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Exploring opportunities and challenges regarding Carbon Capture and Storage in hydrogen production (blue hydrogen) in the Netherlands, A SWOT analysis

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List of Abbreviations

GHG	Greenhouse Gas
CO_2	Carbon Dioxide
CC(U)S	Carbon Capture (Utilization) and Storage
CBAM	Carbon Border Adjustment Mechanism
CTBO	Carbon Talk Back Obligation
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
SDE++	Stimulation of Sustainable Energy Production and Climate Transition
SWOT	Strengths, Weaknesses, Opportunities, Threats
EU ETS	European Union Emission Trading System
SMR	Steam Methan reforming
GWI	Global Warming Impact
RES	Renewable Energy Sources

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Abstract

This master thesis investigates the opportunities and challenges associated with Carbon Capture and Storage (CCS) in hydrogen production the so-called blue hydrogen in the Netherlands. Employing a comprehensive SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis, the study aims to identify and analyze the complexities surrounding the promotion of blue hydrogen in the Dutch context.

The research methodology combines an in-depth literature review with interviews involving specialists, particularly those engaged with ongoing blue hydrogen projects in the Netherlands like Porthos. By integrating insights from literature and stakeholder interviews, the study provides a holistic understanding of opportunities, challenges, and recommendations related to blue hydrogen initiatives in the Dutch context.

The research identifies significant opportunities for blue hydrogen, such as its cost-effectiveness in mitigating greenhouse gas (GHG) emissions in a large-scale, among other opportunities. However, despite the Dutch government's proactive approach addresses previous barriers to CCS implementation, creating a favorable environment for blue hydrogen initiatives, public perception has been found a thread toward successful implementation of blue hydrogen projects. While the study highlights the crucial role of blue hydrogen in meeting national climate targets, it also emphasizes the need for transparent communication about blue hydrogen's sustainability to gain public and investor support.

Recommendations include establishing a fit-for-purpose engagement plan for all stakeholders involved in a specific project, early engagement with potential CO_2 pollutants in each cluster for the sake of efficiency and scalability, exploring opportunities for CO_2 network expansion, exploring opportunities to establish regulations to address the issue of ambiguity around sustainability of blue hydrogen and carbon lock-in associated with investment on fossil fuel-based initiatives, advancing capture technology and improving energy-intensity of CCS. The study acknowledges limitations in the selection process of interviewees and time constraints and suggests future research directions to address these gaps.

Keywords:

Hydrogen production, blue hydrogen, CCS, low-emission hydrogen, opportunities and challenges, environmental impact, public perception, carbon lock-in

Chapter 1: Introduction

1.1. Background

The Paris agreement, adopted in 2015, sets a global target of keeping the temperature rise below 2°C, and preferably to 1.5°C, compared to pre-industrial levels (Scheepers et al., 2022). This target can only be achieved through significant reductions in national greenhouse gas (GHG) emissions (the so-called Nationally Determined Contributions), which must add up to the required global reduction (Schleussner et al., 2016).

In this context, the Netherlands has initiated an energy transition to meet its European and international commitments. To be more specific, the legally binding Climate Act (Rijksoverheid, 2019), in line with the Paris agreement and European Green Deal, set out specific targets to reduce GHG emissions such as carbon dioxide (CO_2) by 49% by 2030, and 95% by 2050 compared to the 1990 level (Dutch government, 2019; Scheepers et al., 2022). The targets are specified in Climate Act, while the non-binding public-private Climate Agreement (Dutch government, 2019) outlines the roadmap towards sustainability goals in the Netherlands (Akerboom et al., 2021a).

Carbon Capture and Storage or Sequestration (CCS[1]) plays a crucial role in the Climate Agreement, offering potential annual emission reductions of up to 7.2 Mt until 2030 (Akerboom et al., 2021a; Dutch government, 2019). CCS is a technology designed to separate, transport, and permanently store CO_2 underground, preventing its release into the atmosphere (Budinis et al., 2018). One of the application of CCS mentioned in the Climate Agreement is in hydrogen production to make the process less carbon intensive (Dutch government, 2019).

As of 2020, the overwhelming majority of globally produced hydrogen (96%) was originated from fossil fuels, commonly referred to as grey hydrogen which has been responsible for emitting around 830 and 900 million tons per year of CO_2 by 2020 and 2021, respectively (Kouchaki-Penchah et al., 2023; Kumar & Lim, 2022; Mosca et al., 2020).

CCS can be deployed to grey hydrogen production (see Figure 1) to capture part or most of carbon dioxide emitted during the production process - based on the level of capture rate - to make the process less carbon intensive. The process of hydrogen production from fossil fuels

[1] In this research, CCUS covers the capture of carbon dioxide for both utilization (CCU) and storage (CCS), including situations where CO2 is both employed and stored, such as in enhanced oil recovery or the production of building materials, provided that some or all of the CO_2 is permanently stored.

equipped with CCS is so called “Blue Hydrogen” (Dickel, 2020; Incer-Valverde et al., 2023; Svendsen et al., 2011).

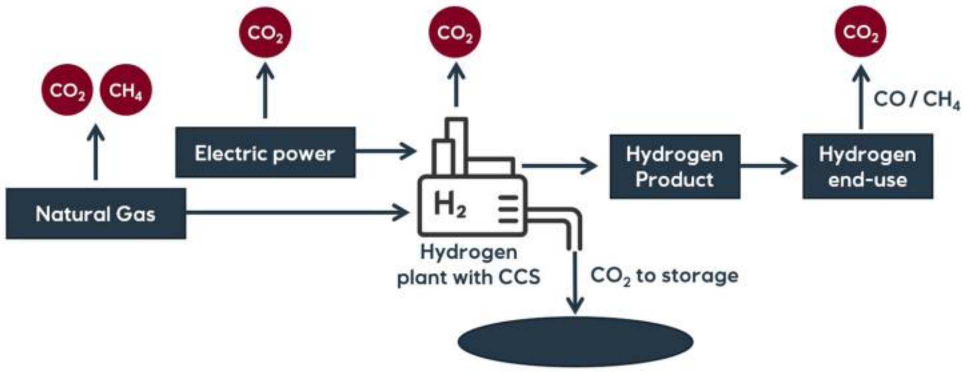

Figure 1 - Blue hydrogen production chain (Pettersen et al., 2022)

Blue hydrogen share was less than 1% of total hydrogen production by 2021 (D. D. IEA, 2021; Kouchaki-Penchah et al., 2023).

Nevertheless, the other main potential alternative source for grey hydrogen is green hydrogen. Green hydrogen is regarded as hydrogen produced through electrolysis process given that the electrolysis facility is powered by renewable energies (Kumar & Lim, 2022; Razi & Dincer, 2022). Notably, there is zero GHG emissions associated with green hydrogen production which makes it a truly sustainable way of hydrogen production (Incer-Valverde et al., 2023).

Beside green hydrogen as truly sustainable way of hydrogen production, blue hydrogen is widely acknowledged as one of the main primary sources of low-emission hydrogen to be an alternative for grey hydrogen (Durakovic et al., 2023; Dutch government, 2019; IEA, 2021, 2023a; IPCC, 2015; Noussan et al., 2021). The International Energy Agency (IEA) has emphasized that blue hydrogen can effectively reduce emissions by approximately 50% compared to grey hydrogen. This reduction can be achieved with a relatively modest increase in production costs of around 18% (IEA, 2023c).

In recent years, there has been a notable surge in the momentum of CCS application particularly in blue hydrogen production, supported by the Dutch government (Rohith Nair et al, 2022). One significant step was witnessed in the years 2021 and 2022 with the incorporation of CCS technology into the Stimulation of Sustainable Energy Production and Climate Transition

(SDE++) subsidies (Netherlands Enterprise Agency, 2021, 2022). This strategic move represents a departure from the previous focus solely on promoting renewable energy sources such as solar and wind. The expanded scope, including CCS alongside existing renewable technologies, reflects a broader commitment to reducing CO_2 emissions by leveraging a diverse set of technologies (Janipour, 2023). The significant emphasis on CCS in current Dutch policies has led to the introduction of several blue hydrogen projects in the horizon, including Porthos, Aramis, H-vision, and others (Akerboom et al., 2021a; Rohith Nair et al, 2022). In Europe, Great Britain with 17 projects and the Netherlands with 8 projects have the largest number of blue hydrogen projects in horizon, forming CCS infrastructure consortia particularly within the refinery sector (Riemer & Duscha, 2023).

1.2. Problem statement

Blue hydrogen as a first-of-a-kind large scale initiative in the Netherlands could face challenges to be successfully implemented.

First challenge could be related to CCS implementation as indispensable part of blue hydrogen initiatives. Historically, CCS projects in the Netherlands faced significant challenges in progressing from the conceptual stage to actual operations. So far, three CCS projects (Barendrecht CCS project, Nothern Netherlands CCS initiative, and ROAD project) have been proved to be unsuccessful in the Netherlands around a decade ago. Technical, economic, legal, and societal resistance are among obstacles along the way (Akerboom et al., 2021b). Due to mainly social resistance, there has been a notable shift in CO_2 storage from onshore locations to offshore ones in the Netherlands (Akerboom et al., 2021b).

Moreover, the uncertainty surrounding the decarbonization potential of blue hydrogen, as indicated in certain studies (Howarth & Jacobson, 2021; Pettersen et al., 2022; Riemer & Duscha, 2023) coupled with the potential carbon lock-in effect resulting from investments in fossil-fuel-based assets (Unruh, 2000), could add to the complexity of blue hydrogen's challenges to achieve social and governmental support to be successfully implemented in the Netherlands (Janipour et al., 2020; Janipour et al., 2021).

As previously noted, the Dutch government has propelled blue hydrogen initiatives forward, with some projects currently in their conceptual design and early stages of development. However, the challenges and opportunities associated with their successful implementation have not received adequate attention in existing literature to date, which is crucial for understanding and navigating the complexities surrounding the successful implementation of blue hydrogen projects in the country. To address this gap, it is essential to thoroughly investigate the opportunities and challenges associated with blue hydrogen initiatives in the Netherlands. The purpose of this research is to identify the strengths, weaknesses, opportunities and threats (SWOT analysis) regarding the blue hydrogen initiatives in the Dutch context.

1.3. Research objective

The aim of this research is to find out the opportunities and challenges regarding CCS in hydrogen production (blue hydrogen) in the Netherlands. By conducting a comprehensive SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis, this study intends to identify and analyze the challenges and opportunities associated with the promotion of blue hydrogen in the Dutch context. The ultimate goal is to provide informed recommendations that guide future developments and decision-making in the context of blue hydrogen in the Netherlands.

