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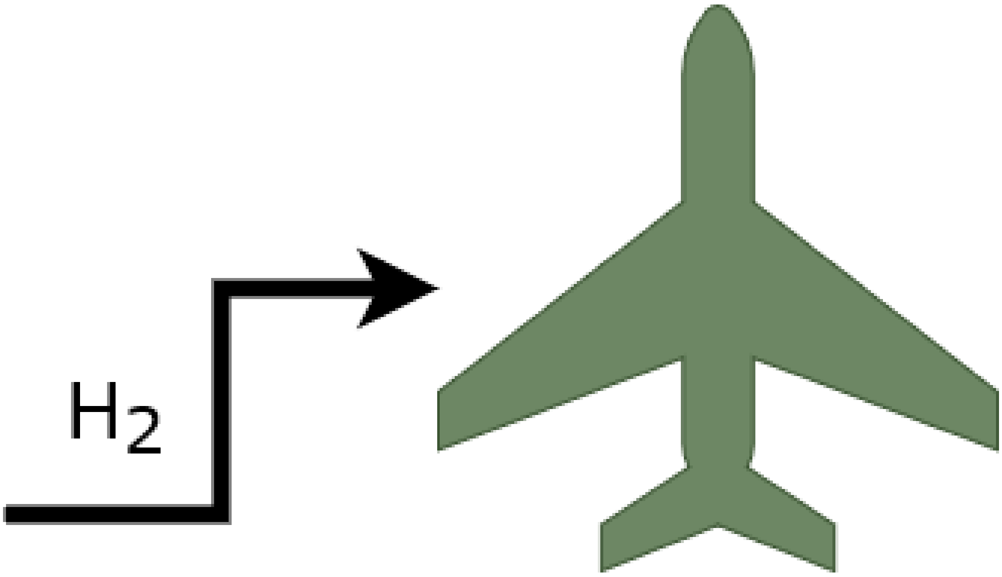

Evaluating potential supply chains for hydrogen as aviation fuel on the Swedish west coast

A quantitative and qualitative study in how hydrogen can potentially be distributed to airports to supply hydrogen-based aircraft

Master’s thesis in Industrial Ecology & Quality and Operations Management

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Cover: Generic illustration of hydrogen transported to an aircraft

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Abstract

Aviation is one of the main polluters within the transport sector and is continuously growing. To be able to meet environmental goals and at the same time fulfill societal demands for transport, hydrogen may be used as an alternative fuel to lower emissions, but research into infrastructure is needed. This thesis uses two methods to quantitatively and qualitatively investigate the potential of different supply chains to supply aircraft with green hydrogen, by conducting a techno-economic analysis and semi-structured interviews with stakeholders. The results of this study show that a transition to hydrogen in aviation is believed to be feasible by stakeholders, and synergetic effects along the Swedish west coast are expected. Centrally produced alternatives are found to be the cheapest alternative early on when volumes are low, while on-site production of hydrogen emerges as the cheapest alternative when demand increases. The results can be used to form an understanding of future airport fuel supply chain planning.

Keywords: hydrogen, aviation, supply chain, LCOH, airport, LH2

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Hjalmar Boström & Wim Lundell Frostensson, Gothenburg, May 2024

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List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

GH_2	Gaseous Hydrogen
LCOH	Levelized Cost of Hydrogen
LH_2	Liquid Hydrogen
PEM	Proton Exchange Membrane
SAF	Sustainable Aviation Fuel

1

Introduction

1.1 Background

Aviation stands out as one of the main perpetrators of greenhouse gas (GHG) emissions. As aviation traffic continues to grow, and with global goals of lowering GHG emissions, and no obvious direct substitute to jet fuel, the aviation industry is seen as hard-to-abate (Nakano et al., 2022). Among the few alternatives to jet fuel, hydrogen emerges as a promising candidate due to its lower GHG emissions and a combination of properties that are demanded in aviation (Yusaf et al., 2024).

