perspective is 442 million euros, while the perceived CO_2 benefit amount to 10,711 million euro for reducing CO_2 from high temperature heat in refineries. These subsidies depend on contract for difference schemes (CFD). However, these CFD contracts are not accurately tailored to accommodate blue hydrogen initiatives. CFD do provide insurance against low CO_2 prices, the challenge arises in defining what a (too) low CO_2 price is relative to the cost of the specific decarbonisation option.

8.1.5. Implications for SDE++

Research of (ICIS, 2023) shows that government has allocated approximately 6.7 billion euros of subsidy for CCS-related projects. The blue hydrogen intervention scenario stated in this report receives approximately 133 million euro in subsidy based on current KEV CO_2 price assumption. This indicates a potential inefficiency in the reserved capital versus the SDE++ effect for corporate. In addition to undervaluing benefits and incentives for companies, this can also create opportunity costs for the public. It seem unlikely that the full 6.7 billion will be allocated to blue hydrogen projects, but there is potential for improving efficiency in the use of reserved capital versus the efficient subsidy effect.

This research shows that the Dutch Levy CO_2 floor price offers relatively low levels of incentives for decarbonisation projects compared to the projected CO_2 EU ETS price. From a corporate perspective, the value of CO2 avoided through the EU ETS is 2,038 million euro compared to 96 million euro though the Dutch carbon levy. This suggests that Dutch carbon levy is less ambitious compared to the EU ETS CO_2 price.

I would propose further research into the potential of a combination between the Dutch Carbon Levy and the SDE++ Subsidy. An increased Dutch carbon levy in combination with a higher SDE++ subsidy could offer a incentive to decarbonise. This by the increased revenue for the public through the Dutch Carbon Levy which can be used in a higher SDE++ subsidy towards the corporates, ultimately enhancing decarbonisation projects. Hereby a mechanism is created in which major emitting companies are paying more Dutch Levy which will finance the subsidies of the ones who are willing to decarbonise. This study shows that the Dutch Levy is not generating significant revenue due to not being high enough to surpass the EU ETS price. This makes the Dutch Levy not efficient in incentivising.

Figure 8.1 shows the value of the SDE++ per tonne CO_2over the shown time slots. Importantly to note, is that the EU ETS price is subject to inflation whereas the SDE++ strike price is not, this causes inefficiency.

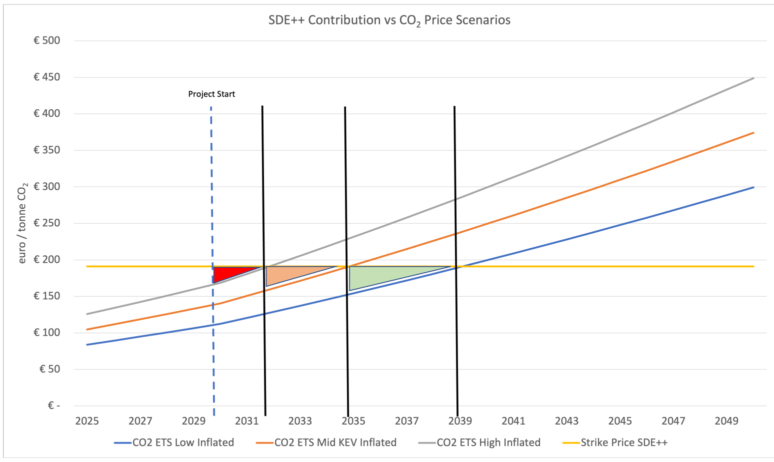

Figure 8.1: SDE++ Value for Corporates Compared to CO_2 EU ETS Price

8.2. Corporate versus Public Perspective: Bridging the Gap

The results reveal a significant contrast between the corporate and public perspectives regarding the intervention scenario for decarbonising high-temperature heat demand in refineries. This disparity is primarily driven by differing valuations of effects.

From the corporate perspective, the results indicate a positive value. Even though the NPV is showing a positive value of €172 million, this does not necessarily result in investment. Corporations base their investments on their ability to generate financial returns that exceed a certain threshold, known as the hurdle rate. An €172 million NPV translates to an 8.4% IRR, which falls short of the commonly used oil and gas hurdle rate of approximately 18% (Boston Consulting Group, 2023). To meet this 18% hurdle rate, an NPV of approximately €800 million is required. Comparing the oil & gas hurdle rate with those in other energy sectors, such as wind (7-10%), solar (5-7%), and heat pumps (6-8%) (Hanley, 2023; MacGregor, 2024), reveals that the oil and gas hurdle rate remains significantly higher. This higher hurdle rate is largely due to the heavy reliance on oil and gas (products) we as people have, which leads to a carbon lock-in [1]. Oil and gas companies continue to invest in high-margin projects rather than lower-margin decarbonisation projects. Despite the positive NPV, refineries are likely not to invest in this project due to an unfavorable risk/reward ratio. Oil and gas companies have differentiated between upstream projects with a minimum hurdle rate of approximately 22% and new energy projects with a hurdle rate of about 18% (NERA, 2018). This is can be seen as a step in the good direction towards accepting and investing in climate urgent projects, but it still raises the question: is this the correct hurdle rate for today's decarbonisation urgency, or does it need reassessment? Researching the appropriate hurdle rate could provide insights in the willingness to invest.

Hutchison, 2023 argues that when corporate hurdle rates are significantly different within the same market or sector, it can impact the competitive position of companies. If one refinery aims for major returns while another accepts smaller returns, global investors and stakeholders tend to choose larger, stable and predictable returns. This affects the companies future and profitability. Shareholder value is a significant priority for oil & gas companies, especially during discussions about climate change (Financial Times, 2024). Shareholders are willing to continue to support these companies despite the climate challenges. This is particularly relevant in areas like the Port of Rotterdam, where five refineries operate in a highly competitive environment. A weak performing refinery is at risk of closure due to strong (global) competition and shareholder and national pressure. Stronger incentives for decarbonisation projects could increase the value of new energy project and reduce the typical oil and gas project value, bringing the hurdle rates closer together.

The gap in NPV that is found in this report aligns with the findings of Stern, 2007 which highlights the gap between private and social returns in climate investments. The public value is often greater than

[1] Carbon lock-in refers to the self-perpetuating inertia created by large fossil fuel-based energy systems that inhibits public and private efforts to introduce alternative energy technologies

the corporate value, as seen in projects that increase social surplus, such as those in healthcare and infrastructure. The social value is sometimes lower than the corporate value this can be seen in tobacco, mining, and short-term investment projects. The opportunity cost of not performing decarbonisation projects is significant. Research of Stern, 2007 shows that the costs of not taking action on climate change far exceed the costs of taking action. Stern determined that climate change can reduce global GDP by up to 20%, compared to the cost of mitigating climate change which is approximately 1% of global GDP annually. This significant difference underscores the high opportunity cost of not investing in decarbonisation. The findings in this research indicate a similar relationship, only in a lesser extent, due to the intervention being national rather than global. This reflects the benefits of reducing CO_2 emissions relative to the overall cost of taking action.

The public decision to subsidize corporate decarbonisation efforts presents a challenging and ethical trade off. While maintaining these companies within the country ensures aspects like energy independence, economic benefits, and the opportunity for collaboration on decarbonisation, it also raises ethical and social concerns about financing their decarbonisation efforts giver their record profits. (Shell 2022: €43 billion; Exxon 2022: €56 billion; BP 2022: €26 billion (Witness, 2022)) The Porthos report is a recent example of where big corporate companies financially profited from public investment. This was due to a signed contract in which a (too) low CO_2 storage tariffs was agreed on (Rekenkamer, 2021). This resulted in a corporate NPV of 1.093 billion dollars with a 34.2% IRR. This while government had indented to accept a max IRR of 9% for the corporate. Despite errors in signing contracts and unexpected delays, claiming public money as potential profit as a corporate raises concerns about the ethical implications of such financial gains (Thomas, 2023).

Although refineries contribute to other sectors of the Dutch economy by providing products, jobs, and trade opportunities, their negative environmental impacts also need to be assessed. The necessity of refineries must be weighed against their environmental impact and the potential benefits of transitioning to a more sustainable industrial operation. Refineries in the Netherlands contribute €3.84 billion yearly, accounting for 0.36% of the Dutch GDP (VEMOBIN, 2020). Refineries are emitting 20% of the CO_2 emissions within the Dutch industrial sector and 6% of total national emissions (Centraal Bureau voor de Statistiek, 2024). When this is compared to the total 16% GDP contribution by the whole industrial sector, refineries are relatively small in terms of GDP contribution but significant in terms of CO_2 emissions. It could be beneficial to research the relationship between GDP contribution, domestic CO_2 emissions, and the public value of decarbonisation. This study may provide new insights without implying that sectors with higher economic contributions necessarily emit more.

