United States Hydrogen Infrastructure and Market Overview

A Northeast Purchasing Scenario Analysis

Master's thesis in Supply Chain Management

ALBIN BENGTSSON PHILIPSSON
LINUS LEJON

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF SUPPLY AND OPERATIONS MANAGEMENTS

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023

www.chalmers.se
Report No. E2023:100

REPORT NO. E2023:100

United States Hydrogen Infrastructure and Market Overview

A Northeast Purchasing Scenario Analysis

ALBIN BENGTSSON PHILIPSSON
LINUS LEJON

Department of Technology Management and Economics
Division of Supply and Operations Management
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023

United States Hydrogen Infrastructure and Market Overview
A Northeast Purchasing Scenario Analysis
ALBIN BENGTSSON PHILIPSSON
LINUS LEJON

Report no. E2023:100
Department of Technology Management and Economics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Gothenburg, Sweden 2023

United States Hydrogen Infrastructure and Market Overview
A Northeast Purchasing Scenario Analysis

ALBIN BENGTSSON PHILIPSSON
LINUS LEJON

Department of Technology Management and Economics
Chalmers University of Technology

SUMMARY

The unique properties of hydrogen make it a promising candidate in the transition towards a sustainable society. As hydrogen is a rapidly evolving market where the U.S government is pursuing efforts to develop a clean hydrogen industry, the novelty of the topic is evident. This study examines the as-is infrastructure and market landscape for hydrogen in the U.S. It also develops and evaluates purchasing scenarios to gain insights into the feasibility and implications of adapting hydrogen to plants of heavy-duty truck production. By understanding the potential of hydrogen and assessing its existing market dynamics, this study contributes to the ongoing explorations of hydrogen as a fueling solution. The qualitative research comprises literature research, semi-structured interviews, internal seminars, and internal company events. Data gathered is analyzed through a thematic analysis approach. The hydrogen market currently relies on high majority gray hydrogen (>99 %). There are targeted efforts in the selected northeast area for developing supply infrastructure like hubs and refueling stations. Technological advancements will play a key role in shaping the market's potential. The emergence of new buyers and the increasing demand for clean hydrogen to decarbonize hard-to-abate industries will be drivers of the market. Two important acts, IIJA and IRA, are also driving the market with a notable $ 9.5 billion funding for hubs and several valuable tax credits. One specific tax credit being the 45V, encouraging clean hydrogen production through tax credits per kg of hydrogen produced, over a ten-year period. The study explores four purchasing scenarios, with their viability dependent on timing and contextual factors. Extending the first purchasing solution of mobile stations is critical to navigate market uncertainties. The solution has an estimated switching point above 13 tons of hydrogen demand per year or at a breach of 500 kg peak volume needed within relevant delivery occurrences, currently at once every two weeks. Lastly, the color categorization of hydrogen should probably be switched to a numerical carbon intensity based one instead.

Keywords: U.S. Hydrogen Infrastructure, Hydrogen Supply Chain, Clean Hydrogen Hubs, Purchasing of Hydrogen, Sustainable Development

Acknowledgements

The master thesis was conducted in the spring of 2023 as a final assignment of the M.Sc. Supply Chain Management at the Chalmers University of Technology. It was done in collaboration with the Volvo Group, to support their knowledge of the hydrogen market. We would like to express our appreciation to the Volvo Group people who have supported us, with a specific thank you to Camilla, Kevin, Sophie, and Frida for their valuable input. The time with the Volvo Group has been inspiring and your expertise has been of great help navigating the intense world of hydrogen. A special thank you to Camilla Nilsson and Girish Kotegar for the opportunity to write this thesis.

An additional huge thank you to our supervisor at Chalmers, Patricia van Loon, for valuable insights and support during this spring. Your knowledge of academia and guidance during the thesis has been of immense help, thank you!

Albin Bengtsson Philipsson & Linus Lejon
Gothenburg, June 2023

List of Acronyms

ALK - Alkaline Electrolyzer

BEV - Battery Electric Vehicle

CCS - Carbon Capture System

DOE - U.S Department of Energy

EIA - U.S Energy Information Administration

FCEV - Fuel Cell Electric Vehicle

GHG - Greenhouse Gas Protocol

HRS - Hydrogen Refueling Station

IEA - International Energy Agency

IIJA - Infrastructure Investment and Jobs Act

IRA - Inflation Reduction Act

NDA - Non-disclosure Agreement

OEM - Original Equipment Manufacturer

PEM - Proton Exchange Membrane Electrolyzer

QDCFTSR - A Volvo Group Acronym for Supplier Evaluation Metrics

QDCFTSR - Quality, Delivery, Cost, Features, Technology, Sustainability and Risk

ZEV - Zero Emission Vehicle

Table of Contents

List of Figures

List of Tables

1. Introduction

The hydrogen topic is introduced with emphasis on the decarbonization journey, which leads into the problem at hand - to understand the current situation. This is followed by the aim, purpose and research questions alongside relevant delimitations chosen to facilitate the study.

1.1 Background and Problem Description

In order to face challenges of climate change and reach the goals set up by governments in the Paris Agreement, society and industry need to collaborate. There are certain parts of society which are considered more difficult to decarbonize, one being the transportation sector which is a so-called hard-to-abate industry (Heid et al., 2022).

The transport sector has already established electric vehicles, which act as a decarbonizing solution. But electricity alone is not enough according to Denholm et al (2022), where the power output of electric vehicles will not be enough for heavy-duty long-distance transportation. Further, the electricity grid and availability will become a problem as demand increases for all sectors - there is a need for further sustainable solutions which can act as enablers of decarbonization in society (Denholm et al, 2022). One such solution being “clean hydrogen” that can act for example as fuel with promising features, with water as the only by-product. The industry sector alongside the transportation sector is described by Heid et al. (2022) to be the sectors with the most potential of utilizing hydrogen. These sectors combined have potential to support the facilitation, with an estimated decrease of carbon dioxide emissions by 80 gigatons until 2050 through the use of clean hydrogen. Which represents 11% of the required decreased emissions by 2050 (Heid et al., 2022). The importance for society to become sustainable remains and is becoming more crucial, where governmental actions and international collaborations is the foundation towards a sustainable future. Such actions and collaborations are on-going and rapidly expanding, with hydrogen importance increasing as well. Changes in the hydrogen field are therefore happening at a rapid pace all over the world in the forms of projects, incentives, and regulations. There are on-going developments of over 680 announced large scale hydrogen projects globally with potential investments of over 240 billion dollars (Heid et al., 2022).

Volvo Group has committed to reach Science Based Targets, which is a clear, defined way forward in reducing greenhouse gas emissions for society and can facilitate the goals of the Paris Agreement (Andersen et al., 2021). As a result, Volvo Group is reaching for rolling fleet net-zero value chain emissions by 2050. Because of this, hydrogen is seen as an important area to consider, with expectations for hydrogen trucks to be available before 2030. Currently, hydrogen is limited by lack of infrastructure and high costs, which creates the key development areas (de Pee et al, 2022). A company like Volvo Group in this context must align their capabilities, existing strategies, and infrastructure to best navigate this new developing area. It also becomes important to consider the acceleration of hydrogen and fuel cell initiatives all over the world in order to support their own objective of having net-zero value chain emissions.

In order to reach the goal set up by Volvo Group and to strategically position themselves, an increased knowledge about the fast developing market, the ecosystem, its infrastructure and costs related to hydrogen is needed. This in turn, will assist with securing availability of hydrogen for testing and further on also for their products and customers. The knowledge needed is for all parts of the hydrogen supply chain such as production, storage, distribution and refueling. This report will add to academic knowledge of key drivers and barriers in development of hydrogen infrastructure as well as to the understanding of different parameters for hydrogen procurement. Knowledge of the current- and developing hydrogen supplier base is needed to create an understanding of the changing ecosystem and its trends, which relates to developing initiatives in major geographical areas in both Europe and the U.S, as well as development of clean hydrogen. The current bigger knowledge gap is within the U.S region, where the Infrastructure Investment and Jobs Act (IIJA) and Inflation Reduction Act (IRA) are driving initiatives. The IIJA aims at developing clean hydrogen distribution- and supply networks through so-called "hubs". The IRA is seen as critical for advancing the U.S hydrogen market and consists of heavy incentivization towards clean hydrogen development. The thesis focuses on the U.S region with specific deep dive in surrounding areas of Volvo Group plants, the plants in focus for hydrogen is:

- New River Valley - Virginia (Volvo Trucks)
- Shippensburg - Pennsylvania (Volvo Construction Equipment)
- Lehigh Valley - Pennsylvania (Mack Trucks)
- Hagerstown - Maryland (Engine/Transmission)

The understanding of the as-is infrastructure and its development in the U.S, constitutes the base of analysis for what the strategic position of purchasing should be for Volvo Group. The thesis includes a description of the as-is situation and then utilizes an analytic approach to recommend Volvo Group with a strategic purchasing position for their U.S plants through scenario analysis.

1.2 Aim

The thesis aims to contribute to the understanding of key drivers and hydrogen market developments for the U.S region with emphasis on areas surrounding the Volvo Group plants, which are found in the northeast of the U.S. This will be done by integrating the current, available knowledge of the supplier base and market intelligence to further research about developing infrastructure, like the hydrogen hubs. This is to create an understanding of how the fast-changing market of hydrogen is developing in the foreseeable future, by relating to current and future requirements as well as identifying key actors and initiatives in the market. This understanding will be analyzed through a purchasing perspective to identify key parameters of different purchasing scenarios and recommend Volvo Group with a purchasing strategy for hydrogen availability in the coming months and years.

The objective is to understand how the developing infrastructure looks, together with its ecosystem in the selected northeast area. Also investigate parameters of different purchasing scenarios. Further analysis will put barriers and drivers into contextual perspective for the U.S plants of Volvo Group with positioning recommendations. The purpose will be to deepen the knowledge about infrastructure developments, the current ecosystem and how it will impact a purchasing decision.

1.3 Research Questions

Because hydrogen is a fast-developing field and knowledge quickly gets outdated. The first objective is to understand the as-is situation, by mapping the current and developing infrastructure around the Volvo Group plants in the U.S. This regards governmental strategy and incentives, together with hub developments, supplier availability and OEM collaborations. Which creates the foundation for the first research question:

RQ1: What is the as-is situation of hydrogen infrastructure and ecosystem with emphasis on the northeast of the U.S?

Based on this situation, Volvo Group can obtain hydrogen in different ways. These scenarios come with different advantages and disadvantages, they also come with different costs and risks which are of interest to understand. A scenario analysis for purchasing hydrogen to use on-site for the plants over a short- and longer-term perspective, is the foundation for the second research question:

RQ2: What are the key parameters influencing the purchasing decision of hydrogen?

1.4 Delimitations

As stated in the aim of the thesis, an analysis regarding the hydrogen market infrastructure is done from a purchasing perspective and will regard on-site availability of gaseous 700 bar hydrogen. Therefore, the focus of analysis will not be on the aftermarket. Processes and technologies implemented and used in the field of hydrogen that will relate with the project are not to be looked at in depth, but rather used to create an understanding of how processes are working and are developed. Technical solutions related to the hydrogen market and its infrastructure will therefore act as a topic for understanding and discussion rather than a point of analysis. Such processes and technology can for example be related to the production of hydrogen as well as the fueling stations, storage, and transportation to name a few. Technologies used and implemented by the Volvo Group to enable hydrogen as an operating fuel for their trucks will not be looked at through a technical perspective. Therefore, an understanding of the processes will be kept at a basic level, as the thesis regards the market and infrastructure rather than the technical aspects.

There are hydrogen hub concepts developing in all regions of the U.S and a multitude of actors from different sectors involved. With a focus on the Volvo Group interests combined with limited resource capacity, the maintained focus throughout the report will be on the east side of the U.S with the biggest emphasis on hub concepts in close proximity to Volvo Group plants. The focus will also be on suppliers within the hubs that have access to hydrogen production and can benefit the Volvo Group purchasing agenda.

1.5 Thesis Outline

A descriptive configuration of the study together with a brief summarization of each chapter is presented here. In Figure 1, the outline is illustrated.

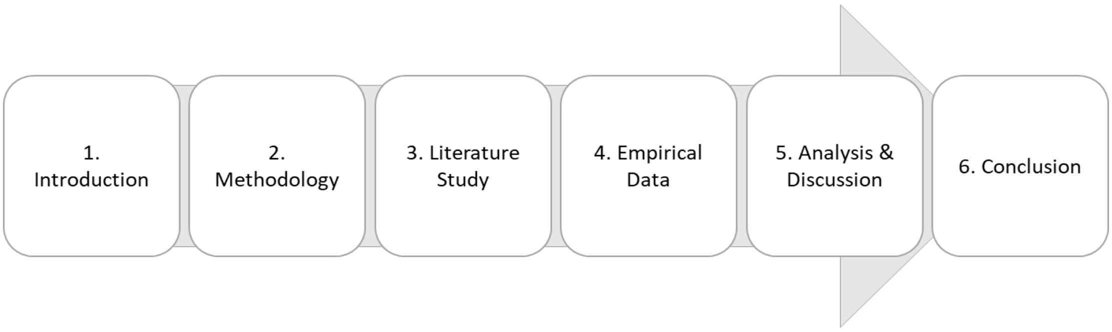

Figure 1. The outline of the study.

Chapter 1 - Introduction. The first chapter introduced the subject by providing a contextual background that led into the problem description. This was followed by the aim, purpose and research questions alongside relevant delimitations chosen to facilitate the study.

Chapter 2 - Methodology. This chapter includes research strategy and design, the approach for data- collection and analysis as well as reflections regarding the method used, in terms of validity, reliability and ethics.

Chapter 3 - Literature study. The third chapter captures interesting information and provides context to the subject by creating a foundation of hydrogen knowledge for the reader. It also creates understanding around the as-is infrastructure, its developments and purchasing scenarios. This is done from available literature and non-confidential internal company documentation.

Chapter 4 - Empirical data. A chapter consisting of interviewee expertise and reflections based on answers during the semi-structured interviews. It also includes observations and learnings from conferences, workshops, and general day-to-day activities. A U.S hydrogen supply study is also displayed.

Chapter 5 - Analysis and Discussion. This chapter compares, applies, and argues previously introduced data with relevant theories. It also visualizes the purchasing scenario analysis from the perspective of the plant requirements. The findings are applied in context of the research questions. This is also discussed in a broader context, with the goal to fulfill the purpose of the study and answer the research questions.

Chapter 6 - Conclusion. The final chapter summarizes key findings, repeats recommendations, and finalizes answers to the research questions.

2. Methodology

This chapter describes the research approach and methods that were used for the thesis. The first section presents the research strategy and design, which is followed by the research approach. Afterwards follows a data collection description and the data analysis approach. The chapter is concluded with research quality considerations.

2.1 Research Strategy and Design

The research was mainly a qualitative research study, with a few simple calculations to increase perspective understanding. The focus was on the hydrogen market and its rapid development, to create a high-level overview of what is going on, factor in the requirements that exist and the parameters of different solutions. All this was put into context of Volvo Group in the U.S, how they should position themselves, what solutions to utilize and what type of strategy they should embrace in regard to purchasing hydrogen. The research strategy to perform this was a combination of exploratory research and desk research due to the developing nature of the topic, with semi-structured interviews to support through triangulation. Involvement of internal hydrogen buyers at the Volvo Group was also an important strategic aspect for realistic scenario creation.

The report was done with an abductive approach, that is, a combination of the top-down theory approach of deductive strategy with the empirical data focus of inductive strategy (Bryman and Bell, 2015). It was also written in an iterative process, to allow the research conducted and new data to continuously guide the process and develop it as it evolved (Bell et al., 2019).

The design of the research had five key areas, which each had certain activities tied to it. The first area was to create an understanding of the topic and to design the research questions. The second area was to gather information and comprehensively explore the topic. Third, to develop realistic purchasing scenarios connected to the Volvo Group situation. Fourth area, to analyze findings. Lastly, fifth area, to conclude and provide recommendations. These five areas and their connected activities can be found in Figure 2 below.

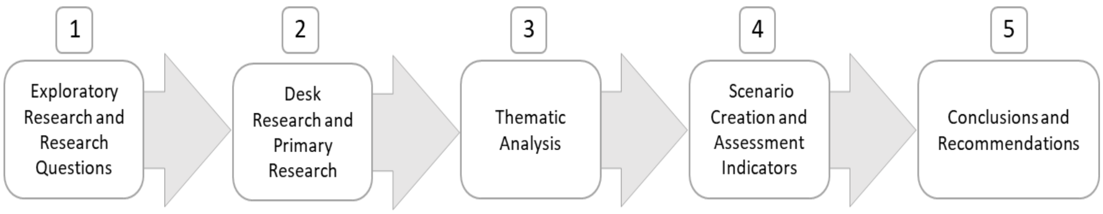

Figure 2. Overview of the five key areas of the thesis and the activities linked to each.

2.2 Research Approach

Because of the novelty of the topic of the thesis, new- and changing information is continuously emerging. There is also a competitive nature surrounding the topic, making data about the as-is situation considered sensitive in many aspects. As a result, the topic itself has not been thoroughly researched previously, and there are few academic articles covering what the thesis intends to analyze. Therefore, the following research approach was designed and followed in order to build an understanding of the topic and later deep dive into specific areas of interest to analyze. The study was conducted in a qualitative fashion due to it being more realistic with the information available and from the nature of the as-is mapping aspect.

2.2.1 Explorative Research

The research methodology adapted for the thesis is based on the characteristics described about the topic. It is highlighted by a lot of new, changing, and sensitive data. Therefore, the research methodology that was adopted is based on exploratory research. Which can be defined in different ways and consists of different exploration types (Stebbins, 2001). Explorative research generally aims at creating a good overview- and understanding of the topic and to identify the nature of the problem (Chenail, 2014). The type used for this thesis is *exploration of discovery*, which is considered well-fitting to the topic of this thesis. This is because it enables a flexible research method and utilization of many different sources for the data collection on a new topic that is scarce of scientific knowledge (Stebbins, 2001). It allows the thesis to provide a necessary understanding of key issues and trends, as well as highlighting specific areas of interest for the topic. After gaining a better understanding of the topic and the nature of the problem, specific methods for conducting research were used to gain further insights.

2.2.2 Desk Research

To build on the knowledge gained through the explorative research approach and gain further insights about the topic under investigation, desk research was conducted. It is a form of secondary data collection, with the basis of using information that is already public and does not need to be gathered directly (Woolley, 1992). This allowed the use of existing resources as a gateway to other-, similar in topic sources and thereby increasing the knowledge and further insights into the topic analyzed (Snyder, 2019). This was done through several different sources that consisted of both qualitative and quantitative characteristics, which is said by Woolley (1992) to increase variety and strengthen the case. To provide qualitative data, relevant literature on the topic was gathered, consisting of a combination of academic articles, public reports from well-established actors in the field as well as U.S governmental resources about the topic.

2.2.3 Primary Data Collection

To validate information from the findings and gain further insights, adding on to the knowledge about the topic, a primary data collection was also conducted. This was done through semi-structured interviews with key stakeholders, this way results could be compared between the interviews while each interview still was flexible enough to bring new context and further learnings (Bell et al., 2019). The goal of conducting interviews was to reach a point where no further insights were gained, reaching saturation (Morse, 1995).

Achieving saturation is a challenging approach as described by Baker and Edwards (2012) and cannot be viewed as a linear process, resulting in saturation not always being possible or practical. The topic was characterized by new- and changing data which also contains sensitive information, it is important to acknowledge the challenges of reaching saturation in this type of environment. It was therefore of importance to have other forms of data backing up the information, to reach arguably saturated answers (Morse, 1995). The interview data could be used to validate other findings that were gathered through the previous methods of data collection. Additionally, an interview was conducted with a research analyst who is knowledgeable within the field of hydrogen. This further highlighted and gave perspective on already obtained information. Which is referred to as triangulation of data and is described by Bryman and Bell (2015) and Griffee (2005) to be an efficient way of increasing the validity and trustworthiness of the data. It was important to have the novelty of the topic in mind when performing the interviews and to respect potential confidential topics and privacy of said information (Bell et al., 2019).

2.2.4 Scenario Analysis

Lastly, in order to answer the second research question, a scenario analysis was performed. The scenario analysis acted as a foundation of the strategic planning for Volvo Groups' U.S plants when purchasing hydrogen.

A scenario analysis consists of developing different scenarios that should resemble potential outcomes of the future, with regard to a certain context (Schoemaker, 1995). The scenarios act as a basis for understanding and assessing different future potential impacts. By creating several different scenarios, one can envision multiple potential futures and capture a range of different outcomes that enables a more informed decision-making (Wack, 2014). The main purpose of a scenario analysis is therefore to increase understanding of future events, through scenarios, which can provide insight into potential risks and opportunities for several different outcomes of the future (Koshow & Gaßner, 2008).

The scenario approach is interesting because there are many different ways of acquiring hydrogen, and with its inherent characteristics, it becomes crucial to consider the options available since it is reflected across many parameters. The fact that hydrogen is a rapidly changing- and developing market, strengthens the use of scenarios because of the uncertainties of the future. Because of this, it becomes of interest to identify and understand what underlying parameters determine- and play an impact on the different purchasing scenarios, which can help in creating an understanding of upcoming events and their potential impact (Knight et al., 2020).

When there is an uncertain future regarding the business environment of an organization, the purchasing- and supply chain management will have to be adapted accordingly in order to face such uncertainty (Pettit et al., 2013). Therefore, it is of interest for organizations to have knowledge of upcoming events that will have an impact on purchasing decision factors, such as costs, risks, and investments. It is also important to have an understanding of the anticipated events' significance in order to analyze and assess these future events (Knight et al., 2020). To create an understanding of such upcoming events which are characterized by an uncertain future, one can perform a scenario analysis (Schoemaker, 1995). Which is fitting for the topic of the thesis, as it is characterized by a lot of rapid developments. Therefore, together with the second research question, it is of interest to perform a scenario analysis on purchasing parameters. Knight et al. (2020) argues that when performing a scenario analysis, the scenarios should reflect the strategic targets that have been set up by the organization in order to enable relevant comparisons and reflections between the scenarios. In such a scenario analysis, different scenarios are developed in order to assess their potential impact on purchasing- and supply chain management (Knight et al., 2020).

There are several ways of performing a scenario analysis, which all depend on different contexts (Schoemaker, 1995). Because of this, Koshow and Gaßner (2008) explains that methods to perform an analysis can be combined depending on what context scenarios are being developed. They further argue that methods should consider uncertainty of changes and different time horizons. Therefore, methods should consider the short-term impacts of events that may occur such as economical, environmental, political and technical. It is also of importance to consider long term developments that regard technological and geopolitical advancements as its impact regarding many actors (Koshow & Gaßner, 2008). Knight et al. (2020) further elaborates on this through a purchasing perspective, with the importance of strategic planning of future events, while considering potential collaborations and interactions of the future. It is important to state that it is evident from (Koshow & Gaßner, 2008; Knight et al, 2020) that context regarding the scenarios is the most important aspect to consider, since scenario analysis regards making sense of the future through a short- and long-term perspective. The exact parameters used will be discussed with support from literature in section 3.5 “Purchasing Parameters and Investment Strategies”.

2.3 Data Collection

Secondary data presented in the literature chapter was collected through various public reports, academic articles, and U.S government sources. Empirical data (primary data) was gathered through a combination of internal sessions and semi-structured interviews with key stakeholders, which was held until a good understanding was achieved (Baker & Edwards, 2012). The U.S as-is supply and demand situation were also placed in the empirical data. This is because a various mixture of sources was used to understand the supply and demand, when no single source available covered everything needed. Using the author's reasoning, the combination of sources to paint the full picture was selected, which is why it can be found in the empirical data over the literature study chapter.

2.3.1 Literature Research

When searching for qualitative data, specific keywords concerning the theme of the thesis were used to find relevant literature. The selected keywords for the search were: “Hydrogen developments in the US”, “Hydrogen infrastructure in the US”, “Inflation Reduction Act” and “Hubs”. Different databases such as Chalmers library, Google Scholar, MDPI and ScienceDirect were utilized. Additionally, due to the government being a big driver in the on-going change and a key source when it comes to the hydrogen hubs, government websites and published reports were utilized as well. The decision was made to only have the most recent information included, therefore only academic articles from 2022 and onwards were selected. This was done because there is a lot happening within hydrogen at the moment and articles in this selection will include the important and still relevant aspects of previously published articles as well as keeping up with the most recent information.

2.3.2 Internal Events

The overview of the internal sessions can be found in Table 1 below. Involved actors cannot be mentioned by name, however they regard big players in the hydrogen market and various legislative representatives (for the conference). Both the conference and the workshop highlighted the current trends, drivers, and incentives for a developing hydrogen market. The seminars included key hydrogen buyers which was a constructive way of reaching a joint agreement for the problematization of the thesis. The other three seminars were targeted on the purchasing scenarios, to reach both realistic scenarios and a fair business-case-based way of analyzing them.

Session	Description	Date	Duration	Event
1	Hydrogen Day Conference	2023-02-01	8 hours	Conference
2	Thesis Problematization with Hydrogen Buyers	2023-02-06	1 hour	Seminar
3	Hydrogen Workshop	2023-02-07	8 hours	Workshop
4	Purchasing Scenario Development with Hydrogen Buyers	2023-03-23	1 hour	Seminar
5	Purchasing Scenario Parameter Indicators with Hydrogen Buyers	2023-04-20	30 min	Seminar
6	Purchasing Scenario Indicator Stress Test and Assessment	2023-04-24	30 min	Seminar

Table 1. Internal sessions with the Volvo Group to gain knowledge on the topic, formulate the problematization of the thesis and to align the purchasing scenarios.

2.3.3 Semi-structured Interviews

Data was gathered internally from three different semi-structured interviews together with stakeholders from the Volvo Group, with key insight into the topic from a position with great overview. Both the technical and operations business units were involved, with the final purchasing unit being conveniently part of the thesis as supervisors. The technical department as a business unit in this context, has a focus that revolves around the development and testing of the products. The operational department is more product- and investment oriented with production for large scale-up to customer. Whereas the purchasing department is the supporting unit, like a mediator of requirements to suppliers - with certain technology requirements themselves. The three interviews conducted were enough to reach saturation due to the novelty of the topic and its limited coverage as of now internally. All three interviews had similar (the same) responses. The purpose of the internal interviews was to create an understanding of how hydrogen is going to be used in the different Volvo plants in the U.S and consequently understand the future need and its requirements.

Data was also gathered from external semi-structured interviews. The initial goal of speaking with one leading supplier actor and one leading non-supplier actor for each hub was not attainable. A total of 22 interview requests were sent out, 12 suppliers and 10 non-suppliers. 10 suppliers declined and 5 non-suppliers declined, leaving the acceptance rate at ~68 % in total. 50 % for the non-suppliers and ~18 % acceptance rate for the suppliers. These were all related to the identified hubs. The secrecy and NDAs involved in the various projects made it difficult to reach actors willing to participate. In total, actors from 6 hubs out of the 9 identified were interviewed. An additional 3 supplier interviews were conducted through Europe connections, with a general market view focus, to add to the credibility of supplier understanding. Lastly, a hydrogen research analyst was also interviewed to triangulate the findings of their quality, depth, and recency.

2.3.3.1 Interview Preparation

For the interviews, general actor specific templates can be found in the Appendices chapter below, they acted as the interview guides. In total there are three templates, one internally and two externally - with the two external being split between supplier actor and non-supplier actor. The reason for different templates for these interviews is that the actors have a very different role to play in terms of interaction with the Volvo Group. It was created and based on information gathered through the literature study, but the nature of the semi-structure allowed for several interesting topics to be deeply discussed when certain expertise was present. Because of this, areas which would not have been considered or touched upon given a structured interview, were able to get covered and created a flexibility and openness of the interviews that gave deep insights (Rowley, 2012). The templates were given to the interviewees prior to the interviews, in order for them to prepare and gave them a chance to ask for clarifications if needed.

The templates were also discussed and approved both internally with the Volvo Group and with the thesis supervisor prior to any interview being conducted. The templates were designed with the actor in mind and their potential future involvement with Volvo Group in the hydrogen space. If they had a potential role to play, the interview followed the "supplier" template, which is a bit more focused on product offerings and other supplier related activities. If the actor didn't fit in that role the interview followed the "non-supplier" template and was focused on more broad hub knowledge and role. Both templates still cover similar topics to allow cross referencing.

2.3.3.2 Interview Selection

The internal selection for interviews was based on people who are knowledgeable about the plants, their current operations, and future plans within the Volvo Group for hydrogen. The interviewees possessed the knowledge and understanding of the plants to express and argue for the future need, timeline, and requirements in regard to hydrogen. The interviews can be seen in Table 2 below. These interviews established a timeframe for needs and requirements. Which is confidential information but gave a perspective that facilitated both the creation and the comparison criterias of the purchasing scenarios.

Session	Description	Date	Duration
1	Group Manager Vehicle Strategy	2023-03-09	30 min
2	Industrial Dev Mnr Electromobility and Fuel Cell Technology	2023-03-22	1 hour
2	Manufacturing Platform Manager	2023-03-22	1 hour
3	Senior Product Planning Manager Fuel Cell and Hydrogen	2023-03-31	45 min

Table 2. Internal Volvo Group interviews to create an understanding of the internal situation.

The external selection for interviews was based on hub actor involvement, where actors with an already established connection with the Volvo Group got priority for contact. This was to ensure an entry point and enable the setup for the interview to be easier. Also, selection was prioritized based on the influence of the actor involved in a chosen hub, since a leading actor would be more involved in the development process. However, due to the competitive- and confidential nature of the hub developments, it was determined that more actors had to be contacted to generate more information. Therefore, it was of interest to contact actors which were not necessarily connected to the Volvo Group, like non-profit companies, universities, and other researchers in the field. The reasoning behind this was that such actors might be more open to share information regarding the hubs, providing a more general overview of the hub developments but still specifics about the hub that they are part of - from the point of a heavily involved leading actor perspective. These external interviewees were more approachable, all external interviews conducted can be viewed in Table 3 on next page.