The transportation sector is the largest contributor to global warming in Europe (Transport & Environment, 2017). There are incentives to decrease transportation's contribution to global warming, such as the Paris Agreement. Aviation is the second-biggest emitter of GHG in the transportation sector, accounting for 13.9 % of emissions (European Commission, 2023). The EU has presented a new set of policies that applies from 1 January 2024, stating that by 2050, 70 % of jet fuels at EU airports will have to be synthetic fuels and/or certain biofuels, adding that 35% of the fuels must consist of synthetic fuels. Synthetic fuels are defined as e-fuels and hydrogen produced from renewable energy electrolysis, sometimes referred to as "green hydrogen" (European Parliament, 2023). To support this transition, the EU emissions trading system (ETS) will set aside funds that should help operators narrow the cost gap between fossil kerosene and sustainable fuels (O'Malley, 2024). Different fuels are split into different tiers, and synthetic fuels can receive larger funding than bio-based fuels, as synthetic fuels are the only Sustainable Aviation Fuel (SAF) with the potential to reach 100% CO2 reduction (O'Malley, 2024; Soone & Claros, 2022). Consequently, hydrogen stands out as a particularly environmentally benign option due to its potential to significantly reduce carbon emissions.

Green hydrogen availability is based on access to renewable energy and water, and there is a growing share of renewable energy in the EU (Soone & Claros, 2022). The EU's support for green hydrogen development aligns with efforts to advance aviation using hydrogen as an energy carrier, creating synergies for the energy industry within Europe (European Commission, 2020). However, hydrogen should not be considered an all-in-one solution. Hydrogen can be one of several solutions to reduce the environmental impact of aviation. For instance, fully electric aviation is primarily focused on regional, short-distance flights due to the low energy density in batteries (Hoelzen et al., 2022a; Larsson et al., 2019). Hydrogen flights are instead projected to fill medium-distance flights, which could benefit the EU, as trade and tourism within Europe could then continue with a low environmental impact (Hoelzen et al., 2022a; Larsson et al., 2019). Different low-emission technologies will need to find a symbiosis that can create a more sustainable aviation industry. Additionally, advancing hydrogen-based systems across Europe will contribute to this goal, potentially creating synergies across various industries.

There are initiatives from the aviation industry within Sweden that are separate from the EU policies. An example is the collaboration between Swedavia, Rise, SAS, and Energimyndigheten, called “Fossilfritt flyg 2045” (Al-Ghussein Norrman & Talalasova, 2021). The targets are for Swedish domestic flights to be fossil-free by 2030 and for all aviation from Swedish airports to be fossil-free by 2045. Bio-based products are considered fossil-free in this project, but to reach the EU goals, synthetic fuels are also needed. Sweden already has large projected hydrogen producers and users, namely HYBRIT, H2 Green Steel, and Ovako. There is also an incentive to utilize synergies, where energy based on hydrogen can create an efficient local energy system (Energimyndigheten, 2021; Vätgas Sverige, 2023). Al-Ghussein Norrman and Talalasova (2021) emphasizes the importance of research and technical development in emerging technologies to supply the future aviation industry. This includes the supply chain, commercialization of hydrogen, and the synergies and scalability of infrastructure efforts which currently are largely unexplored from a Swedish airport perspective. The problem has become one of acting on developing infrastructure first or producing hydrogen first, as the current hydrogen price is not competitive, customers are reluctant to invest in infrastructure. To advance hydrogen infrastructure development, it is essential to research viable supply pathways.

Developing the infrastructure and processes to enable the use of hydrogen as a fuel in aviation will be a large transition. Airports face a decision to develop the capabilities to produce hydrogen on-site or to invest in a local central production that produces hydrogen for several industries simultaneously. It is important to create a hydrogen strategy that creates synergetic effects for the hydrogen system to be efficient, either internally at the airport or externally between industries locally (Degirmenci et al., 2023; Hoelzen et al., 2022a; Sabio et al., 2010). Airbus together with several European airports has created the “Hydrogen Hub on Airport” program. The initiative intends to gather knowledge on how hydrogen can be stored, created, and used to supply Airbus’s innovation within hydrogen aviation (Airbus, 2023).

This study seeks to explore the benefits and drawbacks of different supply chain pathways for hydrogen supply to airports and weigh them against each other, with a focus on Göteborg Landvetter Airport in Gothenburg, Sweden. By looking into policy and regulation, water constraints, and economic aspects of the distribution chain through interviews and financial models, the study will cover parts of the knowledge base missing for the Swedish aviation industry. This ties back to the call for further research in emerging energy technologies and explores important aspects of synergies between other local/regional industries.

1.2 Aim

The study aims to support future hydrogen infrastructure investments at airports, by evaluating different hydrogen demand scenarios and their effect on the supply chain pathways. The analysis will be based on the different supply chain pathways which will be considered from the perspective of future scalability, cost, and feasibility. This is done to understand what decisions are most beneficial to make without requiring large restructuring in the future.