In conclusion, bridging the gap between corporate and public interests is a delicate task. Many multidisciplinary parameters are interconnected and the dependency on oil products continues. Refinery products are currently essential for customers as a necessity of life, this means that products need to be affordable and available (Mabro, 2006). However these products need to be decarbonised (European Environment Agency, 2024). Bridging this gap requires collaboration between the public and corporate perspective but also a combined effort from the refinery sector as a whole. The sector must move collectively rather as individual entities, enabling a level playing field. Additionally, it is evident that substantial public value can be achieved. There is sufficient motive for the government to intervene, support, and incentivise the refinery sector in their decarbonisation efforts. This discussion raises critical questions which will displayed in section 9.2.1 together with further research recommendations.

8.3. Limitations

Given the uncertainty of decarbonisation pathways and the challenges in reaching targets with specific decarbonisation options, future projections of demand and forecasted price sets are highly uncertain. This study used a fixed ratio between the forecasted refinery activity in the Netherlands and the demand for high temperature heat to simplify the reference scenario. Further detailing this relationship could determine if the energy-split is linear across time, enhancing the accuracy of the reference scenario.

This study assumes that the timing and availability of infrastructure, technology, and demand are aligned with high-level assumptions of (blue) hydrogen initiatives. In this report the decarbonisation targets were leading in terms of critical path of decarbonisation, in reality the critical path can be determined by technology, investment, and policy. Variations in these paths could significantly affect the overall result. For the corporate effects many input cost assumptions are confidential, leading to the use of public price sets for analysis. Differences between corporate assumptions and reality could affect the overall outcome regarding the corporate perspective. This study only focuses on a singular option within the (hydrogen) energy transition, combining options can achieve other results.

In this CBA, not all effects are monetisable or the ability to monetize the effect is relatively low. Qualitative effects are described in terms of their potential effects and severity, but are not included in the NPV calculation due to their reasonable small or hard to calculate impact. Within this research the key parameters are included, but there can be many additions in terms of effects which spread across many disciplines such as ethical, social, technological, and geographical effects. Further examination and incorporation of these parameters into the CBA, or possibly through a multi criteria analysis (MCA), could add value. The MCA would also have placed greater emphasis on the weight that stakeholders assign to their interests. Furthermore, since this study has defined the BAU scenario for high temperature heat within PoR refineries, other technology options can be tested against this scenario. This could enable a Cost-Effectiveness Analysis to compare different intervention options, allowing for evaluation from multiple perspectives. This can be combined with a cost-benefit analysis (CBA) for a more comprehensive analysis.

Generalisability

This study is performed on the Port of Rotterdam refinery cluster with EU and Dutch regulations and policies. This makes the study specifically focused on effects that arise for this particular case. Policy and subsidy schemes and strategic position towards infrastructure are big aspect that determine the results of this study. Methodology and results can be used to extrapolate to other regions but a check on local subsidy schemes and pricing needs to be performed for correct results. The results regarding the PoR region can be generalised towards the whole of Netherlands. Since the PoR has +/- 90% of the Dutch refining capacity and are under the same policy framework as the other refinery in the Netherlands, this can be extrapolated.

Most assumptions are based on Dutch values and European values. What can be seen is that these values are aligned due to the European framework of regulations. This increases the potential to use this study framework for other scenarios within the EU. To ensure generalisability, refineries must be interconnected at a scale where it is perceived as efficient to connect them through infrastructure. This makes refinery clusters preferred for this study.

9 Conclusion

This study has evaluated the net (social) costs and benefits of using blue hydrogen to decarbonise high-temperature heat generation within refineries in the Port of Rotterdam. The analysis aligns with the Dutch/EU net zero targets for 2050, considering both corporate and public perspectives. While prior research has primarily focused on a single perspective on decarbonisation paths, this study examines both corporate and public viewpoints on one specific decarbonisation option. The focus is on assessing the potential discrepancy of these perspectives regarding the use of blue hydrogen.

This study was mainly guided by the following main research question:

What are the net (social) costs and benefits of using blue hydrogen for the decarbonisation of high-temperature heat generation within refineries in the Port of Rotterdam considering the Dutch/EU net zero targets for 2050?

This research question is addressed through five sub-research questions, which will be answered below.

9.1. Conclusion Main Findings

Sub Research Question 1: What is the business as usual energy and CO_2 reference case for refineries in the Port of Rotterdam?

The findings indicate that the energy consumption and CO_2 emissions for refineries in the Port of Rotterdam have a total high temperature heat demand of 82.9 PJ in 2020. This energy demand is forecasted to decrease over time under the business as usual reference scenario which has been determined in chapter 4. The energy demand will decline from 82.9 PJ in 2020 to 53.3 PJ in 2030 and declining further to 33.5 PJ in 2050. CHP is excluded as it falls outside the technological scope of this research. This energy business as usual case translates to a CO_2 BAU scenario which moves from 5.1 Mtpa in 2020, to 3.3 Mtpa in 2030 and eventually to 2 Mtpa in 2050. These energy demand and CO_2 emission scenarios provide a baseline while taking into account the 2020 policies, geographical parameters and the natural technological advancements.

Sub Research Question 2: What is the projected emission reduction from using blue hydrogen for heat generation in Port of Rotterdam refineries compared to the business-as-usual reference case in the time period between 2024 - 2050?

Based on the intervention scenario which is configured in chapter 5 a total emission reduction of 44.4 Mtonne can be realised compared to the reference scenario which is set up in chapter 4. This emission reduction is performed within the time frame of 2024 - 2050 to reach the targets set by the EU and the Dutch government. The total reduction of 44.4 Mtonne results from: 36.4 Mtonnes of CO_2 reduction from PoR refineries & 8 Mtonnes of CO_2 reduction from third party sales.

The emission reduction is realised by investing in a 1400 MW Auto Thermal Reformer including Carbon Capture and Storage plant. The produced blue hydrogen is used for high temperature heat purposes.

The implication is that blue hydrogen could be a viable solution for reducing CO_2 emissions in the high temperature heat refinery sector, this in terms of reduction capacity, technology size and future infrastructure such as the hydrogen backbone and CCS systems.

Sub Research Question 3: What are the costs and benefits effects of the blue hydrogen intervention from a corporate perspective?

To identify the costs and benefits effects from a corporate perspective, the intervention model was researched in terms of corporate orientated cost and benefit effects. The costs and benefits effects of implementing blue hydrogen were identified via literature research and are presented in Table 9.1. Mainly public sources are used as input for this analysis. The assumptions in terms of price sets are provided in a low - base - high range to provide a range of outcomes. This analysis outlines all direct cost and value drivers of the intervention scenario from a corporate standpoint.

Table 9.1: Cost and Benefit Effect of Blue Hydrogen Intervention Scenario from the Corporate Perspective

Intervention Effects	Cost / Benefit	Monetizable (Y/N)
Direct effects		
CAPEX H2 + CCS	Cost	Y - Market Price
CAPEX Burner Modification	Cost	Y - Market Price
CAPEX Infra ISBL	Cost	Y - Market Price
CAPEX PSA UNIT	Cost	Y - Market Price
OPEX	Cost	Y - Market Price
Electricity Cost	Cost	Y - Market Price
H2 Conversion Loss	Cost	Y - Market Price
CO_2 Transport & Storage H2 for Fuel	Cost	Y - Market Price
CO_2 Transport & Storage H2 for Commercial	Cost	Y - Market Price
Reputational Damage	Cost	N
Avoided EU ETS Burning	Benefit	Y - Market Price
Avoided Dutch Levy Burning	Benefit	Y - Market Price
Avoided EU ETS Steam	Benefit	Y - Market Price
Blue Steam	Benefit	Y - Market Price
H2 Sales (Commercial)	Benefit	Y - Market Price
Free Allowances	Benefit	Y - Market Price
Subsidies SDE Fuel Only	Benefit	Y - Market Price
Subsidies SDE Commercial	Benefit	Y - Market Price
Maatwerk Subsidy	Benefit	Y - Market Price
Reputational Impact	Benefit	N

Sub Research Question 4: What are the costs and benefits effects of the blue hydrogen intervention form a public perspective

To determine the costs and benefits from the public perspective, the configured intervention scenario was researched to identify cost and benefits relevant for the public perspective. The overall cost and benefits are outlined in section 9.2. This perspective takes external, indirect, and direct effects into account. Non monetizable qualitative effects like employment, innovation, and a stronger national position in refining provide value to the public. These qualitative effects are excluded from the SCBA. The effect of employment depends on the unemployment rate which is assumed. Employment has a positive impact when the unemployment rate is low.

Table 9.2: Cost and Benefit Effects from a Public Perspective of the Blue Hydrogen Implementation

Project Effects	**Cost / Benefit**	**Monetizable (Y/N)**
Direct Effects	Cost/Benefit	Y-Corporate Perspective
Indirect Effects		
SDE++ Subsidy	Cost	Y - Market Price
Potential Subsidy (Maatwerk - CAPEX)	Cost	Y - Market Price
Energy Prices	Cost	N
Hydrogen Backbone	Cost	Y - Market Price
OPEX Backbone	Cost	Y - Market Price
CO_2 Transport and Storage CAPEX	Cost	Y - Market Price
Innovation	Benefit	N
Employment	Benefit	Y - Market Price
Leading position Refinery Decarbonisation	Benefit	N
External Effects		
CO_2 Reduction	Benefit	Y - Social Price
Safety	Cost	N
Global Warming Potential	Cost	N

RQ5: How do the perspectives of the corporate compare to those of public regarding the costs and benefits effects of the intervention scenario?