Session	Type of Company	Description	Date	Duration
1	Nonprofit	Leading Hub Applicant (Hub 6)	2023-03-29	30 min
2	Supplier	Major Hub Project Sponsor and Supplier (Hub 2)	2023-03-30	45 min
3	Supplier	Leading Hydrogen Supplier (Global)	2023-03-30	1 hour 30 min
4	University	Leading Hub Applicant (Hub 3)	2023-04-06	45 min
5	Nonprofit	Leading Hub Applicant (Hub 8)	2023-04-14	1 hour
6	Nonprofit	Research Analyst and Hydrogen Expert	2023-04-20	1 hour and 15 min
7	Supplier	Major Hub Project Sponsor and Supplier (Hub 2)	2023-04-24	1 hour
8	Supplier	Electrolyzer Supplier Europe	2023-05-02	1 hour 30 min
9	Nonprofit	Leading Hub Applicant (Hub 4 and 5)	2023-05-18	45 min
10	Supplier	Leading Hydrogen Supplier (Global)	2023-05-26	1 hour 30 min

Table 3. External actor interview sessions.
**Session 3, 8 and 10 are not hub or U.S specific but gave insights into supplier market views.*

2.3.3.3 Interview Procedure

The interviews were all conducted over video calls on Teams, this was since all interviewees were based in the U.S while author's residence is Sweden. The participants were all asked beforehand if the interviews could be audio-recorded and transcribed in order to efficiently organize and analyze findings (Bell et al. 2019). Initially the anonymity question was asked as well but became a statement that it would be so after 3 interviews, since all prior interviews requested that, and coherency would look better in the report. It was an appreciated gesture. The reason participants of external interviews requested to be anonymous was due to the sensitive topic and various non-disclosure agreements held around projects. The description of the type of organization will be available but the organization will not be mentioned by name, this is because role description combined with organization would give away interviewee identity. The structure of the interview was that one researcher took notes while the other led the interview, this supported the process to oversee findings while the recording could clarify and double check facts. Not all interviews were recorded due to permission being denied.

2.4 Data Analysis

The method for analysis that was used is thematic analysis, this is a qualitative research approach that relies on identifying patterns and themes within a collected set of data (Nowell et al., 2017). This is a flexible and commonly used method that allows for interpretation of the researched theme, in this case hydrogen, and its various aspects. According to Attride-Stirling (2001) this allows for an in-depth analysis and is particularly useful when it comes to analyzing qualitative data. The method also allows recurring themes throughout multiple sources to be analyzed (Nowell et al., 2017). The themes were based on the grouping of questions in the interview templates, which subsequently gave areas to analyze in the thesis. These themes were the foundation for analysis of the empirical data later on. By dividing the interview template into different themes, categorization of the data was made to highlight areas of importance for the project. This then enabled the research direction to be adjusted throughout the project as the amount of data increased (Kerssens-van Drongelen, 2001). By categorizing data into different themes, it was easier to handle and compare relevant data with existing data. Similarly, data not relevant to any theme could be disregarded (Smith, 2015). The thematic approach was supported through thorough explanations of the hydrogen related activities, to give a further understanding of the themes before them being discussed and analyzed.

These themes and areas are based on a subjective judgment by the authors, which may lead to different interpretations of themes and their relevance by other researchers. The selection criteria used for the themes were relevance and context for the thesis, which was also discussed internally with the Volvo Group stakeholders to frame it. Further triangulation was used for the findings presented to strengthen their credibility.

2.5 Research Quality

When evaluating qualitative research, it is important to look at metrics such as credibility, validity as well as internal- and external reliability (Bell et al, 2019). These aspects are discussed below and were considered during the report process.

2.5.1 Reliability

With hydrogen being a new emerging area, common knowledge gained through the study will with high likelihood change quite rapidly in the future, so guaranteeing external reliability is difficult despite a thorough explanation of methodology. Qualitative research in general is also more difficult to replicate as no standard practices exist, as argued by Bell et al (2019). With regard to internal reliability, there are possibilities that misunderstandings occurred during the semi-structured interviews. However, measures were taken, such that both authors attended all interviews, and the interviews were recorded if possible to verify interpretations.

2.5.2 Validity

Regarding external validity, the question is to what extent findings in the study are generalizable to similar actors outside the study. Through the use of different stakeholders within Volvo Group, external suppliers, partners and key people of interest, alongside comparison of the multiple perspectives with data in the literature study, findings made should increase the external validity of the study as argued by Lewis (2009). The hydrogen area is however developing and reliant on geographical location. Therefore, there will most likely be multiple ways of interpreting the market and infrastructure of today, which means that the findings may not apply to a generalizable degree across sectors or even actors. Lastly, a technique called triangulation was used to assess internal validity. This is a way to add credibility to the study since author bias can influence the outcome.

2.5.3 Ethical Considerations

In a project of this manner, where interviews were held and used as a foundation for the empirical data, ethical aspects are important to take into account (Bell et al, 2019). Therefore, the authors made sure to provide interviewees with how and what the data was going to be used for, bringing a purpose to the data collection as well as enabling interviewees to participate anonymously due to privacy reasons. Also, since confidential topics were discussed, it was of importance to have discussions with interviewees whether specific information discussed could be published or not. These were all measures taken to ensure avoidance of harm and deceiving the participant, while respecting their integrity and privacy (Bell et al, 2019).

3. Literature Study

The chapter provides context to the subject by creating a foundation of hydrogen knowledge though a hydrogen introduction. It also creates understanding around the as-is infrastructure, its developments and purchasing scenarios.

3.1 Introduction to Hydrogen

Hydrogen (H2) is the lightest, most commonly appearing element in the universe. When found in its pure elemental state it is most commonly found as gas due to the more extreme mediums required for liquid and solid to exist (EIA, 2022a). The state of hydrogen is like any other element decided by its thermal energy and the strength of its intermolecular bindings, which is created by the surrounding conditions of temperature and pressure (Soult, 2020). Hydrogen has a common occurrence on earth in water and organic compounds, which means that when free hydrogen is desired it must be produced. This is achieved through forceful separation of compounds using various energy sources, which, due to hydrogens' reactive nature, comes at a great energetic cost (Agyekum et al, 2022; Soult, 2020). This means that hydrogen is not a source of energy itself, but rather an energy carrier that can be utilized as either fuel, storage or to create electricity (IEA, 2022b). Hydrogen as an energy carrier is interesting, partly because it emits no GHG emissions upon combustion but also, as can be observed in Figure 3 below, because it has a very high energy content per weight unit, almost three times as much as gasoline (DOE, n.d (a)). That coincides with a low energy content per volume unit though, about four times less than gasoline, which together with some other attributes of hydrogen like low ignition temperature, facilitates itself through transportation and handling difficulties (EIA, 2022a).

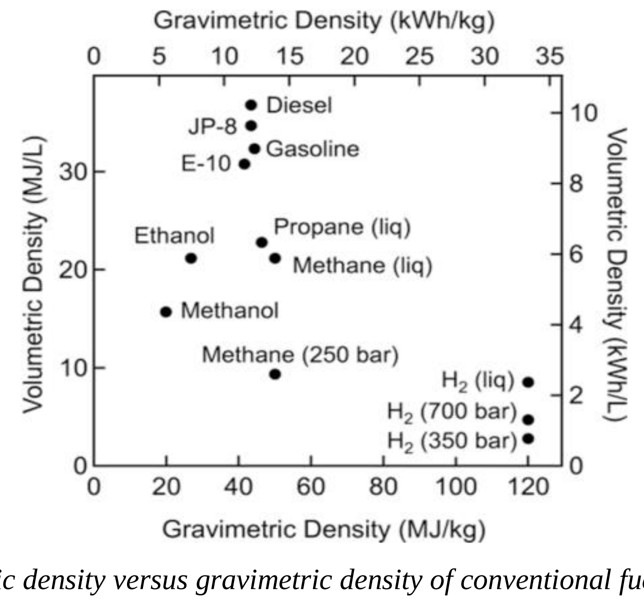

Figure 3. Volumetric density versus gravimetric density of conventional fuels (DOE, n.d (a)).

3.1.1 Hydrogen as a Fuel

The different phases of hydrogen fuel can be observed when looking at Figure 4 below, what is seen is that different phases carry different energy potentials. Cryo-compressed hydrogen is a technique that handles both liquid and gaseous hydrogen at cold temperatures (Langmi et al., 2022). This technique in conjunction with liquid hydrogen on its own, both look very interesting from an energy carrier perspective, but they require very low temperatures which come with high- storage requirements and handling costs. They are under development and therefore currently less utilized than compressed gaseous hydrogen (Langmi et al., 2022)

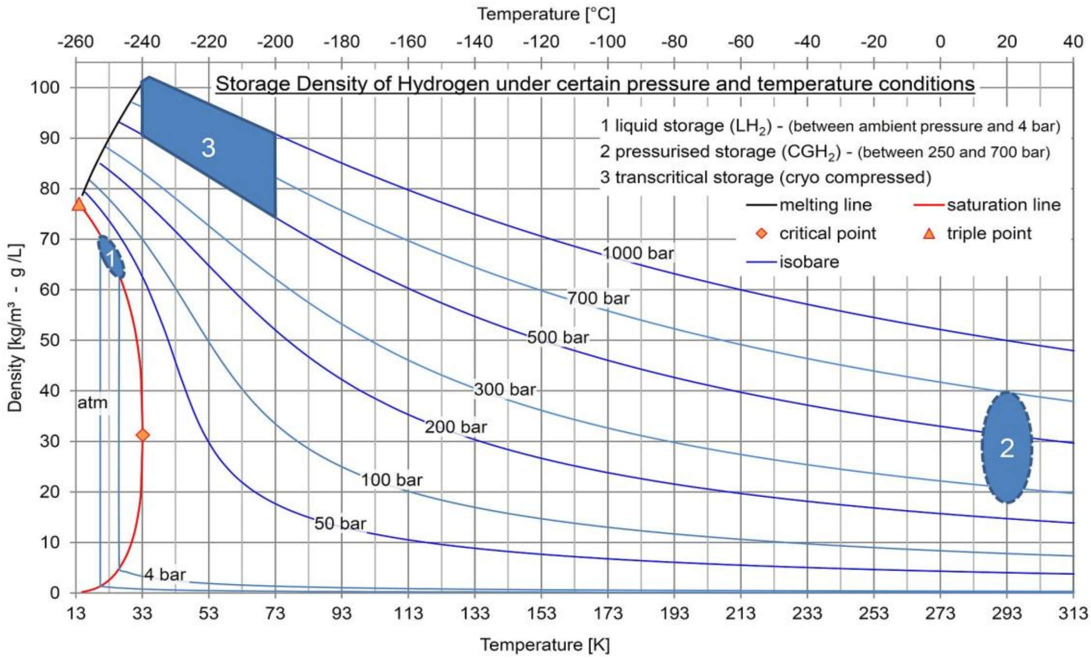

Figure 4. Hydrogen energy density, as dependent on temperature and pressure (Kuhn, 2015).

For hydrogen as gas there are multiple possible pressures in which it can exist, the different pressures dictate properties of the gas which in turn can affect things like efficiency reached in the engine, power output and the filling speed of refueling (IEA, 2023a). For personal vehicles like cars, where hydrogen deployment has come further, it is currently common to find it fueled by hydrogen gas at 350-700 bar pressure (DOE, n.d (a)). The lower end of this range is not sufficient in terms of power output for commercial vehicles (IEA, 2023a). Because hydrogen in the form of gas is currently used for personal vehicles, it is the most regulated type of hydrogen fuel and has come the furthest in terms of technological maturity in hydrogen fuel implementation (Volvo Internal documents). Therefore, even though there is not an established standard yet for commercial vehicles, which may result in various changes down the line, the natural transition will be through hydrogen as a gas for commercial vehicles (Volvo Internal documents). Which is why the focus will be on gaseous 700 bar hydrogen.

3.1.2 Hydrogen Colors

Hydrogen can be produced in many different ways and the resulting hydrogen is given a color code for categorization. This is in order to separate between the amount of carbon dioxide emissions the production method and its inputs has produced (Kusoglu, 2022). The different color definitions vary depending on source, in this report the colors are as follows: Green, Pink, Gray and Blue.

3.1.2.1 Green Hydrogen

Green hydrogen uses electrolysis of water through electricity generated from renewable energy sources. This is considered completely renewable with no emissions since the byproduct of the process is water and energy. This is the most desirable type of hydrogen releasing zero GHG emissions and can be used to achieve sustainable practices (Valavanidis, 2022). The process of electrolysis requires 40 kWh of electricity and 8.9 kg of water for 1 kg of hydrogen (Energy Futures Initiative, 2023).

3.1.2.2 Pink Hydrogen

Pink hydrogen is referred to as hydrogen that is produced with nuclear energy, which utilizes the process of fission (separating uranium) in order to create steam which then powers generators that generate electricity. This electricity is then used for the process of water electrolysis to produce “pink” hydrogen. The process of creating pink hydrogen has no GHG emissions but does use uranium which is a finite radioactive element and cannot be considered renewable in the same sense as green hydrogen (Valavanidis, 2022). The input is similar in process to green hydrogen, with 40 kWh of electricity and 8.9 kg of water needed for 1 kg of hydrogen (Energy Futures Initiative, 2023).

3.1.2.3 Gray Hydrogen

Gray hydrogen is an umbrella term for production methods which are based on fossil fuels and most commonly done through a method called steam methane reforming (SMR) (EIA, 2022b). This is the most cost-efficient method of producing hydrogen at a large scale today (Kim & Maxwell, 2022). It is also the method with the most GHG emissions out of the methods used (EIA, 2022b). The carbon emissions from producing gray hydrogen are explained by Energy Futures Initiative (2023) to be 5.5 times the amount of hydrogen produced. For example, per 1 kg of hydrogen produced there are 5.5 kg of carbon dioxide emitted. It is not clearly stated, but this 5.5 kg of emissions looks to target the SMR process only and not the full life cycle, which means that more emissions must be accounted for as well. The input requirement to get 1 kg of hydrogen is 5.7 kWh of heat, 4.5 kg of water as well as 2 kg of natural gas (Energy Futures Initiative, 2023).

3.1.2.4 Blue Hydrogen

Blue hydrogen is similar to gray, as it uses the same processes for production, but utilizes an additional system to capture the carbon emissions released during production and store it safely underground. This process is referred to as a Carbon Capture Storage (CCS) system (Kusoglu, 2022; Ishaq et al., 2022). The efficiencies of this technology, as can be read about in subchapter 3.1.3 below, are not clear. Blue hydrogen as a color is considered “lower emission” hydrogen as of now (Agarwal, 2022). If the goals of reaching the theoretical efficiency at 95 % expressed by (Global CCS Institute, n.d) were reached, that would be 0.05*5.5 kg = 0.275 kg carbon dioxide emissions per kg of blue hydrogen produced. This requires an additional 2.2 kWh of electricity to the gray hydrogen input in order to capture the carbon dioxide (Energy Futures Initiative, 2023). There is no data for lifecycle emissions, as described in the paragraph above 3.1.2.3 Gray Hydrogen, but it should be considered as well.

3.1.2.5 Turquoise and Other Categorizations of Hydrogen

Turquoise hydrogen is the result of a pyrolysis process that produces hydrogen from a methane hydrocarbon source, with the byproduct as carbon in solid form instead of carbon dioxide like other processes (Agarwal, 2022). Depending on how the solid carbon is utilized or disposed of it can have as little emissions as green hydrogen, or emissions closer in line with blue hydrogen. This “either or situation” results in the color in between the two - Turquoise.

There is other more “niched” categorizations of hydrogen. It can be important to note their existence, but there is no substantial availability of them and therefore no need to go into detail. The most relevant and considered colors are gray, blue, pink, and green. Therefore, these will be in focus during the thesis.

3.1.3 Carbon Capture Storage (CCS) System

The CCS system’s intended use is to capture carbon dioxide from processes or even the atmosphere and then store or use it in order to prevent the carbon dioxide from contributing to global warming (Nationalgrid, 2023). This allows for the possibility to lower the emissions from processes utilizing fossil fuels and making the end product more attractive. According to IEA (2021a), the process consists mainly of three steps: the capture part, the transport part and finally either the use- or storage part. Carbon dioxide is captured through various technologies, like chemical absorption or physical separation, it is then compressed or liquidized to ease the transport (IEA, 2021a). Usually, the transport is made with ships, pipelines, trucks, or tankers - which is dictated by the distance. For the use part, Herzog (2023) and Global CCS Institute (2022) talk about three different potential uses, the most common one today is in “enhanced oil recovery”. This is utilizing carbon dioxide gas to squeeze out the last oil in wells while replacing that oil with the carbon dioxide functioning like a storage. The two other uses are product creation and agricultural use. Where chemical companies are looking into making materials like carbon fibers or graphene from carbon dioxide, while the agricultural side aims to stimulate growth in plants, bacteria, and algae (Herzog, 2023). For the storage part, geological formations underground is utilized to store the carbon dioxide, which is then carefully monitored in order to make sure that there is no leakage (IEA, 2021a). This is deemed a key process in the transition phase into completely carbon free hydrogen at scale (Agarwal, 2022).

The goal of CCS reduction efficiency is aimed at the theoretically achievable 95 % (Global CCS Institute, n.d). The current efficiency is very difficult to determine, where sources vary a lot. The one source found with the most substance was Robertson and Mousavian (2022), which states that current efficiency of carbon capture technology is around 50 - 60 %. It is also commented that it is far lower in the trials conducted than expected, with a high majority (90 %) of projects also failing under implementation or getting suspended early. Other sources like c2es (n,d) state that achieved rates are around 90 %, but no comments are made as to in what scale these were achieved, if they were made on life cycle-based emissions or which projects these numbers were based on. Further, IEA (2022a) states that 90 % is an achievable capture rate from flue gas, meaning that this is on the production part only and not the full life cycle. It is stated that higher rates are needed for the net zero system, but no comments are made in regards to life cycle focus or requirements. Estimates are made in accordance with current projects pipeline that about 70 Mt carbon dioxide can be captured annually by 2030 on a global basis from hydrogen production (IEA, 2022a). Allowing the estimate to be 20 million tons of clean hydrogen to be available in blue color worldwide by 2030 (70 Mt / (5.5 - 2) kg = 20 Mt). Where 5.5 kg is from carbon emissions per 1 kg of hydrogen produced as explained in 3.1.2.4 above and 2 kg is from the clean definition in the paragraph below. 42.5 % of the carbon capture projects are in the U.S., which leaves the U.S. with 30 Mt of planned hydrogen related carbon capture available at 2030 (IEA, 2022a). Which allows for 8.6 Mt annually of blue hydrogen.

Carbon capture technology is a necessity to turn fossil fuel-based production “clean”, if the carbon capture efficiency is enough to meet the DOE standards of carbon intensity, which is maximum of 2 kg of carbon dioxide emission per kg of hydrogen produced - as can be seen as a quote in section 3.3 below from DOE (2022), then the hydrogen will be categorized as blue. According to Robertson and Mousavian (2022) the overwhelming majority (80 - 90 %) of carbon emissions from fossil fuel-based production is in “scope 3 emissions” which is a type of emission that carbon capture technology cannot do anything about. Hence, applying heavy critique to the potential of blue hydrogen when looking at the full life cycle of emissions. They are supported in their claims by Jacobson (2019), who found that about 10 - 30 % of life cycle emissions could be captured at a fossil fuel-based plant.

Producing gray hydrogen through SMR is described by EIA (2022b) as the most common way of producing hydrogen today. It is also the most cost effective way and is anticipated to continue to be the most utilized production method for larger scale production in the near future (Kim & Maxwell, 2022). Gray hydrogen, with the most carbon emissions and projected to be on the forefront going forward, leads to carbon capture technologies becoming increasingly important to meet the goal set up of decarbonizing society according to IEA (2020) and will play an important role in enabling a clean hydrogen economy (DOE, 2022a). Currently, there are not many large-scale carbon capture and utilization facilities operating in the world, and the ones that do exist are tied to big industrial processes like steel or cement and not related to hydrogen production (Herzog, 2023). Today, 35 - 45 Mt of carbon dioxide is captured annually and there are currently 35 commercial operations actively aimed towards industry (IEA, 2022a; Herzog, 2023). To put into context, there was a total of 9.2 Gt of carbon dioxide emission from industry alone in 2022, with 36.8 Gt in total emissions globally from all sectors. This means that at best about 0.1 % was captured globally (45 Mt / 36.8 Gt = 0.0012) (IEA, 2023b).

3.1.4 Takeaways from Introduction to Hydrogen

Hydrogen is a complex element which possesses favorable characteristics to help decarbonize society if it is produced accordingly. Because of these characteristics it is common to pressurize hydrogen at 700 bar in order to use it as a fuel today, which comes with limitations. Hydrogen also faces challenges due to the many ways to produce hydrogen, where the majority today is gray, and the production method heavily influences the sustainability aspect of hydrogen as a fuel. Carbon capture is an existing technology; however, the efficiency rates vary heavily by source. The difference between full life cycle emissions and emissions related specifically to the production process has a big discrepancy, focus should be on lowering the life-cycle emissions. Current project pipeline suggests availability of 8.6 Mt of blue hydrogen in the U.S. for 2030. But the life cycle versus process-based capture is still uncertain, leaving potentially less volumes available depending on the finalized definition of “clean hydrogen”.

3.2 Supply Chain Overview

The attributes found in hydrogen result in several challenges when it comes to fulfilling hydrogen demand at a specific location due to distribution and storage requirements (EIA, 2022a). Hydrogen can be produced and transported in different ways as well as it can be utilized at different states of matter (DOE, n.d (b)). Since the combination of volume and pressure dictates the state of hydrogen, that means that transitions can occur between the different states (Soult, 2020). This ultimately means that hydrogen can take many different routes towards end use. An important thing to understand is the costs involved in facilitating it. The whole supply chain can be viewed as a system, where all losses, condition requirements, and transitions should be considered for a total system cost of hydrogen from A to B in the supply chain (DOE, n.d (b)). This system cost can be divided into three equally costly parts, consisting of: production-, distribution- and conversion costs of hydrogen (Volvo Internal Documents). The two main categories of choices would be to either produce hydrogen at the location of demand or to produce hydrogen at a central location and transport it to the location of demand via either pipelines, ships, trailers or trucks (IEA, 2023c).

3.2.1 Hydrogen Production Methods

The production methods of hydrogen can be categorized into two main groups, first one being "clean hydrogen", that is hydrogen produced with renewable energy or together with a carbon capture storage (CCS) system and the second one "gray hydrogen", that is hydrogen produced with non-renewable energy and without a CCS. It can also be categorized based on the feedstock it uses as a resource, which is either water, fossil fuels or biomass (DOE, n.d (c)). Table 4 below illustrates the different production methods and their resulting color based on the categorizations mentioned. The definition of clean hydrogen can be found below in subchapter 3.3 and is based on DOE (2022).

Prerequisites to Produce		Clean Hydrogen			Gray Hydrogen
Feedstock Consumed	**Production Method**	**Renewable**	**Nuclear**	**CCS**	**Non-Renewable**
Water	Electrolysis	Green	Pink	Blue	Gray
Fossil Fuels	Steam Methane Reforming	-	-	Blue	Gray
Fossil Fuels	Partial Oxidation	-	-	Blue	Gray
Fossil Fuels	Autothermal Reforming	-	-	Blue	Gray
Fossil Fuels	Coal Gasification	-	-	Blue	Gray
Biomass	Biomass Gasification	-	-	Blue	Gray

Table 4. The resulting color of hydrogen, based on feedstock and production method.

3.2.2 Storage

Hydrogen storage is a key part of enabling a hydrogen supply chain, it is necessary for transportation, for stationary power generation and for portable moving applications (Tashie-Lewis & Nnabuife, 2021). Storage of hydrogen faces different challenges. One hindering factor is that when hydrogen is stored it has a much lower volume energy density compared to other fuels, such as diesel (DOE, n.d (a)). This results in larger volume systems needed, which has a big impact on portable power generation solutions (in for example trucks) and also in hydrogen transport (Tashie-Lewis & Nnabuife, 2021). With larger storage systems, a lot of space is occupied but also requires higher investment costs. Another challenge of storing hydrogen relates to its flammable characteristics, which concerns safety issues and requires additional protocols (Tashie-Lewis & Nnabuife, 2021). Lastly, the key challenge mentioned by Agarwal (2022), is the huge uncertainties and expenses that are involved in building the hydrogen infrastructure, with storage system development as one of the key challenges within.

There are a couple of different solutions to storing hydrogen, which differ depending on storage-time. Currently, a mature and cost-effective solution for small scale and short-term storage, is compressed gas in high pressure tanks (Clarke et al, 2022). High pressure tanks have the problem of volume density, despite being a mature technology, it is limited by how much hydrogen it can store and doesn't scale economically to higher volumes very well (Tashie-Lewis & Nnabuife, 2021). Another short-term solution but for way larger volumes would be in gaseous form in pipelines known as "line packing" (Pascal, 2022). Line packing can be used to store hydrogen within pipeline networks by continuous alteration of pressure, however it is not a feasible long term storage solution and the amount of hydrogen pipelines available is very low (Pascal, 2022).

For medium- and long-term solutions, hydrogen can be stored in liquid form in cryogenic tanks, within chemical carriers like ammonia or in underground geological formations (IEA, 2021b). Liquid hydrogen in cryogenic tanks has a lot greater volume density than gaseous hydrogen, which means that it scales better with volume and is more economically viable at larger quantities. The process of liquefaction is however expensive and relies on specialized equipment and processes for maintenance of very cold temperatures (-253°C) (Tashie-Lewis & Nnabuife, 2021). The chemical carrier route, specifically ammonia, is a popular method of longer-term storage which the agriculture sector utilizes diligently (Aziz et al, 2020). However, its use as a fertilizer doesn't translate well when intended for hydrogen fuel use, the storage medium requires two transitions - from hydrogen to ammonia and then back. Thereby increasing the ownership cost a lot (Aziz et al, 2020). There are studies of using ammonia as a fuel without cracking it (transitioning it back to hydrogen) which could be an interesting avenue if successful to utilize a cost effective and proven way of both hydrogen storage and transportation for the combustion part as well (Aziz et al, 2020).

Geological underground storage is most commonly done through the use of salt caverns, which enables large quantities of hydrogen to be compressed and injected into the salt rocks for safe storage (Mokhatab et al., 2018). This method is considered by many to be the best solution regarding storage of hydrogen (Lankof et al., 2022). However, underground formations like salt caverns have long lead times, flushing out the residues to make room for the gas can take between 2-5 years (Neuman & Esser Group, 2022) whereas permits and construction could be 7 years not including planning time (Hystock, 2022). Still, methods like salt caverns are a proven technology that has been implemented since the 70's. And its underground storage offers a set of advantages compared to above ground storage, mainly because costs are significantly lower. However, despite its industrial adaptation, salt caverns are regionally dependent due to geographical conditions and cannot be applied everywhere (IEA, 2021b).

3.2.3 Transportation of Hydrogen

Hydrogen can be transported as a compressed gas, as a liquid or within a chemical carrier (IEA, 2023c). Optimal choice will be case specific depending on final use, but the general rules explained by Hydrogen Council (2021) is that hydrogen transportation will behave very similarly to natural gas transport solutions. Where large volume combined with large distance is economically best done by shipping. Medium and short distances dominated by pipelines and trucking as a more expensive but flexible complement (Hydrogen Council, 2021). Natural gas solutions have had tremendous investments made in infrastructure, which make it unlikely that hydrogen can just copy best practices in neither the short- nor the medium term.

Hydrogen has a very high versatility in terms of possible solutions and usages, this requires careful and systematic analysis to avoid inefficient and costly infrastructure (IEA, 2021b). Pipelines are going to be key due to cost reasons observed in the natural gas case, but they involve and require a lot of upfront investments (Hydrogen Council, 2021). There are possibilities to retrofit current natural gas pipelines into hydrogen pipelines, which could reduce costs down to ⅓ of building new pipelines according to Hydrogen Council (2021). Clarke et al (2022) found that costs for laying retrofitted pipelines could be as low as 10% of new pipelines when factoring in necessary network planning permits that new pipelines would require. Currently in the US, there are over 3 million miles of gas pipelines, where about 1.600 miles of pipeline is dedicated to transporting hydrogen (EIA, 2022c).

Whichever way the infrastructure will be built, pipelines are both a costly investment and time consuming to build and/or retrofit. The pipeline solutions will take many years to build on a larger scale, however locally, given a favorable business case it could be arranged for shorter distance microgrid solutions sooner (Volvo Internal documents). In terms of larger scale infrastructure, adding to the fact that it takes years to build, careful planning is necessary due to the investment risks involved, which may add several years to that timeline. IEA (2021b) points to the fact that the high upfront investment costs for hydrogen pipeline infrastructure will be a problem when demand is still prospective and regulatory frameworks are yet to be established.

One shorter term solution could be blending hydrogen with other natural gases, this way existing infrastructure of pipelines could transport hydrogen given its smaller demand in comparison (Mahajan et al, 2022; Topolski et al, 2022). Only a small amount of refurbishment could enable around 15-20% of hydrogen to be blended into the existing natural gas system (Melaina et al., 2013). However, IEA (2023a) points out that due to characteristics of hydrogen, embrittlement happens faster and would therefore reduce the lifetime of current natural gas pipelines. They refer to the American standard ASME B31.12, for the specific requirements and stricter rules around hydrogen pipelines. This would also require a gas separator solution at the hydrogen usage point when high purity is required (Topolski et al, 2022).

3.2.4. Hydrogen Offtakers and Avenues of Utilization

There are many potential and already existing offtakers of hydrogen. It is important to mention all of them in order to understand the hydrogen supply chain for the as-is situation, despite the focus of the report being on the transportation sector.