1.4. Research main question

What are the opportunities and challenges associated with the CCS application in hydrogen production (blue hydrogen) in the Netherlands?

1.5. Research sub questions

- What are the specific strengths and weaknesses associated with the CCS application in hydrogen production (blue hydrogen) in the Netherlands?
- What are the opportunities and threats related to the blue hydrogen initiatives in the Netherlands?

Chapter 2: Literature Review

This chapter illustrates the primarily research regarding various aspects essential to understanding opportunities and challenges associated with the blue hydrogen initiatives in the Netherlands.

While some parts of this literature review delve into global perspectives on opportunities and challenges related to CCS technology and subsequently the blue hydrogen initiatives, it is essential to recognize that the Netherlands operates within the broader global context. Even though specific information and literature regarding blue hydrogen promotion in the Netherlands may be limited in certain areas, the inclusion of global insights serves a purpose. By exploring the wider discourse, valuable insights can be achieved into potential barriers and opportunities that may impact the Netherlands's endeavors in blue hydrogen initiatives. In other words, these parts aim to shed light on the international landscape of CCS and its application in hydrogen production (blue hydrogen), providing a foundation for understanding potential challenges and opportunities that are transferable to the Dutch context.

As CCS is an indispensable element of blue hydrogen initiatives, the exploration begins with a comprehensive overview of the barriers and opportunities influencing the implementation of CCS within the Dutch context.

The chapter further explores the uncertainty regarding the decarbonization potential of blue hydrogen in the existing literature. This allows for a focused exploration, addressing the significant attention this uncertainty has received in the literature. Although no literature found specifically mentioned this uncertainty in the Netherlands, it found to be relevant to bring about this discussion here.

2.1. Barriers of CCS implementation in the Netherlands

The progress of CCS has failed to gain significant momentum globally over the past two decades including in the Netherlands (Hendriks & Koornneef, 2014; IPCC, 2018). This lack of momentum, despite the dominant presence of CCS in three out of four Net Zero Emission (NZE) scenarios in the Intergovernmental Panel on Climate Change (IPCC) report on global warming (Akerboom et al., 2021a, 2021b; IPCC, 2018), can be attributed to the following main factors: public perception, a lack of political will and clear regulatory framework, a lack of a sound business case and governmental support, and uncertain environmental impact of CCS technology in the long term in the Netherlands (Akerboom et al., 2021a; Ashworth et al., 2012; Ashworth et al., 2013; Boyd et al., 2017; Curry, 2004; Hendriks & Koornneef, 2014).

2.1.1. Public perception

Several studies have delved into public perceptions that may promote or hinder the successful implementation of CCS and argued that a critical enabler for the deployment of CCS is receiving public support for the technology (Ashworth et al., 2009; Ashworth et al., 2012; Ashworth et al., 2013; Boyd et al., 2017; Curry, 2004; Kuijper, 2011; van Os et al., 2014).

The social resistance has also been flagged in some studies mentioning it as a major barrier in CCS deployment in the Netherlands (Akerboom et al., 2021a; Ashworth et al., 2012; Brunsting et al., 2011; Hendriks & Koornneef, 2014; Kuijper, 2011; van Os et al., 2014). For example, the first onshore CCS project in the Netherlands has put on hold due to the social resistance in Barendrecht in 2008 after critical questions have been raised regarding safety issues and potential negative impacts on human health and the environment (Ashworth et al., 2012). At the same time, earthquake incidents resulting from the extraction of natural gas from subsurface reservoirs occurred in proximity to Groningen. In this regard, media have turned CO_2 blowouts from underground sources into frightening stories (Feenstra et al., 2010). Finally, due to concerns about the upcoming general election for a new Parliament, political support for the project diminished, resulting in the cancellation of the Barendrecht project in 2010 (Akerboom et al., 2021a; Ashworth et al., 2012; Brunsting et al., 2011; Kuijper, 2011). Communication inadequacies between stakeholders and communities have also been recognized and presented as instructive lessons for developers of future CCS projects (Feenstra et al., 2010; Lockwood, 2017).

In light of the Barendrecht project's failure, Brunsting et al. (2011) present a set of recommendations to enhance stakeholder involvement in future CCS endeavors. The authors emphasize the need for initiating meaningful conversations involving diverse stakeholders to collect insights into opinions on energy solutions like CCS. Furthermore, they advocate for early engagement of stakeholders in the process to ensure a comprehensive consideration of varying perspectives. A central aspect highlighted by Brunsting et al. is the initiation of dialogues that acknowledge and respect each participant's identity, values, knowledge, and perspectives regarding CCS. Additionally, the authors stress the importance of promoting transparency concerning both the costs and benefits associated with CCS initiatives (Brunsting et al., 2011).

2.1.2. The lack of political will and clear legal framework

There was substantial global momentum for CCS projects during the period 2005 to 2010, and this trend was also evident in the Netherlands. The national government and Northern provinces had ambitious plans for CCS during this time. However, following the Dutch national election in 2010 and the provincial election in 2011, there was a significant shift in the political stance on CCS (van Os et al., 2014). The newly elected national government prioritized nuclear energy over CCS, considering it a more cost-effective means to achieve policy goals, particularly in reducing CO_2 emissions. Additionally, the policy objectives advocated for alternative uses for depleted gas fields, such as Underground Gas Storage (UGS). This highlighted the importance of the political will for a realization of CCS projects in the Netherlands (van Os et al., 2014).

The absence of clear regulatory framework mentioned as another barrier to large-scale CCS implementation in the Netherlands (Hendriks & Koornneef, 2014). The other project at around the same time as Barendrecht project - Northern Netherlands CCS initiative - was also cancelled short after its announcement. Despite public resistance being a concern, the project's failure was attributed to an inadequate legal and governance framework (Hendriks & Koornneef, 2014; van Os et al., 2014). The selection of storage locations for both the Barendrecht and Northern Netherlands CCS projects demonstrated a top-down-oriented approach dictated by the Dutch government decisions. In this approach, according to the Mining Act which governs all subsurface activities in the Netherlands, the Minister of Economic Affairs bears accountability while lower tiers of government and local residents possess restricted or no influence. This approach limited the influence of lower tiers of government and local residents, contributing to perceptions of unfairness and a lack of transparency in the location selection process. Consequently, this legal and regulatory ambiguity resulted in negative attitudes among citizens in the host communities (van Os et al., 2014).

As a result of cancellation of two projects, the approach was shifted from onshore storage to offshore storage in response to the recognition that implementing CCS in a densely populated country like the Netherlands is not merely an engineering challenge, but involves public resistance challenges (Akerboom et al., 2021a).

2.1.3. The lack of a sound business case and governmental support

The financing structure for CCS projects has also been unclear or inadequate, deterring potential investors and stakeholders from committing to the development and deployment of CCS technologies in the Netherlands (Hendriks & Koornneef, 2014). The third CCS project in the Netherlands, the ROAD project, regarding coal-fired power generation in conjunction with CCS was also failed due to the lack of financial clarity, the absence of political support and a sustainable business case (Akerboom et al., 2021a).

To more specific, the lack of governmental subsidies along with the low prices in the European Union Emission Trading System (EU ETS) failed to sufficiently motivate CCS projects, making them economically unattractive to investors. The fundamental challenge lies in the discrepancy between the costs associated with establishing a CCS value chain and the alternative option of paying a CO_2 price within the ETS (Golombek et al., 2023). While cost estimates vary across sources and sectors (Rubin et al., 2015), it is crucial to highlight that even the most conservative estimate of the overall expenses for capture, transportation, and storage exceeds the historical average annual prices within the EU ETS (Golombek et al., 2023).

2.1.4. Uncertain environmental impact of CCS technology

The reasons to hinder CCS development further include concerns such as CO_2 leakage, environmental contamination, underground contamination, and ambiguity regarding the net environmental effect of the CCS technology in the long-term (Akerboom et al., 2021a; Ashworth et al., 2009; Boyd et al., 2017; Oltra et al., 2010; Palmgren et al., 2004; Sharp et al., 2009).

From the perspective of experts, one of the potential negative impacts of CCS could be "the failure of geological sequestration schemes, "which may result in disruptions to biogeochemical processes and marine biodiversity in case of huge leakage (J Blackford et al, 2009). In the event of geological leakage, a substantial amount of stored CO_2 may find its way back into the atmosphere. A study investigated the tolerance for geological leakage among four stakeholder groups, namely industry, policymakers, environmental NGOs, and the public. The study highlighted the risk of geological leakage and concluded that "Zero is the only acceptable carbon leakage rate" (Ha-Duong & Loisel, 2009, p. 312).

The long-term environmental impact of CCS technology is a topic of ongoing study and debate. While CCS has the potential to contribute to net negative emissions by removing CO_2

from the atmosphere, there are also concerns about its environmental effects. A comprehensive comparison of the environmental impacts of CCS technologies has been presented in a study (Cuéllar-Franca & Azapagic, 2015). The study highlights that CCS technologies are assumed to play a central role in helping Europe achieve significant reductions in domestic GHG emissions by 2050. However, it also emphasizes the importance of understanding the trade-offs associated with these technologies, as the implementation of CCS could lead to increased emissions of certain air pollutants. Furthermore, the energy required to operate some carbon removal technologies, including CCS, may lead to increased pollution near the sites where they are deployed (Burtka, 2023).

In summary, while CCS has the potential to contribute to climate change mitigation by removing CO_2 from the atmosphere, there are concerns about its underground leakage and contamination, energy requirements for running CCS, and potential increases in certain air pollutants.

2.2. Opportunities of CCS implementation

While recognizing the challenges that hinder the implementation of CCS in the Netherlands, there exist promising opportunities for CCS to significantly contribute to reducing industrial emissions that aligns with the climate targets by 2050 (Hendriks & Koornneef, 2014).

These opportunities include CCS contribution to a just energy transition through cost-effectiveness of CCS (Dutch government, 2019; Hendriks & Koornneef, 2014; Janipour et al., 2021) along with preserving jobs in the fossil fuels-based industry and job creation in the development of CCS (Janipour et al., 2021), and the lack of scalable renewable alternatives in some sectors such as hydrogen production to supply the current demand (Ashworth et al., 2009; Boyd et al., 2017).

2.2.1. Just energy transition

The fundamental concept of a just transition revolves around connecting environmental objectives with social and economic development goals. The idea of the just transition has arisen due to the recognition of insufficient consideration for social justice in the transition towards a low-carbon future (Jasanoff, 2018).