Corporate perspective mainly focus on financial returns and operational efficiency which mainly consists of CAPEX, OPEX, and market prices of hydrogen and CO_2 EU ETS avoidance. The public perspective considers broader societal impacts such as, environmental and health benefits, which are often not monetized in the perspective of the corporate. The societal value of carbon reduction and the strategic importance of energy transition are key factors for the public perspective.

A difference in valuation arises when the market price for EU ETS allowances is compared with the societal price of CO_2. The EU Emissions Trading System sets the market price to incentivise companies to decarbonise by lowering the cap on emissions allowances. Despite this incentivising motive of the EU ETS there remains a substantial price difference. The EU ETS significantly undervalues CO_2 compared to the social price of carbon.

Companies value the avoided costs of EU ETS as a direct impact on their profitability, while the public perceives it as an external factor affecting quality of life. The motives are contradictory; if the EU ETS had no impact on a companies operations, they would assign no value to it. The public perspective continues to value carbon reduction the same.

Corporates use market prices to assess costs and benefits, which are subject to economic fluctuations, whereas public assessments rely on more stable theoretical social prices. The corporate and public viewpoints on the costs and benefits of the blue hydrogen intervention scenario reveal both shared objectives and areas of divergence.

Main Research Question: What are the costs and benefits of using blue hydrogen for the decarbonisation of high temperature heat generation within refineries in the Port of Rotterdam considering the Dutch/EU net zero targets in 2050, from the perspective of the corporate versus the public?

The implementation of blue hydrogen presents a net present value (NPV) of 172 million euros for the corporate perspective. This positive financial outcome is mainly driven by avoided EU ETS credit costs, commercial hydrogen sales and the SDE++ and Maatwerk government subsidies. The NPV is low compared to corporate standards as discussed in chapter 8. Additional support in the form of, subsidies or policy may be necessary to stimulate investment.

The total corporate discounted cost of 4,009 million euros is driven by costs such as CAPEX and CO_2 transport and storage expenses. Corporate discounted benefits of 4,181 million euros result from value drivers such as early project hydrogen sales and overall CO_2 EU ETS cost avoidance. The projects blue hydrogen price is on average 3.66 euros per kilogram this aligns with forecasted prices and suggests a competitive future market price. The main impacts that were shown in the sensitivity analysis consists of, fluctuations in CO_2 prices, CAPEX, transport & storage costs, and the discount rate. The scenario analysis shows a NPV of -618 million euros in the pessimistic case and a NPV of 836 million euros in the optimistic case.

From a public perspective, the benefits of using blue hydrogen go beyond direct financial returns by capturing societal and environmental value. These include CO_2 emission reductions, improved air quality, and enhanced public health. The public perspective presents a NPV of 8,834 million euros. This is a result of a total discounted cost of 6,057 million euros which mainly consists of investments in the hydrogen backbone, carbon capture & storage, and subsidies. The total discounted benefit is 14,891 million euros coming from external benefits of CO_2 reduction and corporate NPV contribution. Sensitivity analysis shows that the public NPV is mainly responsive to variations in the public CO_2 price and the discount rate. The public perspective is less sensitive compared to the corporate perspective in the scenario analysis. Scenarios range from 7,324 million euros in pessimistic scenarios to 9,977 million euros in optimistic scenarios.

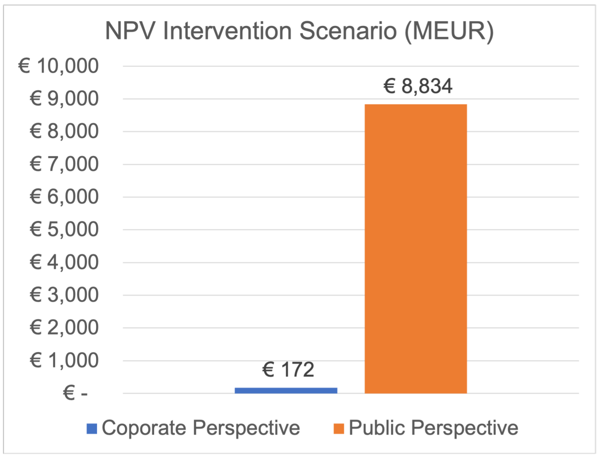

Figure 9.1: NPV Intervention Scenario - Corporate Perspective & Public Perspective

This results in a NPV difference between the 2 perspectives of 8,787 million euros. This highlights a non-alignment between the valuations of the intervention scenario. This discrepancy is mainly due to the difference between the social CO_2 price used by the public perspective compared to the EU ETS price used by the corporate perspective.

Based on the outcomes of the two perspectives it is not expected that, under current conditions, corporations will invest in the blue hydrogen intervention scenario due to the non-mandatory nature of decarbonisation and the risk versus reward ratio of such a uncertain project. This creates a potential public versus corporate dilemma, as the public social value of such a decarbonisation project is significant. Next section will recommend further research on the dilemmas.

9.2. Recommendations & Further Research

As shown in the results and highlighted in the discussion, the main finding of this research is the significant difference in the valuation of the blue hydrogen project intervention between the corporate and public perspective.

The primary reason for the discrepancy lies in the valuation of CO_2. The EU ETS price which is designed to incentivise corporates to reduce carbon emissions by lowering the EU ETS cap, does not fully internalize the external effects of CO_2. A comparison between the EU ETS Price and the Social Cost of Carbon valued in the WLO 2 Degree Scenario reveals a misalignment. To better align these valuations, further research is recommended to assess the theoretical EU ETS price necessary to internalize external effects of CO_2, this while taking the market trade mechanism of the EU ETS into consideration. Furthermore the feasibility of lowering the cap of the EU ETS could give insights in how to increase the EU ETS CO_2 Price.

The Social Cost of Carbon which is valued in the WLO 2 Degree priceset is currently considered as standard practice, since the Low and the High scenarios are considered outdated. This report highlights the significance of the Social Cost of Carbon and suggests reassessing this priceset with an update evaluation as of the years of 2024/2025.

Further recommendations include assessing and researching the impact of a increased Dutch CO_2 Levy. This reports indicate that current Dutch CO_2 Levy is not valued high enough to have additional impact next to the EU ETS. Evaluating what the theoretical value of the Dutch CO_2 Levy should add on top of the EU ETS to internalize external effects, could offer insights into adjusting localised policies. Additionally, exploring a potential mechanism combining the increased Dutch CO_2 Levy with a increased (SDE++) subsidy expenditure, could create a mechanism in which the emitter funds the subsidy for those who are willing to decarbonise.

9.2.1. Further Research

As mentioned in the discussion and in the conclusion the outcomes of this study poses decision makers with dilemmas, and hereby create critical questions. These critical questions and ways of studying them are described below.

Ethical & Economical

Research is suggested regarding the question if it is ethically justifiable to use public funds to subsidize highly profitable oil and gas companies. This research could provide context to the governments motives for offering such subsidies, especially considering the significant public value of decarbonisation efforts.

Furthermore, the examination of the balance between benefits and environmental impact, specifically considering the refinery substantial CO_2 emission compared to its relatively low GDP contribution. This research can provide insights in the trade-offs with regards to future industrial and environmental policies. Researching the relationship between GDP contribution, domestic CO_2 emission share and societal value of decarbonisation options, could provide insights into how the refinery activities impact economy and society as a whole. The following critical questions can be raised:

- Is it ethically justifiable to use public funds to subsidize highly profitable oil and gas companies for decarbonisation efforts?
- What alternative strategies could be employed to achieve decarbonisation without providing financial support to these companies?
- What are the costs and benefits of the Netherlands reducing its refinery operations to lower CO_2 emissions and primarily serve domestic demand? How would this impact carbon leakage, national decarbonisation efforts, and economic contribution?
- Given the relatively low GDP contribution of the refinery sector compared to its significant CO_2 emissions, how should policymakers reevaluate the balance between economic benefits and environmental impact when formulating future industrial and environmental policies?
- What can be learned from the ratio between GDP contribution, domestic carbon emission share, and social value?

These questions can be researched through ethical analyses of subsidising the energy transition, and comparative studies of alternative decarbonisation strategies of other sectors. Also broader economical research is considered, this by analyzing the contribution of refineries to GDP compared to their negative impact of climate damage.

Corporate Hurdle Rate vs. Public Value

There is potentially value in researching the current investment hurdle rates and investment parameters to determine if the hurdle rates account for long-term decarbonisation benefits rather than short-term gains. This consists of examining whether these hurdle rates consider the intrinsic value of environmental and societal benefits.

Investments have a strong relation with a level playing field. Examining the level playing field nationally and international for companies that need to decarbonise could give insights. This by, identifying the obstacles to investment when competitors prioritize short-term profit and share price. Research mechanisms that can prevent the loss of competitive edge for companies investing in long-term decarbonisation initiatives. This raises the following questions:

- Is the traditional hurdle rate an outdated metric in the context of urgent decarbonisation needs?
- Should the hurdle rate be adjusted to incorporate the intrinsic value of environmental and societal benefits?
- How can a company justify significant investment in decarbonisation if its competitors do not follow suit?
- What mechanisms can ensure a level playing field to prevent the loss of competitive edge?