3.2.4.1 Existing Offtakers

The existing offtakers of hydrogen are actors in industries who utilize it as a feedstock for production of another product (IEA, 2019). This can either be by using hydrogen as a direct source, like in heating or chemical processes or it could be in the making of fuels with hydrogen as its base (Energy Futures Initiative, 2023). The specific U.S supply and demand partition is further elaborated in section 4.4 below.

The largest offtakers of hydrogen in the U.S are refineries, which use hydrogen as input in order to facilitate the operations to make petroleum. Because of their large offtake, refineries often utilize SMR to make their own hydrogen to be used at the refinery (captive hydrogen). Refineries are also said to create hydrogen as a by-product when utilizing chemical processes in the production of petroleum (EIA, 2016).

Another large area for hydrogen offtake in the U.S is explained by Energy Futures Initiative (2023) to be the chemical industry and processes. Where ammonia and methanol are the largest offtakers used for industrial products. Similarly to petroleum refining, the chemical industry uses hydrogen to facilitate operations, while ammonia- and methanol production uses hydrogen as a feedstock for their respective products. Ammonia is primarily used for agricultural industries as fertilization while methanol is used for plastics and fuels. Therefore, similarly to petroleum refineries, ammonia- and methanol producers also make their own hydrogen commonly though SMR technology.

3.2.4.2 Transportation Sector

The use of hydrogen in transportation is currently quite limited, however there are various options for it being developed. The use today is mostly as rocket fuel for space exploration, with small amounts for hydrogen cars - specifically in California when it regards the U.S. Other transportation avenues are shipping, garbage trucks, buses, and heavy-duty vehicles. Rocket fuel is an outlier in terms of how they require hydrogen delivered, but for the others, with heavy duty as the focus of the report. Refueling stations are key.

An interesting part for the transportation sector at the end of the hydrogen supply chain is the hydrogen refueling stations (HRS). They enable storing- and fueling of hydrogen and is considered a crucial part in order to accelerate the deployment of FCEVs around the world (Genovese & Fragiacomo, 2023). As previously mentioned, hydrogen fuel in gaseous form has come the furthest in hydrogen fuel implementation, it is therefore currently common to find HRS with hydrogen in gaseous form at 350-700 bar pressure (DOE, n.d (a)). If other fuel technologies like liquid hydrogen gains usage in vehicles, the HRS available will most likely cater to that, similar to how both diesel and petrol are available in other fueling stations.

HRS are, however, limited by the high investment costs needed, the uncertainty of the demand as well as the insufficient connectivity of the infrastructure. This leads to HRS being developed in areas which are considered early adopters of FCEVs (Genovese & Fragiacomo, 2023). It is stated in the Road Map to A US Hydrogen Economy (2020) that policies in such areas act as enablers for the advancements of HRS and development of the hydrogen economy. Because of this, it is important to analyze and consider where to develop HRS, as it cannot be developed in the same way as for traditional petrol gas stations (Lin et al., 2020). Safety, location, demand, interoperability, and cost are important factors to consider in order for a HRS infrastructure to be developed effectively (Lin et al., 2020).

When looking at the U.S, the state of California stands out as an area which is leading in the HRS infrastructure advancement. That has resulted in all the current 57 HRS available in the U.S to be located in California according to a tracking tool provided by the Department of Energy (U.S Department of Energy, n.d (a)).

As of now, there are currently 38 other HRS planned in the U.S in the short term, but it is also increasing with the on-going developments happening in the U.S. Out of the identified 38 projects, 32 of them build on to the current infrastructure available in California (U.S Department of Energy, n.d (a)). But there are also developments expanding throughout the U.S, where five HRS can be seen on the east coast in close proximity to New York, located throughout the Interstate-95 and one in Ohio (U.S Department of Energy, n.d (a)). From H2 Matchmaker (n.d), another digital tool can be found, it is developed by The Department of Energy in order to highlight hydrogen projects in the U.S. In it another eight planned HRS can be found on the east coast of the U.S but it is not stated when they are planned to be developed.

California is not an area of interest for this thesis, due to the distance from Volvo Group plants, but also since their focus is more aimed towards light-duty passenger vehicles rather than heavy-duty (Road Map to A US Hydrogen Economy, 2020). It is however of interest to look at California to see how developments have been made in this region. The reason why all of the current HRS are located in the state of California is due to their public-private collaborative approach as well as their regulatory approaches in incentivizing decarbonization. As an example, in California there is a law to have 100% of the light- and medium vehicles sold to be ZEVs by 2035, with similar restriction for heavy duty at 2045 (U.S Department of Energy, n.d (b)). Resulting in all of the HRS being publicly funded and therefore incentivized to be developed (Road Map to A US Hydrogen Economy, 2020). The reason for developments beginning to form in the northeast area can be connected to the legislative enforcements of zero emission vehicles (ZEV) made in New York, which are adopted by Californian standards (U.S Department of Energy, n.d (b)) This standard aims to incentivize ZEV refueling stations by granting funding for developments, as well as further state initiatives such as an infrastructure tax credit (U.S Department of Energy, n.d (b)). This likely needs to happen in other states as well for them to also start planning HRS. The hubs may very well push for this. Overall, it would be fair to assume that the recency regarding hydrogen development and the hydrogen hubs will create expectations for more than the 46 HRS mapped to be developed over the longer term. But there is no certainty as to where or when these will be mapped or later implemented.

3.2.4.3 New Avenues

According to the Energy Futures Initiative (2023) there are several industries which can utilize hydrogen in order to decarbonize their processes. They further argue that some of these industries are more able to adapt and implement clean hydrogen in their processes than others.

One of these industries is the steel industry where hydrogen can be used instead of carbon-based feedstock, for heating and chemical reactions. Which would remove the carbon emissions and leave end products of steel and water. This similar process of using hydrogen as a feedstock for heating is said by IEA (2019) to be used for other industries as well which require high heating temperatures. Such industries are described to be, for example, glass-making industries. Hydrogen heating can also be utilized for commercial heating but is said to be less efficient compared to today's options (IEA, 2019).

Another avenue for hydrogen is that it can also be used to give stability to the renewable electricity grid, where a fluctuating nature in both use and price is common (Frankowska et al, 2022). Hydrogen production could be utilized at favorable times for electricity producers, given available storage solutions, to meet hydrogen demand at a fair production cost and find use for the electricity produced when general usage is low (Tashie-Lewis & Nnabuife, 2021). They also say that it could act as an energy backup for emergencies or power outages.

3.2.5 Supply Chain Takeaways

Hydrogen is an element that is difficult to handle from its inherent characteristics, but that also makes it very versatile, where it can be utilized in many of its different states and through different hydrogen vectors like ammonia. The existence of both clean- and non-clean hydrogen stems from its production method and geographical resource availability. Storage is one key aspect of the supply chain which faces challenges, from the volume density characteristics and flammability. The storage systems need to be large while also safe and non-penetrable, which is expensive. The storage solutions will need to be both above ground and underground, with underground storage heavily dependent on geographical location and cavern availability. The transport solutions are looking to match best-practice solutions with natural gas; however, copying will not happen in the short to mid-term due to the heavy investments and planning that has gone into the natural gas grid system. Refueling infrastructure is key for the customer business case in transportation. There are developing refueling stations in the U.S but still very focused on California, with New York attempting to follow. The rest of the country is far behind. Different states of hydrogen can be optimally stored, transported, and utilized in different ways. It is important to understand that all the different factors should be accounted for and that a system view is important when evaluating the costs and emissions of hydrogen.

The key long-term solutions will be pipeline developments and underground storage solutions due to the geographical dependencies of both hydrogen production, carbon storage and hydrogen storage. This has a long timeline when looking at permits, the scale of the investment decision that must be made and is heavily dependent on uncertainties regarding technologies and their advancements. Current offtakers of hydrogen are heavily involved in emitting carbon dioxide and the majority of the hydrogen use further accelerates more fossil fuel use and more carbon emissions. There are however multiple new avenues of hydrogen use, where utilization is heavily dependent on the clean aspects and the decarbonization capabilities. This may speed up technological advancements as the market becomes a target for both interest and investments.

3.3 Hydrogen Developments in the U.S

The U.S has been considered underdeveloped in the field of hydrogen when compared to other regions, such as Europe and Japan (IEA, 2023a). Developments and innovations in the hydrogen technology market are dominated by large European chemical companies who specialize in the development of fuel cell- and electrolysis technology, which have acquired them a competitive advantage (IEA, 2023a). Even though hydrogen technology has been around for a long time, it has not been a priority in the U.S, as policies regarding hydrogen have seen almost no change during the past 20 years (Kim & Maxwell, 2022).

The U.S governmental structure is organized in three different levels; federal, state, and local. Decisions voted on and passed by the federal government are to be implemented through federal and state- collaboration, where incentivization is used based on the laws and regulations in that state (Kim & Maxwell, 2022). Different frameworks are used for different states to determine their comparative advantages depending on resource access, which means that regulations and incentivization will differ depending on state (Medlock & Shih Yu, 2023).

Since 2017 there has been an annual average investment of $150 Million towards increasing the public hydrogen infrastructure and fuel cell program by the U.S Department of Energy (Agarwal, 2022). In 2020 the U.S developed a hydrogen roadmap, a hydrogen program plan, and a hydrogen strategy during the same year. Which can be seen as frameworks for developing and enabling a hydrogen economy (Agarwal, 2022). The following year (2021), the Hydrogen Shot Program was released with the main goal of lowering the current high costs of clean hydrogen at $5/kg, with the targeted goal of $1/kg for clean hydrogen by 2031 (U.S Department of Energy, 2021). The Department of Energy defines clean hydrogen as:

"Hydrogen produced with a carbon intensity equal to or less than 2 kilograms of carbon dioxide-equivalent produced at the site of production per kilogram of hydrogen produced (<2 kg CO_2e/kg H_2)". (DOE, 2022a)

Further, there are discussions on-going for the U.S. Department of Energy to enforce a clean hydrogen production standard as well. This would consider the complete lifecycle of hydrogen production, rather than just considering the production cite as stated above. The current draft considers an initial target of < 4 kg CO_2/kg H_2 for the entire lifecycle (DOE, 2022b).

Two additional major acts have been passed, to increase the hydrogen- market and development capabilities of the U.S. Which is an illustration of the measures taken to catch up with other regions in hydrogen development and realize the strived for, common national strategy for hydrogen (Gherasim, 2022). The two acts are *"The Infrastructure Investment and Jobs Act"* (IIJA) and *"Inflation Reduction Act"* (IRA).

Initiative	Year	Goal
Hydrogen Roadmap, Program Plan and Strategy	2020	Frameworks for enabling a hydrogen economy.
Hydrogen Shot Program	2021	Reducing current hydrogen prices by 80 % in the coming decade. "1-1-1 goal", 1 dollar per 1 kg in 1 decade.
The Infrastructure Investment and Jobs Act (IIJA)	2021	Accelerate hydrogen production, use and deployment. $ 8 billion funding to 6-10 regional hydrogen hubs. $ 1 billion funding to clean hydrogen manufacturing programs. $ 500 million to clean hydrogen electrolysis program.
Inflation Reduction Act (IRA)	2022	10 year clean hydrogen production tax credit, max $ 3/kg, based on CO2 intensity. Investments tax credits for manufacturing projects; FCEV, hydrogen infrastructure, electrolyzers, carbon capture systems, etc.

Table 5. Summary of the key initiatives mentioned.

3.3.1 The Infrastructure Investment and Jobs Act (IIJA)

One of the major acts the U.S government passed in order to improve the general transportation and infrastructure of the U.S is the IIJA, also known as the Bipartisan Infrastructure law. It has a funding of $550 Billion allocated towards new investments over the five coming years. In the IIJA, according to the U.S Senate (2022) there is $65 billion aimed towards: *"power and grid"*, which considers technologies such as hydrogen and is relevant for this thesis. Of that $65 billion there is a total of $9.5 billion allocated towards hydrogen specifically (U.S Department of Energy, 2022). The act considers and aims to develop the domestic production, use and deployment of hydrogen with the end goal of accelerating the widespread use of hydrogen throughout the U.S. The act is an essential part in moving the U.S towards an hydrogen economy, as it enables and embraces research and development regarding hydrogen technology and infrastructure (Kim & Maxwell, 2022).

The act was passed by the Biden administration in November 2021 to achieve the goals of the U.S Government, which aims for a 100 % clean electricity grid by 2035, as well as having net-zero emissions by 2050 (U.S Department of Energy, 2022). These are the same goals as Europe has. With regard to hydrogen, the goal of the act is to accelerate the development of the complete hydrogen value chain from hydrogen- supply, storage, distribution and end use applications (IEA, 2023c). The IIJA requires developing hubs to consider the industrial end use of the four sectors: industry, transportation, power and heating. To incentivize developing hydrogen projects to work in hubs and to adhere with the considerations, the IIJA pledged $ 9.5 Billion funding for development of six to ten regional hydrogen hubs authorized through 2026 (Office of Clean Energy Demonstrations, 2022). Beyond the four-sector focus, the Department of Energy which was put in charge of the monetary distribution from the IIJA, demands that the hub focuses on clean hydrogen manufacturing as well as renewable electrolysis price reduction (U.S Department of Energy, 2022). The total funding of the act is distributed between the period of 2022-2026. The act results in $8 Billion funding towards regional hydrogen hubs, $1 Billion towards a clean hydrogen roadmap to reduce costs and technical complexity. Lastly, $500 Million towards research and development of electrolysis technology (U.S Department of Energy, 2022).

3.3.2 Inflation Reduction Act (IRA)

Another major act related to this thesis is the Inflation Reduction Act (IRA), which was passed by the U.S Government in August 2022. With regard to hydrogen, the IRA adds on to the existing framework established in the IIJA of accelerating hydrogen developments in the U.S, such as extending already existing tax credits (Medlock & Shih Yu, 2023). This act is the most significant policy regarding hydrogen in the history of the U.S (Energy Futures Initiative, 2023). It is considered a heavily influential enabler of hydrogen production within the U.S and seen as very competitive for the global hydrogen market (Gherasim, 2022). What makes it so powerful is the incentives available for the hydrogen market, with heavy subsidies and available tax credits for both producing and investing in hydrogen. Incentives such as tax credits are described by Nellen and Miles (2019) to be an important tool to consider in order to encourage companies and to promote sustainability aspects. These incentives are applicable for investments in hydrogen technology, infrastructure, and production, with subsidies heavily targeted at big hydrogen hub structures that cluster together knowledge, research and favors big-scale collaboration (The Department of Energy, 2022).

The following sections from the IRA which are important for the scenario analysis of this thesis will now be presented, based on a summary of information from the Department of Energy on the IRA, called Inflation Reduction Act Summary (n,d). This will constitute the source in these following subchapters if nothing else is stated up until subchapter 3.3.3 “Hydrogen Development Takeaways”.

3.3.2.1 Advance Energy Project Credit (48C)

This credit is an extension of an already existing tax credit called (*“S.622 - American Jobs in Energy Manufacturing Act of 2021”*), In the IRA, this is extended to fulfill up to 30% tax credit for projects supporting energy conservation technologies and clean hydrogen production. Examples of such projects are electrolyzers, FCEV production and associated charging infrastructure. The credit aims to provide $ 10 Billion as funding for projects, which will be divided over time for projects applying. The starting date for initial funding projects is 31st July 2023. The amount of tax credits granted for a project is dependent on the carbon intensity of the produced hydrogen, however, to fully qualify there are also subordinate requirements related to labor wages and working quality. The credits received increases with decreasing emissions, where the maximum tax credit can be reached at 30% of project cost. To see full tax credit rates, see Table 6 below.

3.3.2.2 Clean Hydrogen Production Tax Credit (45V)

The IRA imposes a new tax credit which is called "45V" for hydrogen production of up to $3/kg depending on the carbon emissions of the hydrogen produced, this is a tax credit that will be applicable for up to ten years (DOE, n.d (d)). It is also stated by the Department of Energy that the credit can be combined with the investment tax credit 48C, which is described and mentioned above. To be eligible for the credit, hydrogen projects must start construction prior to 2033, but will have a ten-year rolling time span from project beginning (latest run out in 2043). The tax credit eligibility increases with decreasing emissions of hydrogen production, see Table 6 below for price production tax credit rates.

Carbon Intensity per kg of Hydrogen	Tax Credit per kg of Hydrogen (45 V)	Tax Credit of Project Cost (48C)
4 - 2.5 kg	$ 0.6	6,0%
2.5 - 1.5 kg	$ 0.7	7,5%
1.5 - 0.45 kg	$ 1.0	10,0%
0.45 - 0 kg	$ 3.0	30,0%

Table 6. The tax credits 45V and 48C visualized (DOE, n.d(d))

3.3.2.3 Alternative Fuel Refueling Property Credit (30C)

Another extension of an already existing tax credit (*"S.975 - Securing America's Clean Fuels Infrastructure Act"*), which enables alternative fuel refueling properties like hydrogen refueling stations**,** to get a grant up to 30 % of cost as tax credit, with a maximum of $100 thousand dollars per unit.

3.3.2.4 Carbon Capture and Sequestration Credit (45Q)

As mentioned previously, the IRA incentivizes development of clean hydrogen, which is dependent on renewable energy development and carbon capture solutions. Therefore, the IRA extends and increases another tax credit (*"S.986 - Carbon Capture, Utilization, and Storage Tax Credit Amendments Act of 2021"*) which takes this into consideration. The tax credit is called "45Q" and refers to tax credits which give incentives for CCS, storage, and utilization (DOE, n.d (d)). All of which is key for producing blue hydrogen, which is based on fossil fuels (Ishaq et al, 2021; Agarwal, 2022). Similarly to the 45V credit, to be eligible for the 45Q credit, hydrogen projects must start construction prior to 2033. Important to mention is that the 45Q tax credit is not stackable with the 45V credit.

3.3.3 Hydrogen Development Takeaways

As seen in the chapter, there are many incentives to industrialize and accelerate the clean hydrogen market with considerations to many parts of the hydrogen value chain. Overall, the two acts aim to increase hydrogen related- capacities and technologies in order to lower production prices for hydrogen. The intent is that this will enable a competitive market landscape, with a lot of interest from a variety of actors to take part, by utilizing the available incentives and tax credits to organize for hydrogen development.

3.4 Regional Hydrogen Hub Developments in the U.S

With the passing of the IIJA Act, came the foundation for development of six to ten regional hydrogen hubs that will be operating around the U.S (U.S Department of Energy, 2021). They are seen as vital parts in enabling the clean hydrogen economy for the U.S (Gherasim, 2022; Medlock & Shih Yu, 2023). Important to note here is how a regional hydrogen hub is defined according to the IIJA:

"a network of clean hydrogen producers, potential clean hydrogen consumers, and connective infrastructure located in close proximity." (DOE, 2022a).

Where exactly these six to ten hubs are to be located is not decided yet. However, regions of interest for hub developments have been identified by the Department of Energy as a result of the Hydrogen Shot initiative (DOE, 2021). The regions are made up of several states and each cluster has specific geographical characteristics and advantages that would favor the development of a hub, as seen in Figure 5 below. These clusters divide the U.S country into nine different regions (DOE, 2021). The specific location of a hub will depend on several different criteria and considerations of regional- resources, influences, and end-uses (DOE, 2021). This will help determine and compare regional advantages for hydrogen developments which are based on the governmental policies and frameworks present for that region in the U.S (Medlock & Shih Yu, 2023).

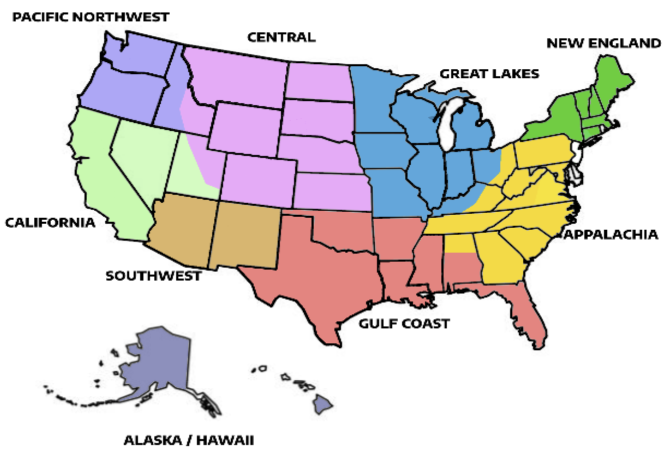

Figure 5. Regional clusters in the U.S (DOE, 2021).

As of now, the process of developing hubs is in the first of four initial steps which is the concept stage. Here, applicants can apply for the grants enabled by the IIJA, which up until publication of this report, has resulted in 79 applicants. Of these, 33 have been granted "encouragement" to advance in the process towards a full application (Office of Clean Energy Demonstrations, 2022). However, encouragement towards full application does not mean that the concept is selected for development, but rather going to the next phase of selection. Where a continued improvement to the concepts and involved actors is expected. This means that concepts do not include currently available capacity but focus on planned potential future capacity. The U.S Department of Energy (2022) specifies that the hubs that proceed through all application phases, will be hubs that can provide a formal feasible plan, with experienced expertise, a time schedule, a good funding structure, wide capacities and will provide communal benefits alongside contributing to a hydrogen network in the country.

The Department of Energy has also released a Notice of Intent stating different selection criterias for the hubs to be developed. Such criteria state that a hub shall have the production capacity of clean hydrogen to be a minimum of 50-100 tons (Metric tons) per day (DOE, 2022a). Other criterias for the selection of hubs to be developed regard the different resources available in the U.S. Therefore, the following different criterias are set up by the (DOE, 2022a):

- At least four hubs should be developed in separate regions of the U.S.
- At least one hub should be based on fossil fuels, with CCS.
- At least one hub should be based on renewable energy.
- At least one hub should be based on nuclear energy.
- At least two hubs should be located in regions which are rich in natural gas.

3.4.1 Areas of Interest

The Volvo Plants are located in the eastern U.S as can be seen in Figure 6 below. By following the resource delimitations set in subchapter 1.4, the regional clusters of interest for this thesis are therefore the east side region clusters. This is because hydrogen is costly and difficult to transport, which requires solutions with close proximity to the plant (Volvo Internal Documents). The addition of the Gulf Coast region was made, due to the existing presence of Volvo Group key suppliers, as well as Texas natural gas resources and pipeline network connecting most of the U.S (Medlock & Shih Yu, 2023). The regions selected are Great Lakes, Appalachia, New England, and The Gulf Coast - also marked in Figure 6 below.

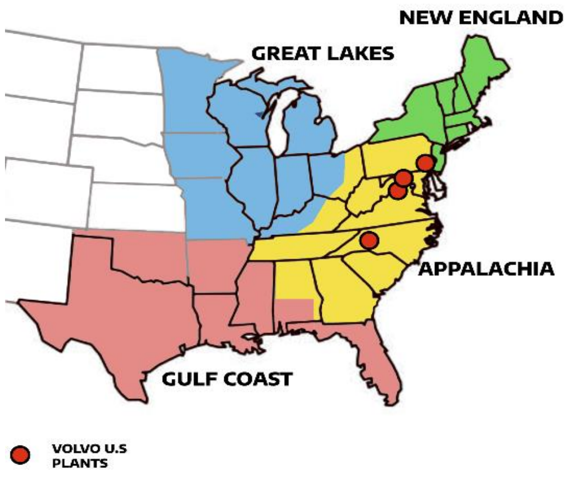

Figure 6.The Volvo Group U.S plants with hydrogen interest together with the regional clusters of interest (Volvo Group Internal Documents).

3.4.1.1 Great Lakes

The first regional cluster of interest is the Great Lakes, which according to DOE (2021) considers the states of Ohio, Michigan, Illinois, Indiana, Wisconsin, Minnesota, Iowa, and Missouri and is highlighted in Figure 6 above.

The regional cluster is located in the northeast of the U.S and considered a region of interest for a hydrogen hub by the Department of Energy due to its connection to industry and potential end consumers, where for example industries in the state of Ohio are seen as major offtakers of hydrogen (University of Toledo, n.d). The region is described by DOE (2021) to have a strong steel- and chemical industry, which all are considered big potential end users of hydrogen, as well as enablers of the currently established long-haul trade corridors available. The Great Lakes also have a great potential for storage of natural gas, as exemplified in Michigan, with the state possessing the most natural gas storage fields in the country according to EIA (2022d). Michigan also has existing salt caverns which can be used to store hydrogen (DOE, 2021). This regional cluster is the location with the most nuclear power plants in the U.S, in total 11 plants capable of 20500 MW of nuclear energy (University of Toledo, n.d).

The Great Lakes energy consumption comes, however, mainly from coal, nuclear power and natural gas, the latter which is connected through the current available pipeline network in the U.S (EIA, 2022c). In terms of renewable energy generation and consumption, it is low in the Great Lakes compared to its natural gas and coal consumption. Michigan is the leading state in the region with renewable energy production totaling 11 % of Michigan's net generated energy (EIA, 2022d).

3.4.1.2 Appalachia

Appalachia is a regional cluster which according to DOE (2021) consists of Ohio, Pennsylvania, West Virginia, Indiana, Virginia, Tennessee, Georgia, North Carolina, South Carolina, Kentucky, and Alabama as highlighted in Figure 6 above.

Appalachia's main source of energy comes from the great resource availability of natural gas, which makes this regional cluster the biggest producer of natural gas in the U.S (The Appalachian Energy and Petrochemical Renaissance, 2020). The northern region of Appalachia accounted for the biggest increase in natural gas production during the last decade, accounting for 85% of the growth in the whole U.S during that period and is forecasted to continue growing the coming decades (The Appalachian Energy and Petrochemical Renaissance, 2020). Appalachia has a well-connected natural gas pipeline infrastructure which can be utilized to potentially deliver hydrogen blended with natural gas. These major pipelines are connected to, for example, the Gulf Coast. The northern Appalachia is therefore a central point for distribution of natural gas for the east of the U.S (Singh et al., 2022).

The southern part of the regional cluster is more dependent on coal, as it historically has been known for its coal mining capabilities (The Appalachian Energy and Petrochemical Renaissance, 2020). Besides natural gas and coal as sources of energy, Pennsylvania stands out in comparison with the other states of the Appalachia because of their utilization of nuclear power, accounting for around 40% of electricity generated in the state, which also makes them the second biggest state in the U.S to do so according to EIA (2022e).

Even though the possibility for developing green hydrogen is low in this regional cluster, it is still considered an area of interest, as at least two hubs will be based in regions that are rich in natural gas DOE (2022). Also because of the existing infrastructure of natural gas found in northern Appalachia together with its storage capacity and industrial demand in the region (The Appalachian Energy and Petrochemical Renaissance, 2020). This drives the potential to generate large amounts of blue hydrogen and gives Appalachia an advantageous position (Singh et al., 2022). According to DOE (2021) the biggest industrial sectors in the region are steel, cement and chemicals, which are sectors that constitute the majority of potential end consumer volumes of hydrogen, thereby increasing the region's appeal for a hydrogen hub.

3.4.1.3 New England

New England is a regional cluster that according to DOE (2021) consists of the following states: New York, Connecticut, Massachusetts, New Jersey, Rhode Island, Maine, and Vermont and is highlighted with green in Figure 6 above.

The region has good capabilities of producing electricity based on nuclear energy and renewable energy sources (DOE, 2021), which allows for potential pink and green hydrogen production. The greatest producers of renewable energy in the cluster are Maine and Vermont, where the latter generated almost 100% of their electricity from renewables (EIA, 2022f). Maine stands out in the cluster due to its coastal advantages in the Gulf of Maine, which has great resources for renewable energy in hydro-, solar- and offshore wind power (DOE, 2021). There are also nuclear power capabilities in the state of New Jersey, where currently the majority of their electricity produced is generated from nuclear power (EIA, 2022g). However, it is not sufficient yet to cover the whole region, as natural gas is the major resource used to generate electricity in the U.S as well as in this regional cluster as a whole (EIA, 2023a).

3.4.1.4 The Gulf Coast

The last area to be looked at in more detail is the Gulf Coast Cluster, which according to DOE (2021) considers the states of Texas, Mississippi, Alabama, Louisiana, and Florida and is highlighted in Figure 6 above. The regional cluster is considered to have a good starting point in the developing hydrogen market due to their already established competitive advantage in the natural gas market and geographical location (Medlock & Shih Yu, 2023). This is based on the fact that the region already has a very strong and mature industrial sector, where the main competence is in the oil and gas, as well as the chemical sector (DOE, 2021). Another key element is the already existing hydrogen market and infrastructure existing in the region of the state of Texas (Medlock & Shih Yu, 2023). In the U.S today there are 140 operational hydrogen plants, 43 of which are in the state of Texas (Medlock & Shih Yu, 2023). Looking at the infrastructure, there are currently over 1.000 miles of hydrogen pipelines located in Texas out of 1600 miles total in the U.S (DOE, 2021).

Geographical advantages that the regional cluster possess revolve around their natural gas and oil assets. However, the state of Texas has great solar and wind access as well, which allows for great potential in generating renewable energy (EIA, 2023b). There is also great long term storage availability of carbon dioxide and hydrogen in the region (Medlock & Shih Yu, 2023; DOE, 2021).

3.4.2 Publicly Encouraged Hub Concepts

It is stated by the Department of Energy that hub applicants for the same regional cluster can combine their concepts into one. This creates an incentive for collaboration and partnership between hubs that have their concepts in the same region, as this combined effort could be considered a stronger applicant (Office of Clean Energy Demonstrations, 2022). This would also increase the likelihood of selection given that there will only be (six to ten) hubs across the whole U.S out of the 33 (for now) encouraged hubs (Office of Clean Energy Demonstrations, 2022). The hubs that are publicly encouraged according to Bioret et al (2023), fulfill the requirements expressed by the U.S Department of Energy (2022) and are located with close proximity to the Volvo plants are selected per the subchapter 1.4 resource delimitations and in accordance to the description in 3.4.1 Areas of Interest. The hubs in relation to the Volvo plants can be seen in Figure 7 below.