In regards to a just energy transition, CCS favours this main argument that it provides a cost-effective transition pathway for rapidly and significantly reducing CO_2 emissions, exceeding what could be achieved by alternative methods such as electrification and renewable fuels in the near future (Ajanovic et al., 2022; Akerboom et al., 2021a; Al-Qahtani et al., 2021).

Without CCS, other scenarios become prohibitively expensive (IEA, 2017; IEA, 2011; IPCC, 2018; Janipour et al., 2021). For example, the Intergovernmental Panel on Climate Change (IPCC) has estimated that the cost of reducing CO_2 without CCS would rise by a substantial 138% between 2015 and 2100 (IPCC, 2015). IEA has also forecasted that the cost of mitigation would rise by an additional 40% by 2050 if CCS is not included (IEA, 2006). This indicates that CCS deployment as a cost-effective method including its application in hydrogen production could contribute to a just energy transition decreasing financial burdens for end-users (Janipour et al., 2021).

Additionally, proponents of CCS argue that it has the potential to safeguard employment in the fossil fuel industry while simultaneously generating new jobs in CCS development (Janipour et al., 2021; Patrizio et al., 2018; Swennenhuis et al., 2020). This dual impact is seen as a positive contribution to a just and orderly transition. For example, a study conducted in Norway focused on potential CCS value creation and employment, aligning with CCS scenarios consistent with IEA and IPCC climate projections and examined the industrial opportunities and employment outlook associated with large-scale CO_2. The findings indicated the potential to secure 80,000 to 90,000 jobs in the process industry, natural gas, natural gas to hydrogen operations, and shipping by 2050. Additionally, it suggested the creation of between 160,000 and 200,000 jobs in a Norwegian CCS industry and related businesses offering products and services to the industry (Størset et al., 2019; Størset et al., 2018).

Furthermore, CCS can be pivotal in creating a level global playing field for industries, preventing carbon leakage. This ensures that industrial activities remain within regions with strong climate policies, like the EU, rather than relocating to areas with less stringent climate regulations (Janipour et al., 2021; Swennenhuis et al., 2020). However, it’s important to note that financial support would be necessary to address the additional costs associated with implementing CCS (Janipour et al., 2021).

2.2.2. The lack of scalable renewable alternatives in hydrogen production

Utilizing CCS in some industrial sectors like hydrogen production becomes a compelling option due to the absence of a readily scalable renewable alternative like green hydrogen (Lagioia et al., 2023). In fact, the widespread application of green hydrogen has been impeded by technical and infrastructure barriers both in terms of performance factors and the availability of renewable energy. To be more specific, predominant share of globally produced hydrogen (96%) relies on fossil fuels (grey hydrogen), while green hydrogen accounts for only 4% of the hydrogen supply as of 2020 (Hermesmann & Müller, 2022; Kumar & Lim, 2022; Mosca et al., 2020).

Given the lack of a scalable renewable alternative, and the reliance of fossil-based hydrogen production in foreseeable future offers a less complex and cost-effective approach to deploy CCS in existing infrastructure for decarbonizing hydrogen production in the short term (Akerboom et al., 2021a; AlHumaidan et al., 2023; Antzaras & Lemonidou, 2022; Lagioia et al., 2023).

2.3. Uncertainty around the decarbonization potential of Blue Hydrogen

The environmental impact of blue hydrogen has been a significant unknown, sparking debates among researchers regarding its entire life cycle assessment in establishing its viability as a low-carbon hydrogen production method (Ajanovic et al., 2022; Bauer et al., 2022; Howarth & Jacobson, 2021; Ishaq et al., 2022). Riemer et al. concluded that the actual decarbonization potential of blue hydrogen in the short to medium term is probably more restricted than what the initially reported (Riemer & Duscha, 2023).

Environmental concerns surrounding blue hydrogen production in the literature can be systematically categorized into distinct factors. First and foremost, there is considerable attention given to upstream and midstream emissions associated with natural gas extraction and transportation, serving as a primary feedstock for blue hydrogen production (Pettersen et al., 2022; Riemer & Duscha, 2023). The extent to which CCS effectively captures emissions at hydrogen plants emerges as a critical aspect, influencing the overall environmental impact (Howarth & Jacobson, 2021; Riemer & Duscha, 2023). Additionally, the energy consumption of CCS facilities stands out as a noteworthy concern, contributing to the evaluation of the technology’s sustainability (Noussan et al., 2021). Finally, the literature underscores the potential carbon lock-in issue stemming from a heavy reliance on natural gas in blue hydrogen production

(Janipour et al., 2020). This structured categorization provides a comprehensive framework for understanding and addressing the multifaceted environmental challenges associated with the production of blue hydrogen.

Blue hydrogen, which predominantly relies on natural gas as feedstock, particularly methane, faces this uncertainty because of upstream emissions so-called fugitive methane emissions during natural gas extraction, and other emissions associated with gas processing and transportation through the energy consumption (Pettersen et al., 2022; Riemer & Duscha, 2023; Timur Gül, 2023). Furthermore, the emissions intensity of the electricity source used to power hydrogen plants with CCS adds to the overall uncertainty in evaluating the viability of blue hydrogen as a truly low-carbon energy product (Pettersen et al., 2022; Riemer & Duscha, 2023).

Bauer et al. demonstrates that the environmental impacts of blue hydrogen production can vary significantly based on the methane emission rate in the natural gas supply chain (upstream and midstream emission), and the CO_2 capture rate at the hydrogen production plant. They suggested that only advanced Steam Methan reforming (SMR) with high CO_2 capture rates, along with a natural gas supply characterized by low methane emissions, enables substantial reductions in GHG emissions compared to conventional natural gas reforming and direct combustion of natural gas. Under these conditions, blue hydrogen aligns with low-carbon economies and exhibits positive contributions to climate change mitigation (Bauer et al., 2022). Howarth and Jacobson came into the same conclusion, emphasizing the significance of upstream and midstream emissions in the production process (Howarth & Jacobson, 2021). Although, the authors showed that GHG emissions from blue hydrogen is lower than grey hydrogen with only a modest reduction of 18%-25%, but it remains higher than those from burning even natural gas per unit of heat energy. They considered the methane and carbon dioxide emissions in the whole life cycle of blue hydrogen production. Then the authors concluded that even with assuming the best-case scenario and best available technologies for blue hydrogen production, and “not consider the energy cost and associated GHG emissions from transporting and storing the captured carbon dioxide” ..., “blue hydrogen has large climatic consequences. We see no way that blue hydrogen can be considered ‘green’ ” (Howarth & Jacobson, 2021, p. 1685).

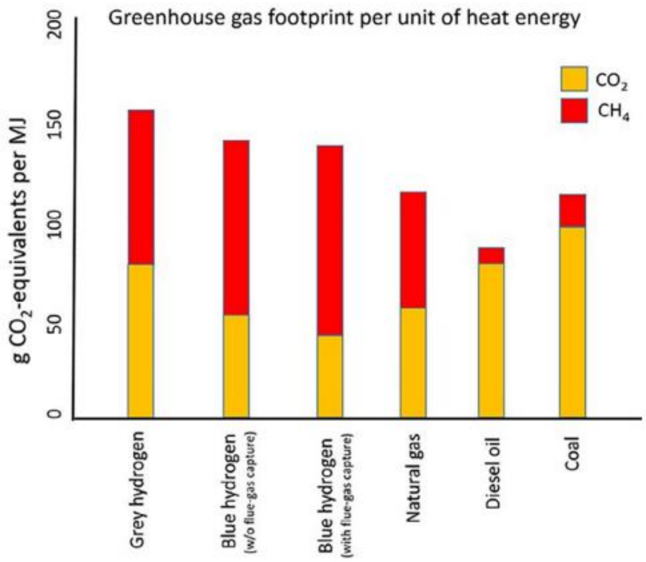

Figure 2 - Comparison of GHG footprint per unit of heat energy for 6 categories. Carbon dioxide emissions, including emissions from developing, processing, and transporting the fuels, are shown in orange. Carbon dioxide equivalent emissions of fugitive, unburned methane is shown in red. The methane leakage rate is 3.5% (Howarth & Jacobson, 2021).

As shown in Figure 2, blue hydrogen with CO_2 capture from both the SMR process and the exhaust flue gases (where the capture rate is either 90% or 93% depending on the technology) exhibits higher upstream methane emissions compared to blue hydrogen without capturing from exhaust flue (60% capture rate). This discrepancy is attributed to the additional natural gas required to operate an extra CCS facility, resulting in increased energy consumption for capturing CO_2 from more diluted flue gases. This increased energy demand, using natural gas as fuel, contributes to the elevated upstream methane emissions in the process (Bauer et al., 2022; Howarth & Jacobson, 2021). In this regard, Noussan et al. showed that the overall process efficiency of SMR, which typically ranges from 60% to 85%, decreases by 5% to 14% when equipped with CCS (Ajanovic et al., 2022; Noussan et al., 2021).

Hermesmann & Müller conducted a comprehensive life cycle assessment of the hydrogen production technologies to identify promising solutions for the evolving energy transition in this field. The study analyzes several hydrogen production technologies, including grey, blue, turquoise[2], and green. The authors demonstrated that the grey hydrogen exhibits the highest impacts in the climate change category across most of the considered countries while in the long

[2] Hydrogen production via methane pyrolysis (MP) which is at the early stage of research and development.

run, green hydrogen, has the potential to become the least environmentally harmful technology following blue hydrogen. However, the reliance on natural gas and the need for long-term CO_2 storage in limited suitable geologic storage sites constrain the long-term viability of blue hydrogen. Then, the authors suggested that blue hydrogen may serve as a valuable bridging technology, facilitating the transition to other sustainable solutions. Furthermore, from an environmental point of view, the authors suggested that nations with low or no immediate need for further reduction in the Global Warming Impact (GWI) of electricity supply, such as Norway and Sweden, may prioritize green hydrogen production technologies. Conversely, countries heavily reliant on non-renewable resources for electricity generation, like Ireland, the Netherlands, and the United Kingdom, might consider implementing bridging technologies or relying on renewable hydrogen imports as an interim solution until their energy transitions progress further. Finally, the authors concluded that choosing the most environmentally friendly method for hydrogen generation will be a trade-off, influenced by geographical and economic constraints. However, the political will to significantly increase the share of Renewable Energy Sources (RES) in the grid mix is crucial for driving the energy transition toward green and sustainable hydrogen production, ensuring economic viability, and protecting the environment (Hermesmann & Müller, 2022).

Carbon lock-in, linked to the development of CCS in fossil-fuel base assets like blue hydrogen, is another major concern among experts that could hinder the deployment of CCS technology in hydrogen production. The argument suggests that by implementing CCS, continued use of fossil fuels may be legitimized, making it challenging to transition away from fossil fuels in the long run (Janipour et al., 2021; Shackley & Thompson, 2012).