1.3 Research Questions

The main questions derived from the aim are:

- To what extent are the studied supply chain pathways viable to supply liquid hydrogen fuel at airports, given different demand scenarios?
- How do the studied supply options perform in terms of:
  - policy & regulation in terms of safety,
  - leakage of hydrogen in the supply chain,
  - synergies within the organization and with local industries,
  - and future scalability?
- Does local water availability constrain hydrogen production?

1.4 Limitations

This study will be conducted through a Swedish lens and with the EU/Swedish policies regarding hydrogen and emissions in mind. The study will only consider green hydrogen and not any other type of hydrogen, and a criterion of the analysis is that the hydrogen is to be liquefied into Liquid Hydrogen (LH_2) at the airport or delivered as LH_2 to the airport. Further, we will limit the study to exploring the supply to the airport storage only. Refueling and such operations are not considered, assuming that most of the LH_2 would be distributed through the same methods at the airport. The spatial boundary is within Sweden, for hydrogen supplied by import, the study will only consider transportation from the port of Gothenburg and disregard its production outside of Sweden.

2

Theory

This chapter provides a summary of current literature on hydrogen production, distribution technology, usage scenarios, and its application in aviation today, based on a literature review. This is aimed to act as a foundation for the study and provide data for the quantitative analysis.

2.1 Hydrogen production

Edvall et al. (2022) categorizes hydrogen into 3 different groups. These are "Grey Hydrogen", "Blue Hydrogen", and "Green Hydrogen". Grey hydrogen is produced by Steam Methane Reforming (SMR) which uses natural gas and water steam to produce hydrogen, resulting in significant carbon emissions. Blue hydrogen, on the other hand, employs the same SMR process but incorporates carbon capture and storage (CCS) technologies to mitigate said carbon emissions (Edvall et al., 2022).

Green hydrogen is hydrogen made from renewable energy sources or renewable raw material (Edvall et al., 2022). The most common method of producing green hydrogen is through electrolysis, but it is speculated that it could also be achieved via SMR using renewable gases. As the study is limited to green hydrogen, only production through electrolysis with renewable energy will be explored. The section also seeks to deepen the understanding of hydrogen production and what previous studies have found when exploring the liquefaction process and residual products from electrolysis.

2.1.1 Electrolysis

Electrolysis in hydrogen production forces water molecules to split into hydrogen and oxygen with the help of an electrical current (Shiva Kumar & Lim, 2022). The electrolysis process is an energy-demanding task. To ensure that renewable electricity is not diverted away from other uses, a requirement by the EU is to ensure additionality. This means the EU requires hydrogen to be produced exclusively from additional renewable energy sources built to create green hydrogen (Erbach & Svensson, 2023). According to IRENA (2020), there are two commercialized electrolyzer technologies today, Alkaline electrolyzer and Proton Exchange Membrane (PEM) electrolyzer. PEM electrolyzers are by some seen as the best opportunity for producing green hydrogen due to their fast dynamic response time, which can be important due to fluctuations in renewable electricity availability (Ayers et al., 2021). The PEM electrolysis technical specifications are presented in Table 2.1 (Danish Energy Agency, 2024a; IRENA, 2022b). In addition to the energy needs, there is a water demand for water which is split into hydrogen.

Table 2.1: Characterization of electrolyzer technologies (Danish Energy Agency, 2024a; IRENA, 2022b)

Process	**Unit**	**PEM**
Operating temperature	C°	50-80
Operating pressure	bar	<70
Development status	N/A	Commercialized
Lifetime	years	25
Capital costs (system) minimum 10 MW	EUR/kW	950

There is a distinction between water consumption and water withdrawal. Direct water consumption is the water used directly to produce the hydrogen and water withdrawal is characterized as the water consumption plus water taken incidentally in the process (Senthil Kumar & Yaashikaa, 2019). The water taken incidentally can be returned to a water source.

To produce 1 kg of hydrogen in theory, 9.6 liters of water is required, however, the direct water consumption is usually 25% higher, giving approximately 11.1 liters of water per kg of hydrogen (Shi et al., 2020). IRENA and Bluerisk (2023) instead states that for the entire process of electrolysis with water pre-treatment and cooling, the water consumption for producing green hydrogen is on average 17,52 L/kGH_2 for PEM-electrolysis. The water withdrawal intensity for the same process is 25,70 L/kgH_2. According to Shi et al. (2020) there is a lack of research regarding the water footprint of hydrogen production and its impact on water scarcity, but, according to the research of IRENA and Bluerisk (2023) the water withdrawal for hydrogen production can be significant at a local scale.