The questions listed above can be studied through empirical (case) studies which compare hurdle rates across industrial sectors. Also financial studies in the form of a business case assessment can be performed to determine the minimum needed hurdle rate of a IEC using public data. In terms of studies towards the level playing field, its recommended to investigate regulatory frameworks and industry standards. Case studies and policy analysis could give insights in mechanisms to balance the competitiveness in the urgency of decarbonisation.

9.3. Relevance

This section reflects on the research performed, emphasizing its relevance from academic, MOT, and societal perspectives. Research result relevance and implications are discussed in section 8 discussion.

9.3.1. Academic Relevance

This study contributes to academic knowledge by identifying the gap between the public and corporate perspective valuations of blue hydrogen as a decarbonisation option in refineries, marking a step forward in bridging the gap between the perspectives and thus decarbonising. This is done by analyzing the value of the effects that occur when implementing a blue hydrogen scenario.

The reference BAU scenario that has been established provides a foundation/framework for further academic studies towards decarbonisation options of high temperature heat emission coming from PoR refineries. Facilitating the basis for the comparison of different scenarios and options. Since PoR refineries account for 90% of the Dutch refining capacity, the findings are representative for the Netherlands as a whole and have the potential to be applied internationally to similar refineries.

The business case of the blue hydrogen intervention scenario is developed with public assumptions, creating a transparent framework for further research from a corporate perspective. By comparing the perspectives, this study enables the positioning in to other perspectives regarding the same decarbonisation option.

Furthermore, this research highlights the gap of the corporate and public perspective on urgent climate change problems, encouraging on the discussion on the valuation of CO_2 damage, the role of PoR refineries and the need for a specific policy framework. It encourages critical thinking to overcome potential inertia with regards to decarbonisation efforts. This study provides insights and a framework to valuate single decarbonisation options from multiple perspectives, helping to identify cost and benefit drivers.

9.3.2. Management of Technology Relevance

This study shows high relevance to the MOT program due to the assessment of societal versus private implications within the technological context of decarbonisation. The change in technology that awaits us as society and the private sector, to be able to change the direction of global warming, is significant. This asks for a multidisciplinary socio-techno-economic approach which is taught within the MOT program. This multidisciplinary study is focused on the position and synergy between major companies, the government, and the public, specifically on how refineries and the government position them selfs in terms of value with regards to decarbonisation options. A MOT perspective is well suited for this analysis due to the synergies of private stakeholders and the public, the usage of technology to be able to improve the status quo, and displaying commercial positions against decarbonisation obligations. From a MOT perspective, it would be interesting to explore the public-private partnerships in Hydrogen and CCS further, to develop decarbonisation strategies.

9.3.3. Social Relevance

Climate change and decarbonisation is a ongoing and urgent social topic. This study has social relevancy by studying the decarbonisation options of significant CO_2emitters. Society can expect long-term benefits by reducing carbon emissions within the PoR refineries. Although these benefits will not be noticed on the short term, since climate change is a 'slow' moving process. By making the positions of key stakeholders on decarbonsation and policy more transparent, this study generates valuable information for decision making. All improvements and efforts regarding decarbonisation will have direct effect for society. A reflection that can be made is, that while this study addresses the decarbonisation of refineries, the ultimate driver behind the demand for oil products is societal consumption and behaviour. Therefore it is essential for society to evaluate whether 'we' are genuinely committed to mitigating climate change.

9.3.4. Corporate Relevance

From the perspective of the corporate, which is extensively researched in this study, the main relevance lies in the public understanding of decarbonisation projects. By revealing how the public values these initiatives and their underlying motives, the study helps corporates to engage more effectively with governmental institutes. Additionally, the study shows that a comprehensive view of this decarbonisation option has potential for profit in the upcoming blue hydrogen markets. Also designing a decarbonisation option based on a reference scenario could give new insights to the corporate sector. Overall this study informs the corporates about a holistic view on the blue hydrogen decarbonisation option, offering insights in the public valuation, and the need and size to decarbonise high temperature heat demand.

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A

Socioeconomic Analysis Methods

Table A.1: Comparison of Theoretical Background, Evaluation Criteria, and Measurement Methods (Agency, 2024)

	Cost-benefit analysis (CBA)	**Multi-criteria analysis (MCA)**	**Cost-effectiveness analysis (CEA)**
Theoretical background	Microeconomics and Welfare Theory	Operations Research	Health economics and public policy
Evaluation criteria	Social welfare	Weighted sum of effects	Effectiveness in achieving specific outcomes relative to costs
Measurement through	Willingness-to-pay for effects and willingness-to-accept effects	Political or consumer weights for project effects	Ratio of cost to non-monetary units of outcome (e.g., cost per life-year saved)

Table A.2: Advantages and Disadvantages of CBA, MCA, and CEA (Agency, 2024)

Aspect	**Cost-benefit analysis (CBA)**	**Multi-criteria analysis (MCA)**	**Cost-effectiveness analysis (CEA)**
Decision support	+ (Discerns attractive from unattractive policies)	+/- (Ranks policies in terms of attractiveness)	+ (Identifies the most cost-effective option among alternatives)
General quality of weights	+ (Weights based in utility functions)	- (Subjective weights open to ambiguity and manipulation)	+ (Uses consistent metrics, often standardized across studies)
Completeness	+/- (Some effects are hard to valuate in monetary terms)	+ (All effects can be included)	+/- (Focuses on specific outcomes, may ignore broader impacts)
Connection with political process	+/- (Conclusions are clear to politicians, but distributional issues are not considered)	+ (Stakeholders apply their own weights related to their interests)	+ (Results are relevant to policy goals, but may oversimplify issues)

B

CPI Index

Consumentenprijzen; prijsindex 2015=100

: Gewijzigd op: 7 mei 2024

Bestedingscategorieën: 000000 Alle bestedingen

	Onderwerp			
Perioden	CPI	CPI afgeleid	Jaarmutatie CPI	Jaarmutatie CPI afgeleid
	2015 = 100		%	
2005	84,88	87,28	1,7	1,4
2006	85,82	88,60	1,1	1,5
2007	87,20	89,90	1,6	1,5
2008	89,37	91,92	2,5	2,2
2009	90,44	92,71	1,2	0,9
2010	91,59	93,71	1,3	1,1
2011	93,73	95,74	2,3	2,2
2012	96,04	97,71	2,5	2,1
2013	98,44	98,97	2,5	1,3
2014	99,40	99,60	1,0	0,6
2015	100,00	100,00	0,6	0,4
2016	100,32	100,25	0,3	0,3
2017	101,70	101,62	1,4	1,4
2018	103,44	103,01	1,7	1,4
2019	106,16	104,64	2,6	1,6
2020	107,51	105,94	1,3	1,2
2021	110,39	108,55	2,7	2,5
2022	121,43	121,31	10,0	11,8
2023	126,09	124,98	3,8	3,0

Bron: CBS

Figure B.1: CPI Index Centraal Bureau voor de Statistiek, 2023

C

Validation Memo

See the validation summary on the next page, performed together with Energy Consultant Renze Straatsma from Berenschot on May 24, 2024, from 10:15 to 11:00.

Bevestiging tekst thesis

Renze Straatsma

di 11-6-2024 09:13

Aan:Jerre van Dongen <S.W.J.vanDongen@student.tudelft.nl>;

U ontvangt niet vaak e-mail van r.straatsma Meer informatie over waarom dit belangrijk is

Beste Jerre,

Dankjewel voor het toesturen van de samenvatting van onze gesprekspunten. Er zijn geen aanpassingen nodig aan de tekst en geef toestemming voor het als zodanig verwerken in je Thesis.

Veel succes nog!

Dear Jerre,

Thanks for sending me the summary of our conversation. No adjustments are necessary in the text below. Therefore, I give you permission to incorporated the text as such in your Thesis.

Good luck!

24-5-2024 || 10:15 - 11:00
Jerre van Dongen - TU Delft
Discussion / Validation with Renze Straatsma Energy consultant at Berenschot Consultancy

Berenschot is a Dutch company which is active in the public and private sector, Berenschot has a track record of public socio-economic and socio-technic analysis and advices.

Renze Straatsma was willing to discuss and verify the methodology in terms of perspectives and effects of the SCBA performed. The overall findings were:

Make sure that the perspectives are strictly separated, this is essential so common values and motives can be identified. This makes sure that there is no sense or idea that perspectives are completely orienteted against eachother but also have common goals and objectives.

For most public assumptions such as discount rate and prices (WLO CO2 price), maintain prices which allign with the scope and motive of the research (in this case the net zero trajectory) and the current regulation and policies which are active. This means that the WLO CO2 2 Degree scenario is most in line with the current policies. WLO Hoog scenarios could be used as sensitivity.

Shortly explain that qualitative parameters are not so straightforward. Show the bigger context of the qualitative effects besides a yes or no idea. Dont eleborate to much on qualitative parameters which are not monetizable, mention them, give the context and recommend further action.