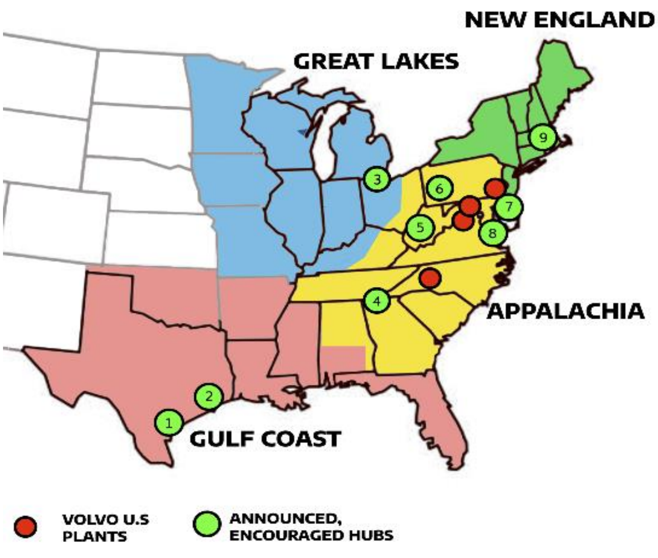

Figure 7. The identified publicly encouraged hub concepts in their respective regional clusters and in relation to the Volvo Group plants.

The hubs are, as previously stated, concepts. A lot of information regarding the hubs, like their capacity- and production plans, is not publicly available due to the on-going application process and its competitive nature. However, it is stated that the hubs will have their focus on clean hydrogen - that is either green, blue or pink hydrogen currently (DOE, 2022a). However other methods may fulfill the requirements in the future.

The hubs involve a multitude of different types of actors, some actors are part of one hub while others are involved in multiple hubs (Bioret et al., 2023). The hub concepts are based around different resource accessibility, that stem from the different regional clusters they are located in, as explained in 3.4.1 Areas of Interest. Certain hubs are therefore more inclined to develop a certain type of hydrogen, for example pink hydrogen in the Great Lakes from nuclear accessibility, green hydrogen in The Gulf Coast from the wind and solar accessibility while blue hydrogen can come from the natural gas resource accessibility in both Appalachia and The Gulf Coast. The information that is available regarding the selected hubs follows in the paragraphs beneath. Table 7 below showcases their public plans currently available.

Identified Hubs			Feedstock				Type of H2			
Region Cluster	Hubs	Producers	Natural Gas	Renewable	Nuclear	Carbon Capture	Gray	Green	Blue	Pink
Gulf Coast	Hub 1	6	No	Yes	No	No	No	Yes	No	No
Gulf Coast	Hub 2	11	Yes	Yes	No	Yes	No	Yes	Yes	No
Great Lakes	Hub 3	4	No	Yes	Yes	No	No	Yes	No	Yes
Appalachia	Hub 4	2	Unknown	Yes	Unknown	Unknown	No	Yes	Unknown	Unknown
Appalachia	Hub 5	11	Yes	No	No	Yes	No	No	Yes	No
Appalachia	Hub 6	3	Yes	No	No	Yes	No	No	Yes	No
Appalachia	Hub 7	3	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
Appalachia	Hub 8	5	No	Yes	Yes	No	No	Yes	No	Yes
New England	Hub 9	20	No	Yes	Yes	No	No	Yes	No	Yes

Table 7. Information available from public announcements regarding stated plans for the hubs (Bioret et al, 2023).

3.4.2.1 “Hub 1” Horizons Clean Hydrogen Hub

Based in Texas, the Horizons Clean Hydrogen Hub, is a result of a collaborative effort between two previous hub applicants: Port of Corpus Christi Authority (PCCA) and MMEX Resources Corporation, this merge was made with the intention of creating an integrated solution for hub development within the region of Texas (PCCA, 2023). The reasoning behind this is to utilize and leverage existing competitive advantages available in the state of Texas (PCCA, 2023).

The collaboration, according to PCCA (2023) connects different facilities throughout Texas as a combined effort to develop a regional hydrogen hub. Such facilities include production, storage, and consumer usage points; they also aim to integrate with the already existing hydrogen market and utilize the Port of Corpus Christi as a focal point for the hub. The PCCA is the leading actor for the hub application. Other important actors involved in the project are Apex Clean Energy, EPIC Midstream, MMEX Resources Corporation and Green Hydrogen International, in total there are around 30 partners (PCCA, 2023).

3.4.2.2 "Hub 2" HyVelocity Hub

Also based out of Texas is the HyVelocity hub. The concept is driven by Center for Houston's Future, GTI Energy and University of Texas. They aim to produce around 14% green hydrogen in the hub from the start, scaling up to 40% in the future. They also plan to produce blue hydrogen, in order to utilize the already existing hydrogen resource capabilities (HyVelocity, 2023). Sponsors of the hub are Air Liquide, ExxonMobil, Chevron, Shell, Ørsted, Mitsubishi Power, Energy Transfer LP and Sempra Infrastructure. In total there are around 90 organizations that are supporting the project, where 53 of those are industrial partners involved in the development of the hub (HyVelocity, 2023). They also state an interest in creating a single hub for the Gulf Coast region and are making collaborative efforts with other hub applicants.

3.4.2.3 "Hub 3" Great Lakes Clean Hydrogen Hub

In this regional cluster the development of one hub that may be close enough to Volvo Group plants has been encouraged. Because of the regional characteristics highlighted in the Great Lakes region, the feedstock utilized will be a mix, consisting of mainly nuclear but also renewable sources, like solar energy (Energy Harbor, 2023). However, pink hydrogen is emphasized to be the most crucial feedstock for this hub, as the Great Lakes region has great assets of nuclear power (University of Toledo, n.d). The leading actors in the development of the hub are Energy Harbor, Linde, General Electric Aerospace, Cleveland-Cliffs and University of Toledo.

3.4.2.4 "Hub 4" Southeast Hydrogen Hub

There is not much publicly available information regarding the Southeast Hydrogen Hub. It is located between two regional clusters, the Gulf Coast, and the Appalachian through the state of Kentucky. They state that the hub will revolve around renewable hydrogen (Hydrogen Central, 2023). The project is led by eight partners, but the total involved partners are unknown. The eight leading actors are: Dominion Energy, Duke Energy, Louisville Gas & Electric Company, Kentucky Utilities Company, Southern Company, Tennessee Valley Authority and Battelle (Hydrogen Central, 2023).

3.4.2.5 "Hub 5" Appalachian Regional Clean Hydrogen Hub (ARCH2)

The ARCH2 hub considers the states of Ohio, Pennsylvania, West Virginia, and Kentucky. It will be based in West Virginia but connect to the other states and will utilize the existing resources available in the Appalachian region - the aim is to produce blue hydrogen (Businesswire, 2023). The hub has a total of 160 strategic partners and the leading actors involved are: State of West Virginia, EQT, Battelle, GTI Energy and Allegheny Science & Technology (Businesswire, 2023).

3.4.2.6 “Hub 6” Decarbonization Network (DNA H2Hub)

This hub is in the same regional cluster as ARCH2, the Appalachia. However, the DNA H2hub will be based in Pennsylvania and considers the states of Ohio, Pennsylvania and West Virginia. They are going to be producing blue hydrogen due to regional resources available (Neuschwander, 2023). The hub is led by Team Pennsylvania and has a main leading collaboration with Equinor and Shell USA. These suppliers will oversee technical aspects of developing the hub (Neuschwander, 2023). According to Newuschwander (2023) there are six leading actors, but the total number of partners is not publicly available.

3.4.2.7 “Hub 7” Mid-Atlantic Hydrogen Hub (MAHH)

Located in between Appalachia and New England is the MAHH concept hub. It considers the states of Maryland, DC and Virginia. The development is led by Connected DMV and has over 40 partners and aims to produce green, blue, and pink hydrogen (Connected DMV, 2022).

3.4.2.8 “Hub 8” Mid-Atlantic Clean Hydrogen Hub (MACH2)

Similarly to MAHH, the Mid-Atlantic Clean hydrogen hub (MACH2) is located in between Appalachia and New England, however this instead includes the states of Delaware, Pennsylvania and New Jersey. The hub's leading actors are not publicly stated; however it is described that over 40 partners are involved in the hub (MACH2, n.d). It is also stated that the hub will be based out of Delaware and utilize existing technology and geographical strengths to generate clean hydrogen in the form of green and pink (MACH2, n.d).

The hub is similarly named to and shall not be confused with the (MACHH2), the Midwestern Alliance Clean Hydrogen Hub, which is not in the vicinity of the Volvo Group plants. It is therefore not part of the selected northeast area which henceforth will not cause any confusion for the reader but did cause a minor headache for the authors.

3.4.2.9 “Hub 9” Northeast Clean Hydrogen Hub

The last hub considered is located in the New England regional cluster. The leading actor for their application process is the New York State Energy Research and Development Authority (NYSERDA). They along with over 100 partners such as Linde, Plug Power, and Massachusetts Institute of Technology to name a few aims to build this hub (New York State Government, n.d). The hub will strive to generate green- and pink hydrogen through their access to renewable resources and nuclear power plants in the region.

3.4.3 Regional Hydrogen Hub Development Takeaways

Takeaways from the chapter is that there are a lot of things happening at the moment within hydrogen. There are numerous hydrogen infrastructure projects in planning phases and a lot of them are driven through hub formats. This is because the IRA is the kickstart of the clean hydrogen market and big fundings are available for hubs. The hub(s) also works as an aggregation to collect projects that were already under construction to allow these projects to potentially subsidize their cost with governmental money while strengthening the hub application. There are hub concepts evolving around the existing Volvo Group plants in the northeastern part of the U.S and these hub concepts are located in regions with different characteristics that enable different hydrogen production methods.

Public information regarding the hubs is limited due to the confidentiality present in the competitive nature of the hub concept developments. Therefore, more insights hope to be found in chapter four, where interviews will be conducted with different actors of the related hubs, in order to investigate hub developments and get further insights into what is being done in the individual hubs.

3.5 Purchasing Parameters and Investment Strategies

To facilitate the purchasing scenarios and answer research question 2, some literature was used to understand how this best should be done. When approaching the purchasing scenarios, it is of importance to understand that scenarios will consider a rapidly changing business environment, which characterizes the market for hydrogen. The hydrogen market is also something which is considered new and regards an area which is not the core competence of the Volvo Group. Therefore, it is of interest to understand the dynamic capabilities present in such a business environment. According to Teece (2016), dynamic capabilities consider not only rapid technological change, but also when there is a lot of uncertainty regarding the market. Teece (2016) further argues that it concerns an organization's adaptation abilities to such a market landscape and is vital to consider. Because of this, there’s an argument to be made that this should be considered in the development and evaluation of purchasing scenarios. Since, when approaching the purchasing scenarios, it is important that they align with the strategic targets set up by the organization (Knight et al., 2020).

With this argumentation, scenarios should be as realistic as possible, and should consider contextual aspects of the hydrogen market. For the market of hydrogen in the U.S today, there are many different ways of purchasing hydrogen, and in order to facilitate a common understanding of what affects the costs for the different scenarios, a common foundation of parameters should be used and act as criterias for a potential investment decision for clean hydrogen. Since the scenarios are intended to be as realistic as possible in the context of the thesis, relevant parameters will now be discussed.

3.5.1 Purchasing Parameters in the Context of Hydrogen

For the context of this thesis Volvo Group has prerequisites on certain parameters that should be considered when making a purchasing decision. Therefore, relevant, and important parameters have been discussed and compromised internally that should be included in the scenarios developed. This is put into relation to the dynamic capabilities of the Volvo Group and the business environment of hydrogen. One important and crucial strategic goal to consider is how the Volvo Group aims to decarbonize their operations, where clean hydrogen may play an important role. Contextual aspects to consider when developing purchasing scenario parameters for hydrogen are the flexibility of the solution, what technology is utilized and what are potential delivery times. It is also important to consider what kind of hydrogen is going to be handled, since it can be considered a dangerous good.

It can be concluded by the article Knight et al. (2020) that cost, and risk are good and common parameters to consider in order to compare different scenarios. Also, in the context of hydrogen developments, sustainability as a parameter is explained by both Koshow and Gaßner (2008) and Knight et al. (2020) to be relevant for scenario analysis.

This builds a good foundation for analysis and coincides with some of the parameters suggested to be used from the internal assessments as well. The further parameters that were discussed were aimed to cover the contextual aspects needed for the case of hydrogen. The internal discussions acted as inspiration with learnings from the way hydrogen has been purchased in Europe as the base for discussion. Further U.S contextual aspects, specifically differences in legal and permitting processes were also discussed.

The parameters that were deemed relevant both contextually, product-wise and for the investment decision were the following: Product Features, Delivery, Support, and Time to Market. On top of the common parameters found in literature, Cost, Risk and Sustainability. That will be put into context of both short- and long-term evaluations.

3.5.2 Purchasing Scenario Takeaways

As a conclusion, a scenario analysis should consider different contextual aspects both in the short- and long term to be able to assess and evaluate different scenarios that are developed. Scenario analysis can be done through several different methods or combinations of methods. It is however essential to consider the contextual factors in order to evaluate costs, risks and investments related to the different scenarios, and therefore the methods for developing the scenarios should consider this. The parameters that will be the foundation for analysis of the scenarios are Product Features, Support, Time to market, Cost, Risk and Sustainability.

4. Empirical Findings

This chapter consists of interviewee expertise and reflections based on answers during the semi-structured interviews. The chapter also includes observations and learnings from conferences, workshops, and general day-to-day activities. All interview template guides can be found in Appendix. Subchapters 4.1 and 4.2 only consider information based on internal events and interviews while 4.3 showcases the information gathered from external interviews.

4.1 Hydrogen Market Knowledge Overview

The conference and workshop highlighted the current trends in the developing hydrogen market, its challenges and current situation. With specific insights into the U.S market summarized below.

4.1.1 Hydrogen Market in the U.S

There is an already established and developed market for hydrogen within the U.S, it considers mainly gray hydrogen but an overview of how it looks was researched and can be observed in section 4.4 below. The current market focus is on expanding and shifting towards more sustainable options and aims to develop the clean hydrogen side of the market. The various governmental acts and incentives in the U.S are constructed with the intention of kick-starting that clean market.

When developing a market, it was stated in the hydrogen workshop that there are three main factors to consider in order to do so efficiently. And as one leading presenter put it: *"Product offering, policies and infrastructure are equally important"*. But product will only really play a role if the other two, policy and infrastructure, are sufficiently accounted for - you can picture it like a triangle with product on top, standing on the base of policy and infrastructure. For hydrogen specifically, infrastructure will play a very interesting role as transporting hydrogen is expensive and accounts for roughly ⅓ of the total cost to consumers, as was highlighted in the hydrogen workshop and in a majority of the conducted external interviews. Therefore, it is emphasized that the conventional economic theory of economies of scale might have a strong competitor in local development (since ⅓ of cost is removed in that case). And as one interviewee stated: *"it is extremely important to understand that big scale does not necessarily equal cheap when it comes to hydrogen"*. Because of this reasoning, smaller actors may play a more influential role in the hydrogen ecosystem than they do in other developing markets. Regarding the policy side, as highlighted in both the conference and the workshop, policies should be established in a way that does not hinder market development and enables for a fair and inclusive market where demands of all parties through the value chain are considered. For hydrogen, an external presenter from the conference stated that: *"bottlenecks for hydrogen today are infrastructure and* *regulations"*. The general case for hydrogen is that there is a lot in the midst of happening and probably more will come in the following years as well, which makes it difficult to say whether current policies and infrastructure plans are sufficient or not. The best estimate would be "not", since it's so new.

4.1.2 The Hubs

The hydrogen hub aspects were known internally in terms of the application existing, however there was a big knowledge gap in what it entailed or how things were going. This facilitated the direction of the thesis.

4.1.3 The IRA

The U.S market has quickly become a region of interest regarding developing hydrogen due to its passing of heavily influential acts to incentivize and kickstart a hydrogen market, as has been highlighted in all of the interviews (both internal and external), the conference and in the workshop. Previously, the European hydrogen market has been seen as the dominating one and has prior to now been in the forefront of hydrogen developments. However, with rapid developments that are on-going in the U.S, the IRA is seen as a highly competitive legislation that needs to be taken into consideration. Therefore, the relative view on the EU market can be considered to have changed for many actors in the market.

The main argument as to why the U.S market is now viewed as almost more competitive than the EU is because of the different approaches to industrialize hydrogen, which was emphasized in the conference by an external presenter representing hydrogen developments in Europe from a EU level. It was highlighted in the conference by different actors along the value chain that policies and regulations regarding hydrogen in the European hydrogen market can be considered slower moving and currently less incentivizing when compared to the U.S IRA act. The passing of the IRA will have a big impact on the price of hydrogen, as it enables a heavy tax credit subsidy for every kg of hydrogen produced over a ten-year period. But also, other subsidies for production of clean hydrogen as well as other tax credits for technologies that enable clean hydrogen production. As highlighted in a majority of the interviews and stated by the hydrogen researcher through the interview in regard to the IRA: *"it definitely changed anticipations regarding future hydrogen costs"*. Therefore, as expressed by several actors in the hydrogen production market, through interviews and at the conference, the U.S is now viewed as a more appealing market to produce hydrogen and they will accelerate business development there. This is due to its incentives and subsidiaries, specifically the producing tax credit 45V. As stated by a leading actor in the development of electrolyzers: *"the U.S is one of the most attractive places to produce hydrogen"*.

There are however limitations and some uncertainty regarding the U.S market and the IRA since cheaper production prices may not necessarily be reflected in the price for the customers at the pump. It is also stated that there are still uncertainties regarding policy and regulation development, which can hinder developments. When discussing this internally, a knowledgeable employee said that: *"different sections of the IRA may not be combined and therefore not utilized fully"*. This can however be overcome through collaborations and separations of projects that are interested in the different sections of the IRA. It should also be mentioned that in the interviews with the bigger hydrogen supplier actors of today, that they are still not fully satisfied with the 45V tax credits, it was expressed as: *"it is definitely good, but it is not great"*.

4.1.4 Technological Aspects

While the IRA will be a good way to incentivize- and accelerate clean hydrogen in the U.S, there are still a lot of technological advancements- and innovation needed in order to enable a clean hydrogen market to be developed. This was highlighted through a majority of the interviews and the main issue revolves around all of the energy that would be needed in order to transition towards a hydrogen economy, especially electricity. This was further highlighted at the conference and in the workshop, where the demand of electricity was discussed to potentially become a great problem for enabling hydrogen and is today voiced by many critics as the main bottleneck for the hydrogen economy to be fully plausible. The reasoning behind this is that there is not enough energy today to enable the ambitious plans the governments around the world have set up, it will require advancements in energy production capacity, energy grid and energy technology beyond the hydrogen technology advancements needed as well. Just the grid system to move around all the electricity will require great developments but also refurbishment of the current grid to enable such a transition. This is something that takes time and costs a lot of money.

Another crucial part for enabling clean hydrogen in the U.S, is CCS. It can enable generation of blue hydrogen from fossil fuels, which without the capture part, is currently the main source of energy in the U.S. As of now, demonstrations have illustrated that the CCS technology does work. It is, however, uncertain how efficient this is, or will be in the future, says the hydrogen researcher interviewed. But it was a clear statement that this is not effective enough to meet the criterias for clean hydrogen at the moment. Which is a statement that is supported by literature presented in subchapter 3.1.3. The timeline for efficient CCS systems is not clear either because of the uncertainties. It is however a common view amongst the interviewees that the implementation of the CCS will take a lot of time to develop. Therefore, CCS can, as of now, be seen as a barrier for enabling clean hydrogen to be produced.

There is also hope and expectations for hydrogen, as expressed throughout most of the interviews, the workshop and in the conference. Especially when looking at hydrogen as a supporting source of energy, as an enabler rather than the end goal, because the renewable future will be dominated by electricity. It was said that it is important to keep in mind that developments, while slow starting, happen quickly when picking up pace which creates a rippling effect. This was highlighted and exemplified by an external researcher from the conference, who showcased other renewable energy options and their effective development in both cost and effectiveness over the last decades.

The common emphasis from the workshop and conference revolves around reaching the 2050 goals, which require hydrogen to be a solution in some way. Therefore, hydrogen is- and needs to be considered as a part of the future. This is also the focus of many actors that have been interviewed and are striving to industrialize hydrogen. As said in one of the interviews: *"Right now it is pushing for hydrogen technology, more electrolyzers and hydrogen production plants rather than looking at the electricity problem!"*

To state whether or not the hydrogen development is plausible is not the intended objective of the thesis, it is however important to consider the possibilities, opportunities and challenges in order for a hydrogen economy to be developed. It is important to highlight and raise questions regarding the ambitious goals set up by governments around the world, in order to create an understanding of challenges ahead. This is also an important contextual aspect to consider when making a purchasing decision.

4.2 Internal Requirements and Future View

The three internal Volvo Group interviewees states in unison that the acts and incentives that recently was passed by the Biden administration has expedited internal work regarding hydrogen in the US. Questions asked can be found in the interview template guide in Appendix A. The timelines are consistently being updated, but what can be shared is that there are on-going projects involving testing of technical hydrogen related aspects on the testing side. These projects require some volumes of hydrogen. On the operational side (the production facilities), there are not currently any volumes needed, which will change in the future, but the timeline cannot be shared publicly. The internal interviews all considers and highlights hydrogen in the form of pressurized gas at 700 bar following the Society of Automotive Engineers (SAE) J2719 standard for purity (>99%). As one interviewee put it: *"that is a requirement for the fuel cell"*.

4.2.1 Volvo Group Requirements

The requirements that were expressed for larger vehicle production with on-site accessibility for the operations department, were due to safety measures, that a solution would be preferred outside the facility somewhere in the building's vicinity with nearby access. The access should always be available with a minimum of 2 slots, with hydrogen supply upkeep by supplier to happen during off hours for the plant or in otherwise non-interfering ways. There was also a coherent emphasis among the interviewees in expressing the need for quick filling speed and that the solution was stationary. As one interviewee put it: *"We should be able to fill it at any time, the trucks cannot wait"*. Expanding on this, all of the internal interviews expressed the need for purity to follow the SAE's J2719 standard. Overall, the need is for a seamless experience with no interruptions to ensure that the production line can flow freely.

4.2.2 Future Volume Need

In terms of technology department need, with some current volumes for testing, the requirements expressed by the several interviewees are on purity of the hydrogen, flexibility on supplier's end to quickly change the solution in regard to developments happening as well as the cleanliness (in terms of carbon dioxide emissions) of the hydrogen received. Safety is also very important for the hydrogen solution, where Volvo Group has strong safety assurance requirements beyond their regular QDCFTSR supplier evaluations. To further highlight the importance of safety measures, one interviewee expressed some important parameters to be surrounding permitting requirements, leak detection, fire protection and maintaining storage conditions, which are all costly to set up in an existing plant.

In several interviews they spoke about the expectancy of fluctuations in future demand, with the majority of volumes to come in on the operational side. One comparative example given was related to natural gas trucks, where volumes spiked heavily with occasional big orders from a few different actors who decided to replace their current fleet of trucks. As expressed in one of the interviews: *"volumes were (for natural gas) and will be (for hydrogen) uncertain"*. The big orders, in the natural gas example, required large infrastructure to be put in place in selected Volvo Group plants, however it did not get much use in the down period between the irregular orders. This eventually led to the decision to delegate all natural gas truck orders to a different company when the realization hit that natural gas trucks would not reach the anticipated mainstream follow-through. As said by one interviewee: *"be cautious and probably look at a more flexible solution when it comes to hydrogen"*.

In conjunction with this, the infrastructure issue was also discussed in the interviews. That is, orders and volumes needed from Volvo Group side are tied to their customers' business case. Which in turn is tied to the price of hydrogen at the pump, the availability of hydrogen refueling stations and the ease of having a hydrogen fueled vehicle in society. Similarly, however, the actors involved and needed to build out that infrastructure are not incentivized to pursue the expansion of this infrastructure, unless there is certainty that there exists a demand for hydrogen vehicles. This was referred to as *"the chicken and the egg scenario"* by one of the interviewees.

The actual future hydrogen needed was described in the interviews to be difficult to determine at the moment. But as highlighted by one interviewee, each current truck (disregarding fuel type) is sold with enough fuel to drive roughly 100 miles (160 km).

Depending on the efficiency of the fuel cell in the future, the per vehicle requirement would be somewhere between 10 and 30 kg of hydrogen. This was derived from the U.S Department of Energy (2020): Where it is illustrated that an average class 8 truck drives 5.29 miles per gallon of gasoline. That is 19 gallons per 100 miles (100 miles/5.29 miles per gallon = 18.9 gallon per 100 miles). They also state that in terms of energy, 1 gallon of gasoline represents approximately 1 kg of hydrogen, which means that 19 kg of hydrogen are current estimates to drive that distance. Which is subject to change depending on technological advancements but would suggest between 10 and 30 kg of hydrogen per truck sold, as the future needs from the operational side. Certain safety levels would be in place, to ensure that the fuel will not be the limiting factor stopping the production lines, however the wide span of 10 - 30 kg should acknowledge that safety limit.

For a total number reference, in Volvo Group annual report 2022, there were 1211 fully electric vehicles delivered globally out of the 232 558 total truck deliveries. That is the second full year in which they offer the fully electric solution and based on assumptions that hydrogen up-scale would be somewhere similar in speed, that is 0.5 % of trucks two years in (1211 / 232 558 = 0.5 %). Which would be somewhere around 300 trucks per year (56 535 North America deliveries * 0.5 % = 282), or a 9000 kg hydrogen demand per year at maximum estimates (300*30 = 9000 kg). This is for the combined volume of all production plants for the second year of hydrogen truck availability. The number of truck deliveries are taken from the annual report of Volvo Group and are based on global numbers since they do not specify how many of the electric vehicles are from each region, only the total number (Volvo Group Annual Report, 2022, pp. 221). This is the estimated number that will be used going forward, since the estimations are based on non-internal information. It was decided to look at the estimated need of 9000 kg as a consolidated need for all of the plants, resulting in the scenarios to be developed with this limitation. Determining the specific needs for the individual operations plants is impossible to do without disclosing internal information. Supporting this simplification was mentioned in previous subchapter 4.2.2, where cautiousness was emphasized, it would probably make sense to begin hydrogen production in only one plant given the losses that had to be taken in the natural gas case mentioned. Which is why the volumes are aggregated in the scenarios below.

The technical department has a certain need per day, which is a need that was required to remain undisclosed. The overall demand is going to be very unpredictable on a longer time frame, but Volvo Group has a regular forecasting interval-schedule that will allow suppliers to be notified well within their lead times of supplying hydrogen when it comes down to an identified need - the difficulty in predicting arises when the timeframe is extended, and uncertainties are applied. To give an example, one interviewee expressed the forecasting as: "*We have a long order forecast of several months. Then a "firm" schedule of 14 days.*

4.3 Hub Interview Overview

The following information covers the 9 hubs identified for the report. Because of the competitive nature (declined interviews, secrecy, and NDAs), this subchapter has been summarized. Rather than explaining in detail what each hub consists of, it has been compromised into a generalized hub overview. Different themes of interest have been discussed in the interviews and act as a foundation for comparison. This was stated in subchapter 2.4 and was used in order to get a common overview of the hubs for comparison and reflection. The interviews held can be seen in Table 3 in the 2.3.3.2 Interview Selection subchapter.

4.3.1 Driving Partners

The driving partners of the hubs are described to be a combination of large industry players from different sectors, both suppliers and offtakers, combined with non-supplier organizations. These non-supplier organizations are seen to be either universities, nonprofits, states, or laboratories. They have different competencies and therefore different roles, as said in one interview: *"with each bringing different expertise to meet all potential needs of a hub"*. It is described through several interviews that the leading actors of the hubs, which often are lead applicants, are overseeing the planning of the different projects as well as their funding. They are making sure that the different requirements and deadlines established by the Department of Energy are met.

One leading hub applicant interviewee explained that their role will function as both a middleman to connect demand and supply, but also as an auditor to make sure the funding is used properly, and projects progress as intended. The common goal as explained through all of the interviews with the leading actors, is that the main goal of the hub is to stimulate- and increase the demand of hydrogen, as well as being able to match such an increase in demand with supply. Another interviewee explained their role as finding target utilizations with potential offtakers and focusing efforts in the state to make sure communities involved can prosper.

Several leading hub actors emphasize that the hub developments are based on already existing projects, some which were already years in the making. As an example, according to one of the interviewees, their hub stems from a 3-year on-going project between a nuclear power plant and a university. Therefore, some of the interviewees argue that this is one reason as to why they have taken a leading role in the development of the hubs. Since, as the interviewee expressed: *"they had already started connecting people"*.

Being a partner of a hub gives the potential to take part in funding, which can be utilized to accelerate any hydrogen endeavors through specific projects. There are commitments required to receive that type of funding, which were highlighted in the interview: *"for* *example a promise to offtake a specific volume each day for a number of years"*. However, many of the interviewees state that one can become a partner afterwards, and welcome actors to do so. They might not take part in the same funding as partners who have shown support early on but could take part of the knowledge-base that the hub has. Also, it was said in the majority of interviews that commitments are not necessary, one does not necessarily need to take part in funding. But rather, endorsing the hub and taking part in collaborative efforts in order for it to function.

4.3.2 Functionality of the Hub

The hubs are described through all of the interviews to have various offtakers for hydrogen, and there are partners in the hub from many different sectors. Also, some of the offtakers are identified as more essential to consider. That is because they have a greater need for hydrogen. The most common industries, as highlighted in the interviews are steel, construction, glass and power generation. And as one interviewee put it, with regard to these industries: *"these are main industries of focus".*

The supply and demand equation were highlighted through the interviews as one of the big challenges, with potential demand said by one interviewee to be: *"enormous"*. Because of this, it is discussed that there will be a huge increase in demand for hydrogen, and a coherent opinion expressed through the interviews is that the overall goal of the hub is to utilize economies of scale combined with innovation to increase demand and drive the price of hydrogen down.