In the region where Göteborg Landvetter Airport is situated, Västra Götaland Regionen (VGR), the total freshwater withdrawal during the year 2020 amounted to 142,187,000 m3 which would create about 5,5 million tonnes of hydrogen (Statistics Sweden, n.d.). This includes all water withdrawn within the VGR.

2.1.2 Ammonia decomposition

Another method to acquire hydrogen is by extracting it from ammonia (NH3) (Spatolisano et al., 2023). To consider this green hydrogen, the ammonia used must be "green ammonia" made from green hydrogen in combination with nitrogen from the atmosphere. The reason to turn hydrogen into ammonia and then back again, is that ammonia is easier to handle in the supply chain (Spatolisano et al., 2023). Then the ammonia must be decomposed in a process called decomposition or cracking

($2\,NH_3 \longrightarrow N_2 + 3\,H_2$). The reaction is favored at high temperatures, over 400°C, and low pressures (Spatolisano et al., 2023). The high temperatures of the cracking process are energy demanding, Aziz et al. (2020) states that the energy demand is 30,6 kJ/moLH_2 which translates to 4.25 kWh/kGH_2. Jackson et al. (2020) presented an energy consumption of 14.5 kWh/kGH_2 for the decomposition and purification of the hydrogen with fuel-cell grade quality.

17.8% of ammonia's weight is hydrogen (Lucentini et al., 2021), and it has been found by Rouwenhorst et al. (2019) that it is possible to obtain 0.1773 kg hydrogen from 1 kg of NH3. The conversion efficiency for this process is generally at 95% (Lucentini et al., 2021; Nasharuddin et al., 2019). With these numbers, the hydrogen yield is calculated to be $0.1773 \cdot 95\% = 0.1684$ kGH_2/kgNH3.

2.1.3 Residual products from hydrogen electrolysis

When producing hydrogen from water electrolysis, oxygen and heat will also be created, 8 kg of oxygen to 1 kg of hydrogen (Hönig et al., 2023). To fully utilize the electrolyzing process – these residual products should be used for other applications to keep efficiency high and the cost of production low. According to Gustavsson et al. (2023), the price of oxygen varies by quality but has been averaging a price of 0.9-1.0 SEK/kg, and production volumes in Sweden have been around 1.25-1.5 million tons/year. With Sweden's projected electrolysis production of hydrogen, mainly from the steel industry, we will see about 7.5 million tons of oxygen being produced from electrolysis in 2030 which is an increase of 6-7 times the current volumes (Gustavsson et al., 2023; Vätgas Sverige, 2023).

The oxygen purity from PEM electrolyzers is higher than from Alkaline electrolyzers (Gustavsson et al., 2023). Usually, the purity of oxygen produced from electrolysis is very high, with the highest reported purity of 99.7%. Some potential use cases for oxygen, which Gustavsson et al. (2023) presents, include: aquaculture, oxygen enriched environment for insects, seabed aeration, feedstock in industrial processes, oxygen-enhanced combustion, steel/pulp/paper production, and more. Healthcare uses oxygen as well and needs 99.5% purity (Gustavsson et al., 2023). Today most of the oxygen production is made on-site for specific purposes. Many of the electrolyzers in Sweden vent the excess oxygen into the atmosphere as the equipment to bring it to market is too expensive (Gustavsson et al., 2023).

2.2 Hydrogen distribution technology

When distributing hydrogen, several technologies can be utilized (Tashie-Lewis & Nnabuife, 2021). Currently, the main technologies are compressing gaseous hydrogen, liquifying hydrogen, transporting it as ammonia, or using Liquid Organic Hydrogen Carriers (LOHC) (Edvall et al., 2022). This study will investigate compressed hydrogen gas (GH_2), liquefied hydrogen (LH_2), and ammonia. When using these distribution technologies, there is always energy used towards transforming the hydrogen back and forth between states/substances (Edvall et al., 2022). In Table 2.2 the energy used to convert and re-convert the hydrogen is shown in terms of the percentage of the hydrogen's own energy content (IEA, 2019). Further, the table shows the characteristics of the different distribution technologies.