Effects list seem complete, a few suggestions were effects such as safety, and Dutch competition position which is related to being leading in the energy transition. These effects may be qualitative but worth mentioning and discussing. Safety aspects could be the implications of hydrogen to the public safety, this in your case is maybe partly related due to the fact that operational activity is active in the industrial region context. Potentially later hydrogen export could expand this safety context.

Met vriendelijke groet,
Renze Straatsma

D

Reference Scenario

The reference scenario for this analysis is constructed based on the EU/Dutch Reference Scenario 2020 Commission et al., 2021. This scenario integrates historical data including; energy usage, emission data, and energy splits to forecast future trends and provide a solid basis for comparison.

Determining PoR Refinery Reference Scenario

To understand the projected energy and emission trends, the EU and Dutch Reference Scenarios are used. These projections serve as benchmarks for the analysis. Within these databases, EU ETS and Industrial category numbers are used.

DECARBONISATION	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	'10-'20	'20-'30	'30-'50
Total GHG emissions, excl. international excl. LULUCF (MtCO2eq) [6]	**4570,0**	**4209,4**	**3849,3**	**3216,2**	**3099,3**	**2725,4**	**2391,1**	**2115,2**	**1957,9**	**1895,2**	**-2,7**	**-1,6**	**-1,8**
of which ETS sectors (stationary installations) GHG emissions [7]	2062,0	1787,7	1600,8	1196,6	1120,5	985,6	808,6	648,8	575,3	560,2	-3,9	-1,9	-2,8
International bunkers emissions (MtCO2) [8]	**245,4**	**246,4**	**232,0**	**153,2**	**262,5**	**269,6**	**275,4**	**283,0**	**289,5**	**296,2**	**-4,6**	**5,8**	**0,5**
of which aviation	93,3	96,1	105,4	55,7	122,1	124,9	126,3	127,9	128,1	128,8	-5,3	8,4	0,2
of which maritime	152,1	150,3	126,6	97,5	140,5	144,7	149,1	155,1	161,5	167,3	-4,2	4,0	0,7
Domestic energy-related CO2 Emissions (MtCO2)	**3383,3**	**3119,1**	**2827,9**	**2254,9**	**2191,0**	**1869,5**	**1607,8**	**1361,7**	**1231,7**	**1193,5**	**-3,2**	**-1,9**	**-2,2**
Power generation/District heating	1298,1	1182,6	1058,9	699,3	628,5	526,4	415,9	295,7	243,3	246,6	-5,1	-2,8	-3,7
Energy Branch	169,6	159,0	150,1	120,9	104,3	95,9	86,7	78,7	72,5	68,5	-2,7	-2,3	-1,7
Industry	450,3	369,6	337,4	323,2	323,6	281,3	237,4	202,3	191,6	187,0	-1,3	-1,4	-2,0
Residential	403,5	384,3	311,8	304,1	259,7	211,6	190,6	171,0	160,1	152,1	-2,3	-3,6	-1,6
Services (and agriculture)	243,8	233,4	203,3	169,2	176,5	137,7	129,3	118,4	112,2	108,6	-3,2	-2,0	-1,2
Transport [9]	817,9	790,1	766,4	638,3	698,5	616,5	547,9	495,6	452,0	430,6	-2,1	-0,3	-1,8
Other CO2 Emissions (non land-use related) (MtCO2)	**349,1**	**308,1**	**283,6**	**263,1**	**278,6**	**275,2**	**234,0**	**224,8**	**214,8**	**200,6**	**-1,6**	**0,4**	**-1,6**
Non-CO2 GHG emissions (MtCO2eq) [6],[10]	**819,4**	**762,4**	**747,3**	**701,6**	**631,3**	**582,1**	**551,7**	**531,0**	**513,7**	**503,2**	**-0,8**	**-1,8**	**-0,7**
Correction for emissions inventories (MtCO2)	**18,2**	**19,7**	**-9,5**	**-3,5**	**-1,7**	**-1,5**	**-2,4**	**-2,3**	**-2,3**	**-2,0**	**-**	**-8,3**	**1,6**
Carbon Intensity indicators													
Electricity and Steam production (tCO2/MWh)	0,45	0,40	0,37	0,27	0,22	0,18	0,13	0,09	0,07	0,07	-4,0	-4,0	-4,4
Final energy consumption (tCO2/toe)	1,94	1,83	1,78	1,70	1,65	1,48	1,37	1,27	1,20	1,16	-0,7	-1,4	-1,2
Industry	1,65	1,54	1,48	1,47	1,40	1,25	1,10	0,97	0,92	0,89	-0,5	-1,6	-1,7
Residential	1,50	1,38	1,26	1,21	1,11	0,95	0,88	0,81	0,77	0,75	-1,3	-2,4	-1,1
Tertiary	1,48	1,34	1,26	1,21	1,11	0,90	0,84	0,78	0,74	0,72	-1,0	-2,9	-1,1
Transport [9]	2,93	2,85	2,83	2,76	2,71	2,59	2,49	2,40	2,30	2,24	-0,3	-0,6	-0,7

Figure D.1: European Reference Case Commission et al., 2021

DECARBONISATION	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	'10-'20	'20-'30	'30-'50
Total GHG emissions, excl. international excl. LULUCF (MtCO2eq) (6)	**215,8**	**215,0**	**199,0**	**169,6**	**162,2**	**129,2**	**120,9**	**107,4**	**100,4**	**93,4**	**-2,3**	**-2,7**	**-1,6**
of which ETS sectors (stationary installations) GHG emissions (7)	91,0	86,4	94,2	74,7	74,1	48,0	46,1	39,1	35,5	30,2	-1,4	-4,3	-2,3
International bunkers emissions (MtCO2) (8)	**61,3**	**54,9**	**49,8**	**32,9**	**51,2**	**53,4**	**53,9**	**55,7**	**57,9**	**60,8**	**-5,0**	**5,0**	**0,7**
of which aviation	10,9	10,2	11,4	5,7	12,2	12,7	12,4	12,3	12,2	12,2	-5,7	8,4	-0,2
of which maritime	50,4	44,7	38,4	27,2	39,0	40,6	41,5	43,4	45,8	48,6	-4,8	4,1	0,9
Domestic energy-related CO2 Emissions (MtCO2)	**164,3**	**168,6**	**156,5**	**130,8**	**125,4**	**93,4**	**86,3**	**73,5**	**67,3**	**66,0**	**-2,5**	**-3,3**	**-1,7**
Power generation/District heating	59,4	60,4	63,0	46,8	48,1	25,1	25,0	21,5	18,6	18,8	-2,5	-6,1	-1,4
Energy Branch	12,3	11,0	11,8	8,7	7,3	6,8	5,8	5,0	4,8	4,9	-2,3	-2,4	-1,6
Industry	21,8	21,5	20,6	20,7	20,5	17,0	15,9	12,6	12,4	12,2	-0,4	-2,0	-1,6
Residential	19,4	23,0	16,1	15,5	14,2	13,0	12,4	11,5	10,8	10,3	-3,8	-1,8	-1,1
Services (and agriculture)	17,5	18,7	15,0	13,4	9,8	8,6	9,1	9,0	9,0	8,9	-3,3	-4,4	0,2
Transport (9)	33,8	34,0	29,9	25,7	25,4	23,0	18,1	13,9	11,7	10,9	-2,8	-1,1	-3,7
Other CO2 Emissions (non land-use related) (MtCO2)	**11,4**	**11,2**	**11,1**	**10,3**	**10,5**	**10,2**	**9,1**	**8,7**	**8,1**	**2,3**	**-0,8**	**-0,1**	**-7,1**
Non-CO2 GHG emissions (MtCO2eq) (6),(10)	**37,9**	**32,4**	**32,2**	**29,2**	**27,0**	**26,1**	**26,0**	**25,7**	**25,5**	**25,4**	**-1,1**	**-1,1**	**-0,1**
Correction for emissions inventories (MtCO2)	**2,2**	**2,8**	**-0,8**	**-0,7**	**-0,6**	**-0,6**	**-0,5**	**-0,4**	**-0,4**	**-0,4**	**-**	**-2,2**	**-2,0**
Carbon Intensity indicators													
Electricity and Steam production (tCO2/MWh)	0,59	0,51	0,56	0,42	0,33	0,17	0,16	0,14	0,11	0,11	-1,9	-8,5	-2,4
Final energy consumption (tCO2/toe)	1,90	1,92	1,88	1,83	1,67	1,56	1,48	1,35	1,28	1,23	-0,5	-1,6	-1,2
Industry	1,42	1,52	1,60	1,63	1,55	1,40	1,39	1,22	1,18	1,12	0,7	-1,5	-1,1
Residential	1,81	1,84	1,69	1,64	1,62	1,57	1,53	1,48	1,42	1,35	-1,1	-0,4	-0,7
Tertiary	1,57	1,53	1,42	1,38	0,92	0,81	0,83	0,84	0,85	0,86	-1,0	-5,2	0,3
Transport (9)	2,97	2,92	2,89	2,80	2,79	2,72	2,56	2,32	2,13	2,04	-0,4	-0,3	-1,4

Figure D.2: Dutch Reference Case Commission et al., 2021

Historical split between ETS sectors is based on:

The table below shows the historical distribution among the ETS sectors. Refineries account for approximately 13% of the EU ETS emissions. When comparing this 13% against the actual historical emissions in table D.2, it can be concluded that the distribution and historical values align closely. (13% of 91 Mtpa in 2005 equals 11.83 Mtpa, which is close to 11.6 Mtpa; 13% of 94.2 Mtpa in 2015 equals 12.2 Mtpa, which is close to 12 Mtpa)

Sector	Split
Energy	59%
Chemical	22%
Refineries	13%
Metals	5%

Table D.1: ETS Sector Split Emissions (Centraal Bureau voor de Statistiek, 2024)]

Historical emission data is based on:

The historical emission data provides a foundation for understanding past trends and calibrating the model. The following table outlines the emissions over selected years. This data is checked with the historical data in the Dutch Reference case.