All in all, this literature review has explored the complexities of blue hydrogen initiatives in the Netherlands, focusing on the barriers, opportunities and uncertainties associated with CCS deployment along with uncertainty around the blue hydrogen as a truly low-carbon hydrogen production. The analysis underscores the need for effective policies to navigate public perception, political support, and technological challenges. As the Netherlands aims to integrate blue hydrogen into its energy transition, addressing these issues will be pivotal. This foundational understanding sets the foundation for further research, which aims to provide deeper insights into the complexity of blue hydrogen initiatives in the Dutch context.

Chapter 3: Methodology

This chapter explains how the main and sub-questions have been answered. It covers the case selection, research methodology, data collection, data analysis, and the ethical consideration.

3.1. Case selection

The choice of the blue hydrogen initiative within the Netherlands as the primary research unit for this study is strategically justified by the country's prominent position in the emerging field. As indicated by (Riemer & Duscha, 2023), Europe, particularly Great Britain and the Netherlands, leads in the number of blue hydrogen projects, with the Netherlands hosting eight projects. This abundance of projects positions the Netherlands as a crucial focal point for investigating the opportunities and challenges associated with blue hydrogen initiatives, providing a comprehensive understanding of the implications for CCS technology, which is imperative to blue hydrogen production. Therefore, the case selection aligns with the strategic aim of understanding the dynamics and nuances within a region with a substantial concentration of blue hydrogen projects, making it a relevant and insightful context for this research.

3.2. Research methodology

To ensure the comprehensiveness and inclusiveness of the research, the research methodology included in depth literature review in combination of interviews with specialists preferably involved with blue hydrogen projects in the Netherlands namely Porthos[3] project. Most participants were chosen from experts directly engaged in Porthos, given that the project represents a first-of-its-kind large-scale CCS project applied to hydrogen production in the Netherlands. These interviews were useful in gathering knowledge, expert opinions, and detailed perspectives on the blue hydrogen project's strengths, weaknesses, opportunities, and threats.

The first and second sub-questions were answered through a thorough examination of relevant literature. Additionally, insights from interviews with stakeholders involved in Porthos project along with specialists familiar with CCS/Hydrogen initiatives was integrated to provide a comprehensive understanding of opportunities and challenges. This integrated approach, combining literature review and interviews, provided a holistic and well-informed perspective on the dynamics of blue hydrogen initiatives in the Dutch context.

[3] Port of Rotterdam CO_2 Transport Hub and Offshore Storage

Finally, the main research question, "What are the opportunities and challenges associated with the CCS application in hydrogen production (blue hydrogen) in the Netherlands?" was addressed through a comprehensive examination of the literature, SWOT analysis, and interviews.

Table 1 - Methods per research sub-question

Research sub-questions	Required data-information	Source of data-information
What are the specific strengths and weaknesses associated with the CCS application in hydrogen production (blue hydrogen) in the Netherlands?	Strengths and Weaknesses associated with blue hydrogen in the Netherlands	Primary data: Literature review Secondary data: Interviews
What are the opportunities and threats related to the blue hydrogen initiatives in the Netherlands?	Opportunities and Threats related to the promotion of blue hydrogen in the Netherlands	Primary data: Literature review Secondary data: Interviews

3.3. Data Collection

3.3.1. Literature

The primary focus of this study involved gathering primary data by conducting a thorough review of existing literature, utilizing Google Scholar, Scopus, and scientific magazines and websites as databases, and considering only articles in English. To gain an initial understanding of CCS and its application in blue hydrogen production, the following keywords were initially employed: "Hydrogen production", "blue hydrogen", "CCS," and "low-emission hydrogen". As the research progressed, the keywords were refined to include more targeted terms such as "opportunities and challenges regarding blue hydrogen", "CCS: drivers and barriers" and "environmental impact of blue hydrogen".

3.3.2. Interviews

To better address the research's main and sub-questions, information was gathered by talking directly to relevant stakeholders and experts. More specifically, semi-structured interviews were conducted with some key stakeholders directly involved in the first large scale CCS application in hydrogen production (blue hydrogen) in the Netherlands, Porthos project. In addition, experts familiar with CCS/Hydrogen initiatives were also interviewed to gain a comprehensive understanding of the strengths, weaknesses, opportunities, and threats (SWOT) related to the promotion of blue hydrogen in the Netherlands.

The interviews were conducted online through Microsoft Teams due to logistical considerations. This virtual platform allowed for efficient communication and facilitated the inclusion of geographically dispersed participants. The interviews were recorded with participants' consent and were subsequently transcribed for analysis, always adhering to a transparent procedure. Careful consideration was given to selecting a diverse group of participants to ensure a well-rounded perspective on blue hydrogen initiatives. To be more specific, three stakeholders from the Porthos project - Air Liquide, EBN, and Gasunie - were among interviewees. Additionally, experts from RABO Bank's Energy Transition department and CE Delft research center were chosen for their extensive knowledge and experience in CCS and hydrogen production within the Dutch context (Table 2).

Table 2 - List of interviewees and their roles

Interviewee	Role/ Responsibilities
A	Manager, Air Liquide Benelux Industries
B	Porthos Technical Manager Storage Systems, EBN
C	Energy Transition Specialist at Rabobank
D	Porthos Commercial Manager, Gasunie New Energy
E	Manager Energy and Fuels, CE Delft

The interviews were conducted over a two-week period in January 2024, allowing for a thorough exploration of the topics with each participant. While efforts were made to include diverse perspectives, the number of interviews was limited due to time constraints, the availability and willingness of other stakeholders to participate in the interview. Conducting interviews online may have limitations in capturing non-verbal communication and establishing a personal connection.

Open-ended questions were carefully formulated to explore the participants' perspectives on blue hydrogen promotion in the Netherlands, emphasizing the SWOT framework. Questions were designed to get nuanced responses, encouraging interviewees to share their insights and experiences. A detailed list of interview questions can be found in the annex.

3.4. Data analysis using SWOT framework

The SWOT analysis has been chosen as an analytical framework in this research due to its capacity to provide a comprehensive examination of the opportunities and challenges (Puyt et al., 2023) linked to blue hydrogen production within the Netherlands. This analytical framework aligns seamlessly with the research objectives, facilitating a systematic exploration of the strengths, weaknesses, opportunities, and threats associated with blue hydrogen initiatives. Its widespread acceptance and strategic decision-making orientation contribute to its suitability (Hill & Westbrook, 1997), ensuring the research delivers informed recommendations for successful blue hydrogen project's implementation in the Netherlands.

A variety of SWOT analysis methods exist with its own set of advantages and disadvantages, which can be selected based on specific circumstances. However, all these methods serve as strategic planning tools facilitating the identification of strengths (S), weaknesses (W), opportunities (O), and threats (T) within a given model or system (Gurl, 2017).

SWOT analysis method has been frequently applied in energy transition literature to evaluate specific measures like hydrogen promotion, in conjunction with other frameworks such as an institutions, economics, technology, and behaviors (IETB) framework (Pal et al., 2023).

The SWOT analysis is based on internal and external factors or criteria. The internal factors are used to identify strength and weakness for realization of a specific initiative, while external factors can determine opportunities and threats contribute to or pose challenges to that initiative (Figure 3).

Figure 3 - Diagram illustrating the structure of a SWOT Analysis framework (Elavarasan et al., 2020)

The SWOT analysis in this study follows a structured methodology outlined by Gurl (Gurl, 2017). First, both internal and external factors were identified, followed by categorization into strengths, weaknesses, opportunities, and threats. Next, a thorough analysis and assessment of these factors were carried out, leading to the development of strategies based on the findings (Gurl, 2017). To ensure a comprehensive and accurate analysis, the research incorporated a combination of literature review and interviews with companies and experts, recognizing the importance of engaging key stakeholders in the process (Gurl, 2017).

This research aimed to meet its objective through a two-phase data analysis. Initially, the first phase contained scrutinizing primary data obtained from a literature review, and in the subsequent phase, the focus shifted to analyzing secondary data gathered from interviews. The collected information from both the literature review and interviews were assessed by qualitative data analysis.

During the first phase, a literature review was conducted to gather data addressing the first and second research sub-questions. Specifically, the secondary data collected were scrutinized and analyzed to construct a comprehensive SWOT analysis, considering all four dimensions (Strengths, Weaknesses, Opportunities, Threats).

In the second phase, interviews were conducted. The information gathered from these interviews was assessed using content analysis to pinpoint the Strengths, Weaknesses, Opportunities, and Threats linked to the promotion of blue hydrogen in the Netherlands. Content analysis was chosen for the interviews to discover common patterns aligning with the findings from the literature review.

Taking into account all the steps mentioned above, the main research question was addressed. Additionally, recommendations were proposed to achieve successful implementation of blue hydrogen projects in the Dutch context.

3.5. Ethical Considerations

Ethical considerations include obtaining informed consent from interview participants, ensuring data privacy, and maintaining the confidentiality of sensitive project-related information.

Chapter 4: Findings

This chapter presents the findings of literature review and the data obtained from interviews using SWOT analysis. The findings from both the literatures and interviews are collected in this chapter to answer two sub questions and eventually the main research question. Then, these findings have been discussed in detail under the chapter 5 “Discussion”.

While it’s worth noting that some of the findings from literature may not explicitly focused on the Netherlands, it is essential to underscore the global nature of the CCS application in hydrogen production (blue hydrogen). While some literature may not be region-specific, it often highlights universal principles, industry practices, and technological advancements that are transferable. This broader understanding can serve as a foundation for adapting strategies to the specific conditions of the Netherlands. The lack of location-specific studies doesn’t diminish the significance of these insights; instead, it emphasizes the need for a comprehensive, comparative analysis to identify similarities and differences. The findings from the literature that are considered as universal opportunities or challenges for the blue hydrogen initiatives are marked with a star (*) in Table 3 in the following section.

The Table 3 shows a brief overview of the SWOT analysis’s factors identified in this research.