Table 2.2: Characteristics comparison of compressed hydrogen, liquid hydrogen, and liquid ammonia.(Aziz et al., 2020; Edvall et al., 2022; IEA, 2019)

Properties	**Unit**	**GH_2**	**LH_2**	**Liquid Ammonia**
Transportation methods	N/A	Pipeline, truck	Pipeline, truck, railway, vessel	Pipeline, truck, railway, vessel
Storage method	N/A	Compression	Liquid	Liquid
Pressure	Bar	690	1	9.9
Temperature	°C	25 (room T)	-252.9	25 (room T)
Density	kg/m^3	39	70.8	600
Volumetric energy density	MJ/dm^3	4.5	8.49	12.7
Gravimetric energy density	MJ/kg	120	120	18.6
Volumetric hydrogen content	kgH_2/m^3	42.2	70.8	121
Gravimetric hydrogen content	wt%	100	100	17.8
Hydrogen release	N/A	Pressure release	Evaporation	Catalytic decomposition T> 400°C
Energy used of hydrogen energy content for conversion	%	6-15 (Truck 350-700 bar)	25-35	27-38

2.2.1 Compression

Compressing GH_2 for storage today is usually done at 350 or 700 bar for automotive applications (Cheng et al., 2024; IEA, 2019). Higher compression of the hydrogen results in a higher density, which makes it easier to move more energy due to the decreased volume. These storage units can be moved with tube trailers for road transport, and are used today (Tashie-Lewis & Nnabuife, 2021). Compressed GH_2 can also be moved by pipeline, which is done at 70 or 140 bar, which is viable for larger quantities and longer distances (Danish Energy Agency, 2024b; Tashie-Lewis & Nnabuife, 2021). As compressed GH_2 carries only 15% of the energy density (in volume at 700 bar compression) of gasoline, a lot of space is needed to store compressed hydrogen (IEA, 2019). Lined-rock caverns or salt caverns have been explored for large-scale storage of compressed hydrogen gas and are done in Germany, the US, and Britain today (Abdin et al., 2024). However, this study will not explore lined-rock caverns as it is not suitable for LH_2.

2.2.2 Liquid Hydrogen

Hydrogen occurs naturally in its gaseous form and must be cooled down to its melting point of -253 °C to become a liquid (Cheng et al., 2024). There are several theoretical methods for this, called liquefaction cycles. The most established cycles, without particular order, are the Linde-Hampson liquefaction cycle, Claude liquefaction cycle, and the Brayton liquefaction cycle (Abdin et al., 2024; Krasae-in et al., 2010; Zhang et al., 2023). A generic model of the liquefaction process is displayed in Figure 2.1(Al Ghafri et al., 2022).

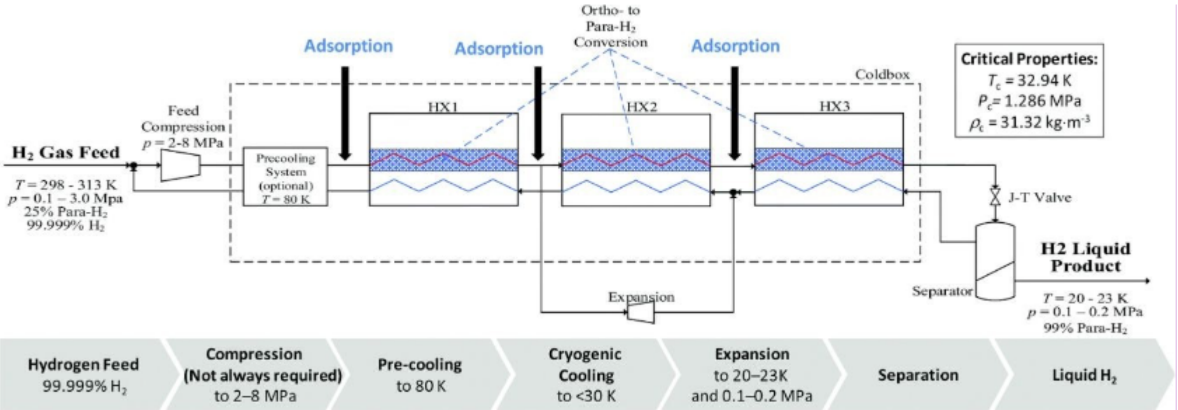

Figure 2.1: Simplified schematic diagram of the hydrogen liquefaction process based on simple Claude cycle. Critical properties of para-hydrogen are shown in this schematic. (Al Ghafri et al., 2022), (Licensed under CC BY 3.0)

Liquefying the hydrogen makes distribution easier in terms of moving large quantities of hydrogen at a time (Cheng et al., 2024). However, LH_2 has to be moved in cryogenic tanks which are costly, and evaporation of the hydrogen will have to be ventilated to prevent pressure build-up inside the cryogenic tank, this evaporation is also known as boil-off (Cheng et al., 2024). LH_2 is suitable when delivering short and medium distances by road transport and for large volumes as it holds larger amounts of hydrogen volume-wise than GH_2 (Tashie-Lewis & Nnabuife, 2021).