Year	Emission
2005	11.6
2010	11.1
2015	12
2020	9.6

Table D.2: Historical Emission Refineries the Netherlands (CPB, 2016)

Split between High Temperature Heat Demand within refineries

Now the total refinery emission are know, the reference scenario needs to be specified to high temperature heat. Refineries have specific high temperature heat demands, which are significant for the energy and emission calculations. PBL did research to the usage and generation/demand of high temperature heat. The data below is derived from PBL research Netherlands Environmental Assessment Agency (PBL), 2020.

Historically, these high-temperature energy streams have remained very stable. For future energy streams, a similar stability is assumed, and extrapolation is performed using fixed ratios. This method ensures consistency and reliability in the projected data.

Table D.3: High Temperature Heat Energy Streams - 2020 (PBL, 2022)

High Temperature Heat Streams	PJ
CHP NG	13.7
CHP RFG	6.8
Boiler RFG + NG	9.8
RFG Combustion	66.3
Total	**99.6**
Total – CHP NG	**82.9**

Subsequently, energy streams are converted to emission streams using emission factors: 0,20 tonnes CO2/MWh for Natural Gas and 0,22 tonnes CO2/MWh for Refinery Fuel Gas. This conversion enables accurate emission forecasting per energy stream aligned with energy consumption.

Once all emission and energy data are historically aligned, they are extrapolated according to the future trajectory outlined in the Dutch reference scenario. See figure D.3 for the reference scenario streams.

Years	CHP NG	CHP RFG	Boiler RFG + NG	RFG Combustion	Total	Total (CHP-NG Excluded)	CO2 Emitted
	PJ	*PJ*	*PJ*	*PJ*	*PJ*	*PJ*	*MtCO2eq*
2020	13,7	6,8	9,8	66,3	96,6	82,9	5,1
2021	13,7	6,8	9,8	66,2	96,4	82,8	5,1
2022	13,7	6,8	9,8	66,1	96,3	82,6	5,0
2023	13,6	6,8	9,8	66,0	96,1	82,5	5,0
2024	13,6	6,8	9,7	65,9	96,0	82,4	5,0
2025	13,6	6,7	9,7	65,8	95,8	82,2	5,0
2026	12,6	6,3	9,0	61,1	89,1	76,4	4,7
2027	11,7	5,8	8,4	56,5	82,3	70,6	4,3
2028	10,7	5,3	7,7	51,9	75,6	64,9	4,0
2029	9,8	4,8	7,0	47,2	68,8	59,1	3,6
2030	8,8	4,4	6,3	42,6	62,1	53,3	3,3
2031	8,7	4,3	6,2	42,3	61,6	52,8	3,2
2032	8,7	4,3	6,2	41,9	61,1	52,4	3,2
2033	8,6	4,3	6,1	41,6	60,6	52,0	3,2
2034	8,5	4,2	6,1	41,3	60,1	51,6	3,2
2035	8,5	4,2	6,0	40,9	59,6	51,2	3,1
2036	8,2	4,1	5,9	39,7	57,8	49,6	3,0
2037	7,9	3,9	5,7	38,4	56,0	48,1	2,9
2038	7,7	3,8	5,5	37,2	54,2	46,5	2,8
2039	7,4	3,7	5,3	35,9	52,4	44,9	2,7
2040	7,2	3,6	5,1	34,7	50,6	43,4	2,7
2041	7,0	3,5	5,0	34,1	49,6	42,6	2,6
2042	6,9	3,4	4,9	33,4	48,7	41,8	2,6
2043	6,8	3,4	4,8	32,8	47,8	41,0	2,5
2044	6,6	3,3	4,8	32,1	46,8	40,2	2,5
2045	6,5	3,2	4,7	31,5	45,9	39,4	2,4
2046	6,3	3,1	4,5	30,6	44,5	38,2	2,3
2047	6,1	3,0	4,4	29,6	43,2	37,0	2,3
2048	5,9	2,9	4,2	28,7	41,8	35,9	2,2
2049	5,7	2,8	4,1	27,7	40,4	34,7	2,1
2050	5,5	2,7	4,0	26,8	39,1	33,5	2,0

Figure D.3: Modelled Reference Scenario Model - High temperature Heat Demand Refineries PoR

E

Hydrogen Backbone Netherlands

Figure E.1: Hydrogen Backbone Netherlands

F

RFG Composition

Component	Mol%
H_2	20
CH_4	45
C_2H_6	10
C_3H_8	10
C_{4+}	15

Table F.1: High Level Composition of Refinery Fuel Gas Mixture (Ditaranto et al., 2013)

RFG is not always constant in terms of compositions. The refinery process can be adjusted to form other forms of compositions. The figure below displays potential ranges of RFG compositions

Table 3. Representative compositions of fuel gas.

Compound		C1	C2	C3	C4	Natural Gas (NG)
CH_4	Methane	55	70	25	35	97
C_2H_6	Ethane	10	0	8	3	1
C_3H_8	Propane	0	16	25	35	1
C_4H_{10}	n-butane	4	5	10	12	0
C_2H_4	Ethylene	5	3	10	7	0,5
C_3H_6	Propylene	2	0	5	8	0,5
H_2S	Hydrogen sulfide	4	1	2	0	0
H_2	Hydrogen	20	5	15	0	0

Figure F.1: Range of RFG Compositions (Cala et al., 2015)

G

Hydrogen Demand Netherlands

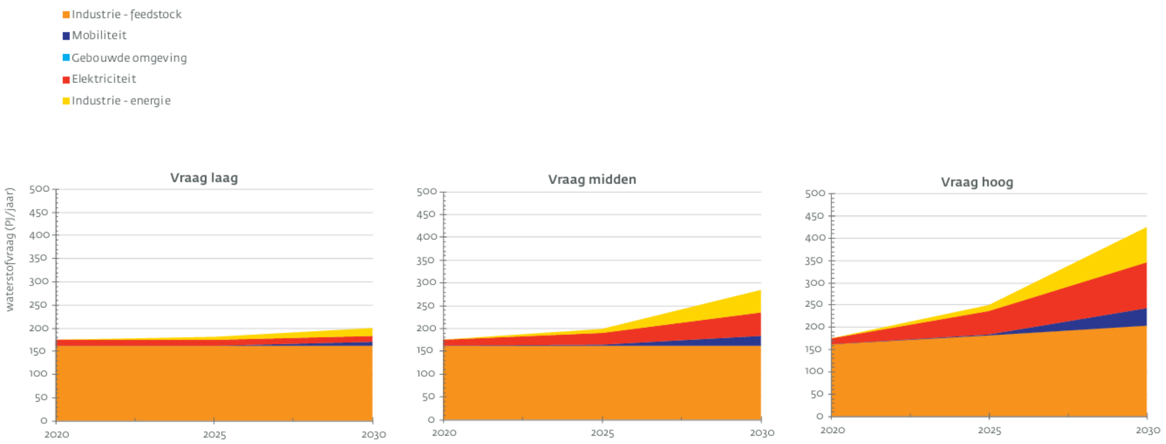

Figure G.1: Hydrogen Demand - 2030 Gas Unie Gasunie, 2018

H

PSA Calculation & Hydrogen Energy Content

PSA H2 recovery		83%		Feedgas				Product stream				Tails Gas			
PSA product purity		99,60%	kg/h	1000				634				366			
			kmol/h	374				303				71			
			MW	25,1				20,4				4,8			
			Mwt	2,68				2,09				5,16			
			MJ/kg	90				116				47			
	Mwt	MJ/kg		mol%	kmol/h	mass (kg/h)	MJ	mol%	kmol/h	mass (kg/h)	MJ	mol%	kmol/h	mass (kg/h)	MJ
H2	2,015	120		97,25	363,3	732	87856	99,60	301,6	608	72921	87,17	61,8	124	14936
CO2	44,01			0,1	0,4	16	0	0	0,0	0	0	0,53	0,4	16	0
CO	28,01	10,08		0,75	2,8	78	791	0	0,0	0	0	3,95	2,8	78	791
Ar	39,95			0,06	0,2	9	0	0,01	0,0	1	0	0,27	0,2	8	0
N2	28,02			1,2	4,5	126	0	0,19	0,6	16	0	5,52	3,9	110	0
CH4	16,04	48		0,64	2,4	38	1841	0,19	0,6	9	443	2,56	1,8	29	1398
			total	100,00	373,6	1000	90488	99,99	302,8	634	73364	100,00	70,9	366	17125
						39,7841283	kg/MWh			31,122046	kg/MWh				