Table 3 - SWOT analysis employed for blue hydrogen promotion in the Dutch industry. The findings from the literature that are considered as universal opportunities or challenges for the blue hydrogen initiatives are marked with a star (*)

Strengths	Weaknesses	Opportunities	Threats
Cost-effectiveness	Environmental concerns*	Contribution to a just and orderly energy transition*	Public perception
Dutch infrastructure Landscape	Carbon Lock-in*	Technological advancement*	
Proven and ready-to deploy CCS technology *		Cross-border hydrogen trade	
		Effective national policy instrument	
		The lack of alternative (s) at scale	
		Market competition*	

4.1. Strengths from literature and interviews

4.1.1. Cost-effectiveness

Blue hydrogen offers a cost-effective pathway for rapidly scaling up the production of low-emission hydrogen while mitigating GHG emissions, which is a critical component of a sustainable energy future (Durakovic et al., 2023; Noussan et al., 2021; Pettersen et al., 2022; Rohith Nair et al, 2022). Specifically, regarding the hydrogen production in the Netherlands, the Ministry of Economic Affairs and Climate predicted that the cost of reducing CO_2 with blue hydrogen would be €250 per ton lower than green hydrogen production by 2030 (Cor Leguijt et al, 2022).

Furthermore, EBN[4] reported that the Dutch government provided approximately 4.5 billion euros in subsidies to various sectors through the SDE subsidy scheme between 2008 and 2019, leading to a reduction of 42 million tons of CO_2 emissions in the atmosphere. The Porthos project as the first large-scale CCS application in hydrogen production (blue hydrogen) expected to capture roughly 37 million tons of CO_2 over 15 years by receiving nearly half of these subsidies through the SDE++, amounting to 2 billion euros (EBN, 2021). These evidence in the literatures underscores the significance of blue hydrogen as a cost-effective pathway for rapidly scaling up low-emission hydrogen production in the Netherlands while remarkably contributing to the national climate target.

All Interviewees emphasis on the cost-effectiveness of blue hydrogen initiatives as a key element to gain significant momentum in the Netherlands. Interviewee A mentioned blue hydrogen presents the most cost-effective method to decarbonize current hydrogen production and poses lower financial risks for investors compared to other alternatives like green hydrogen. "*At the moment, green hydrogen in around three times more expensive than blue hydrogen, Interviewee A says*". Interviewee B pointed out the current advantageous ETS prices for blue hydrogen production in the Netherlands with no need for SDE++ subsidies at the current ETS prices. The high EU ETS price was also seen by interviewee C as relieving for blue hydrogen projects, making them more economically viable for investors without significant additional subsidies.

[4] Energie Beheer Nederland (EBN) is fully owned by the Dutch government.

4.1.2. Dutch infrastructure landscape

The Netherlands is geographically and economically well-suited for implementing CCS particularly in hydrogen production, providing an ideal foundation for the decarbonization of its energy-intensive industries (Rohith Nair et al, 2022; Scheepers et al., 2022). This advantageous positioning is attributed to the following factors:

4.1.2.1 Configuration of industrial clusters

The Dutch industrial sector is characterized by both being energy intensive and geographical concentration within a few key industrial clusters such as Rotterdam-Moerdijk (R-M) cluster, among other five energy clusters (Figure 4). This strategic clustering feature allows for advantageous economies of scale and scope in transportation and carbon capture efforts (Akerboom et al., 2021a; Janipour et al., 2021; Rohith Nair et al, 2022). Additionally, the Netherlands, ranking as the second-largest hydrogen consumer in the EU (Cor Leguijt et al, 2022), possesses a clustered configuration that enhances its attractiveness and cost-effectiveness for CCS applications in decarbonizing hydrogen production. Within the Porthos's project, Air Liquide and Air Products, major hydrogen suppliers for oil refineries such as Shell, ExxonMobil, BP, and others, are strategically located in proximity in the Port of Rotterdam. Additionally, chemical industries that predominantly demand oil products from these oil refineries are also situated in the same cluster, fostering a synergistic relationship within the industrial ecosystem (Rohith Nair et al, 2022).

Some interviewees highlighted the favorable attributes of the industrial cluster configuration in the Netherlands for blue hydrogen production. Interviewee A emphasised the strategic commercial ties between oil refineries as supplier and chemical industry as consumers in Port of Rotterdam. In this regard, Interviewee A predicted that certain strategic refineries in EU – e.g., Shell, ExxonMobile, and BP in the Port of Rotterdam in the Dutch context - are expected to be operational by 2050 or beyond. It was mentioned that this will be required to supply certain industries that still need oil as feedstock such as chemical industry. Recognizing their significance in oil supply, the need to decarbonize hydrogen production in these strategic refineries was stressed to supply their targeted chemical industry in Rotterdam cluster.

Cluster configuration of Dutch energy-intensive industries was also highlighted by interviewees B and C, enhancing the suitability and cost-effectiveness of CCS applications in hydrogen production in the country. However, Interviewee C stated that being part of a cluster could have potential disadvantages related to existing dependencies and the need for harmonious and effective collaboration between all stakeholders.

Interviewee B mentioned that in a densely populated country like the Netherlands with an industrial cluster configuration, it is essential for careful planning of facility locations, considering existing infrastructure and optimizing the placement of CCS facilities, compressor stations, and pipelines. Interviewee B also highlighted the need for early engagement of potential CO_2 emitters to the extent possible to scale-up in CCS operations. According to this perspective, such early engagement can contribute to cost reduction.

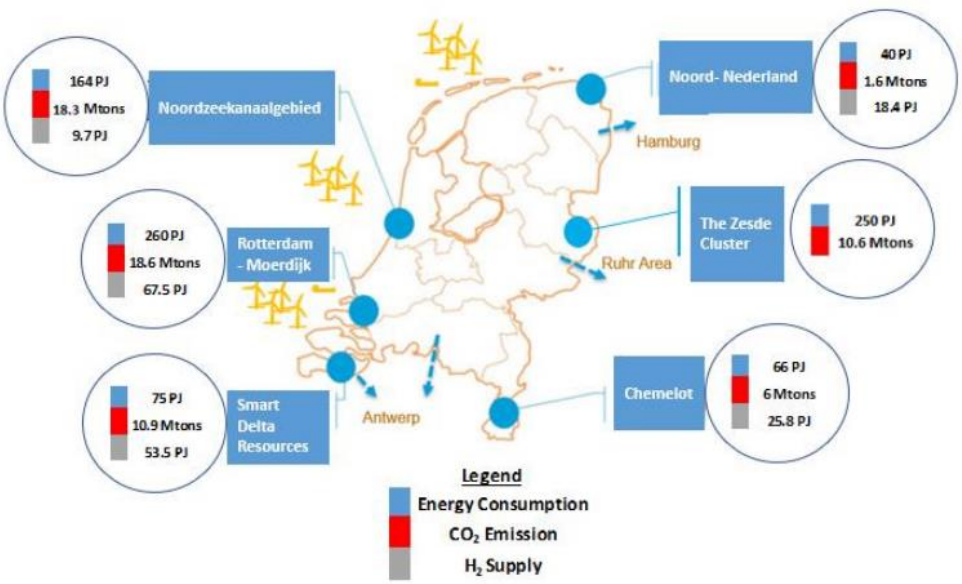

Figure 4 - Overview of six key Dutch industrial clusters: the total industrial emissions of each cluster and their respective hydrogen production capacities (Rohith Nair et al, 2022)

4.1.2.2 Offshore infrastructure and CO_2 capacity storage

The Netherlands is frequently recognized as one of highly favorable locations for carbon storage due to its proximity to the North Sea and the feasibility of storing captured carbon in depleted gas reservoirs (Akerboom et al., 2021a; Durakovic et al., 2023; Rohith Nair et al, 2022). In fact, the ample offshore storage capacity enable strategic planning for the storage of captured carbon, extending to cross-border projects such as CO2TransPorts, which involves the potential

CO_2 storage from Port of Rotterdam, the Port of Antwerp in Belgium and the North Sea port (Rohith Nair et al, 2022).

The offshore CO_2 storage capacity of the Netherlands as a strength for blue hydrogen production was highlighted by all interviewees. Interviewee D mentioned in more technical details that the Netherlands possesses substantial storage capabilities in North Sea, around 2000 megatons, emphasizing its adequacy to decarbonize refineries and industries in the port of Rotterdam. Interviewee D contrasted this with Belgium and Germany, highlighting the strategic positioning of the Netherlands for building a robust value chain regarding blue hydrogen while handle and store 22 megatons per year of CO_2.

The accessibility and proximity of the Port of Rotterdam to depleted reservoirs in North Sea to store CO_2 was also mentioned by Interviewee A as a beneficial cost factor for blue hydrogen production. Interviewee B underscore the significant advantage of existing non-producing oil and gas wells in the North Sea to store captured CO_2. In Interviewee B's view, this is because it eliminates the necessity of drilling new wells for underground CO_2 storage which could end up at a much higher initial cost for blue hydrogen projects.

4.1.3. CCS as a proven and ready-to deploy technology*

Blue hydrogen benefits from the maturity of CCS technology, making its deployment more feasible and "obvious quick win" (Bui et al., 2018). CCS application in fossil fuels has been considered as a proven and ready-to-implement technology to rapidly and massively mitigate GHG emissions from existing fossil fuel assets (Bhave et al., 2017; Kearns et al., 2021).

Among fossil fuel assets, oil and gas companies are at the forefront of CCS deployment, playing a significant role in reducing their emissions while boosting of their value chain, currently account for 90% of the world's operational CO_2 capture and storage capacity (Bui et al., 2018; IEA, 2023a). Therefore, oil and gas companies hold a strategic advantage over other sectors in leveraging CCS for the decarbonization of their existing assets including hydrogen production, thanks to their extensive experience in CCS applications (Bui et al., 2018).

Interviewee D highlighted that the stakeholders involved in the blue hydrogen initiatives in the Netherlands, like Porthos project, are mainly oil and gas companies and state-owned energy organizations, possess this specific advantage in effectively employing CCS technology for blue hydrogen production.

Interviewee A underscored that Carbon Capture Utilization (CCU) technology is currently in use in the Netherlands, emphasising the carbon capture – not storage - is quite mature in the country. Interviewee A also highlighted Air Liquide company employing CCU to capture CO_2, which is subsequently utilized by beverage and greenhouse industries in the country.

4.2. Weaknesses from literature and interviews

4.2.1. Environmental concerns*

The comprehensive life cycle assessment of blue hydrogen production, given current technologies regarding capture rate and energy intensity of CCS along with the absence of regulations addressing upstream and midstream emissions associated with natural gas - the primary feedstock in the SMR process - raises considerable concerns about the viability of blue hydrogen as a genuinely low-emission source of hydrogen production (Durakovic et al., 2023; Howarth & Jacobson, 2021; Pettersen et al., 2022).

None of the interviewees explicitly highlighted the environmental concerns related to the genuine decarbonization potential of blue hydrogen as a weakness of the initiatives in regard to upstream/midstream emissions. In this regard, Interviewee A did not acknowledge the issue, instead highlighted other countries as "free riders" that continue to utilize even coal to produce hydrogen, which poses greater environmental pollution compared to the aims of blue hydrogen initiatives. Interviewee A further emphasized that imposing strict regulations to address upstream and midstream emissions could result in "carbon leakage," potentially leading to the relocation of the hydrogen industry outside the Netherlands. This, in turn, could have adverse economic effects on the country.