Because of the many actors and partners of a hub, it is described by the majority of the interviewees that the actors within the hubs have priority to hub produced volumes. This is because each project has certain guarantees and commitments that link together both supply and demand. However, suppliers that are interviewed said that they possess greater capabilities than what will be offered through the hub, and therefore will be able to provide volumes outside of the hub through other projects. From all of the interviews, an actual price point for the hydrogen produced was considered a sensitive topic, it will be contracts deciding that in the future.

4.3.3 How Different Feedstock Affect Hub Development

Since interviews represent different hubs, which will be based on different feedstocks, they have some specific individual characteristics. What is evident in all of the interviews is that the nature of the DOE funding will not allow a mediary solution of gray hydrogen to kick-start the hub. Because of this, it is stated through several interviews that there are advantages of being an electrolysis-based hub, with the energy from both renewable and nuclear sources. With this, they can begin production on a faster time horizon than natural gas-based hubs and operate more consistently compared to only renewable based hubs. In terms of availability, no timeline was explicitly stated, however general goals were for 2028 regarding all feedstock-based production while the DOE requirement is to be in operation before 2032. Certain electrolysis-based hubs did not specify their timeline, instead used the phrase: *"we are ready to move"*, implying that they can begin faster.

In contrast, hubs that will utilize natural gas and produce blue hydrogen will have a longer time period in order to get production going as explained in the interviews. That is because the requirements on carbon sequestration are described as: *"a limiting factor that will need years to scale-up"*. However, there are advantages to utilizing natural gas as a feedstock for hydrogen. That is explained in the interview because of the existing infrastructure and knowledge of natural gas. Alongside that, there is natural gas available in huge quantities which could support the hydrogen offtake even at a large increase (given that carbon capture has a high efficiency). This can be done with quite targeted investments, really only in the carbon capture part. That is because the scale of operations and experience of hydrogen production is already existing and has been optimized over a long time. Not like green hydrogen who needs widespread improvements through investments in electricity production, electricity grid and electrolysis efficiency. It was expressed in some interviews that there is an anticipated similarity between the hydrogen- and natural gas market in regard to transportation. As of now, transport without a pipeline in gaseous format is described to be feasible for distances around 100 miles in the hydrogen case.

An interesting topic which was discussed in all of the interviews is that certain suppliers are part of multiple hubs. Arguments as to why this is, from the supplier point of view, are that they want to be involved in the hydrogen hub economy and they increase their chances of being involved in it by being part of many hub applications. In regard to how that is possible even though there is competition amongst the hubs, is that the nature of the hubs likely are different and stated in the interview that: *"for example blue hydrogen production and green hydrogen production involves different technologies and expertise"*. This allows the hubs to compete on the hydrogen market in terms of output without competing on the input. From the non-supplier point of view the various suppliers bring knowledge and experience. Being part of many hubs increases the knowledge shareability and is a connection for the further collaborations between hubs. In terms of infrastructure, several interviewees highlight that this is planned for the long term for the hubs to be connected to other hubs and later on in a national grid. This would enable actors to be part of many hubs as well since they will combine available volume for the entire grid in the future. Which is similar to the connected grid of natural gas today.

4.3.4 Department of Energy and Application

The application process, with its competitive elements, leaves a lot of secrecy through various NDAs involved. It is highlighted in the interviews that various parts of the application will leak over time, aspects like price sensitive information will however not. The application is quite massive, and as described by one interviewee: *"at 400* *pages"*. To put this into context, the encouraged pre-phase application was roughly 30 pages.

The Department of Energy's intent is to fund 6-10 hydrogen hub projects with various specializations in resources, feedstock, and technologies. They will aim for certain criterias, but the very essence is that they want hubs with a clear business plan. As stated in one interview: *"they will not fund a science project"*. It is clear from all of the interviews that the Department of Energy wants to see a relationship between their kick-starting seed money and the implementation of projects that create a market. This is explained in the interviews to be the reason as to why it is important for hub applicants to both manage to produce hydrogen but also have a plan for offtaking and a market-building focus.

The supplier view on the Department of Energy and its funding is somewhat different compared to the non-suppliers. In interviews, they argue for the complexity of utilizing governmental funds. Since there can follow a lot of work in regard to oversight etc. Because of this, being part of a hub and applying for a hub might not be seen as a necessity due to their already established hydrogen capabilities (from a bigger supplier point of view). It is therefore stated that they are interested in being part of a hub if it is of benefit for them as an actor and have a more cautious approach towards the application.

4.3.5 Biggest Driver of the Hydrogen Market Going Forward

Drivers of the hydrogen market in the U.S is described through the interviews as a combination of suppliers with a global presence which through they have pledged to net-zero efforts, and the IRA combined with other incentives from government side. There are various incentives provided by the IRA, the producers would themselves apply for tax credits and other benefits. The DOE funding is viewed as a kickstart of the market, and a clear important driver as stated in all of the interviews. As one non-supplier interview put it: *"definitely the IRA through the works of the Department of Energy"* in regard to the most important drivers.

Previously, in regard to hydrogen in the U.S, there have been a lot of conversations on-going, but nobody taking the initiative to be the first mover. As was stated in one interview: *"The big producers - the big companies are ready but lack consumers"*. The supplier side has been ready to move but was faced with big uncertainties regarding consumers. From suppliers, it is heavily emphasized to create an increased demand for hydrogen. As stated in one interview, in regard to driving factors: *"a direction of demand, if people want to be environmental, in some way or another"* and that the demand will steer the market that way. It is highlighted by the supplier interviews that cost is seen as an extremely important factor. And in order for hydrogen to really take off, it needs to be able to compete with available solutions. That could be through increasing the attractiveness of the hydrogen opportunity by decreasing the costs, it could also be to decrease the attractiveness of other solutions (like gas and diesel) through penalties, taxes or other regulations for carbon intensive uses.

This stalemate of having capabilities to increase production, but no demand to meet it has left the market in a standstill. However, as found in the interviews, the IRA with policy incentives and governmental money is appearing to change this with more demand emerging. The driver going forward to really change the market is to get the demand side pushing the market to move even more. This demand side is viewed to come from hard to decarbonize industries, like steel and construction, but also from heavy duty vehicles amongst other things. The demand, which is said to be the effect of improvements in the triangle presented through the internal workshop, with all factors of infrastructure, policy and product needed for demand to increase.

4.3.6 Summary of Additional Hub Findings

What can be found as the common, general hub understanding from all of the interviews is that the hubs together with the IRA acts as a kickstarter enabling the acceleration of the clean hydrogen market within the U.S. As was stated in a supplier interview: *"Hydrogen is expensive, it's a great decarbonization technology, however it requires policies and support from governmental level to get anywhere"*. Therefore, the ultimate common goal as expressed through all of the interviews is that the hubs will help drive hydrogen costs down by increasing the demand and production of clean hydrogen to already existing- and new offtakers. To do so, the hubs are described in all of the interviews to operate through a collaborative approach within the hub, to ensure that there is an increased supply and demand for clean hydrogen. As one interviewee put it: *"it is very common to have an agreement to ensure a constant level of hydrogen produced and offtaked, this is highly encouraged"*.

This collaborative approach is also seen as part of a bigger, longer-term plan to connect all the hubs through a national grid. Which was described in several interviews to be similar to the existing natural gas grid in the U.S today. This connection is also what will enable actors to be part of several hubs, and not seen as competitive since they will eventually share the same grid. Another argument as to why an actor can be part of several hubs is that the hubs will utilize different feedstock, and therefore not necessarily compete against one another. Lastly, the focus in the short term will be in providing hydrogen on a local level rather than competing against other regions, since there as of now is not any connected grid and transportation costs are too high.

Connected to this, it was coherent throughout the interviews that pipelines are the way forward to transport large volumes of hydrogen through the hubs. Which later on will be connected through a national grid. When it comes to delivering hydrogen outside of the hubs, where there is no pipeline infrastructure that supports transportation, it was expressed by a majority of the interviewees to be done by trucks or trailers. And that it would be economically feasible below 100 miles. This is because transportation costs are considered ⅓ of the total price of hydrogen, and an important factor to consider, as stated in the majority of the interviews. As one supplier interviewee put it: *"10s of miles and not 100s of miles, important to be close"*. To illustrate, the hubs have been highlighted in Figure 8 below with their span of reach, considering no connective pipelines and a radius of 99 miles. This is to highlight how, and which hubs, that could be considered of potential interest to the Volvo Group plants.

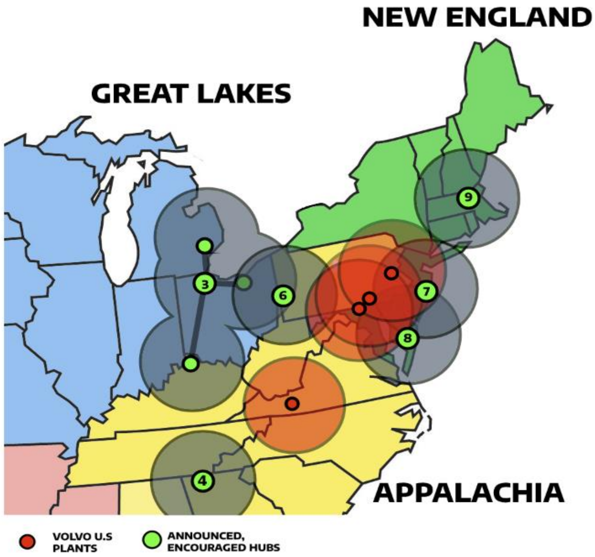

Figure 8. The identified publicly encouraged hubs in their respective regional clusters and in relation to the Volvo Group plants. With approximate delivery distance potential of <99 miles.

4.3.7 Supplier Key Takeaways

From the supplier interviews there is a shared view on the hubs between them, which is a slightly different view when compared to the non-suppliers interviewed. The shared view is that the hubs are viewed as an accelerator of the hydrogen market, with potential for improvement. It is emphasized by all of the suppliers that the IRA is more crucial than the actual hubs. Since being part of a hub can come with complications, like heavy oversight. As one supplier put it: *"the IRA plays a bigger part in the hydrogen economy rather than the hubs themselves"*. This is specifically put into context when the available $8 billion funding is split out into the hubs selected and then compared with these big supplier profits and already pledged money to hydrogen investments. The hubs are more targeted for smaller companies who need that extra funding to get going, this doesn't discourage the big suppliers from participating, but it is not seen as vital for their own hydrogen journey. This was followed up by: *"it is definitely good, but it is not great"*. Concluding that there are more important factors to consider at the scale in which they operate, such as policy and regulation. As of now they are highlighted as key, in order to accelerate and develop the hydrogen market in the U.S. Where involvement in a hub may positively affect the ability to influence.

Another shared view is that driving down the price is key to increase offtaker interest. Making hydrogen available at the right price, where the market is going to decide on which technology will prevail. This might mean that the color of hydrogen is not necessarily what pushes the hydrogen developments, but instead looks to pricing to fill that role. One aspect highlighted is the hydrogen to diesel cost parity for consumers to be truly interested in hydrogen. The suppliers expressed willingness to expand the supply, but absence of demand leaves no incentives to justify it. The hubs are for this, viewed as a good start for new industry offtakers, such as glass, cement, and steel to stimulate hydrogen demand. Because, as put by one of the interviewees: *"No one wants to be the first mover"*. Implying that the first movers are going to take large financial hits when taking part in developing a market. Because of this reasoning for low volumes in the hubs, the suppliers interviewed explain that their production capacities exceed those expressed by the hubs, and that even though they might be involved in hub(s) their production capacity can and will be available for the bigger market. Hub(s) is not a necessity, but could bring benefits which are important to consider.

4.3.8 Non-Supplier Key Takeaways

The common shared view of the hubs, by the non-supplying actors, are more focused on the collaborative nature that the hubs facilitate through the IIJA and IRA acts. These acts and the money towards hubs are seen as major kickstarters of the hydrogen market. It is however stated from several of the non-supplier interviews that the IRA tax credits are not finalized and are still being worked on, where conditions to qualify for the credit are still uncertain.

The non-supplying actors all possess a leading position in the different hubs and share the task of distributing the funds across the projects within a hub. They are part of their own hub with a more overseeing role to ensure that requirements put on them by the DOE will be met. All non-supplier actors agreed that being a partner of a hub puts expectations on you for collaborative efforts to create connectivity both within the hub, but also between hubs on a longer time frame. As one interviewee stated: *"first capacities within the hub, then outside"*. Insinuating that the main focus will be on the hub, with priority to partners and that the left-over capacity can be provided to actors outside of the hub.

The focus is on producing clean hydrogen through the hubs and this means that the timeline is at least a couple of years away. Electrolysis production is stated to move quicker than blue with carbon capture and therefore hubs that utilize this are guesstimated to be able to start producing in a shorter time frame.

4.4 U.S Hydrogen Supply and Demand Overview

As can be seen on the left side of Figure 9 below, the current hydrogen supply is heavily natural gas dependent, with about 76 % of hydrogen coming from natural gas reformation (Energy Futures Initiative, 2023). What can also be seen is that 23 % of supply comes as a by-product of chemical processes, that is leftovers from chemical or petrochemical companies that they gather and sell. Which leaves less than 1 % currently being produced through electrolysis with the potential of being either gray, green, or pink depending on the source of the electricity used (Energy Futures Initiative, 2023). With global carbon capture utilization rates according to IEA (2023b) of just over 0.5 % as seen in subchapter 3.1.3, with the assumption that U.S numbers are similar - means that 0.5 % of hydrogen potentially could be blue today, which leaves a high majority of hydrogen production today "gray".

In the same Figure 9, on the right side, the partition of hydrogen demand across different sectors can be observed. The sector of interest, transportation, currently consists of less than 1 % of hydrogen demand in the U.S (Energy Futures Initiative, 2023). The total current supply and demand of hydrogen in the US, is mostly self-sufficient with only 0.2 Mt of demand being filled through out-of-country production, with a total supply of 11.4 million metric tons per year available (Energy Futures Initiative, 2023).

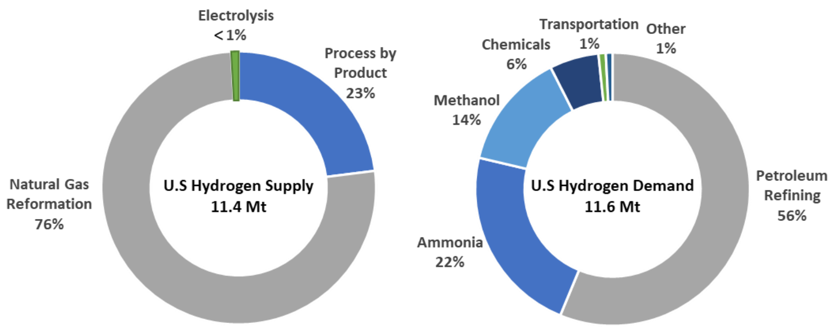

Figure 9. U.S hydrogen supply and demand. Data from Energy Futures Initiative (2023).

4.4.1 Current Production

The current U.S production is spread across three different segments, merchant hydrogen, captive hydrogen and by-product hydrogen (Connelly et al, 2019). Merchant hydrogen is the hydrogen that is produced and sold, captive hydrogen is hydrogen produced for internal use and by-product hydrogen is hydrogen recovered from processes and can be either sold or internally used (Connelly et al, 2019).

Supply and demand numbers from Energy Futures Initiative (2023) are recent and up to date, as available in Figure 9 above, so is the data based on the 47 hydrogen producing refineries (Pacific Northwest National Laboratory (2022a); Pacific Northwest National Laboratory (2022b). The current merchant hydrogen capacity numbers are, however, not accessible without funds but could be purchased from

IndustryARC (n.d) for example. Publicly available U.S merchant capacities are from 2014 presented in an excel file by Pacific Northwest National Laboratory (2016) and was financially supported from the Department of Energy. This data is still deemed relevant for the thesis, given that 128 production facilities were running in the U.S in 2014 according to the Pacific Northwest National Laboratory (2016), whereas today it is said to exist 12 more - 140 production facilities (Medlock & Shih Yu, 2023).

Of the 11.4 million tons of hydrogen supply in the US, around 4 million (35 %) are merchant hydrogen (Connelly et al, 2019). From Figure 9 above, 23 % is by-product at 2.6 million (0.23*11.4 = 2.6) (Energy Futures Initiative, 2023). Which logically leaves 42 % (100%-35%-23% = 42 %) as captive hydrogen, that is equal to just under 4.8 million tons (0.42*11.4 = 4.788). All numbers can be viewed in Table 8 below.

Segments	Supply(Mt)	Percentage
Merchant	4	35%
Captive	4.8	42%
By-Product	2.6	23%
Summary	11.4	100%

Table 8. U.S capacity across different segments in million tons.

4.4.1.1 Hydrogen Production Facilities

The excel file by Pacific Northwest National Laboratory (2016) presents 128 hydrogen production facilities in the U.S that are spread across the country in 25 states, with Texas (41), Louisiana (23) and California (11) as the states having the most. The 128 production facilities are owned in majority by three different companies, Air Liquide (19), Air Products (53) and Linde (50) (Pacific Northwest National Laboratory, 2016). These 128 facilities combined produced 13 642 941 kg/day during 2014, which is just under 5 million tons per year (given 365 days operation) (Pacific Northwest National Laboratory, 2016). The capacity is in majority provided through the SMR technology (Pacific Northwest National Laboratory, 2016). Most of the capacity is in Texas with the regions of interest Appalachia, New England, Great Lakes and Gulf Coast with volumes per year of 0.41 million tons, 0.20 million tons, 0.13 million tons and 3.28 million tons respectively (Pacific Northwest National Laboratory, 2016). Table 9 below illustrates the numbers for both merchant, refinery, and their combined volume.

Region Cluster	Merchant (Mt)	Refinery (Mt)	Total (Mt)
Appalachia	0.41	0.25	0.66
New England	0.2	0.08	0.28
Great Lakes	0.13	0.36	0.48
Gulf Coast	3.28	0.6	3.88
Total	4.02	1.28	5.3

Table 9. Breakdown of merchant- and refinery production of hydrogen in million tons based on regional clusters of interest (Pacific Northwest National Laboratory, 2016)

4.4.1.2 Refineries

Excel files regarding hydrogen capable refineries provides 47 refineries in the U.S spread across 22 states with Chevron owning 22 % of them (Pacific Northwest National Laboratory (2022a); Pacific Northwest National Laboratory (2022b). The total capacity of all 47 refineries is 2893 million standard cubic feet per day according to both (Pacific Northwest National Laboratory (2022a); Pacific Northwest National Laboratory (2022b), which is equal to 6.86 million kg per day or 2.5 million tons per year (assuming 365 days operations) at (NTP) standard temperature and 1 atm pressure (Hydrogen Tools, n.d.). The majority of the capacity is located in California (33.5 %) with the regions of interest Appalachia, New England, Great Lakes and Gulf Coast with volumes per year of 0.25 million tons, 0.08 million tons, 0.36 million tons and 0.60 million tons respectively (Pacific Northwest National Laboratory (2022a); Pacific Northwest National Laboratory (2022b). Table 9 above illustrates these numbers.

4.4.1.3 Electrolyzer

Electrolyzer could be either merchant or captive production, according to Energy Futures Initiative (2023) it can be found that < 1 % of total hydrogen supply is electrolyzer produced, at 4000 tons per year. There are two main types of electrolyzers that are currently commercially available according to IEA (2022c), these are Alkaline- and Proton Exchange Membrane (PEM) electrolyzers. The report showcases the use of Alkaline and PEM, with the split for 2022 to be 67 % Alkaline and about 26 % PEM for all electrolyzer production globally, the remaining 7 % is other types or unknown sources (IEA, 2022c). There is no indication that North America or the U.S would look different.

The PEM electrolyzer availability is described by both Arjona and Buddhavarapu (2021) and IEA (2022d) as 13.4 MW capacity installed across the country with an additional 159 MW currently under construction. Specifically for the east side region of interest, there is 4.77 MW installed and 152.74 MW planned, as can be viewed in Table 10 below. At 26 % of total U.S hydrogen supply by electrolysis, PEM stands for 1040 tons of hydrogen production per year (0.26%*4000 tons = 1040 tons), which results in about 212 kg per day (1 040 000 kg/(13.4MW*365 days) = 212.2 kg per day). External Interview 8 with the electrolyzer company added that capacities should be about 400 kg per day per MW electrolyzer, meaning that current electrolyzer does not run on full capacity.

Region Cluster	Installed (MW)	Planned (MW)	Total (MW)
Appalachia	0.72	32	32.72
New England	2.39	120.24	122.63
Great Lakes	1.18	0.5	1.68
Gulf Coast	0.48	0	0.48
Total	4.77	152.74	157.51

Table 10. PEM electrolyzer capacity in the regional clusters of interest. (Arjona & Buddhavarapu, 2021)

PEM electrolyzers are currently located mostly along the coast of the U.S, with California and the New England area as leaders (Arjona & Buddhavarapu, 2021). A worthy mention within the thesis boundary is the Great Lakes area which looks to have a lot of projects under construction - which would make sense given their nuclear accessibility and electrolysis plans (Arjona & Buddhavarapu, 2021).

According to logical sense and presented calculations, the remaining capacity for ALK should be 2680 tons per year (0.67 %*4000 tons = 2680 tons) or about 34.6 MW (2 680 000 kg/(212.2 kg/day*365 days) = 34.6 MW) assuming similar efficiency. Despite this clear logic, neither IEA (2022d) nor any other source found covered the Alkaline capacities, which leaves a question mark in regard to location and its actual operational availability.

4.4.1.4 Unknown Capacity

Summarizing the capacities, 5 million tons from hydrogen production facilities, 2.5 million tons from refineries, 2.6 million tons from by-product and 4 thousand tons from electrolyzers equals 10.1 million tons. There are 1.3 million tons missing (11.4Mt - 10.1 Mt), which must be attributed to a combination of upgrades to facilities and the 12 new hydrogen production facilities not covered in the available excel files (Pacific Northwest National Laboratory, (2016); (Pacific Northwest National Laboratory (2022a); Pacific Northwest National Laboratory (2022b)).

4.4.2 Supplier Situation Overview

It is of interest for this thesis to understand the hub concepts as well as the current ecosystem developing within them in order to answer research question 1. The further investigation of suppliers involved in the hubs will target producing suppliers with potential interest to the Volvo Group as per subchapter 1.4 delimitations. Their current hydrogen production, different technologies available, product offerings, what color and type of hydrogen being produced as well as available- and planned capacity follows underneath. It will be presented per hub, to avoid targeting specific suppliers by name. Table 7 above from 3.4.2 showcases the hub intentions.

A decision was made internally with the Volvo Group to assess the availability of suppliers of certain technologies of interest to Volvo. The technologies of choice to map were decided together with the Volvo Group hydrogen stakeholders, specifically regarding their interest in supplier technologies. It was researched specifically targeting each supplier - however is best visually presented here in a group cluster with the hubs as the denominator over the long list of each individual supplier which was provided to Volvo Group.

That is shown through Table 11 below, which was extended to include feedstock and hydrogen availability. It is based on the fact that Table 7 seems to miss a lot of availability that suppliers involved in the hubs state themselves that they can provide after research. The hub involved suppliers are likely focusing on the specific hub requirements when showcasing their offers in projects within the hub, which is why this is highlighted in Table 7. Overall, this will not be their entire supply chain, as mentioned in interviews. Therefore Table 11 represents what the actors within the hub have access to and plans to do, in terms of what is publicly stated about their individual accessibility based on internal research conducted. The feedstock part of Table 11 was shortened to NG (Natural Gas), R (Renewables), N (Nuclear) and CCS (Carbon Capture) to provide a visually observable table.

Identified Hubs			Feedstock				Technology						
Region Cluster	Hubs	Producers	NG	R	N	CCS	Fuel cell	Mobile station	Trailer	HRS	Electrolyser	Storage	Distribution
Gulf Coast	Hub 1	6	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Gulf Coast	Hub 2	11	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Great Lakes	Hub 3	4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Appalachia	Hub 4	2	-	Yes	Yes	-	-	-	-	-	Yes	-	-
Appalachia	Hub 5	11	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Appalachia	Hub 6	3	Yes	Yes	-	Yes	-	-	-	-	Yes	-	-
Appalachia	Hub 7	3	-	Yes	Yes	-	Yes	-	-	Yes	Yes	Yes	Yes
Appalachia	Hub 8	5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
New England	Hub 9	20	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

*Table 11. Information available from hub-partnering supplier websites, press releases or other related online available sources regarding current and planned capabilities and offerings. *This is not guaranteed to be covering everything, hydrogen is a new area and only online sources were used to gather this information. RFI's should be conducted with each individual supplier to receive the full picture.*

4.4.3 Suppliers Outside of Hubs

Supplier ecosystem outside of the hubs is an additional factor to consider, however research of their existence and availability would lack structure in terms of a literature study and theoretical saturation would be difficult to argue. This was therefore researched and done internally with the Volvo Group and kept outside the thesis report.

4.5 The Investment Decision for Clean Hydrogen

The scenarios, as interpreted from the literature in section 3.5, should consist of make or buy alternatives for assessment of the plants, with regard to their context. What is shared amongst the different plants is the need for hydrogen through some type of fueling solution in both the operational and technical case. For the technical department the case is an on-going need with flexibility, cleanliness, purity, and safety as requirements. While the operational department has a need that will come and scale over time, with a stationary solution requirement as described in section 4.2. The requirements for the operational case were described as fuel slot accessibility, fueling speed and supply upkeep through non-interfering ways. This is on top of the in-common requirements of cleanliness, purity, and safety.

The question is how these needs can be accounted for, what solution that best fits and how that solution can be facilitated. An additional question is where the hydrogen supply, the source, to that solution should come from. The approach was to divide these areas into three subchapters: Source Options, Delivery Options and Refueling Station Options. This was done to convey the complexity of potential scenarios and the investment decision which lays ahead. Further, a "Partnership Options" subchapter was added to convey the complexities within that as well. Everything presented below comes from the internal seminars held with hydrogen buyers at the Volvo Group.

4.5.1 Source Options

Hydrogen has multiple production pathways, as described in section 3.2, which above the different color variations as a consequence also has different types of actors specialized in producing them. This gives multiple different ways of sourcing hydrogen for the scenarios. The options that were discussed in the internal seminars regarding how to get the source was, a spot market like acquisition of hydrogen (Ad-hoc), having one or a few dedicated suppliers (Contractual), produced internally (In-house) or it could be produced and delivered through a partnership (Collaborative). There are probably some other niche ways of sourcing hydrogen as well, but these are considered the main options available.

Different color hydrogen comes from different production pathways and are different levels of clean. While some actors are capable of supplying all types of categorized hydrogen, others are specialized. The actors from whom to purchase are therefore dependent on the type of hydrogen that is required. Volvo Group has not taken a firm stance on which one, but they do want clean, thereby disregarding the potential of gray hydrogen. As of now, uncertainties with the carbon capture technology removes blue as an option as well, at least for the specific scenarios of this thesis. This does not mean that it is not an option for the Volvo Group to consider, but merely a limitation of the complex situation. The remaining availability of clean hydrogen comes down to green or pink. With pink of course reliant on additional examination regarding the nuclear waste and its “clean” consideration. The safe bet would be to use green hydrogen, but pink is one that will be easier to scale-up in terms of available electricity.

Different actors that can provide green or potentially pink hydrogen are big oil and industrial gas companies, electricity provider companies, renewable electricity producing companies, hydrogen technology companies (like electrolyzer companies) or produced internally. Again, probably some other niche actor types that could provide clean hydrogen as well, however these 5 are considered the main options.

Additionally, the production (or source origin) can result in various forms of hydrogen, like liquid, gaseous or be transitioned to chemical compounds like ammonia. This results in various transportability options and hence very different costs depending on end use. With a focus on 700 bar gaseous hydrogen, having a compressor is necessary - either compressed by the supplier or compressed at point of use. This adds further complexity when, for example, the hydrogen can be delivered as liquid, compressed, and then used like 700 bar gaseous hydrogen. As pointed out in section 3.2, the system view is important for costs and emissions.

4.5.2 Delivery Options

The hydrogen source has to get from supplier to plant, involving the potential use of various transport solutions. This is quite a large part of the total costs (about ⅓) and can only be completely discounted in an internal make scenario. This applies additional complexity to potential scenarios. Further, it is said that delivery without pipelines is economically feasible only below 100 miles in the gaseous case, longer deliveries with liquid may be possible. However, with the phase transitioning and maintenance of the liquid phase during the transport would require huge volumes to be transported, stored (which requires big storages and adds an additional cost) and then utilized as well for it to make economic sense. Since Volvo Group does not have a large volume consumption at the moment and is projected to not scale that much in the coming years to 2030 either, this will not be looked at.

As found, hydrogen pipelines exist in small amounts in the U.S (1600 miles) and are not close to the Volvo Group plants. While also requiring permits, long timelines, high investments, and heavy planning to implement. This means that pipeline delivery is in the distant future. This is also mentioned in both supplier and non-supplier interviews. Since it is gaseous 700 bar hydrogen that is of interest, the source has to be in the vicinity of the plants with a 100-mile radius maximum. This excludes the likes of shipping and train delivery. What is left is either by truck or through trailers.

As an additional alternative, with a nearby source or potentially a built out renewable energy system in the vicinity - a microgrid solution involving Volvo Group plants could likely be arranged, which could be applicable in either a make or a partnership solution.

4.5.3 Refueling Station Options

Finally, a refueling station with a dispenser that Volvo Group can access for either testing or truck production or both. The two cases, technical testing, and the operational production, had quite similar requirements except for some additional specifications for the operations case with filling speed, availability and that the solution is stationary. The refueling station can only really take three different forms with current technology, like a moveable mobile station solution, a semi-stationary modular solution or a stationary built out refueling dispenser system. The first solution, explained like a mobile station, is a refueling system in a trailer which can store and dispense hydrogen. It is highlighted as a temporary "low volume" use, where you can move it and remove it easily. The second type, the modular station, is housed within a container. It consists of a pre-made hydrogen refueling system that can be assembled and also modified over time, like scaling up or down as demand changes. Last, the stationary system with dispenser functionality, is a system dependent on a connected infrastructure. That is either producing hydrogen or setting up a storage and related supply-chain to connect it with. The technical requirements pivot towards one of the first two solutions while the operations requirements, with specifically the "stationary" requirement, pivot towards the stationary solution. Depending on how you define stationary, the other two concepts could probably apply as well if they get anchored to the ground.