Figure H.1: PSA Calculation Showing Entry Stream, Purified Stream, Tail Gas Stream

I

Reference and Interventio Scenario Yearly Numbers

		2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
Reference Scenario											
CO2 Emissions PoR Refinery HTH	Mtpa	3,3	3,2	3,2	3,2	3,2	3,1	3,0	2,9	2,8	2,7
Energy Demand		**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**
CHP NG	PJ	8,8	8,7	8,7	8,6	8,5	8,5	8,2	7,9	7,7	7,4
CHP RFG	PJ	4,4	4,3	4,3	4,3	4,2	4,2	4,1	3,9	3,8	3,7
Boiler RFG + NG	PJ	6,3	6,2	6,2	6,1	6,1	6,0	5,9	5,7	5,5	5,3
RFG Combustion	PJ	42,6	42,3	41,9	41,6	41,3	40,9	39,7	38,4	37,2	35,9
Total	PJ	62,1	61,6	61,1	60,6	60,1	59,6	57,8	56,0	54,2	52,4
Total (CHP-NG Excluded)	PJ	53,3	52,8	52,4	52,0	51,6	51,2	49,6	48,1	46,5	44,9
Intervention Scenario											
Linear Climate Target		55%	59%	62%	66%	69%	73%	76%	80%	83%	87%
1990 Emission	MtCO2eq										
EU / NL CO2 Reduction Target	MtCO2eq	2,6235	2,41945	2,2154	2,01135	1,8073	1,60325	1,3992	1,19515	0,9911	0,78705
Reduction Needed	MtCO2eq	0,63	0,81	0,99	1,17	1,34	1,52	1,63	1,74	1,85	1,96
Blue Hydrogen Ramp Up for Burning	PJ	10,34	13,26	16,17	19,09	22,01	24,93	26,71	28,50	30,28	32,07
Blue Hydrogen Needed	ktonne	86	110	135	159	183	208	223	237	252	267
Installed Capacity	ktonne	289	289	289	289	289	289	289	289	289	289
Residual Hydrogen	ktonne	202	178	154	129	105	81	66	51	36	21
Installed Capacity	MWh	9.308.271	9.308.271	9.308.271	9.308.271	9.308.271	9.308.271	9.308.271	9.308.271	9.308.271	9.308.271
Installed Capacity	MWth	1063	1063	1063	1063	1063	1063	1063	1063	1063	1063
Installed Capacity	MW	1328	1328	1328	1328	1328	1328	1328	1328	1328	1328
Electricity Needed	MWh	837.744	837.744	837.744	837.744	837.744	837.744	837.744	837.744	837.744	837.744
Natural Gas Needed	MWh										
Steam Created	MWh										
BH2 MWh		2.962.779	3.798.773	4.634.767	5.470.761	6.306.755	7.142.749	7.654.360	8.165.972	8.677.584	9.189.196
CO2 Avoided by Burning BH2		631.823	810.102	988.381	1.166.659	1.344.938	1.523.217	1.632.320	1.741.423	1.850.526	1.959.629
CO2 Avoided by bH2 Sales		1.484.260	1.305.981	1.127.702	949.423	771.145	592.866	483.763	374.660	265.557	156.454
Total CO2 Reduced		2.116.083	2.116.083	2.116.083	2.116.083	2.116.083	2.116.083	2.116.083	2.116.083	2.116.083	2.116.083
Cummulative CO2 Reduced		2.116.083	4.232.166	6.348.249	8.464.332	10.580.414	12.696.497	14.812.580	16.928.663	19.044.746	21.160.829
Fossil Fuel Phase Out		42,9	39,6	36,3	32,9	29,6	26,2	22,9	19,6	16,2	12,9

	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Reference Scenario											
CO2 Emissions PoR Refinery HTH	2,7	2,6	2,6	2,5	2,5	2,4	2,3	2,3	2,2	2,1	2,0
Energy Demand	**2040**	**2041**	**2042**	**2043**	**2044**	**2045**	**2046**	**2047**	**2048**	**2049**	**2050**
CHP NG	7,2	7,0	6,9	6,8	6,6	6,5	6,3	6,1	5,9	5,7	5,5
CHP RFG	3,6	3,5	3,4	3,4	3,3	3,2	3,1	3,0	2,9	2,8	2,7
Boiler RFG + NG	5,1	5,0	4,9	4,8	4,8	4,7	4,5	4,4	4,2	4,1	4,0
RFG Combustion	34,7	34,1	33,4	32,8	32,1	31,5	30,6	29,6	28,7	27,7	26,8
Total	50,6	49,6	48,7	47,8	46,8	45,9	44,5	43,2	41,8	40,4	39,1
Total (CHP-NG Excluded)	43,4	42,6	41,8	41,0	40,2	39,4	38,2	37,0	35,9	34,7	33,5
Intervention Scenario											
Linear Climate Target	90%	91%	92%	93%	94%	95%	96%	97%	98%	99%	100%
1990 Emission											
EU / NL CO2 Reduction Target	0,583	0,5247	0,4664	0,4081	0,3498	0,2915	0,2332	0,1749	0,1166	0,0583	0,01
Reduction Needed	2,07	2,08	2,09	2,10	2,11	2,12	2,10	2,09	2,08	2,06	2,04
Blue Hydrogen Ramp Up for Burning	33,85	34,01	34,16	34,32	34,47	34,63	34,40	34,18	33,96	33,74	33,35
Blue Hydrogen Needed	282	283	285	286	287	289	287	285	283	281	278
Installed Capacity	289	289	289	289	289	289	289	289	289	289	289
Residual Hydrogen	6	5	4	3	1	0	2	4	6	7	11
Installed Capacity	9.308.271	9.308.271	9.308.271	9.308.271	9.308.271	9.308.271	9.308.271	9.308.271	9.308.271	9.308.271	9.308.271
Installed Capacity	1063	1063	1063	1063	1063	1063	1063	1063	1063	1063	1063
Installed Capacity	1328	1328	1328	1328	1328	1328	1328	1328	1328	1328	1328
Electricity Needed	837.744	837.744	837.744	837.744	837.744	837.744	837.744	837.744	837.744	837.744	837.744
Natural Gas Needed											
Steam Created											
BH2 MWh	9.700.808	9.745.216	9.789.624	9.834.032	9.878.440	9.922.848	9.859.128	9.795.409	9.731.689	9.667.970	9.557.358
CO2 Avoided by Burning BH2	2.068.732	2.078.202	2.087.672	2.097.143	2.106.613	2.116.083	2.102.494	2.088.906	2.075.318	2.061.729	2.038.141
CO2 Avoided by bH2 Sales	47.351	37.881	28.410	18.940	9.470	-	13.588	27.177	40.765	54.354	77.942
Total CO2 Reduced	2.116.083	2.116.083	2.116.083	2.116.083	2.116.083	2.116.083	2.116.083	2.116.083	2.116.083	2.116.083	2.116.083
Cummulative CO2 Reduced	23.276.912	25.392.995	27.509.077	29.625.160	31.741.243	33.857.326	35.973.409	38.089.492	40.205.575	42.321.658	44.437.740
Fossil Fuel Phase Out	9,5	8,6	7,6	6,7	5,7	4,8	3,8	2,9	1,9	1,0	0,2

Figure I.1: Reference & Intervention Scenario Yearly Energy and Emission Data

Linear Climate Targets are based on existing reduction goals of 55% by 2030, 90% by 2040, and 100% by 2050, using 1990's emissions of 5,9 Mtpa as a baseline. The reduction target for intermediate years is linearly extrapolated.

The reduction target is calculated by applying the linear percentage to the 1990 baseline emissions of 11 Mtpa.

The required reduction is calculated as the difference between the reduction target and the BAU emissions. This needed reduction is back calculated using the RFG and NG emission factors to determine the amount of energy that needs replacement. Based on this energy information the needed hydrogen equivalent can be calculated.

The required blue hydrogen in ktonnes that is needed to reach decarbonisation targets, can be calculated by using the LHV conversion factor of 8.33 GJ/kg. Installed capacity is based on the maximum hydrogen required.

The biggest amount of hydrogen needed in a particular year determines the total production capacity. This capacity will be utilized from when the project starts.

The Residual hydrogen is calculated by subtracting the hydrogen demand for refinery decarbonization from the total installed capacity.

The total produced hydrogen in MWh is calculated by converting the installed capacity using a conversion factor of 97.5% Hydrogen fuel spec and a conversion rate of 31 kg/MWh. This conversion rate be found in appendix H.

The total installed capacity in MWth is calculated by dividing the total MWh per year by the annual operating hours of 8760 hours.

MW installed capacity is calculated by dividing the MWth demand by the efficiency of the Auto-Thermal Reforming (ATR) process.

MWh of natural gas demand is calculated by dividing the hydrogen production by the ATR efficiency.

Electricity demand is calculated using a conversion factor of 0.09 MWh electricity per MWh hydrogen output.