In terms on capture rate at the hydrogen power plant, Interviewee B and E, however, highlighted the concern. Interviewee B underscored the necessity for standardization in capturing techniques to ensure the delivery of captured CO_2 with a specific quality. Regarding energy intensity of CCS, Interviewee B emphasized that although CCS leads to more energy consumption through running the CCS facility, the net GHG emission of hydrogen production will be less than current state. Interviewee B also mentioned that using renewable energy sources to run CCS facility could lower the energy intensity in the whole life cycle. Interview E highlighted the challenge of achieving 100% carbon capture in blue hydrogen projects, noting that some projects only achieve around 80% capture.

Leakage concerns related to CO_2 storage, acknowledged from both social and expert perspectives (Akerboom et al., 2021a; Ashworth et al., 2009; Boyd et al., 2017; Ha-Duong & Loisel, 2009; J Blackford et al, 2009; Oltra et al., 2010; Palmgren et al., 2004; Sharp et al., 2009), represent another environmental concern related to blue hydrogen initiatives. This concern is not exclusive to blue hydrogen but extends to any CCS application in general.

The potential for storage or transportation leakage, recognized as a concern in the literature, was not highlighted by most interviewees. Only Interviewee B explicitly recognized this concern, asserting that the risks associated with pipeline or underground leakage are generally of low probability. However, Interviewee B emphasized of risk mitigation through proper material selection and operational procedures. Introducing specific standards for abandoned wells used to store CO_2 was also recommended by Interviewee B to mitigate the potential leakage risk in the long-term storage.

4.2.1. Carbon Lock-in*

The concept of carbon lock-in is a significant concern among researchers in regard to fossil fuel-based facilities (Akerboom et al., 2021a; Janipour et al., 2020; Janipour et al., 2021; Shackley & Thompson, 2012). This concern arises from the potential for investments that prolong the reliance on fossil fuels and maintain the status quo in extracting hydrocarbon resources. Investors in fossil fuel-based industries, including those supporting CCS for blue hydrogen, seek returns on their investments, creating a potential reluctance to shift towards truly clean technologies such as green hydrogen. Aside from the risk of diverting funds away from green hydrogen investments as the final goal in regard to hydrogen production in the Netherlands (Dutch government, 2019), blue hydrogen promotion could also result in fossil fuel facilities becoming stranded assets in the long run. As green hydrogen matures and fossil fuel usage declines, investments in blue hydrogen may lead to a scenario where these facilities become obsolete and economically unviable (Janipour et al., 2020; Janipour et al., 2021).

Carbon lock-in issue as a potential threat and implications associated with blue hydrogen promotion in the Netherlands has not been raised by the majority of interviewees. Only Interviewee C, mentioned one of the possible implications of carbon lock-in and emphasized that as the cost of green hydrogen is expected to decline, investments in fossil fuel-based supply chains, especially long-term assets, may become stranded.

4.3. Opportunities from literature and interviews

4.3.1. Contribution to a just and orderly energy transition*

In the context of the just energy transition, the potential of CCS – including its application in blue hydrogen production – is to enable the ongoing use of fossil fuels without the need to dismantle existing infrastructure and social systems. This approach helps mitigate substantial economic and social costs while simultaneously addressing the challenges of climate change (Clark, 2015; Spreng et al., 2007). This contribution to a just energy transition through preserving existing fossil fuel assets in the Netherlands was also emphasized in the study by Janipour et al., citing potential benefits in terms of employment preservation, economic growth, and environmental impact (Janipour et al., 2021).

As highlighted by Interviewee A, blue hydrogen can address the challenge of decarbonizing relatively young age of existing hydrogen production plants in the Netherlands at cheapest economic and social cost compared to other alternatives. Regarding to orderly energy transition, Interviewee A emphasized the Dutch industrial commitment to significantly decarbonize the hydrogen production by taking it out of refineries and giving them to specific utility plants like AirLiquide or Air Products from 1997 to 2007 in the first phase. As a result of the first phase, the produced hydrogen via SMR process became more efficient and less carbon intensive than traditional refinery-based hydrogen production methods. Interviewee A added that the next step includes capturing CO_2 from existing SMR facilities with CCS.

4.3.2. The lack of alternative (s) at scale

The inconvenient truth is that green hydrogen face significant challenges in achieving substantial decarbonization of the non-electric energy sector like refineries and chemical industry by 2050 (Dickel, 2020).

While the Netherlands holds significant potential for green hydrogen to emerge as a low-emission alternative to grey hydrogen, the technology encounters various obstacles on the path to meeting current hydrogen demand (Cor Leguijt et al, 2022). Challenges include high capital expenditures for electrolyzes, inadequate renewable energy capacity to power electrolyzes, insufficient power grid capacity and uncertainties for investors surrounding long-term hydrogen demand (Durakovic et al., 2023; Ueckerdt et al., 2023). In light of these challenges, blue hydrogen presents itself as a valuable steppingstone, providing an intermediate solution to pave the way for the eventual viability of green hydrogen as a long-term and sustainable hydrogen source in the Netherlands (Rohith Nair et al, 2022).

Most interviewees explicitly emphasized the absence of a scalable alternative for current hydrogen production, particularly green hydrogen at the time being. Interviewee A, argued that green hydrogen faces technical and financial challenges to scale-up due to the scarcity and also intermittent nature of renewable energy sources such as wind and PV solar, impacting the efficiency of electrolysers. Interviewee A outlined plans to decommission small 1997-built hydrogen production facilities of AirLiquide by 2027 by reaching their 30-year technical lifetime, depends on the scalability of green hydrogen. "*If green hydrogen scales up successfully, these older SMR machines will be retired; otherwise, their operation may be extended for another 15 years, Interviewee A said*".

The recent surge in interest in blue hydrogen in the Netherlands, according to Interviewee D, was due to the challenges faced by the offshore wind industry to supply renewable energies for green hydrogen production, causing the shift in focus from green to blue hydrogen. Interviewee E emphasized on blue hydrogen as a stepping stone that could serve to address the current emission reduction from existing hydrogen production plants while green hydrogen undergoes a learning curve with demonstration projects and policy instruments like subsidies. *"We have a climate issue not hydrogen issue at the moment, Interviewee E said"*. However, he recognized the green hydrogen as the ultimate goal, but acknowledged the practical challenges and time required for its widespread adoption in the country.

4.3.3. Effective national policy instruments

The new category in SDE++ to include blue hydrogen as a separate category could potentially promote blue hydrogen initiatives as an effective policy instrument. While the SDE++ scheme does not specifically support the blue hydrogen as a separate technology, CCS's part of blue hydrogen initiatives has already granted subsidies in the Netherlands under SDE++. However, it is anticipated that blue hydrogen projects will receive adequate subsidies through alternative categories to include costs for installing and operating a new SMR plants, and the operational CO_2 emissions cost (Rohith Nair et al, 2022). The proposed addition of a new category in the SDE++ scheme for 2022 focusing on hydrogen production from residual gases (CO_2 capture during the production of hydrogen from industrial residual gases) is expected to provide support for blue hydrogen projects like H-vision. The aim of such projects is to capture CO_2 from residual gas streams in industrial processes and not only natural gas as feedstock (Rohith Nair et al, 2022).

While all interviewees acknowledged the Dutch government's support for CCS technology - including blue hydrogen - through policy instruments like SDE++, they emphasized that the existing prices within the EU ETS are adequate for ensuring the economic viability of blue hydrogen projects in the Netherlands. Interviewee D also highlighted past unsuccessful CCS projects in the Netherlands due to low ETS prices and a lack of governmental funding. Interviewee D contrasts this with the present situation, where public-state companies like EBN and Gasunie have taken the lead with a lower return on investment and clear legal frameworks, facilitated by SDE++ scheme. This was seen by the respondent as a clear demonstration of political will to implement CCS projects, addressing previous challenges encountered by such initiatives.

The interviewee B emphasizes that governmental permits for CCS projects are currently facing delays and it's crucial to address these delays to speed up and simplify the permit processes effectively. Interviewee C referred to the Porthos project as an example of successful coordination, emphasizing a clear division of tasks and responsibilities, supported by a legal and robust framework. The active involvement of the Dutch government in CCS projects through state-owned entities like EBN and Gasunie was also highlighted by Interviewee C. While Interviewee C emphasized the importance of the existing EU ETS for making a business case for blue hydrogen production, initiatives like the Carbon Border Adjustment Mechanism (CBAM[5]) was emphasized as crucial for blue hydrogen initiatives to remain competitive with non-EU hydrogen producers.

4.3.4. Cross-border hydrogen trade

Cross-border or even global trade opportunities could arise by creating hydrogen market in the Netherlands considering both blue and green hydrogen (Cor Leguijt et al, 2022; Rohith Nair et al, 2022). Given limited opportunities for countries like Germany and Belgium to implement large-scale CCS, and the challenges towards green hydrogen to be scaled up in the near term, the

[5] CBAM is a policy tool designed to address carbon leakage and promote a level playing field in the global market concerning carbon pricing.

Netherlands is well-positioned to seize this opportunity. This could be achieved by providing blue hydrogen as a low-emission hydrogen not just for decarbonizing the energy-intensive hydrogen assets in the Netherlands but also for neighboring countries. This aligns with developing hydrogen infrastructure within and between the large industrial clusters to build a hydrogen network named hydrogen backbone (Cor Leguijt et al, 2022; Rohith Nair et al, 2022).

The opportunity for the Netherlands to take a lead in blue hydrogen production and trade it with neighboring countries was highlighted with most interviewees. Interviewee A mentioned that there is already hydrogen pipeline to the Belgium and blue hydrogen produced in the Netherlands could easily deliver to the port of Antwerp through this network. Interviewee E highlighted the role of blue hydrogen in fulfilling the national hydrogen backbone. Interviewee E was in doubt that national hydrogen backbone could be fulfilled with just green hydrogen based on current announced projects and thus blue hydrogen was seen as a crucial element to the realization of the national hydrogen backbone. This network then can be used to supply neighboring countries with sustainable low-emission hydrogen, in Interviewee E's opinion.

Interviewee D underscore the unique opportunity for expanding a CO_2 network to collect captured CO_2 from nearby clusters and even neighboring countries like the Delta corridor from Germany. Interviewee D also stressed the importance of industrial areas being connected to a CO_2 network, making service provision more accessible.