The additional complexity that is added to this is how to get and finance the solution. The identified possibilities are leased from a supplier, co-funded through a partnership, self-funded by Volvo Group or "self-funded" with support through grants, subsidies or green bonds. Again, there are probably other niche methods to fund such solutions, however these 4 are deemed the key options.

4.5.4 Partnership Options

The previous 3 subchapters explaining all the options, invite heavy complexity if everything is going to be accounted for. Explaining the different avenues, a partnership could potentially take would only add to the already existing complexity. Therefore, in order to define the potential of a partnership it is important to consider what key aspects that need to be considered for the Volvo Group when forming one in hydrogen for the context of the thesis. The most important factors to consider when forming a partnership is the size of the Volvo Group in comparison with the partner, and the power dynamic that follows. Because of the brands' value, it can have heavy influence in partnerships, and should be considered. Also, a partnership is heavily dependent on two different actors with each their own agenda - where a partnership should only be facilitated through similar core values and a common goal.

Therefore, a scenario regarding partnership considers the said aspects in the paragraph above. Such a partnership is based on the fact that the Volvo Groups' core competencies do not lie within hydrogen, the expertise needed should be provided from the other side of the partnership. That specific partnership can take many forms but will be generalized for assessment in the purchasing scenario analysis.

4.5.5 Investment Decision Takeaways

There is a high complexity to consider and a lot of potentially attractive routes to go down when it comes to purchasing a solution for hydrogen availability. In the analysis section 5.6, specifically 4 scenarios are identified where each scenario potentially could be of interest and may look favorable depending on the context of the plant and on input from the volume parameter. Therefore, these scenarios will be analyzed and compared against themselves in different volume intervals rather than against each other at a specific volume. The plants may advance at different speeds and one singular solution across the board is not necessarily going to match the complexity of the real world. Due to the availability of potential solutions and the complexity available, other solutions than the four identified may be of interest as well but will not be covered in this thesis.

5. Analysis and Discussion

The report so far constitutes some long chapters with a lot of information. The following chapter aims to analyze and discuss based on that information. The chapter begins with a throwback to the research questions of the thesis, as a reminder of what the chapter will target and then dives into the various topics of interest to analyze in order to answer them:

RQ 1: What is the as-is situation of hydrogen infrastructure and ecosystem with emphasis on the northeast of the U.S?

RQ 2: What are the key factors influencing the purchasing decision of hydrogen?

5.1 Hydrogen as a Topic in Context for the Volvo Group

The current cost of clean hydrogen is considered too high to create an actual demand which can compete against other resources in the energy market. It can therefore be seen as a barrier, and as highlighted in section 3.2, the total cost of hydrogen is built on three equally costly parts, production, distribution and conversion. Because of this, hydrogen production today is localized, the demand is often based on the locations of the hydrogen production facilities or refineries which create and utilize their own production of hydrogen. Despite costs being a barrier, the market can be seen moving in other early market phases like the BEV, where big costs are present. This may mean that the movement towards hydrogen should happen gradually despite the costs being high and therefore will be necessary to build towards even without a favorable business case on the horizon. A big driver of these initiatives is the commitment that is made towards the science-based targets.

There is still an obvious need for lowering the high costs surrounding hydrogen, and technological advancements are needed in order to facilitate a price reduction that would make hydrogen more attractive to compete on the energy market. It is also of interest to make sure that the produced hydrogen is considered clean, which is less carbon intensive and more sustainable. In order to do so, the U.S government has set up different targets with included frameworks that will enable goals to be achieved. One such governmental goal is shown in section 3.3, the hydrogen shot initiative, which aims at providing 1 kg of clean hydrogen for $ 1 within the next decade. However, as illustrated through the report and highlighted in the supplier interviews, this seems to be an ambitious goal. Still, the technological advancements in the coming years should be enough to at least stimulate price reductions for hydrogen and increased demand in combination with strong commitments from different actors. Which will enable more competitive costs, striving for a cost parity with gasoline and diesel. This has been highlighted by suppliers in section 4.3 to be the main goal and driver, which also can be considered the main factor when constructing a hydrogen business-case for the Volvo Group customers.

The main goal of hydrogen utilization is to decarbonize. With heavy commitments towards science-based targets and a world devoted to fulfilling the Paris Agreement, actions have already been taken (like the law in New York to have 100 % of heavy-duty vehicles sold to be ZEVs by 2045, as mentioned in subchapter 3.2.4) and are likely to increase going forward. That is actions like regulations, taxes, penalties, or other methods to make emitting a more costly option to force the decarbonization to happen. This will likely mean that average prices will rise and solutions with decarbonization abilities are prioritized. Something of essence to facilitate this, will be to track carbon dioxide emissions and have a general comparative base. The current categorizations of hydrogen in colors are probably quite weak, it is difficult to distinguish exactly how good or bad they are. An increasing method is the Carbon Intensity (CI) Index, which could be applicable across fuels and products. Further, a question should be raised, specifically in terms of "clean hydrogen" definitions. The Department of Energy has the definition, as can be seen in section 3.3, at maximum 2 kg carbon dioxide per 1 kg of hydrogen produced, looking at the production process and another one at 4 kg carbon dioxide per 1 kg of hydrogen produced looking at life cycle emissions to be within the "clean" limits. These are, as stated through interviews in section 4.3, like the tax credit conditions still under construction. As shown in subchapter 3.1.2.4, the production process emits 5.5 kg of carbon emissions per 1 kg of hydrogen produced, which raises the question if a 63 % decrease ((5.5-2) / 5.5 = 0.63) is enough to be considered clean and enough to get within boundaries of the science-based targets?

With the current, fast changing environment of events that are unfolding in the U.S hydrogen market, as highlighted in section 4.1, there are a lot of potential pathways for the Volvo Group to consider and act upon in order to be able to position themselves in the upcoming clean hydrogen economy accordingly. It is however important to understand that the future of clean hydrogen is based on optimism and ambitions through the means of governmental acts, which helps incentivize the transition needed to reach the goals set up by the U.S government. Therefore, an actual understanding of today's U.S hydrogen environment is important to have, which facilitates a basis for decision making and planning for the future. The fact is that the current, as-is U.S hydrogen market, is one dominated by gray hydrogen, which is based out of refineries and chemical industries as has been highlighted in section 4.4. Also, in subchapter 3.4.1, when looking at electricity produced (which enables the use of electrolysis) it is also heavily dependent on natural gas. When looking at the current hydrogen market it becomes clear that goals set up by the government are ambitious. As highlighted by supplier interviews, there are more things to consider than acts and incentives to really develop and realize the U.S hydrogen economy that has been envisioned. Therefore, regulations and policies have been stated through interviews in section 4.3 with both suppliers, non-suppliers and researchers to currently be seen as very important for the hydrogen economy. Therefore, hydrogen- policies and regulation are crucial to consider in order for this to be possible. Which means that the hydrogen economy of the future is uncertain in terms of time-, technology- and policy wise.

Nevertheless, when certainties regarding time-, technology and policy emerge, and such a hydrogen future that has been envisioned by the U.S government evolves, Volvo Group needs to be prepared to act. Not only to meet the goals set up by themselves to reach by 2030 and 2050, which are part of their long-term strategy and commitments to science-based targets, but also to enable a favorable position in the evolving market. This does not necessarily mean taking a leading position right now, but rather staying on par with market development. Then, at an identified opportunity, utilize Volvo's great knowledge and experience within large-scale truck production to ensure that Volvo Group can take market share and be a big player in the future hydrogen transportation economy.

There is evidence to suggest that the hydrogen economy will be a part of the future. It is however not the author's decision to state how the Volvo Group should be involved in the future of hydrogen, but rather a suggestion that Volvo Group should facilitate enough means to stay on par with the market and be able to take part in such a future if it scales. That is because of the potential such a future possesses, in combination with the commitment that is made to the science-based targets from the Volvo Group side.

Lastly, connected to how customers will view the blue hydrogen, since it cannot be considered as green or renewable. It is therefore of interest to understand the customer behavior towards the coming hydrogen market. Since, it has been highlighted throughout the report, that the as-is situation is dominated by gray hydrogen, which of course will have the possibilities in the future to turn blue. However, will the customers of Volvo Group even be interested in blue hydrogen. Since, customers' reasoning for buying a hydrogen truck could be considered dependent on green hydrogen. This is based on the fact and assumption that one would buy a hydrogen truck because of its environmental impact, therefore customers can be considered environmentally friendly. It is not clear as of now what kind of customers exactly will be of interest and further research should be done into this. It is, however, important to notice and highlight the situation, to question whether a customer will be interested in buying hydrogen that is not green for their trucks.

5.2 Supply Chain Analysis

As was shown in section 3.4 and illustrated in Figure 6, all of the current hydrogen-interested Volvo plants are situated in Appalachia. This regional cluster is highlighted as a region which is characterized by its richness in natural gas as a resource. Because of this, natural gas heavily influences the energy- production and consumption in the region. This is also seen as the general case for the U.S, to be dependent on fossil fuels and natural gas. Due to this, it is interesting to analyze how clean hydrogen will be produced and available for the market, and how the supply chain will enable this.

One of the most important factors to consider is the enabler of green hydrogen, electrolyzers, and the current capacities within the U.S. It is shown in section 4.4 that the current capacities are low and also that the plans set up for electrolysis are quite far off from the existing demand today. In that same section 4.4, it is shown that planned capacities in the U.S are for 172.4 MW of PEM electrolyzer. PEM being 26 % of the total installed type of electrolyzers, meaning that if plans are similar for ALK there should be 545.6 MW (172.4 / 0.26 - 172.4 = 545.6 MW) of Alkaline electrolyzers planned (however, this is probably lower since PEM is a newer and more powerful version of electrolyzers), but that would result in 718 MW in total planned electrolyzer capacity (545.6 + 172.4 = 718 MW), which could account for 55 thousand tons at current estimated average production rates per day of 212 kg (718*212*365=55 558 tons). Through interview 8, which was an electrolyzer company, they stated that a 400 kg capacity per day would be possible per MW of electrolyzer. Which would bump the number to about 105 000 tons (718*400*365 = 104 828). Both of these numbers are very small in comparison to the total demand at 11.6 million tons, which is a demand that is also projected to massively increase as dependencies on clean hydrogen for decarbonization becomes a reality in many sectors. To put 55 000 tons into context for the transportation sector, if all went to heavy-duty trucks, it would support close to 1900 trucks per year operating daily (55 000 tons available / (80 kg tank/day*365 days) = 1883 trucks). Which is extremely low, looking through a whole country perspective and current numbers of operational trucks.

What is clear is that more capacity is needed for the clean hydrogen economy. In section 4.4 it can be seen that the U.S have a dependency on natural gas, which is reflected in the as-is situation of the production of hydrogen. As has been highlighted through supplier interviews, they are able to provide large volumes today and have the capabilities to meet a rise in demand. A demand which is said to be dependent on the price of hydrogen according to supplier interviews in 4.3. Currently, capacity is heavily dependent on the SMR method, which as of now enables gray hydrogen in huge majority, which is also the cheapest option. This can be changed to clean with the carbon capture technology, which showcases the importance of blue hydrogen to enable a clean hydrogen economy in the U.S. This is since volumes of solely green hydrogen are estimated to be ~55.000 tons which is only 0.5% of the total U.S. demand today (55 thousand / 11.6 million = 0.005). There are however uncertainties regarding this carbon capture technology which is highlighted in subchapter 3.1.3.

Because of the reasons mentioned throughout this chapter, the transition towards clean hydrogen might be more difficult than one thinks. And even though there are drivers which incentivize such a transition, barriers need to be looked at as well. Such barriers are said to be costs and technological advancements within the supply chains. The carbon capture technology remains uncertain as to how efficient it is, literature from subchapter 3.1.3 shows both heavy criticisms regarding carbon capture technology and blue hydrogen production, while others praise and estimate 90 % capture efficiencies. Word of mouth by suppliers also contains discrepancies in availability, some are already “ready” while others estimate for 2028 or onwards. Blue hydrogen will be a crucial enabler for large volume clean hydrogen production within the U.S, but its availability is uncertain. The importance lies in clean definitions, the efficiency which it can achieve and that hopefully this will be looked at through a life cycle approach.

Further discussed through the report are the challenges that hydrogen faces due to its inherent characteristics, which is reflected in the storage- and transportation of hydrogen. Storage of hydrogen takes up a lot of space and the idea is commonly to look at utilizing underground storage of different kinds, which is very geographically dependent and far away in time. Therefore, it can easily become very expensive to store large amounts of hydrogen today. Transporting hydrogen is often compared to natural gas and its pipeline infrastructure, and correlations are made in regard to how the hydrogen grid will evolve. As of now, it is very small in comparison and has really only made some regional advancements in Texas, where the majority of hydrogen pipeline infrastructure exists today. Connected to this is the infrastructure of HRS that is only developed in the state of California as of now, with plans on developing on the east coast in the coming years through the interstates as a main route. There is a big infrastructure gap in most states, hubs are the first stage in closing this gap - but it is years away, DOE has first year operational targets of hubs for 2032.

Combined, both storage- and transportation of hydrogen consists of around ⅔ of the cost and becomes an important aspect to consider and to decrease in the future if hydrogen is to reach cost parity with diesel. This, in combination with development and scaling of HRS are crucial factors to consider when looking at the clean hydrogen market for specifically the transport sector in the U.S. There is a lot of ground to cover, the hubs may be the starting point - but likely requires heavy further initiatives, more policies, and more investments if this truly should be incentivized into reality.

5.3 Hub Assessment

When looking at the hubs and their role in the hydrogen ecosystem it is important to highlight that they are playing an important role in kick starting the hydrogen economy and driving it forward. Even though there are already existing actors, producers, distributors and offtakers there is more needed to accelerate, especially with regard to clean hydrogen. The as-is situation can be said to consist of a hydrogen ecosystem of gray hydrogen. Where the hubs will enable an ecosystem of clean hydrogen to accelerate- and evolve. They also create a solid foundation of both clean hydrogen demand and offtake, which is ensured through the hubs. Therefore, the hubs together with governmental incentives can be seen as a leading force in driving the development forward for the clean hydrogen ecosystem.

Because of the regional characteristics, some hub concepts in close proximity to the Volvo plants will utilize the Appalachian natural gas resource in their plans to produce blue hydrogen, which was showcased in section 3.4. Other hubs in the region can instead be seen to plan to go towards renewable- or nuclear energy to generate green or pink hydrogen. But such hubs will utilize energy resources which are not as common in this region, especially renewable. More importantly, actors within the hubs will, according to interviews held, have priority to volumes produced within the hubs through contractual guarantees, leaving potentially low volumes of green hydrogen on the general market. However, if hubs are able to realize a production of green hydrogen in a region which is dominated by natural gas, there are arguments that support other actors to be able to as well. Actors within the hubs are planning to be capable of producing more volumes than needed for the hub in order to provide green hydrogen for the general market. Also, green hydrogen is expected to be production ready before blue hydrogen. Further, other actors outside of the hubs could be capable of doing so as well. Meaning that there could and should be available volumes of green hydrogen outside of the hubs in the future. Another argument that supports this conclusion is that out of the 22 publicly encouraged hubs, a maximum of 10 will be chosen for governmental funding. Therefore, all hub applications will not be finalized and there should be projects which were planned for a non-realized hub, which is developed independently instead.

Because of the reasoning in the previous paragraph, it can be highlighted that green hydrogen will be available for the market outside of the hubs. But, to a very little extent of what is actually needed. Which indicates that blue hydrogen will be in majority and a necessity to meet the huge demands that exist and will increase. This can also be seen from the calculated potential of the electrolyzers in the planning phase combined with capacity of operational electrolyzers. As seen in section 5.2, estimation is at ~55.000 tons - which is 0.5 % of the current total demand at 11.6 million. The current electricity limitation looks to be a problem for the green hydrogen to fill a high percentage of the demand, blue is a necessity.

In a hub, there will be actors coming together through a cross sectoral collaborative approach, which means that there are a lot of different core competencies and therefore learnings to be made. These competencies and the knowledgebase are something that is not based on a financial pledge, or commitment, but can be based on general encouragement of the hub. The importance of just being a supporting partner can bring significant benefits without investing financially, but rather public endorsement can be considered enough to gain certain benefits.

Because of this, there could be an interest to show such an endorsement. Location-wise there are some hubs which can be considered of interest for the Volvo Group, due to their close proximity to the Volvo plants. But it is very important to consider that not all of the hub concepts will get funding from the DOE. There are different criterias that have been set up by the Department of Energy regarding the development of hubs.

- At least four hubs should be developed in separate regions of the U.S.
- At least one hub should be based on fossil fuels, with CCS.
- At least one hub should be based on renewable energy.
- At least one hub should be based on nuclear energy.
- At least two hubs should be located in regions which are rich in natural gas.

With this in mind, one can speculate regarding the probabilities of one specific hub being developed. When doing so, there’s potential for a hub in the northeast which is based on the fact that there’s great natural gas resources as well as nuclear capabilities. It is however not the intention of this thesis to speculate, but rather to highlight the current situation. Because of this, it is important for the Volvo Group to consider what a potential endorsement of a hub would mean, the possibilities of it not being selected or other potential risks.

Such potential risks could be with regard to the huge energy consumption needed for the hubs to actually work. As has been highlighted there are some hubs in the close vicinity which aim at producing green- and pink hydrogen. But to do so in an area dominated by natural gas may be problematic as an electricity dependent producer where heavy investments are going to be needed in clean electricity production. Important to not just move clean electricity away from current use into hydrogen due to the lower efficiencies in hydrogen production. Clean hydrogen is not the end-goal, it is a facilitator of decarbonization.

5.4 Competitive Analysis

The hydrogen environment constitutes and is based on a lot of willingness to cooperate in order to drive the existing hydrogen market forward, as seen internally through workshops and conferences as well as has been further highlighted through the interviews conducted. The supplier interviews further assert and promote the willingness- and capabilities to scale production up if there is a demand. However, this is heavily based on the emphasis that there is a need for price reductions for hydrogen and that it does not necessarily mean only producing clean hydrogen.

5.4.1 Volvo Side Outlook on the Market / Market Assessment

The Volvo Group is a big and reputable truck producer with great experience, knowledge and understanding needed to produce trucks at a large and global scale. This is where their core competency lies. Because of this, it can be argued that being the first mover in the uncertain future of hydrogen is probably not the goal nor the best approach. But rather utilize their experience and core competence as an advantage, which can enable them to be second in command but still aggressively scale when uncertainties fade. Taking a strong stance and committing to the science-based targets can, as previously argued, potentially mean that efforts should be heavily considered even without a business case on the horizon. That should probably not affect the position as second in command though, as leading the market is a very costly endeavor and is hard to justify.

The role as second in command may also be interesting because of the transport sector's projected small role in the total hydrogen economy, with other sectors required to transition to hydrogen much earlier for decarbonization, while Volvo Group has the electric angle to fall back on as well. This will enable larger sector developments to happen, which all will benefit the hydrogen economy. Through this, developments which will enable lower costs- and learnings for hydrogen, can be utilized according to the business strategy that should be set up. A strategy that should be based on dynamic capabilities since the hydrogen future is uncertain and quick adaptation is necessary.

The Volvo Group is considered to possess brand recognition and the resources to stay on par with other developers and then accelerate when there is a clear customer business case. Where Volvo group can utilize said experience and competence to scale-up and compete. It is therefore not needed to be- or wanted to become a leader in the market, but rather a visionary that can seize opportunities as they arise in the future.

5.4.2 Supplier View on Volvo Group

The supplier view on the Volvo Group will be different depending on the size of the supplier. This is because their relative volume will match differently. Nonetheless, Volvo Group is a company that has huge brand value through their expertise within the automotive industry. This is where their core competence lies and is highlighted by the supplier interviews in section 4.3, that it realistically should continue to be the core focus as well for the Volvo Group going forward in the hydrogen economy. That is because the actual volumes of hydrogen needed by the Volvo Group are considered low, it is rather their customer base that will have the possibility to increase offtake. This means that, despite being reputable in their field, they are not viewed as a super important potential customer in the hydrogen offtake category. One possibility is that involvement in the aftermarket fuel volumes could expand the Volvo Group's appeal towards larger suppliers. Since that would increase the volume potentials and as has been highlighted, the hydrogen ecosystem is characterized by a cooperative nature which enables strategic partnerships to form. Such a partnership will be discussed in subchapter 5.6.6.

5.5 Regulatory Analysis - The Acts and Tax Credits

A regulatory analysis is not the intended focus of the thesis and does not lie in the author's fields of expertise. It is however interesting to see its importance and how regulations, policies and incentives act as a driver of the hydrogen economy. It has been highlighted previously in the thesis that there are three important pillars that build a market: product offering, policies, and infrastructure. Because of this it is important to highlight the importance of IIJA and IRA and what potential benefits they bring, which was done in section 3.4. Where different sections of the IRA can be considered important for the Volvo Group to consider. Also what these acts are missing and what potential further policies that may see the light of day later.

It has been discussed internally how to apply tax credits as beneficial as possible, and there are many ways of getting governmental aid for developing hydrogen in one way or another. There are different combinations that can be utilized through partnerships or solely used internally. As an example, the section 48 tax credit which is highlighted in section 3.4 related to producing storage solutions may interest the Volvo Group due to its fit within hydrogen storage on mobile applications. This, however, may interfere with a collaboration solution in purchasing where the collaboration involves a producer aiming for tax credit 45V. This illustrates the complexity of utilizing tax credits and should be considered by the Volvo Group with regard to potential partnerships and other solutions. Therefore, strategic alignment is, and needs to be, a prerequisite for the Volvo Group in order to capitalize on the incentives made by the U.S Government.

5.6 The Purchasing Scenarios

The potential combination of solutions invites high complexity, while the scenarios all have benefits to them, their reliance is heavily on the context of the plant. By taking a look at the parameters of interest, it is obvious that the parameters affect each other, for example the more product features a solution has the more it will cost. It therefore becomes of interest to assess how the different needs, timelines and volumes will influence the outcome from the choice of the different scenarios developed. This will be done through analysis of the effect that different volumes have on the scenario, but also apply both a short- and long-term outlook on them. There are two ways of looking at this, one is to wait out the favorable business case - the other is to make the decision quicker because it is known that Volvo Group has made commitments to science-based targets. The two different ways will lead to different outcomes.

Based on information presented in section 4.5 in empirical data, simplifications are made in 5.6.1 below, to specify the context and characteristics of specific scenarios identified. Which lays the foundation for 4 concrete scenarios to be analyzed.

5.6.1 The Boundaries and Constraints

As a solution there are numerous complications that may have an impact on the desired solution. These complications can for example be various distances of delivery, various modes of delivery, different types of actors to work with, different ways of sourcing the hydrogen, different cleanliness of the hydrogen or different funding solutions for the refueling station. The complexity of hydrogen availability can be made very high if desired. For the situation of this report, certain simplifications are made to concretize the scenarios to evaluable cases.

Requirements put on the final solution by Volvo Group is that the maximum delivery distance is 100 miles for economic feasibility and that the purity should be in accordance with (SAE) J2719 standard for purity. Further the hydrogen itself will be through an electrolyzer, which means either green or pink. These aspects are considered a general assumption that will apply for all cases. Further, the delivery part, as argued in subchapter 4.5.2. Will consist of clean hydrogen delivery only in gaseous form through trucks or trailers as an assumption for all cases except the in-house production where the transport costs are removed.

Building a hydrogen station requires adherence to multiple types of costs, for example the equipment cost, installation fees, development costs, operational costs and even permit costs due to the safety aspects needed to consider. Other costs are capital costs, alternative costs and other running costs, these are good to be aware of. However, it is not possible to quantify and share a holistic accurate picture of all of this from the available knowledge. Further deep dive with specifics and supplier RFQ’s are needed to quantifiably evaluate exactly. Case specific information is also important, due to regulations varying in the U.S by state. This is important because Volvo Group plants are located in different states.

5.6.2 The Concrete Scenarios

This next subchapter will specify the scenarios, which are based on realistic avenues from available internal resources. When it comes to the actual specifics of the scenario parameters, such as actual costs, actual lead times, etc., it cannot be shared publicly. It will be explained in relative or descriptive terms without revealing any case specific information. A full descriptive summary of all four scenarios and their parameters is showcased in Table 12 below after all four scenarios have been presented in text.

The defined scenarios are mobile station, buy as a service, in-house produced and partnership. Within each, a specific integration of the most sensible available options, which could be backed up by internally held information like quotes, were made in conjunction with Volvo Group hydrogen buyers. This is done because the complexity in its entirety could not be accounted for with the available resources of this thesis.

As highlighted in subchapter 3.5.2 “Purchasing Scenario Takeaways”, the parameters of cost, risk, sustainability, product features, time to market and support of the solution will be presented in relation to each of the defined scenarios.

5.6.2.1 Mobile Station

A mobile station is a trailer with hydrogen inside and a dispenser for fueling outside, the solution can easily be moved around with a truck to meet demand with freedom of location. The refilling procedure can be to take the mobile station to the nearest hydrogen refueling station and fuel it. It can be to move hydrogen tubes to the trailer and refill the tank at locations of use or it can be to swap the whole trailer for a new one to minimize downtime. The idea is that any of these solutions would be facilitated by the supplier of the station as they see best fit to be both the cheapest option while still fulfilling the requirements set by the Volvo Groups requests. As time goes on and the solution needs to be replaced with something else or removed entirely it is easily facilitated with no investment sunk costs. The volume capacities of this type of solution are on the lower end - approximately 500 kg limit as of today's technology (per load). The payment expectations are a lease cost of the mobile station combined with a consumption cost per kg as well, where transportation would be included in that.

When purchasing a mobile station, the cost is one of the main factors to consider. While seemingly a straightforward solution, the technology is quickly advancing, and suppliers of the solution are looking to make a profit. For a mobile station the cost can vary depending on several factors and costs can quickly pile up. For the case of hydrogen, the main aspects to consider is the capacity and volume frequency needed, with a very high cost per kilo of $12 - $20 the solution is viable for smaller volumes. The permit situation is considered to be relatively easier over a stationary solution, allowing the time to market implementation of this mobile solution to be quick - can be counted in weeks.

There is no major technological understanding required in order to utilize it, oftentimes there are learnings of sorts included in the offer. With this in mind, the solution can be considered quite low in risk because the trailers are provided by the supplier and leased from Volvo Group side. Neither are there lots of technical training or similar needed, which means that there is no operational risk in the form of knowledge gap. Dependability is arguable, in one sense the mobile station provider also provides the hydrogen within, meaning there is dependability. But with no real investments the switching costs to an alternative supplier should not be too high. Obviously, there will be a contractual period, but constructing a reasonable contract with good clauses can be beneficial to allow switching if necessary. Other features such as delivery of hydrogen, guarantees and responsibilities will also have to be clarified through contractual agreements. This regards technological aspects such as maintenance etc., that therefore entails some further necessary dependability on the supplier. Overall, support is available but not required. Sustainability is a bit more difficult to argue, but in general terms, this solution is the most flexible and least land consuming. It will require truck transportation which involves some emissions. The ownership aspect lying on the supplier allows mitigation from social sustainability disruptions effect on the Volvo Group brand if occurred.

For the context of the Volvo Group, a mobile station can be favorable as long as volumes are low. The investment decision is not major, and the solution allows quite high flexibility in terms of both the solution itself but also allows for transitioning into more major solutions later on. The dependability can be argued quite low, due to the lower efforts needed to be put in from Volvo Group side combined with the low volume requirement and the changeability of the supplier deemed possible. This is a relevant solution because of the early stages of hydrogen development that is present and the match of low volumes.

5.6.2.2 Buy as a Service

With buy as a service, the station is kitted more towards a modular solution. Meaning that it can be upgraded or downgraded over time. The solution is like a container with all necessary equipment inside, but with the modular function of being able to switch out and upgrade that equipment. The mobile element of it, is that it can be moved, however it is not as simple and flexible with freedom of location like a mobile station - but more forgiving if mobility is needed compared to a stationary dispensing station. The equipment in the modular station is kitted to produce hydrogen, store it and dispense it. The feedstock supply of water and electricity needs to be added with electrolyzer production. Having this as a turnkey solution would mean that despite production happening on Volvo Group plants, the production is still in supplier hands, if ownership and control is stated that way in the contractual agreement. The volume capacities can vary a lot, anywhere from kgs to tons is possible, the size of the modular station and its attachment determine it. The payment expectations would be to pay for availability, thereby having a subscription model based on hydrogen availability which logically may include terms dependent on volume use.

Buying as a Service is characterized by a supplier's specific offering, therefore it is considered highly customized and tailor-made towards customer preference. The solution is based on context and may vary by case. When making a purchasing decision that regard a solution as a service, a lot of variables need to be considered as dependencies are high.

Costs is of course an important factor to consider, it will be higher in this case because the as a service aspect would mean high involvement from the supplier. With a requirement to maintain high technology relevance over time as the market and the technology improves. This can be a difficult solution to figure out, as pricing may heavily vary over time. While technological improvements and similar will improve the cost aspects over time as well. Being locked in from a subscription based as a service model may not have the prices improve on par with the technology as the supplier has an agenda for maximizing profits.

The customization and flexibility of a solution like this allows scale up if need be and also enables the most advanced technology to be provided. The solution also enables a lot of support to be involved "as a service" in contractual agreements. This leaves a lot of dependability on the supplier and a lot of the supporting services such as maintenance, safety procedures, regulatory aspects etc. to be their responsibility. Because of this, risk can be considered not to be handled solely by the Volvo Group but instead is rather shared, because of the dependability the supplier becomes responsible for imposed risks. Also, in order for this solution to be provided there is a lot of planning needed and is of course very dependent on the situation. However, time to market can be counted in months depending on the specifics of the service requested.