CO_2 avoided by burning hydrogen in refineris is calculated based on the CO_2 reduction achieved by substituting NG with hydrogen, using the CO_2 emission factors of Natural Gas and Refinery Fuel Gas. This total avoidance is needed to achieve the decarbonisation targets for purely high temperature heat emissions. For CO_2 avoided by sales, the amount of sold hydrogen is calculated based on the CO_2 emissions that would have been produced if Natural Gas had been used instead.

J

Natural Gas - CO2 - Electricity Price Sets

	CO2 ETS Low	CO2 ETS Mid KEV	CO2 ETS High	Dutch CO2 Levy	CO2 WLO 2 Degree	Electricity KEV	Grid Intensity	Natural Gas KEV
	Euro/Tonne CO2	*Euro/Tonne CO2*	*Euro/Tonne CO2*	*euro/tonne CO2*	*Euro/Tonne CO2*	*Euro/MWh*	*tonne/MWh*	*Euro/MWh*
2020	€ 24	€ 30	€ 36		€ 195	€ 26	0,00	€ 17
2021	€ 35	€ 44	€ 53		€ 204	€ 38	0,00	€ 41
2022	€ 46	€ 58	€ 70		€ 214	€ 50	0,00	€ 45
2023	€ 58	€ 72	€ 86		€ 224	€ 78	0,30	€ 49
2024	€ 69	€ 86	€ 103	€ 74	€ 235	€ 82	0,27	€ 53
2025	€ 80	€ 100	€ 120	€ 87	€ 246	€ 86	0,25	€ 57
2026	€ 84	€ 105	€ 126	€ 100	€ 258	€ 90	0,25	€ 55
2027	€ 89	€ 111	€ 133	€ 112	€ 271	€ 95	0,16	€ 54
2028	€ 93	€ 117	€ 140	€ 125	€ 284	€ 100	0,16	€ 52
2029	€ 98	€ 122	€ 146	€ 138	€ 297	€ 105	0,13	€ 50
2030	€ 102	€ 128	€ 153	€ 150	€ 312	€ 110	0,09	€ 49
2031	€ 109	€ 136	€ 163	€ 163	€ 322	€ 115	0,08	€ 49
2032	€ 115	€ 144	€ 172	€ 176	€ 334	€ 121	0,07	€ 49
2033	€ 121	€ 152	€ 182	€ 181	€ 346	€ 127	0,06	€ 49
2034	€ 128	€ 160	€ 192	€ 186	€ 358	€ 133	0,05	€ 49
2035	€ 134	€ 168	€ 201	€ 191	€ 370	€ 140	0,04	€ 49
2036	€ 141	€ 176	€ 211	€ 196	€ 384	€ 147	0,04	€ 49
2037	€ 147	€ 184	€ 220	€ 201	€ 397	€ 154	0,04	€ 49
2038	€ 153	€ 192	€ 230	€ 201	€ 411	€ 162	0,03	€ 49
2039	€ 160	€ 200	€ 240	€ 201	€ 426	€ 170	0,03	€ 49
2040	€ 166	€ 208	€ 249	€ 201	€ 441	€ 179	0,03	€ 49
2041	€ 173	€ 216	€ 259	€ 201	€ 456	€ 184	0,03	€ 49
2042	€ 179	€ 224	€ 268	€ 201	€ 472	€ 189	0,02	€ 49
2043	€ 185	€ 232	€ 278	€ 201	€ 489	€ 194	0,02	€ 49
2044	€ 192	€ 240	€ 288	€ 201	€ 506	€ 199	0,02	€ 49
2045	€ 198	€ 248	€ 297	€ 201	€ 524	€ 204	0,02	€ 49
2046	€ 205	€ 256	€ 307	€ 201	€ 542	€ 209	0,02	€ 49
2047	€ 211	€ 264	€ 317	€ 201	€ 562	€ 214	0,02	€ 49
2048	€ 217	€ 272	€ 326	€ 201	€ 581	€ 219	0,01	€ 49
2049	€ 224	€ 280	€ 336	€ 201	€ 602	€ 224	0,01	€ 49
2050	€ 230	€ 288	€ 345	€ 201	€ 623	€ 229	0,01	€ 49

Figure J.1: Model Price-Sets - 2023 Price Level

K

Hydrogen Price Forecast

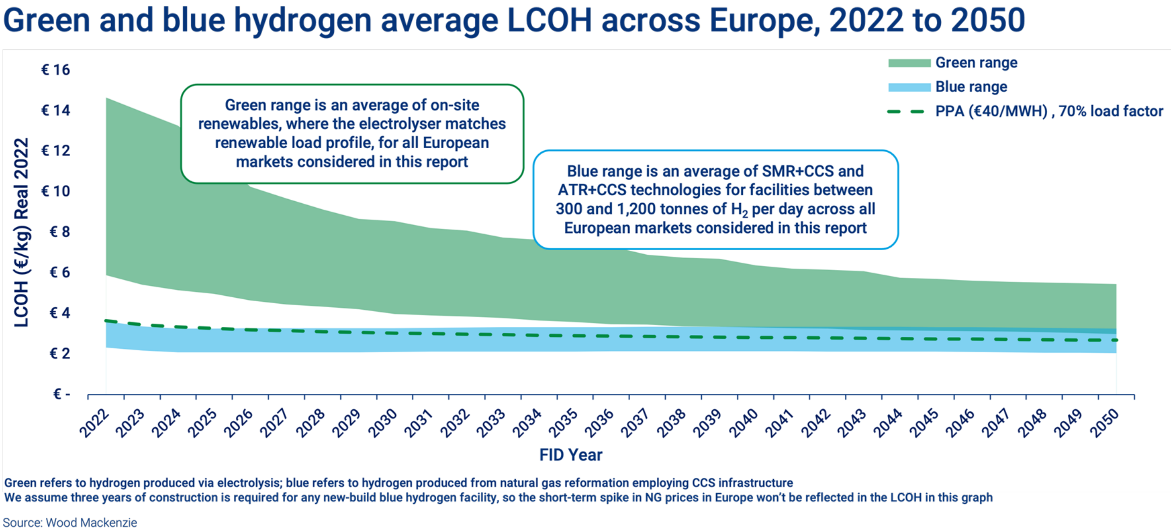

Figure K.1: LCOH of Green and Blue Hydrogen Across Europe Wood Mackenzie, 2024b

L

Free Allowances Phasing

Years	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
FA Phase out	100%	100%	100%	100%	100%	100%	88%	88%	86%	83%	79%	68%	45%	34%	23%	12%	0%

Table L.1: FA Phase Out Over Years

M

Calculated Model Blue Hydrogen Price

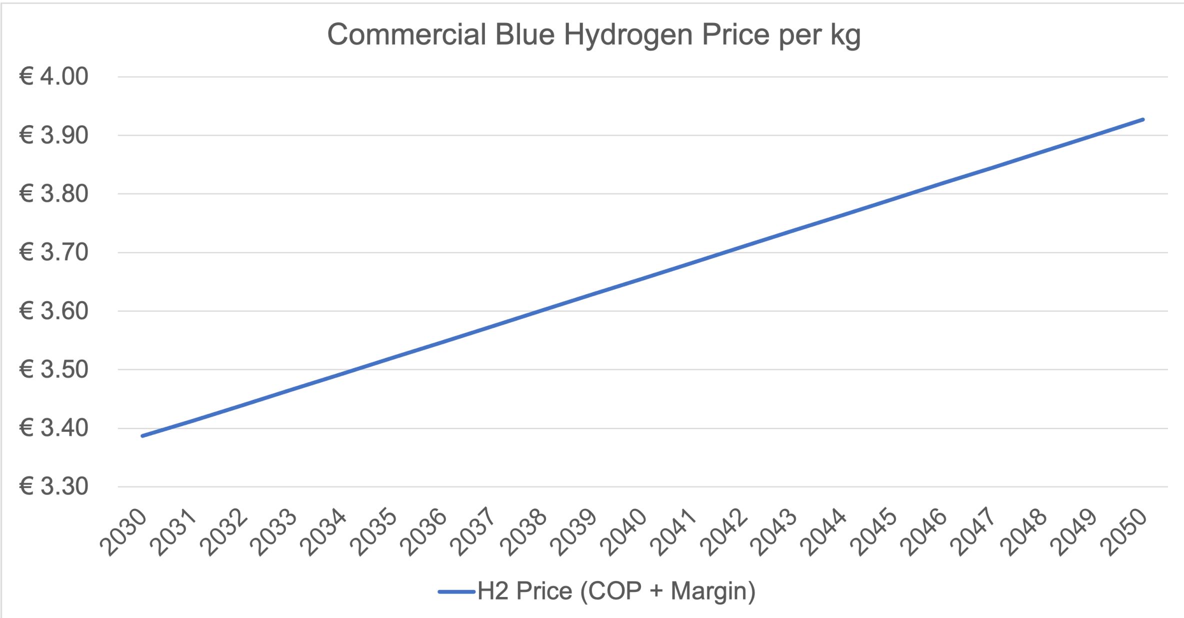

Figure M.1: Commercial Blue Hydrogen Price - Cost of Production (COP) + Margin