4.3.5. Technological advancement*

Technological innovation and advancement holds the potential to create opportunities for more efficient CCS applications including blue hydrogen production (Bui et al., 2018; Pettersen et al., 2022). This advancement could involve innovations in capturing technology, leading to higher capture rates, and a more energy-efficient method for capturing CO_2. Consequently, increased carbon capture rates and reducing the energy consumption of CCS facilities, facilitated by technological advancements have the potential to significantly boost the business case for blue hydrogen and its environmental impact, making it even more appealing for investors and policy makers (Bui et al., 2018; IEA, 2023b; Pettersen et al., 2022).

Interviewee B highlighted the need for continuous technological advancement and innovation in every aspect of CCS operations including CO_2 capturing, transportation and storage that can lead to cost reduction. Interviewee B also emphasized the optimization of these costs as crucial for the business case of blue hydrogen and mentioned that first-of-a-kind projects like Porthos could provide valuable learning curve for cost reduction in future projects.

4.3.1. Market competition*

In terms of competitiveness and integration of blue and green hydrogen - as two main alternatives for grey hydrogen - in the low-emission hydrogen market, some researchers argue that both low-emission options can co-exist and even see blue hydrogen as an enabler for introduction of green hydrogen into the market as soon as it becomes feasible (Almaraz et al., 2022; Dickel, 2020; Durakovic et al., 2023). However, other researchers showed that the inclusion of blue hydrogen could position it as the dominant source in the long run (Blanco et al., 2018; George et al., 2022; Ueckerdt et al., 2023).

In this regard, all interviewees assert that blue and green hydrogen can collaborate synergistically to shape a low-emission hydrogen market in the Netherlands without adversely impacting each other. This assertion was in line with the findings of those researchers who stated that green and blue hydrogen can go hand in hand to shape the low-emission hydrogen market. However, further research is deemed necessary to delve into this dynamic within the context of the Netherlands.

Notably, Interviewee D identified current ETS prices, the expansion of offshore wind parks, and the cost of electrolysers for green hydrogen production as pivotal factors influencing the competitiveness of blue hydrogen. Interviewee D predicted a coexistence of blue and green hydrogen in the long-term, depending on market developments and the evolving cost. Moreover, it was added that big fossil fuel producers such as ExxonMobil, BP, and Shell were identified as key players responsible for diversifying the market and facilitating the shift from fossil to renewable products in the Netherlands. Interviewee D then came with the idea of creating a legal framework to guide the use of blue and green hydrogen in specific applications. Finally, Interviewee D emphasized the role of the government and European Union in steering the industry considering market competition and environmental considerations.

Interviewee A emphasized the challenge of mandating the share of green hydrogen in the hydrogen mix by the Dutch government and stressed the need for a balanced approach, aligning obligations with actual capabilities. "*The key challenge lies in finding a balanced mechanism* *that encourages the shift from blue hydrogen to green hydrogen without exceeding current capabilities, Interviewee A said".*

Interviewee C highlighted that blue hydrogen would follow gas market trends, potentially increasing import reliance and market instability. Furthermore, as the cost of green hydrogen is expected to decline, investments in fossil fuel-based supply chains, especially long-term assets, may become stranded. It was also emphasized that the green hydrogen should be the ultimate winner in the long term based on the Climate Agreement. A balanced approach was then recommended along with careful regulation and addressing societal and environmental concerns in promoting blue hydrogen as a transitional solution while scaling up green hydrogen initiatives.

4.4. Threats from literature and interviews

4.4.1. Public perception

Even though the Dutch governmental approach was shifted from on-shore to off-shore storage, public perception and acceptance including NGO's regarding fossil fuel-based industries might be still a potential constraint to CCS projects in the Netherlands including blue hydrogen (Akerboom et al., 2021a; Janipour et al., 2020). Additionally, a comprehensive review conducted by Tcvetkov et al. covering public perception studies on CCS between 2002 and 2018, comprising 135 articles, underscored a notable emphasis on CO_2 storage. However, the authors emphasised that there is a noticeable gap in understanding public attitudes towards the capture and transportation phases of CCS (Tcvetkov et al., 2019). This could pose a potential social resistance in densely populated countries such as the Netherlands to build surface or underground infrastructures to transport captured CO_2.

All interviews highlighted the importance of public perception in successful implementation of blue hydrogen projects in the Netherlands. Interviewee A expressed industry efforts to inform the public about blue hydrogen as a temporary measure but found it insufficient. The educational campaign to inform the public about the environmental and economic outcomes of such initiatives was proposed to address the public perception. Interviewee A highlighted a challenge posed by the Environmental NGO, Mobilization for the Environment (MOB), resulting in a nine-month delay for the Porthos project to reach its Final Investment Decision. "*NGOs are generally unaware of technical complexities ahead of truly clean alternatives and believe green hydrogen can be implemented faster than industry aims to do, Interviewee A said".*

Interviewee B and C emphasized the importance of early engagement of the public including NGOs for effective communication and collaboration among different stakeholders, including state-owned and commercial companies. Interview B also underscored the importance of strategic planning for facility locations in densely populated countries like the Netherlands. The interviewee B emphasized the necessity of considering existing infrastructure and strategically optimizing the placement of CCS facilities, compressor stations, and pipelines to minimize social resistance in this regard.

Interviewee D expressed concern over the lack of public support and the need for effective communication to address misconceptions. Interviewee D added that the public should be informed about the risk of losing industry and jobs as a result of potential "carbon leakage" if support for CCS diminishes.

Interviewee E acknowledged that addressing public concerns and perceptions is a challenge, especially when it comes to complex technological projects. The example of Barendrecht's case, highlighted the importance of effective communication with public. "*It's not just about the engineering details but about translating technical information into terms that the public can comprehend, Interviewee E said"*.

Chapter 5: Discussion

The findings of this research indicated four key strengths and opportunities related to the current surge in blue hydrogen initiatives in realization of Dutch national climate targets. These include the cost-effectiveness and readiness of blue hydrogen initiatives to rapidly and massively mitigate industrial GHG emissions, along with ideal cluster-based Dutch industry and storage capacity for CCS application in hydrogen production, effective national policy instruments to support CCS, and the lack of other scalable alternative (s) to meet national climate targets at the short-term. On the other hand, the public perception regarding CCS as a mutual theme in literature and interviews has been found to be a potential threat to successfully implement and integrate blue hydrogen initiatives in the Netherlands.

Moreover, three novel opportunities explicitly identified in interviews, and two weaknesses highlighted in literature but largely overlooked in interviews, have been discussed in detail in this chapter.

The identified novel opportunities possess significant potential to enhance the successful implementation and integration of blue hydrogen in the Netherlands. Conversely, weaknesses and threats identified through our analysis could potentially impede this process. Therefore, the discussion chapter prioritizes an in-depth examination of these novel opportunities and associated challenges, leaving aside opportunities and strengths already confirmed through existing literature and interviews in the previous chapter. This ensures a focused and comprehensive analysis of novel opportunities, weaknesses and threads that could potentially drive or hinder the successful implementation and integration of blue hydrogen in the Netherlands.

5.1. Discussion on three novel opportunities

In addition to above-mentioned strengths and opportunities associated with blue hydrogen initiatives in contributing to the realization of national climate targets, three novel opportunities or implications have been explicitly identified through interviews.

Firstly, the importance of establishing a robust value chain around blue hydrogen was emphasized to realize the Dutch national hydrogen network, known as the hydrogen backbone, as scaling up green hydrogen might face challenges in fulfilling the hydrogen backbone solely with green hydrogen. Thus, blue hydrogen could play a crucial role to realize the hydrogen backbone by providing low-emission hydrogen beside green hydrogen. While no literature was found to explicitly support this opportunity, it was mentioned in a report by Cor Leguijt et al (Cor Leguijt et al, 2022). This could be further investigated to clarify what opportunities and challenges can be raised as a result of integration of blue hydrogen to fulfil the hydrogen backbone in the Netherlands.

Secondly, while the expansion of hydrogen network, hydrogen backbone, is up and running, there is an opportunity to expand CO_2 network as well. Expanding this CO_2 network to collect captured CO_2 from potential polluters across six Dutch industrial clusters and extending it to cross-border polluters from Belgium and Germany could significantly enhance the scalability and as a result cost-effectiveness of blue hydrogen production in the Netherlands. This extended national and cross-border CO_2 network could indeed contribute to position the Netherlands strategically for building a robust value chain for the low-emission hydrogen in Europe. The CO_2 network could also be utilized to collect CO_2 emissions from sectors beyond hydrogen production plants. Therefore, researching ways to identify potential polluters in each cluster and cross-border and establishing efficient connections to the CO_2 network is crucial for scaling up blue hydrogen and, consequently, optimizing its cost-effectiveness. However, expanding the CO_2 network could pose challenges in a densely populated country like the Netherlands, requiring the installation of facilities such as pipelines either underground or on the ground. This may face limitations due to potential social resistance, making it crucial to investigate the feasibility and potential success of the CO_2 network expansion.

Thirdly, the crucial task of decarbonizing key and strategic oil refineries in Europe, including three oil refineries in the port of Rotterdam has been mentioned. This can be achieved through proven and readily implementable technologies, such as utilizing CCS in hydrogen production. Embracing these technologies enables oil refineries in the port of Rotterdam to meet future oil demands from specific customers, notably the chemical industry, even beyond 2050, while significantly reducing their GHG emissions. This substantial decarbonization objective in oil refineries is challenging to achieve solely through green hydrogen production, making blue hydrogen a viable option as a transitional pathway to realize this goal. As discussed in interviews, the same trend is observable in other sectors, such as the transport industry. Despite an increasing adoption of Electric Vehicles (EV), there is still the production of petrol or gasoil automobiles to sustain their core business. This is due to the insufficient development of the necessary technical infrastructures or investments required for a complete transition to Electric Vehicles (EV) cars.