The sustainability aspects are difficult to comment on, it would only revolve around the supplier and their decisions. One risk is that the service aspect compels ad-hoc temporary actions to adhere to contractual promises which may be worse in a sustainability perspective than what Volvo Group is aware of. The lack of control is the main determining factor for sustainability, it doesn't necessarily mean that the result would be worse though.

For the context of the Volvo Group, this is probably a solution that will be more enticing in the future, as the market and technology develops. When there is more certainty and a more predictable market, basically when there are more established volumes- and need of hydrogen. Buying as a service is a customizable solution that trades control for convenience, that also enables technology on par with development and the ability to scale up. But it comes with a lot of dependability and risk-sharing.

5.6.2.3 In-house Production

Because of reasons stated in subchapter 4.5.1, the in-house production scenario is based on only electrolysis. With the arguments revolving around green- or pink hydrogen being the way forward, since blue hydrogen possesses a lot of additional uncertainties as of now at least. Therefore, a make scenario constitutes the financing, capacity and technology of an electrolyzer in order to produce the hydrogen themselves. Meaning that the Volvo Group would own and control the electrolyzer, fulfilling the correct regulations doing so as well as considering what technology to be utilized (PEM, alkaline or other). The capacity of said electrolyzer will also be important to consider since that is dependent on the need for the plant. Commonly used are PEM electrolyzers of 1 MW which can produce around 200-400 kg per day. Lastly, the operating costs of the electrolyzers need to be considered as well, since the power supply needed will reflect the running costs. Any potential downtime of production maintenance or availability problems will require a back-up solution ready, which will add potential further costs as well.

Buying an electrolyzer from a company means that they will provide installation, learnings, maintenance amongst other things. So even though the Volvo Group would be in control of their own operations, they are dependent on the supplier to provide such support. The most important parameter for consideration is with regard to support. Since, when purchasing an electrolyzer there are many regulations and policies that need to be followed. It is on the Volvo Group to make sure of this when purchasing an electrolyzer, since they will be the owner and in control of it. This can be considered a time-consuming part which also involves a lot of responsibility with a lot of planning needed, implementation time counted in terms of years.

When purchasing an electrolyzer, there is an upfront investment with regard to the electrolyzer itself along with its needed infrastructure. There are also costs during installation and other costs to consider, like running costs, such as electricity and water needed for running the electrolyzer. The upfront investments can be considered high, while production can be made without any profit margins added on along the supply chain allowing for lower running costs. Additionally, there is no need for transportation or delivery of hydrogen since you produce it internally. Which becomes an economy of scale scenario, the more you can produce the cheaper the per kilo cost will be (given everything is utilized).

The customization abilities can be considered lower since you are buying a finished product, but the offering can of course be customized to some extent. Also, depending on the type it can offer a modular ability to scale up. Even though you own the electrolyzer, and have the ability for support from the supplier, it can be considered a necessity to have technological understanding of the electrolyzer in order to utilize it fully. But there is a certain dependability of suppliers with regard to upkeep, maintenance etc.

Since the electrolyzer will be owned by the Volvo Group they control how it is used and the risks involved with doing so. This allows for a certain control of operations which makes sustainable considerations to be highly controllable and considered. There are however several risks to consider with this solution, for example upkeep with regulation and high dependability on one source - if any problems or maintenance is required with the electrolyzer, then the availability of hydrogen is gone. Additionally, to produce clean hydrogen the electricity is required to be renewable - which is a scarce resource and has a price that fluctuates. Since there will be a limited storage of hydrogen available, the production cannot continue indefinitely - but must adhere to the use of hydrogen on-site. Meaning that production cannot necessarily happen during favorable times but must match the time of the need. A solution could be to potentially expand into the business of selling hydrogen as well to not be limited by the storage capacity on-site, however this is venturing into a completely new business. The offtake volumes should be predictable and large for an electrolyzer investment to make sense. This will probably not make sense in the context of Volvo Group, unless the truck production volumes of hydrogen vehicles become very mainstream and predictable.

5.6.2.4 Partnership

As stated in subchapter 4.5.4, a partnership that has been generalized will be taken into consideration. That is because the field of hydrogen is not considered an area of expertise for the Volvo Group, and there are actors who have more experience in the market. This results in a generalized partnership where the Volvo Groups endorsement, brand awareness and allowance to the partner to use the Volvo brand in exchange for royalty payments per volume sold facilitates the partnership. Where the Volvo Group on top of that would buy regular services with improved conditions to fulfill their hydrogen on-site need. Meaning that the Volvo Group will receive needed requirements, as well as additional potential revenue (in forms of royalty) generated through the partnership and use of the Volvo brand.

Because the described partnership can take many various forms and will have different impacts, specific purchasing parameters will be hard to assess and evaluate. However, parameters will be discussed through a general approach in order to highlight the overall impact a partnership would have, since it comes with various similar characteristics. Such characteristics are said to be due to the fact that partnerships often are based on the foundation of collaboration, which is shown and highlighted through the purchasing parameters.

The product features of a partnership solution are considered to be heavily customizable towards the specific need of the Volvo Group. Where the customization is generated through a collaborative approach that best ensures that requirements are met. The collaborative approach is also reflected in the support parameter regarding the product. Because of customization abilities, through product features, the delivery and time to market will potentially require a lot of planning time. As such a solution needs to be collaboratively developed and implemented.

Based on the purchasing parameters discussed, costs can be considered high since there is a commitment towards providing a customizable product and support around it. The potential royalty or revenue generation may subsidize that cost though. Because of said type of partnership, expertise will be put on the other partner. Meaning that the control over operations is also dependent on their expertise. This dependability will also be reflected in one's own control over operations, which can regard parameters such as sustainability. Most connected to social sustainability, since in such a partnership described, there might be sustainability aspects with regard to operation, solution or work-related issues which may affect the Volvo brand in some way.

The definition of a partnership is a collaborative effort, which is dependent on the power dynamics present, and for the generalized partnership it is considered that the Volvo Group can have a lot of influence in such a relationship. This type of scenario can definitely be interesting for the Volvo Group, where the specifics would guide the answer.

	Scenarios			
Indicators	Mobile Station	Buy as a Service	In-house Production	Partnership
Cost	Leasing cost for the station and a per kg consumption cost	Subscription fee based on availability with a per kg format structure.	Investment in electrolyzer plus running costs per kg produced	Shared investments and a per kg used cost
Risk	Dealing with consolidated volumes in short time periods	One actor dependency and dependent on higher volumes	All risk on Volvo and any downtime needs back-up solution	Dependability, potential lock-in effect and uncertain market
Product Features	Freedom of location, flexibility and efficient for low volumes	High customization, allows scaling and enables some flexibility	Some initial customization and ability to scale	Collaborative customization with a shared risk
Time to Market	Quick with low legal requirements	Relatively quick, some legal requirements	Quite long and dependent on location can be very long.	Case dependent
Support	Supplier competence, easy-to-use product	All inclusive	In-house competence or pay	In-house or partner reliant
Sustainability	Low land use but varies with transportation frequency	Low transport which is good. But also lack of control	No transport and full control of sustainability aspects	Relative control due to influence while also partner reliant

Table 12. The specific scenarios explained in comparison to the indicator parameters.

5.6.3 Purchasing Scenario Analysis

The scenarios will be analyzed and compared against themselves in different volume intervals rather than against each other at a specific volume. The plants may advance at different speeds and one singular solution across the board is not necessarily going to match the complexity of the real world.

5.6.3.1 Mobile Station

While the mobile station has the advantage of being a quick and easy-to-set-up transportable solution with freedom of location. The volume potential is low and depending on volume use may require a frequent refilling protocol. It is not scalable in itself, whereas you theoretically can add multiple stations. But that is probably quite a costly endeavor.

Short term it is feasible and encouraged to start with, given the low volumes and flexibility required. The cost effectiveness of a stationary solution should be determined by finding the volume breaking point and at what point the mobile station should be switched out. With technological improvements happening over time, this is best to push out as far as possible in time because the improvements will conclude a better business case.

For the long term, the role of a mobile station will still be intact as long as the volumes are low, additionally the flexible needs for testing may continue to be necessary and therefore a mobile station can potentially play a role even in a future with much larger volumes as well. It can also act as an "emergency" supplemental solution if any disturbances occur.

5.6.3.2 Buy as a Service

The buy as a service approach with a modular station is an excellent choice for a demand that will rapidly scale, as the station allows for modularity of the volume capacities. Similarly, the choice is there to scale down as well if necessary. This is therefore the most flexible solution when it comes to variability in volume, but for the Volvo case it does not look favorable as of now given the lower volumes.

As a short-term outlook, it would not make sense, as the solution would require high involvement from the supplier and with such low volumes it will not look interesting to them. If the idea was to rapidly scale the truck development and be involved in some aftermarket volumes, the idea of this solution might be enticing. But for the Volvo Group case, this is at the moment not something that looks interesting.

For the long-term outlook, it potentially could come of interest as the technologies have advanced, there is a better overview of the available suppliers, and they have proof of concept for such a dependency role in the supply chain. The added benefit of upgrades and replacements alongside the convenience of a service solution might be valuable at a later stage. However, the volumes most likely need to increase quite drastically to be attractive for a supplier to enter into such a contract.

5.6.3.3 In-house Production

Producing hydrogen in-house can bring an increased production capacity as well as great control over the output. It can be considered a good option if there is a steady, relatively high demand for hydrogen. Depending on what kind of electrolyzer is chosen, the ability to scale through a modular approach can also be seen as an option to meet an increased demand. However, this is highly dependent on the capabilities by the operators to do so.

For the short term, it does not make sense having an electrolyzer and producing in-house since the volumes will be considered too low. Because of the high investment costs and planning needed, it takes time to implement, and a lot of regulations need to be fulfilled as well. Therefore, this is not seen as a viable short-term move. Also, producing in-house requires expertise to operate and therefore learnings need to be made in order to do so effectively.

For the long term, in-house production with an electrolyzer can be seen as a good option since you have great control over your hydrogen production. It can be customizable towards specific needs and generate green hydrogen without any delivery. Therefore, mitigating risks and reliance on suppliers, to a certain extent. This can be considered a more relevant solution for the future, most likely a subsequent solution to the mobile station, due to the years of implementation expectancies. Risks can be considered as expensive and while technology is developing fast, a solution may become outdated fast. This is on top of the short-term similar risks argued above.

5.6.3.4 Partnership

Such a solution described, where the partnership is quite one-sided in terms of hydrogen expertise and output. With favorable delivery conditions to Volvo Group plants and a royalty revenue per kg sold in exchange for utilization of the brand to sell more volumes. This would probably be favorable in terms of any volumes on the Volvo Group side, it would just need to be made sure that the supplier can provide the volumes needed and that the Volvo Group has storage and accessibilities to accept it.

The supplier would probably not think this is super valuable in the short term due to the low volume that is sold in total, and the minimum extra volume sold due to the utilization of the Volvo Group brand. This type of partnership would be conducted with a long-term outlook, through similar values and goals. Where if the long-term hydrogen market does develop, there are quite large volumes on the aftermarket for trucks - in which case, the brand utilization can support a further volume increase making the supplier satisfied with the partnership. The outcome would completely depend on the development of the hydrogen market and the hydrogen fuel market in particular.

But there are other things beyond volume which can impact the interest of a supplier to enter a relationship. Since partnership can act as a good way of exchanging competence and there are many different ways for a partnership to bring value.

A potential partnership within hydrogen could be of interest due to the fact a partner would bring expertise and knowledge which the Volvo Group does not have at the moment. Therefore, it can bring a certain value which is hard to create on your own. Especially when there are such important targets to reach with the science-based targets and the Paris agreement along with the uncertain market landscape which is quickly evolving. Meaning that expected volumes over the long- and short term should not necessarily dictate the foundation of a partnership, since there are many other aspects to consider when getting involved with a partner.

While having some interesting aspects and possibilities, it is probably not of interest to diversify outside the core business and into the fuel business. But rather accept the formalities of the market today, not attempt to predict any outcome, position themselves for a future where hydrogen has a good business case for their customers and is a more commoditized product. This is since it would be a potential large investment, where demand is prospective and uncertain. Additionally, the business case for hydrogen trucks is not attractive yet. Secondly this is not where the core competency of the Volvo Group lies, potentially a lot of resources would be allocated for something that may be difficult to argue in terms of priority of the strategic alignment in the current early phases of the market.

However, with an unpredictable market and moving towards a future of hydrogen without a business case, incentivized through commitments as previously argued, can be the case. The possibility is there for it to become another core competency of Volvo Group. That would imply that partnership is a very interesting aspect to share the risk and handle the uncertainties. As well as gaining further knowledge and expertise in the area of hydrogen. Keeping up with the latest developments may be very difficult on your own, different types of collaborations and partnerships are the essence of business in new areas, it is difficult to do it alone.

Important to remember in what type of business environment a partnership is favorable and through which products and competences it is actually value creating. The argumentation is not for any hydrogen partnership - like the truck, fuel cell or other, but for the specific case of hydrogen as a fuel. Possibly, that could come as a bonus from a partnership, but to have fuel as a main focus of the partnership is the one where caution is emphasized.

5.6.4 Context for Volvo Group and the Purchase Volumes

If Volvo Group is going to follow their 2050 net zero emission roadmap and have a hydrogen vehicle ready before 2030 as said in the introduction. Assuming that is going to be the case, numbers written in subchapter 4.2.3 about BEV's can be applied to speculate regarding volume needs. Two full years in, electric vehicles were 0.5 % of the total number of truck deliveries. If Volvo has a hydrogen truck ready by 2030 - then at 2032 they would have a hydrogen need of maximum 9000 kg for operational plant purposes (depending on efficiencies in the fuel cell) with certain assumptions made as described in 4.2.3 by annual report reference. The increase was a bit more than 3-fold from 2021 to 2022 in electric vehicles, from 371 to 1211, which is highly unlikely to compound - but gives an idea of the speed and the potential flexibility that is needed for a solution.

Now this type of analysis is obviously filled with a lot of ifs and uncertainties, but it still can give somewhat a reference or indication of where to look. As the years go by and the electric vehicle growth can further be studied, more ideas can be held about the hydrogen truck potential growth. One big question mark here is of course, will hydrogen develop at the same speed, slower or faster? There is no real way of knowing, but certain limitations of the electric vehicle, like the filling speed is not a constraint for hydrogen and may be one very appealing angle for customers of the trucks. But then again, the hydrogen refueling infrastructure is incredibly limited at current times and would need a big expansion for the customer business case in hydrogen vehicles to apply. Another thing to remember is that 2030 is 6 and a half years away, which is enough time to expand the infrastructure if pushed for. However, with the hub timelines of 2028 - 2032, and truck availability somewhere around 2030. The real scale-up of clean hydrogen will probably be in the mid of 2030 decade closing in on 2040, at which point any prediction made at this point regarding volumes, technology or other is highly speculative. Postponing big investment decisions is likely the correct move in this environment.

If the estimations are too low or if the investment decision is forced to be earlier due to the commitment to science-based targets. Then the solution will be away from mobile stations, with either make, partnership or buy as a service as the solution. They each could look favorable depending on the exact context, which should be evaluated through RFQ's and comparative analysis from both quantitative point of view and the more qualitative reasons brought up in this report. The volume breakpoint is calculated further down in subchapter 5.6.5 "Recommendation".

With still on-going ramifications from the Covid and Russia's invasion of Ukraine, combined with the recent inflation surge and also the energy disruptions following the Nord Stream pipeline explosion, resilience and supply assurance has become very mainstream and pushed for. This is something that surely should be considered when it comes to hydrogen as well. The nature of the hydrogen market is however uncertain, which may cause a heavier tradeoff than other markets would incur to reach such resilience at the current stage. Optimizing for resilience in the early phases of a developing market is probably not very smart either, given that both market dynamics and context variables will change more rapidly than in a more mature market. It should be kept in mind for the future though and to start thinking about it in the early phases will make the adaptation and transition into it more convenient.

5.6.5 Recommendation

The obvious conclusion from both the need and the time horizons to have solutions available, leaves the mobile station solution as a must for at least the beginning. The interesting aspect is how long this utilization can be extended or at what volumes the transition to another solution becomes favorable.

As presented, the 2032 hydrogen need for the operational department is estimated to be around 9000 kg per year, when compared to the electric vehicle progression and assumed beginning of vehicle deliveries in 2030. A mobile station solution can facilitate a need for up to 500 kg per load with current technology, the uncertainty and potential spikes in orders may lead to big fluctuations in volume needs over time and the peak value is not predictable. When that peak value reaches over 500 kg per load, a new solution will be needed (or potentially some efficient refilling methods can be looked at). When that will happen is not certain, and another solution might be necessary to upkeep the need. However, the recommendation remains invariable and acquiring yet another mobile station can therefore be of interest or potentially some creativity in refilling could be discussed. Getting an additional mobile station may be a costly solution since it means doubling the leasing costs. But what can be argued for is that this solution of two mobile stations enables time for reevaluation, constituting an emergency back-up plan.

Using this approach allows the fast-changing market to evolve during the time it takes to scale to 9000 kg of need (and even beyond as the number of loads per year can probably be extended even further), letting innovation advance and uncertainties fade. The technology of available solutions today will have improved. A better understanding of the market will enable major decisions to be made and should be of interest to make when a more certain development of the market is present. At the point of 9000 kg demand, if the demand is assumed linear across the year (which is known to not be the case, but reality is unknown), the mobile station would need refilling 1.5 times every month, which at "worst case" probably can be scaled to once per week - allowing for up to 26000 kg demand for just 1 mobile station over a year period (52 weeks). The problem is found in the aggregated volume needed over a shorter time period, depending on frequency of the orders and how consolidated they are, which is an unpredictable metric that probably can be adjusted in the production schedule and/or in the promise to the customer in the purchasing exchange. The other issue is the transportation costs, which are known to be high for hydrogen, the frequency of delivery is determined to be within economic reasons for once every two weeks at the moment. That would be supporting 13000 kg of hydrogen demand over the year and transportation costs may improve over the next decade to support more frequent loads. This means that the need estimated for 2032 can be facilitated by a mobile station acquired today, which seems like the fair choice. That is because other solutions require heavy involvement, upfront investments or otherwise dependencies - which are unnecessary risks in a market that is incredibly uncertain and in the early stages at the moment. However, the estimation might be wrong. At that point, the demand could potentially be bigger earlier. If that were the case, the breaking point for the solution would be at the time of breaking 13000 kg over a year or above 500 kg within two weeks. In that case the solution needs to change - there you should probably be looking at the dispensing system with attached supply chain. Potentially the make or partnership solution could also be of interest at that point. The best one is dependent on the case that can be provided and the quantitative evaluation of the best case. From there on have both the quantitative support but also think about the qualitative characters and the risks described with each to understand what type of venture that Volvo is getting themselves into from two different evaluation metrics.

Another argument to support a mobile station as a solution, is from the supplier interviews conducted. Their main argument revolves around the fact that it would not make sense customizing a tailor-made solution in today's business environment. Not only will it be a huge investment, but to diversify in the field of hydrogen by producing or forming a partnership can lead to the Volvo Group shifting focus from their core competence. This is implied as riskful business, due to the present uncertainties and technological bottlenecks. Experienced companies within industry and sectors in larger need for hydrogen should lead the way for the hydrogen market to develop, whereas the Volvo Group or the transport sector does not need to lead in terms of hydrogen availability. Focus should rather be on the technological advancements needed for the hydrogen trucks to be available on the market when there is an increased demand. It is also important that the Volvo Group's dynamic capabilities enable them to be ready, to provide the market with a product which will compete and act on opportunities which will arise in a more certain future of hydrogen.

The author's opinion is that postponing investment decisions as long as possible can be considered the best choice, but Volvo Group's decision may turn out differently and likewise the “correct” decision is open for interpretation.

5.6.6 Potential Partnerships

This will consist of very exciting potential opportunities which have been identified but lack the resources to truly analyze its potential. There are other things than just volumes that may impact a partnership, which facilitated this part and were discussed in subchapter 5.6.3.4. It can function as an idea brainstorming which may feed an idea that could be further investigated.

If decided that it's worth pursuing something more in depth within hydrogen. The first potential partnership pathway to discuss is partnership though a public refueling station. This is considered a possible partnership solution since there is a need for hydrogen at the plants, so why not have it connected through a public HRS to allow certain offtake for Volvo Group and the public as well. Such a partnership would allow for the development of hydrogen infrastructure to take place, at the same time as meeting the need for Volvo Group. At first glance, this makes sense since the infrastructure is in need of development and hydrogen would be distributed to the plants accordingly. However, the foundation for such a solution is very case specific and no resources are available to evaluate it. Important aspects to consider if looked closer upon, should be whether this is a desired strategic path for the Volvo Group to take.

Connected to this is another potential partnership to discuss, which is industrial partnership. As highlighted in subchapter 3.2.4.1, there are many industrial actors who produce hydrogen as a byproduct or in excess amounts for their own operations, which could be used for offtake. This type of actor could be a chemical company, an industrial gas company, a construction company, a steel company or basically any company that has utility from using hydrogen and is left with excess. This kind of partnership is already seen for the Volvo Group together with Ovako and SSAB in Sweden. They utilize green hydrogen, where both the hydrogen as fuel and decarbonized steel is involved, targeting multiple use cases for the Volvo Group. However, for the U.S there is no information about if such actors exist in the vicinity and if so, are open to a partnership. Knowledge and resources therefore limit these pathways as there is not enough evidence that would suggest this is a reasonable partnership approach as of now. But it is something that exists in Sweden, with Volvo Group participation, and could be an interesting avenue to look for in the U.S as well.

Lastly, there is potential partnership though hubs which can be discussed. Because of the hub's importance in developing the clean hydrogen ecosystem in the U.S, it would make sense to collaborate through a hub in order to acquire clean hydrogen. Therefore, a hub could be utilized as a matchmaker to find the solution that would satisfy the Volvo Group need. As highlighted in section 4.3, there is also no need for direct investments or that you must dedicate anything but your endorsement of a hub in order to approach the hub for available knowledge.

5.7 Market Prospects, Barriers, and Drivers

If hydrogen, with the low volumes needed for production (compared to the volume used over the lifetime of the vehicle) is a problem to get ahold of for the Volvo Group, what does that mean for the consumer? Well, quite obviously even more problems, which does not favor the business case at all. Therefore, if the business case is strong for the consumer, that indirectly means that Volvo Group should have no problem getting the volumes needed by the plant. It is difficult today, but the business case does not exist today either. Therefore, the author's reasoning would agree with the supplier statement from the interviews that involvement in hydrogen lies outside of the core competency.

Hydrogen is probably not a commodity today, because there are no standardizations, it is not widely used nor is it widely traded. However, if the customer business case is strong for the hydrogen truck, then arguments can probably be made that hydrogen will behave more like a commodity. Which is not really in the Volvo Group's expertise, core competency or business idea to make possible. It is a question of focus, expertise, investments, and involvement on the Volvo side contradicted with the supply risks, costs, and availability on the other side. As the market conditions look today, the risks and costs are high while the availability is low, which would indicate that a more involved solution has a good argumentative case, like the partnership- or make scenario. The need is probably not critical today. If the hydrogen testing is delayed a week or two the business impact is low, while the green flag for vehicle production and bigger needs will not be required until there is an argumentative business case for the consumer - because otherwise no trucks will be sold. A situation where the business case is favored and hydrogen supply is hard to come by, seems unlikely. Which would indicate that today's market conditions will ease before deliveries of hydrogen become critical to the Volvo Group truck deliveries and therefore the Volvo Group business. Thereby indicating a flexible and non-heavily involved approach for the hydrogen need as of now and reevaluated in a couple years with more overview and information closer to 2030 truck availability.

Current barriers that need to be considered in order to enable the hydrogen economy to really develop are the limited infrastructure for hydrogen. This can also be connected to the high costs of hydrogen since the lack of infrastructure makes transportation of hydrogen difficult and expensive. To further complicate, extending the infrastructure to a national grid will be dependent on policies and regulations. Which is today seen as very complex. This, in combination with technological advancements needed to enable clean hydrogen, are seen as major barriers. To overcome barriers, there are incentives that enable a cross-industrial collaborative approach, aiming to provide clean hydrogen and driving the costs down. With the goal of cost parity with todays' options. Big drivers can be seen as the incentives realized by the U.S government though the hubs as well as tax credits. This is a good start, in need of continuous improvement, where regulations and policies play a key role in enabling the hydrogen market to fully develop.

6. Conclusion

RQ1: To conclude research question 1, the as-is infrastructure situation is heavily influenced and driven by governmental policy and acts. The two most recent acts are the IIJA and IRA, with hub-dedicated money for hydrogen related development and additional money specific to technologies. This is for both hydrogen ($9.5 billion) but also other clean electricity investments and other decarbonization efforts (an additional $56 billion) - this may indirectly benefit the clean hydrogen market since green production is heavily dependent on renewable electricity while a strong renewable electricity grid can support electrolysis. Further, there are incentives in strengthening previous existing tax credits, which is commented upon favorably by interviewees. Specifically, tax credit 45V with a per kg produced-based credit for a 10-year period.

The coherent view is that policies and governmental incentives are a driving factor, but that demand must take over and drive the market to find the needed success, suppliers state that they are ready to scale. This scaling refers to immediate access to gray hydrogen, but also for scaling the investments targeted towards clean hydrogen. With the long timelines estimated for large-scale clean hydrogen, these investments and their focus on the area are crucial. The hydrogen infrastructure relevant to the Volvo Group plants, due to the current distance restriction in hydrogen delivery, is made up of seven publicly encouraged hubs, of which all cannot be selected for funding. The potential of encouraging one of these hubs from Volvo Group side, may give valuable knowledge insight in the area without any major input - the reputation risk is to consider though if the hub ends up not selected. Further, there are suppliers in the area capable of all technologies the Volvo Group listed as technologies of interest to map.

Six hydrogen refueling stations (HRS) are planned in the northeast, which is all of the HRS planned in the country outside of California. This is not enough to support a hydrogen truck business case, where ideally HRS should be located throughout the country, at least along the important truck interstates from south to north - ideally west to east as well. However, one of these “lines” may be enough to support a business case for a certain type of actor. Price is also important, which is said to be needed parity with the diesel costs to truly elevate the business case for the consumer. To get there, it's dependent on technological advancements or penalties on emitting carbon dioxide. The price target would be $ 3-4 per kg of clean hydrogen, which is far from current prices at $12-20. The hydrogen shot estimate of $5 dollar per kg is not a reality on the market.

The hydrogen supply and demand is currently >99 % gray hydrogen at 11.4-11.6 million tons. Clean hydrogen is available from electrolyzers at 4000 tons per year in the country, with all planned electrolyzers running - the potential is around 55 000 tons per year with current estimated production capacity per day. Which could be argued to reach around 105 000 tons with the technically possible capacity per day of 400 kg per MW electrolyzer.

RQ2: To conclude the second research question, the purchasing scenarios are dependent on the investment decision. There's an underlying strategic decision which must be taken regarding the standpoint to hydrogen. This involves investing heavily and getting involved in the hydrogen market, or taking a more standby approach, and building a better understanding of the business environment before taking major actions.

Whichever approach that the Volvo Group decides upon, the customer business case is going to be central. Key questions to paint the picture for a good customer business case are in terms of pricing, infrastructure and how hydrogen must function in order to facilitate a favorable case. The need for hydrogen to function like a commodity is prevalent and in such an environment, a certain type of scenario is applicable. The idea of managing that future with today's solution is not a simple task, but looking for overlapping solutions or solutions that allow for preparing for such a case without investing too much resources today, is the identified best way forward.

Under the specific circumstances the scenarios have been developed, it can be considered that a mobile station facilitates a good starting solution when consolidating the need for the plants. Therefore, it can be argued that a mobile station solution will be able to support high enough volumes up until a certain point. It is however not certain when this point will be reached, but with estimates this is around 13 000 kg over a year or when a demand spike reaches above 500 kg within two weeks. The constraint is that the operational side required a stationary solution, upon which a suggested approach may be the mobile station which can be "anchored" to the ground in a stationary manner. Mobile stations are estimated to be able to support high enough volumes to get the Volvo Group through the second year of full production of trucks - as compared to the fully electric vehicle case numbers. Which strongly would suggest such a flexible solution to be utilized. Otherwise, a dispensing system with an attached supply chain would be the reasonable second choice of currently available methods, which could be through an in-house solution, a partnership solution or contractual service agreements.

The waiting game has a strong case due to the uncertainties of the technologies and the business case at the moment. Because of how the current market conditions look today, it will have evolved in a matter of years due to the innovative- and competitive landscape present. Therefore, waiting for the market seems like the best choice. Especially if the hydrogen market characteristics will be commodity-like for the consumer business case to be favorable and truck production to start scaling for real.

6.1 Further Research

The novelty of the topic invites both risks and opportunities, the many variables to consider results in unknown areas, speculative interpretations and then further variables that have been out of scope for the thesis. Because of this, many interesting areas for further researching the topic both in the academic world as well as for the Volvo Group is highlighted in this subchapter.

With regard to the academic world there is more research to be done, specifically in terms of carbon capture technology and CCS. Since, what can be found in literature is limited and critical towards the technology. On the other hand, other sources state that CCS has great potential and can already be applied. Also, there is not a coherent way of analyzing CCS as some consider the production phase only and not the whole life cycle. Because of the discrepancy found it is of interest to further research the capability and adaptability of CCS, since it is seen as crucial in order for clean hydrogen to be produced, because the U.S has such a dependency on natural gas.

Understanding the necessary decarbonization metrics to get within the boundaries for the science-based targets, specifically for the transportation sector. Could help the internal decision-making when it comes to what solutions within hydrogen to support. As argued in the discussion, is 4 kg of life cycle based emissions enough or should another limit be put in place for hydrogen to be considered clean?

Lastly, further research should be in the deep dive of purchasing scenarios, where a more detailed cost breakdown for the specific cases should be done. This should be based on RFI and RFQ's from suppliers, which were not obtainable in the timeframe of this thesis, in order to create a more in-depth look of realistic scenarios. This should be done internally for Volvo Group and should consider a more in-depth analysis, with option-to-option comparison, than what has been provided in this thesis.

References

Agarwal, R. (2022). Transition to a Hydrogen-Based Economy: Possibilities and Challenges. *Sustainability Journal*, 14(23), 15975. https://doi.org/10.3390/su142315975

Agyekum, B. E., Nutakor, C., Agwa, M.A & Kamel, S (2022). A Critical Review of Renewable Hydrogen Production Methods: Factors Affecting Their Scale-Up and Its Role in Future Energy Generation. *Membranes Journal* 2022, 12, 173, MDPI. https://doi.org/10.3390/membranes12020173

Andersen, I. L., Ishii, N., Brooks, T. M., Cummis, C., Fonseca, G. G., Hillers, A., Macfarlane, N. B., Nakicenovic, N., Moss, K., Rockström, J., Steer, A. C., Waughray, D., & Zimm, C. (2021). Defining 'science-based targets.' *National Science Review Journal*, 8(7). https://doi.org/10.1093/nsr/nwaa186

Arjona, V & Buddhavarapu, P. (2021) Electrolyzer installation capacity in the United States. Record #20009 https://www.hydrogen.energy.gov/pdfs/20009-electrolyzers-installed-in-united-states.pdf

Attride-Stirling, J. (2001). Thematic networks: an analytic tool for qualitative research. Qualitative Research, 1(3), 385–405. https://doi.org/10.1177/146879410100100307

Aziz, M., Wijayanta, A. T., & Nandiyanto, A. B. D. (2020). Ammonia as Effective Hydrogen Storage: A Review on Production, Storage and Utilization. *Energies Journal*, 13(12), 3062. https://doi.org/10.3390/en13123062

Baker, S. E., & Edwards, R. (2012). How many qualitative interviews is enough: National Centre for Research Methods Review Paper. Expert Voices and Early Career Reflections on Sampling and Cases in Qualitative Research. https://www.researchgate.net/publication/277858477

Bell, E., Bryman, A., & Harley, B. (2019). Business Research Methods. (Fifth Edition). Oxford University Press.

Bioret, L., Zhu, Y., Krupnick, A. (2023, February 7th). Hydrogen Hubs: Get to Know the Encouraged Applicants. Resources for the Future. https://www.resources.org/common-resources/hydrogen-hubs-get-to-know-the-encouraged-applicants/

Bryman, A. and Bell, E. (2015) Business Research Methods. Oxford University Press, Oxford.

Businesswire. (2023). Appalachian Regional Clean Hydrogen Hub Encouraged to Submit a Full Application for the Department of Energy's Hydrogen Hub Funding. https://www.businesswire.com/news/home/20230112005591/en/Appalachian-Regional-Clean-Hydrogen-Hub-Encouraged-to-Submit-a-Full-Application-for-the-Department-of-Energy%E2%80%99s-Hydrogen-Hub-Funding

c2es. (n,d). Carbon Capture. https://www.c2es.org/content/carbon-capture/

Chenail, R. J. (2014). Ten Steps for Conceptualizing and Conducting Qualitative Research Studies in a Pragmatically Curious Manner. *The Qualitative Report Journal*. https://doi.org/10.46743/2160-3715/2011.1324

Clarke, Z., Della Vigna, M., Fraser, G., Revich, J., Mehta, N., Koort, R., Gandolfi, A., Ji, C., Patel, A. & Shahab, B. (2022). Carbonomics. Goldman Sachs. https://www.goldmansachs.com/insights/pages/gs-research/carbonomics-the-clean-hydrogen-revolution/carbonomics-the-clean-hydrogen-revolution.pdf

Connected DMV. (2022). Mid-Atlantic Coalition Announces Bid to Advance Its Sustainable Regional Hydrogen Hub. https://www.connecteddmv.org/post/mid-atlantic-coalition-announces-bid-to-advance-its-sustainable-regional-hydrogen-hub

Connolly, E., Elgowainy, A & Ruth M (2019). Current Hydrogen Market Size: Domestic and Global. DOE Hydrogen and Fuel Cells Program Record, October 1st 2019. Record #19002. https://www.hydrogen.energy.gov/pdfs/19002-hydrogen-market-domestic-global.pdf

Denholm, Paul, Patrick Brown, Wesley Cole, et al. 2022. Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035. Golden, CO: National Renewable Energy Laboratory. NREL/TP6A40-81644. https://www.nrel.gov/docs/fy22osti/81644.pdf

DOE (2021). The #H2IQ Hour Webinar. [Online]. (2021, December 8th). Department Of Energy. https://www.energy.gov/sites/default/files/2021-12/h2iq-12082021.pdf

DOE (2022). Funding Opportunity Announcement No.: DE-FOA-0002779 Bipartisan Infrastructure Law: Additional Clean Hydrogen Programs (Section 40314): Regional Clean Hydrogen Hubs. https://oced-exchange.energy.gov/FileContent.aspx?FileID=72980077-30f7-4c57-b1e2-7b0bf8e52697

DOE (2022 (b)). Clean Hydrogen Production Standard. Retrieved 2023-05-18. https://www.energy.gov/eere/fuelcells/articles/clean-hydrogen-production-standard

DOE (n.d (a)) Hydrogen Storage. Hydrogen and Fuel Cell Technologies Office. Retrieved 2023-03-16. https://www.energy.gov/eere/fuelcells/hydrogen-storage

DOE (n.d (b)) Hydrogen Delivery. Hydrogen and Fuel Cell Technologies Office. Retrieved 2023-03-16. https://www.energy.gov/eere/fuelcells/hydrogen-delivery

DOE (n.d (c)) Hydrogen Production Pathways. Hydrogen and Fuel Cell Technologies Office. Retrieved 2023-03-16. https://www.energy.gov/eere/fuelcells/hydrogen-production-pathways

DOE (n.d (d)) "Financial Incentives for Hydrogen and Fuel Cell Projects," Office of Energy Efficiency and Renewable Energy. Retrieved 2023-03-16. https://www.energy.gov/eere/fuelcells/financial-incentives-hydrogen-and-fuel-cell-projects.

Energy Futures Initiative (2023). "U.S. Hydrogen Demand Action Plan," February 2023. https://energyfuturesinitiative.org/wp-content/uploads/sites/2/2023/02/EFI-Hydrogen-Hubs-FINAL-2-1.pdf

EIA. (2016). Hydrogen for refineries is increasingly provided by industrial suppliers. https://www.eia.gov/todayinenergy/detail.php?id=24612. Today in Energy.

EIA. (2022a). Hydrogen explained. https://www.eia.gov/energyexplained/hydrogen/

EIA. (2022b). U.S. Energy Information Administration (EIA). https://www.eia.gov/energyexplained/hydrogen/production-of-hydrogen.php

EIA. (2022c). Natural gas pipelines - U.S. Energy Information Administration. https://www.eia.gov/energyexplained/natural-gas/natural-gas-pipelines.php

EIA. (2022d). Michigan State Energy Profile. https://www.eia.gov/state/print.php?sid=MI

EIA. (2022e). Pennsylvania State Energy Profile. https://www.eia.gov/state/?sid=PA#tabs-4

EIA. (2022f). Vermont State Energy Profile. https://www.eia.gov/state/?sid=VT

EIA. (2022g). New Jersey Energy Profile. https://www.eia.gov/state/?sid=NJ

EIA. (2023a). New England Energy Report https://www.eia.gov/dashboard/newengland/electricity

EIA. (2023b). Texas State Energy Profile. https://www.eia.gov/state/print.php?sid=TX

Energy Harbor. (2023). Great Lakes Clean Hydrogen Coalition Encouraged to Submit Full Application by U.S. Department of Energy. https://www.prnewswire.com/news-releases/great-lakes-clean-hydrogen-coalition-encouraged-to-submit-full-application-by-us-department-of-energy-301721303.html

Frankowska, M., Mańkowska, M., Rabe, M., Rzeczycki, A., & Szaruga, E. (2022). Structural Model of Power Grid Stabilization in the Green Hydrogen Supply Chain System—Conceptual Assumptions. *Energies Journal* ,15(2), 664. https://doi.org/10.3390/en15020664

Genovese, M., & Fragiacomo, P. (2023). Hydrogen refueling station: Overview of the technological status and research enhancement. *Journal of Energy Storage*, 61, 106758. https://doi.org/10.1016/j.est.2023.106758

Gherasim, DP. (2022). A Guide to Solve EU's Hydrogen Dilemmas. In https://www.ifri.org/sites/default/files/atoms/files/gherasim_eu_hydrogen_dilemnas_2022.pdf.The French Institute of International Relations (Ifri), Center for Energy & Climate.

Global CCS Institute. (2022). Global Status of CCS 2022. https://status22.globalccsinstitute.com/wp-content/uploads/2022/11/Global-Status-of-CCS-2022_Download.pdf

Global CCS Institute. (n.d). CCS Explained: Capture. https://www.globalccsinstitute.com/ccs-explained-capture/

Griffee, D.T. (2005). Research tips: Interview Data Collection. Journal of developmental Education, 28(3), 36-37. Retrieved from: https://eric.ed.gov/?id=EJ718580

de Pee, A., El Sayed, T., Ghonima, M., Jain, R., Majiti, R., Rahi, J. & Waardenburg, M. (2022). The clean hydrogen opportunity for hydrocarbon-rich countries. McKinsey & Company. https://www.mckinsey.com/industries/oil-and-gas/our-insights/the-clean-hydrogen-opportunity-for-hydrocarbon-rich-countries

H2 Matchmaker (n.d). H2 Matchmaker Hydrogen and Fuel Cell Technologies Office. https://www.energy.gov/eere/fuelcells/h2-matchmaker

Heid, B., Sator, A., Waardenburg, M., Wilthaner, M. (2022). McKinsey & Company. https://www.mckinsey.com/capabilities/sustainability/our-insights/five-charts-on-hydrogens-role-in-a-net-zero-future

Herzog, H. (2023). Carbon Capture. Climate Portal. MIT Energy Initiative. https://climate.mit.edu/explainers/carbon-capture

Hydrogen Central. (2023). US Department of Energy Encourages Southeast Hydrogen Hub to Submit Full Application for Federal Funding. Hydrogen Central. https://hydrogen-central.com/us-department-energy-encourages-southeast-hydrogen-hub-submit-full-application-for-federal-funding/

Hydrogen tools (n,d). Hydrogen Conversions Calculator https://h2tools.org/hyarc/calculator-tools/hydrogen-conversions-calculator

Hydrogen Council (2021). Hydrogen insights. McKinsey & Company. https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021.pdf

Hystock (2022), Hydrogen Storage in Salt Caverns. https://www.hystock.nl/en/hydrogen/storage-in-salt-caverns

HyVelocity Hub. (2023). Home | HyVelocity Hub. https://www.hyvelocityhub.us/

IEA (2019), The Future of Hydrogen, IEA, Paris https://www.iea.org/reports/the-future-of-hydrogen, License: CC BY 4.0

IEA (2020), The role of CCUS in low-carbon power systems, IEA, Paris https://www.iea.org/reports/the-role-of-ccus-in-low-carbon-power-systems, License: CC BY 4.0

IEA (2021a), About CCUS, IEA, Paris https://www.iea.org/reports/about-ccus. License: CC BY 4.0

IEA (2021b), Global Hydrogen Review 2021, IEA, Paris https://www.iea.org/reports/global-hydrogen-review-2021, License: CC BY 4.0

IEA (2022a), Carbon Capture, Utilisation and Storage, IEA, Paris https://www.iea.org/reports/carbon-capture-utilisation-and-storage-2, License: CC BY 4.0

IEA (2022b). Hydrogen energy system overview. International Energy Agency. https://www.iea.org/reports/hydrogen. License: CC BY 4.0

IEA (2022c). Electrolysers. https://www.iea.org/reports/electrolysers License: CC BY 4.0.

IEA (2022d). Hydrogen Projects Database. https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database License: CC BY 4.0

IEA (2023a), Energy Technology Perspectives 2023, IEA, Paris https://www.iea.org/reports/energy-technology-perspectives-2023. License: CC BY 4.0

IEA (2023b), CO2 Emissions in 2022, IEA, Paris https://www.iea.org/reports/co2-emissions-in-2022, License: CC BY 4.0

IEA. (2023c), Hydrogen Patents for a Clean Energy Future, IEA, Paris https://www.iea.org/reports/hydrogen-patents-for-a-clean-energy-future. License: CC BY 4.0

IndustryARC. (n.d.). Merchant Hydrogen Market - Forecast(2023 - 2028). https://www.industryarc.com/Report/19098/merchant-hydrogen-market

Inflation Reduction Act Summary. (n.d.). Department of Energy. https://www.energy.gov/sites/default/files/2022-10/IRA-Energy-Summary_web.pdf

Ishaq, H., Dincer, I., & Crawford, C. (2021). A review on hydrogen production and utilization: Challenges and opportunities. *International Journal of Hydrogen Energy*, *47*(62), 26238–26264. https://doi.org/10.1016/j.ijhydene.2021.11.149

Jacobson, M. Z. (2019). The health and climate impacts of carbon capture and direct air capture. *Energy and Environmental Science Journal*, 12(12), 3567–3574. https://doi.org/10.1039/c9ee02709b

Kerssens-van Drongelen, I. (2001). The iterative theory-building process: rationale, principles and evaluation. *Management Decision Journal*, 39(7), 503-512. https://doi.org/10.1108/EUM0000000005799

Kim, T., Maxwell, M. (2022) A guide to hydrogen legislation in the USA: a renewed effort, *The Journal of World Energy Law & Business*, Volume 15, Issue 6, Pages 449–461,https://doi.org/10.1093/jwelb/jwac029

Knight, L., Meehan, J., Tapinos, E., Menzies, L., & Pfeiffer, A. (2020). Researching the future of purchasing and supply management: The purpose and potential of scenarios. *Journal of Purchasing and Supply Management*, 26(3), 100624. https://doi.org/10.1016/j.pursup.2020.100624

Koshow, H., & Gaßner, R. (2008). Methods of future and scenario analysis: overview, assessment, and selection criteria (Vol. 39, p. 133). DEU. https://www.idos-research.de/uploads/media/Studies_39.2008.pdf

Kuhn, M. (2015). Storage Density of Hydrogen. Wikipedia Commons. https://commons.wikimedia.org/wiki/File:Storage_Density_of_Hydrogen.jpg

Kusoglu, A. (2022). (Re)Defining Clean Hydrogen: From Colors to Emissions. *The Electrochemical Society Interface Journal*, *31*(4), 47–52. https://doi.org/10.1149/2.f08224if

Langmi, H. W., Engelbrecht, N., Modisha, P. M., & Bessarabov, D. (2022). Hydrogen storage. Electrochemical Power Sources: Fundamentals, Systems, and Applications, 455–486. https://doi.org/10.1016/b978-0-12-819424-9.00006-9

Lankof, L., Urbańczyk, K., & Tarkowski, R. (2022). Assessment of the potential for underground hydrogen storage in salt domes. *Renewable & Sustainable Energy Reviews Journal*, 160, 112309. https://doi.org/10.1016/j.rser.2022.112309

Lewis, J. S. (2009). Redefining Qualitative Methods: Believability in the Fifth Moment. *International Journal of Qualitative Methods*, 8(2), 1–14. https://doi.org/10.1177/160940690900800201

Lin, R., Ye, Z., Guo, Z., & Wu, B. (2020). Hydrogen station location optimization based on multiple data sources. *International Journal of Hydrogen Energy,* 45(17), 10270–10279.https://doi.org/10.1016/j.ijhydene.2019.10.069

Mahajan, D., Tan, K., Venkatesh, T., Kileti, P., & Clayton, C. R. (2022). Hydrogen Blending in Gas Pipeline Networks—A Review. *Energies Journal*, 15(10), 3582. https://doi.org/10.3390/en15103582

MACH2. (n.d) https://mach-2.com/about-mach2/

Medlock, K. & Shih Yu, H. (2023). Developing a Robust Hydrogen Market in Texas. Research paper no. 02.16.23. Rice University's Baker Institute for Public Policy, Houston, Texas. https://doi.org/10.25613/YKKH-8K02.

Melaina, M. W., Antonia, O., & Penev, M. (2013). Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues. National Renewable Energy Laboratory. https://doi.org/10.2172/1068610

Mokhatab, S., Poe, W. A., & Mak, J. Y. (2018). Handbook of Natural Gas Transmission and Processing: Principles and Practices. Gulf Professional Publishing. https://www.academia.edu/43151599/Handbook_of_Natural_Gas_Transmission_and_Processing_Principles_and_Practices_Fourth_Edition

Morse, J. M. (1995). The Significance of Saturation. *Qualitative Health Research Journal*, 5(2), 147–149. https://doi.org/10.1177/104973239500500201

Nationalgrid (2023). Carbon capture technology and how it works. Retrieved 2023-03-03 https://www.nationalgrid.com/stories/energy-explained/carbon-capture-technology-and-how-it-works

Nellen, A. & Miles, M. (2019). Taxes and sustainability. *Journal of Global Business and Technology*, 2(4), 57-64. https://www.scienceopen.com/document_file/a4f5b0f5-b0de-425a-872d-b01ae228f884/API/i1943-4618-2-4-57.pdf

Neuman & Esser Group (2022), Storing Hydrogen. https://www.neuman-esser.de//en/company/media/blog/hydrogen-storage-in-salt-caverns/

New York State Government. (n.d.). Governor Hochul Announces Multi-State Agreement Signed with Major Hydrogen Ecosystem Partners to Propose a Regional Clean Energy Hydrogen Hub. https://www.governor.ny.gov/news/governor-hochul-announces-multi-state-agreement-signed-major-hydrogen-ecosystem-partners

Neuschwander, J. (2023). DNA Hydrogen Hub Application Receives ‘Encourage’ Notice for U.S. Department of Energy Funding - Team PA Foundation. Team PA Foundation. https://teampa.com/2023/01/dna-hydrogen-hub-application-receives-encourage-notice-for-u-s-department-of-energy-funding/

Nowell, L., Norris, J. M., White, D. L., & Moules, N. J. (2017). Thematic Analysis. International Journal of Qualitative Methods, 16(1), 160940691773384. https://doi.org/10.1177/1609406917733847

Office of Clean Energy Demonstrations (2022). Regional Clean Hydrogen Hubs. https://www.energy.gov/oced/regional-clean-hydrogen-hubs

Pacific Northwest National Laboratory (2016). Merchant Hydrogen Plant Capacities North America. Retrieved 2023-03-26, https://h2tools.org/hyarc/hydrogen-data/merchant-hydrogen-plant-capacities-north-america

Pacific Northwest National Laboratory (2022a). US Refinery Hydrogen Production Capacity by State. Retrieved 2023-03-26. https://h2tools.org/hyarc/hydrogen-data/refinery-captive-purpose-hydrogen-production-capacities-state

Pacific Northwest National Laboratory (2022b). Top US Refinery Hydrogen Production Capacities. Retrieved 2023-03-26. https://h2tools.org/hyarc/hydrogen-data/top-us-refinery-captive-purpose-hydrogen-producers

Pascal, T. (2022). Different methods of storing, transporting, and distributing Hydrogen. Structures Insider. Retrieved 2023-03-16. https://www.structuresinsider.com/post/different-methods-of-storing-transporting-and-distributing-hydrogen

PCCA (2023). Port of Corpus Christi Horizons Clean Hydrogen Hub. Port of Corpus Christi. https://portofcc.com/port-of-corpus-christi-horizons-clean-hydrogen-hub-and-trans-permian-h2hub-merge-to-create-integrated-regional-clean-hydrogen-hub-proposal/

Pettit, T. J., Croxton, K. L., & Fiksel, J. (2013). Ensuring Supply Chain Resilience: Development and Implementation of an Assessment Tool. *Journal of Business Logistics*, *34*(1), 46–76. https://doi.org/10.1111/jbl.12009

Office of Clean Energy Demonstrations. (n,d). Regional Clean Hydrogen Hubs Notifications. https://www.energy.gov/oced/regional-clean-hydrogen-hubs-notifications

RoadMap To A US Hydrogen Economy. (2020). Hydrogen Fuel Cell Partnership. https://h2fcp.org/sites/default/files/Road+Map+to+a+US+Hydrogen+Economy+Full+Report.pdf

Robertson, B. & Mousavian, M. (2022). The Carbon Capture Crux. Institute for Energy Economics and Financial Analysis (IEEFA). https://ieefa.org/resources/carbon-capture-crux-lessons-learned

Rowley, J. (2012). Conducting research interviews. Management Research Review, 35(3/4), 260-271. https://www.emerald.com/insight/content/doi/10.1108/01409171211210154/full/pdf?title=co nducting-research-interviews

Schoemaker, P. J. (1995). Scenario planning: A tool for strategic thinking. Sloan Management Review, 36(2), 25-40. https://www.researchgate.net/profile/Paul-Schoemaker-2/publication/220042263_Scenario_Planning_A_Tool_for_Strategic_Thinking/links/0deec5325c34174de2000000/Scenario-Planning-A-Tool-for-Strategic-Thinking.pdf

Singh, H., Clahane, L., Harker-Steele, A., Callahan, C., Warner, T., Wallace, B., Brewer, J., Adder, J., & Morgan, D. (2022). Appalachian Hydrogen Infrastructure Analysis. Department of Energy / National Energy Technology Laboratory. https://doi.org/10.2172/1887788

Smith, J. A. (2015). Qualitative Psychology: A Practical Guide to Research Methods. SAGE Publications Limited.

Snyder, H. R. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, 104, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039

Soult, A. (2020). University of Kentucky Chem 103 Chemistry for Allied Health. Chapter 7, “States of matter”. LibreTexts.

R. Stebbins. (2001). Exploratory Research in the Social Sciences. https://doi.org/10.4135/9781412984249

Tashie-Lewis, B. C., & Nnabuife, S. G. (2021). Hydrogen Production, Distribution, Storage and Power Conversion in a Hydrogen Economy - A Technology Review. *Chemical Engineering Journal Advances*, 8, 100172. https://doi.org/10.1016/j.ceja.2021.100172

Teece, D, J. (2016). Dynamic capabilities and entrepreneurial management in large organizations: Toward a theory of the (entrepreneurial) firm. European Economic Review, 86, 202-216.

The Appalachian Energy and Petrochemical Renaissance. (2020). Department of Energy. Retrieved March 7, 2023, from https://www.energy.gov/sites/prod/files/2020/06/f76/Appalachian%20Energy%20and%20Petrochemical%20Report_063020_v3.pdf

Topolski, K., Evan P. R., Burcin C. E., San Marchi, C.W., Ronevich, J. A., Fring, L., Simmons, K., Guerra Fernandez, O. J., Hodge, B-M., and Chung, M. (2022). *Hydrogen Blending into Natural Gas Pipeline Infrastructure.* Golden, CO: National Renewable Energy Laboratory. NREL/TP5400-81704. https://www.nrel.gov/docs/fy23osti/81704.pdf.

U.S Department of Energy (n.d (a)). Alternative Fuels Data Center: Hydrogen Fueling Station. https://afdc.energy.gov/fuels/hydrogen_locations.html#/analyze?country=US&fuel=HY&show_map=true&status=P

U.S Department of Energy (n.d (b)). Alternative Fuels Data Center: Hydrogen Laws and Incentives in New York. https://afdc.energy.gov/fuels/laws/HY?state=ny

U.S Department of Energy (2020). Alternative Fuels Data Center: Average Fuel Economy by Major Vehicle Category. https://afdc.energy.gov/data/10310

U.S Department of Energy (2021). US Department of Energy Hydrogen Shot. https://www.energy.gov/eere/fuelcells/hydrogen-shot

U.S Department of Energy (2022). DOE Establishes Bipartisan Infrastructure Law's $9.5 Billion Clean Hydrogen Initiatives. https://www.energy.gov/articles/doe-establishes-bipartisan-infrastructure-laws-95-billion-clean-hydrogen-initiatives

U.S Senate. (2022). Bipartisan Infrastructure Investment and Jobs Act Summary. https://www.cardin.senate.gov/wp-content/uploads/2022/09/Infrastructure-Investment-and-Jobs-Act-Section-by-Section-Summary.pdf

University of Toledo. (n,d). Great Lakes Clean Hydrogen. https://www.utoledo.edu/research/rsp/hydrogen-hub.html

Valavanidis, A. (2022). Is Hydrogen the Wonder Fuel for Decarbonization? Department of Chemistry, National and Kapodistrian University of Athens, 1(45). https://www.researchgate.net/publication/366150794_Is_Hydrogen_the_Wonder_Fuel_for_Decarbonization_Scientists_argue_that_there_are_greener_and_more_efficient_options

Volvo Internal Documents.

Volvo Group Annual Report (2022). Volvo Group Annual Report 2022. https://www.volvogroup.com/content/dam/volvo-group/markets/master/investors/reports-and-presentations/annual-reports/AB-Volvo-Annual-Report-2022.pdf

Wack, P. (2014, August 1). Scenarios: Uncharted Waters Ahead. Harvard Business Review. https://hbr.org/1985/09/scenarios-uncharted-waters-ahead

Woolley, M. (1992). Using statistics for desk research. *Aslib Proceedings, Journal of Information Management*, 44(5), 227–233. https://doi.org/10.1108/eb051276

Appendices

Appendix A

Plant Interview (Technical and Operations)

Formalities & Introduction

- Introduction (personal and purpose of interview)
- Confirm format and get statement for recording and anonymity.

Background Information

- What are the current ongoing projects? (Hydrogen related)
    - If any, provide a brief overview of the plant's operations and processes
- Is there any specific hydrogen needs and requirements?
    - Like form of hydrogen, ease of use, quality or delivery?
    - Do you work under specific protocols, safety or other?
    - How are the risks perceived?
- What's the sequential overview of the "internal supply chain"?: how is the need determined, how is the hydrogen then received, stored, and utilized?

Current Processes

- What's your experience with today's processes and usages?
- Any challenges or issues?
- Potential improvement suggestions?

Collaboration

- Your experience in terms of collaboration with suppliers and/or internal functions/teams/plants regarding hydrogen?
- What level of support is received from suppliers, technical assistance, maintenance, or hydrogen handling training?
- Any challenges or issues here?
- Potential improvement suggestions?

Future Expectations

- How do you expect hydrogen use to grow in the plant coming months and years?
- What changes are going to be necessary for volume, deliveries, storage or other?
- Any suggestions for how this can be made possible?
- Suggestions for future hydrogen usage in the plant?

Wrap-up

- Additional comments, feedback, or anything else you would like to share or ask?

Appendix B

Supplier Interview, Capabilities, Investments and Hubs

Formalities & Introduction
- Introduction (personal and purpose of interview)
- Confirm the format and get statement for recording and anonymity.

Background
- Can you tell us about your company's experience as a supplier within hydrogen?
- In which areas does your company specialize, particularly the northeastern US?
- What are the hubs that your company is involved in?
- What is your hydrogen related product offering?

Hydrogen Production and Delivery Processes (QDCFTSR)
- Can you describe the process of your hydrogen offering(s)?
- What types of hydrogen do you work with?
- Do you have quality control measures, certifications and/or regulatory approvals?
- How are your hydrogen offering(s) lead times?
- What can you tell us about your pricing structure and cost drivers? Public price?

Capacity and Future Plans
- What is your current hydrogen capacity? (How is your H2 Color partition)
- What are your projected capacity levels for the future (months and years)?
- How will you expand and improve your hydrogen supply capacities?
- Is your focus on liquid or gaseous hydrogen? What impacts your decision?

Role in Hydrogen Hub(s)
- What is your company's role in the hydrogen hub, particularly in the northeast?
- How do hubs fit your overall supply chain, and why are hubs of importance to you?
- What funding regulations or guidelines do you have to follow?
- How is funding and responsibilities structured, delegated, and incentivized?
- How are stakeholders chosen and used in the formation of a hub?

Collaboration and Benefits of the Hub(s)
- How are decisions made in the hub, including geography, size, technology?
- How are dependencies created in the hub, what is done to ensure reliable supply?
- Benefits & drawbacks of being a supplier in a hub vs independently operating?
- Is there any talk about connection(s) and/or collaboration between hubs?
- How do you view the automotive market, how do Volvo fit in your hydrogen future?

Wrap-up
- If you were the Volvo Group, what is your recommendation to do within hydrogen?
- What are the driving forces and barriers of the hydrogen market?
- Additional comments, feedback, or anything else you would like to share or ask?

Appendix C

Non-Supplier Hydrogen Hub Interview

Formalities & Introduction
- Introduction (personal and purpose of interview)
- Confirm the format and get statement for recording and anonymity.

Background
- Can you tell us about your company's experience with hydrogen?
- What are the hubs that your company is involved in?

Role in Hydrogen Hub(s)
- What is your company's role in the hydrogen hub?
- What other driving actors are in the hub?
- How is funding and responsibilities structured, delegated, and incentivized?
- How are stakeholders chosen and used in the formation of a hub?

Functionality of the Hub(s)
- What is your purpose and through which feedstock will you achieve it?
- How does demand and supply look?
- How will you expand and improve your hydrogen supply capacities?
- Is the focus on liquid or gaseous hydrogen? What impacts your decision?
- Time plan, in how long will there be volumes available to purchase?
- Will there be a hydrogen fuel station focus?

Collaboration and Benefits of the Hub(s)
- How are decisions made in the hub, including geography, size, technology etc.?
- How are dependencies created in the hub, what is done to ensure reliable supply?
- Benefits & drawbacks of being a supplier in a hub vs independently operating?
- Is there any talk about connection(s) and/or collaboration between hubs?
- How do you view the automotive market in regard to hydrogen?

Wrap-up
- If you were the Volvo Group, what is your recommendation to do within hydrogen?
- What are the driving forces and barriers of the hydrogen market?
- Additional comments, feedback, or anything else you would like to share or ask?

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF SUPPLY AND OPERATIONS MANAGEMENT
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se