5.2. Discussion on threads and weaknesses

Public perception, perceived here as a threat, could play a crucial role to successful integration and implementation of the blue hydrogen in the Netherlands, given the fact that at least two out of three past CCS-related projects have been failed in the Netherlands mainly due to social resistance (Akerboom et al., 2021a). To be more specific, findings from interviews showed that despite the social resistance against CCS has been largely addressed by the Dutch government by shifting approach from on-shore to off-shore storage, it’s imperative for the public to be adequately informed about the cost-benefits of such initiatives and how they contribute to a just energy transition in the country. This can help mitigate the risk of social resistance or opposition from environmental NGOs towards fossil-fuel based initiatives such as blue hydrogen. This objective can be achieved through targeted educational campaigns and other public engagement initiatives, and the spread of research findings honestly and transparently (Tcvetkov et al., 2019) that highlight the positive environmental and economic outcomes associated with blue hydrogen initiatives. This also include initiating early and ongoing dialogues with the public, NGOs, and any stakeholder involved to address or mitigate potential concerns (Akerboom et al., 2021a). However, public perception regarding CCS deployment in the Netherlands remains a potential challenge, as quoted by Akerboom et al. “*the journey to CCS deployment beyond single, isolated projects is one into a societal terra incognita*” (Akerboom et al., 2021a, p. 14). This challenge was underscored by the recent experience of the Porthos project as the first large-scale CCS project applied for blue hydrogen, which encountered opposition from the Environmental NGO, Mobilization for the Environment (MOB), due to GHG emissions associated with the construction of surface facilities, leading to a significant nine-month project delay (Porthos, 2023). This challenge underscores the conclusions drawn by Tcvetkov et al., highlighting a significant gap in our understanding of public attitudes toward the capture and transportation phases of CCS, and not only the storage phase.

Apart from the public perception, two weaknesses associated with blue hydrogen could potentially derail the sustainability goals of the Dutch government, despite the crucial role the initiative could play in achieving Dutch climate targets. These weaknesses are not unique to the

Netherlands but are perceived based on a global literature review already elaborated in the previous chapter. These are found to be the ambiguity around the potential decarbonization of the blue hydrogen and carbon lock-in associated with supporting and investing in fossil fuels-based industry.

Firstly, despite the notable literature addressing uncertainties around the environmental impact of blue hydrogen, this issue was unexpectedly overlooked during the interviews. To more specific, the literature identifies ambiguity around the sustainability of blue hydrogen production, with concerns about the comprehensive life cycle emissions (Bauer et al., 2022; Howarth & Jacobson, 2021). The disparity between literature and interviews on the potential decarbonization of blue hydrogen becomes evident when considering the lack of attention in the interview discussions to upstream and mid-stream emissions regarding natural gas as the feedstock of the blue hydrogen. Notably, none of the interviewees raised concerns about this aspect. Conversely, the literature highlights the need for strong regulations and specific thresholds to classify blue hydrogen as low emission (Howarth & Jacobson, 2021; Pettersen et al., 2022). This regulatory dimension was not highlighted by any of the interviewees. Only one interviewee explicitly recognized concerns regarding the challenges of achieving 100% carbon capture rate. However, mid-stream and upstream methane emissions concerns regarding the life cycle blue hydrogen production was not pointed out. The issue may stem from participants' limited knowledge, or some stakeholders may hesitate to acknowledge it, potentially influenced by the fossil fuel industry's support for CCS technology, ensuring the continuity of their core business.

The uncertainty surrounding the environmental impact of blue hydrogen, perceived as weakness, can be effectively addressed (IRENA, 2022; Pettersen et al., 2022), transforming it into strengths and opportunities that support the further development of blue hydrogen. It is suggested that the government establishes and enforces strong regulations and specific thresholds to classify blue hydrogen as low emission as mentioned by International Renewable Energy Agency (IRENA, 2022; Pettersen et al., 2022). Moreover, in the context of this research, it is my contention that mitigating the risk of social resistance as a thread towards this weakness of the blue hydrogen, which contains opposition from NGOs towards the initiative could be effectively reduced but needs in-depth exploration in forthcoming investigations. However, it's important to consider potential implications for the industry and investors, such as the risk of "carbon leakage" resulting from imposing stringent regulations as highlighted in interviews. As mentioned, since this correlation has not been yet investigated, further research could explore the extent to which addressing this issue could reduce social resistance to fossil fuel-based initiatives like blue hydrogen or raise concerns among investors in the Netherlands.

Secondly, carbon lock-in as a potential issue associated with fossil fuel-based initiatives in literatures (Janipour et al., 2020; Janipour et al., 2021; Unruh, 2000) was largely ignored during interviews. Given the fact that there are several blue hydrogen projects on the horizon, this could potentially pose a significant threat to the low-emission hydrogen market by further investment in fossil fuel-based industries in the Netherlands. The inquiry into whether the current surge in blue hydrogen initiatives might transform its perceived opportunities and strengths into long-term weakness in the Netherlands, is of crucial significance. Addressing this concern is vital as it could impede the essential transition away from fossil fuels towards genuinely sustainable alternatives, notably the shift from grey hydrogen to green hydrogen (Blanco et al., 2018; George et al., 2022; Ueckerdt et al., 2023). The presence of blue hydrogen, due to the carbon lock-in effect, could act as an obstacle in this transition process. Therefore, there exists a delicate balance in promoting blue hydrogen in a manner that does not impede the advancement of green hydrogen, which is the ultimate objective (Janipour et al., 2020; Janipour et al., 2021). Further research is imperative to delve into this concern and determine the optimal level of support for promoting blue hydrogen to mitigate the carbon lock-in effect. This exploration is essential to strike a balance that facilitates progress towards sustainable alternatives while avoiding hindrances to the transition away from fossil fuels.

Addressing these two weaknesses and a threat proactively can contribute to a more informed and supportive public response and brings clarity to policymakers and investors to develop blue hydrogen further.

While this research has offered valuable insights, it is important to acknowledge the potential for inherent biases in the selection process of interviewees, which may introduce variations in perspectives. Interviewees were chosen from shareholders of the Porthos project and two energy transition experts. However, it is worth noting that some shareholders expressed reluctance to participate in the interviews. Additionally, due to time constraints, reaching out to other potential stakeholders was not feasible. As a result, this research may not fully capture the holistic views of all stakeholders involved, including policymakers, NGOs, and the public. Also, worth noting that some interviewees might hold perspectives not fully represented in the broader literature, contributing to a potential gap in the comprehensiveness of the study. Future research could benefit from a more extensive and diverse pool of participants to ensure a comprehensive understanding of stakeholders' viewpoints.

Finally, there is a scarcity of literature specifically addressing the opportunities and challenges of blue hydrogen in the Netherlands, particularly in English, given the relatively immature state of this field. This gap could be addressed by incorporating literature in the Dutch language to enhance the understanding and knowledge base.

Chapter 6: Conclusions and recommendations

This research set out to investigate the opportunities and challenges associated with the application of CCS in hydrogen production (blue hydrogen) in the Netherlands.

The qualitative SWOT analysis of the blue hydrogen promotion in the Netherlands indicates its significant potential to contribute to Dutch climate targets by cost-effectively reducing GHG emissions associated with hydrogen production in a large-scale. Despite the positive trajectory facilitated by extensive governmental support to address previous setbacks regarding CCS projects, the challenge of public perception could persist, necessitating a fit-for-purpose engagement plan among all stakeholders through targeted educational campaigns, other public engagement initiatives, and the spread of research findings honestly and transparently with the public. Moreover, further research is required to clarify the true decarbonization potential of blue hydrogen as a low-emission alternative. Transparent communication about the initiative's sustainability is crucial to obtain the public, policymakers, and investors support.

Some recommendations for achieving an effective implementation and integration of blue hydrogen in the Dutch hydrogen market can be formulated as below:

- Early engagement with potential pollutants in each cluster for scalability and cost-efficiency,
- Exploring the possibility to build a CO_2 network through Dutch industrial clusters or even cross-border industries,
- Investigating optimization strategies for CCS facilities, compressor stations, and pipelines to reduce costs and also mitigate the risk of social resistance during surface construction.
- A well-defined governmental strategy to establish the contribution of blue hydrogen to fulfil the hydrogen network, so-called the "hydrogen backbone".
- Exploring the feasibility of implementing stringent regulations on imported natural gas as a feedstock for blue hydrogen production to meet precise upstream and midstream emissions criteria.
- Encouraging technological advancement to improve capture rates while concurrently reducing the energy intensity of the capture process through various policy instruments.

Future research could delve into comprehensive stakeholder analyses to include the viewpoints of NGOs, local communities, policymakers, industry stakeholders, and investors regarding blue hydrogen initiatives. Identifying the primary concerns and barriers contributing to public perceptions toward the capture and transportation phases of CCS and not only the storage phase, environmental impacts of blue hydrogen, perceived risks, or socio-economic disparities.

Moreover, the role of government policies and regulatory frameworks to address the issue of ambiguity around decarbonization potential of blue hydrogen or carbon lock-in associated with blue hydrogen promotion can be assessed in future research.

The outcomes of the recommended lines of future research could proactively contribute to building trust among all stakeholders, thereby facilitating a nuanced approach to integrating blue hydrogen into the low-emission hydrogen market in the Netherlands.

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APPENDIX I: Interviews' questions

1) What would you consider as internal Strengths and external Opportunities[6] regarding CCS initiatives in hydrogen production (blue hydrogen) like Porthos project in a low-emission hydrogen market? (To spark the discussion, please consider the points below, and feel free to add your unique perspective)
   - Most cost-effective abatement measure compared to other measures,
   - Proven and ready-to deploy technology,
   - Dutch industry's cluster configuration,
   - Capacity for storage in North Sea,
   - Sound business case,
   - Sufficient governmental and EU support,
   - Clear division of tasks and responsibilities among stakeholders, public perception,
   - Fit-for-purpose legal frameworks and policy instruments, e,g SDE++, ETS, Carbon tax
   - No green hydrogen currently available on a massive, gigaton scale
   - Technological advancement for improved CCS efficiency
   - etc?

2) What would you consider as internal Weakness and external Threat of blue hydrogen initiatives in a low-emission hydrogen market? (To spark the discussion, please consider the points below, and feel free to add your unique perspective)
   - No large-scale experience with CO2 storage (first-of-a-kind initiative),
   - CAPEX and OPEX cost,
   - Carbon lock-in and maintaining the status quo
   - Ambiguity around blue hydrogen's decarbonization potential
   - Cap for CCS in SDE++,
   - Lack of standardization, e,g, for abandonment
   - Societal challenges,

[6] External factors are those outside the control of the initiative or technology, such as natural gas prices or ETS prices. In contrast, elements within the initiative's area of influence, such as strengths and weaknesses in processes, proven and read-to deploy technology, and technical expertise were classified as internal.

- Standing in the way of green hydrogen to grow
- Emergence of green hydrogen as a competitive alternative (Ongoing technological innovation and economies of scale)
- Natural gas volatile prices
- Permit for storage,
- etc?

3) Are there any synergies between blue and green hydrogen in current infrastructure development?

4) Based on identified strengths, weaknesses, opportunities, and threats regarding blue hydrogen promotion in current Dutch policies, what strategic recommendations would you propose to achieve a balanced integration of blue and green hydrogen production in the low-emission hydrogen market?