2.2.3 Using Ammonia NH3 as an energy carrier

There have been research and tests conducted on utilizing energy carriers for the transportation of hydrogen, one of those energy carriers is ammonia (Ajanović et al., 2024; Aziz et al., 2020; IRENA, 2022a; Ishimoto et al., 2020). According to IRENA (2022a) ammonia is already produced at a large scale and globally traded, therefore the knowledge and infrastructure to support handling ammonia are already well-developed.

The report conducted by IRENA (2022a) states that it is easier to liquefy ammonia than hydrogen and that ammonia contains 1.7 times more hydrogen per unit of volume compared to LH_2. It is also easier to store ammonia, as it only needs to be pressurized to 8 bar, or cooled down to -33 °C IRENA (2022a). According to Aziz et al. (2020) the latter method is preferable if the pressure is unchanged. This creates the possibility of using a light and low-cost tank which is an easier freight method than the LH_2 cryogenic tanks. Ammonia can be transported using pipelines, trucks, rail, or vessels (Aziz et al., 2020).

2.2.4 Leakage in the hydrogen supply chain

As hydrogen is difficult to contain due to the small molecular size, leakages are to be expected (Vargas et al., 2024). The leakage of hydrogen is expected to have an indirect greenhouse effect, but its full effect is still unknown. However, the green hydrogen supply chain could leak up to 37% of the hydrogen and still see a net benefit for the environment compared to the fossil-based fuel currently used (Vargas et al., 2024). A previous study has stated several uncertainties regarding the estimation of fugitive emissions of hydrogen from the entire hydrogen landscape (Frazer-Nash Consultancy, 2022). They found that during the production phase, the leakage can be up to 10%, mainly connected to venting and purging, which is an important step to ensure purity in the hydrogen supply chain. Venting and purging must be done to clear contamination and to prevent safety risks of hydrogen vessels. Usually, this will result in residual hydrogen being vented out into the atmosphere (Frazer-Nash Consultancy, 2022).

2.3 Scenarios of hydrogen use

Hydrogen is believed to be important as a future energy carrier where it is projected to be a bigger part of the fuel and energy sector in the future, especially green hydrogen (Energimyndigheten, 2021; European Commision, 2020; Fossil Free Sweden, n.d.; U.S. Executive Office Of The President et al., 2023). This has led to a plan in the EU to develop a main network of pipelines through Europe, a grid to support a larger hydrogen market (European Hydrogen Backbone, 2022). Although future projections are uncertain, there are several projections for the demand for hydrogen, which are presented in Table 2.3.

Table 2.3: Projected future demand for hydrogen

Year	**2030**	**2040**	**2050**	**Source**
Demand (Mt/yr) Europe	12.35	28.03	45.55	(European Hydrogen Observatory, 2023)
Demand (Mt/yr) Globally	123-126	245-270	404-469	(McKinsey and Company, 2023)
Demand (Mt/yr) Globally	125	N/A	523	(IRENA, 2023)

As seen in Figure 2.3, the increase in demand is projected to be high and is more than doubled between 2030-2040. Investment into hydrogen as an energy carrier is also thought to increase as the EU and the U.S express want to fund more projects for the future development of hydrogen technology (European Commission, 2020; U.S. Executive Office Of The President et al., 2023).

The European Commission believes it is important to understand that hydrogen should not be regarded as a universal solution, but rather an important tool in the energy transformation, changing a fossil-based system to a renewable one (European Commission, 2022). Liebreich (2023) has visualized this in what he calls the Hydrogen Ladder, displayed in Figure 2.2. Alternatives to hydrogen use are color-coded and the further down the ladder you go, the less likely hydrogen is to be the prominent choice. Hydrogen's prospected inefficiency as an energy carrier is the significant energy use of electrolysis, transport, liquefaction, and compression (Bossel & Eliasson, 2006). The author lists Jet Aviation as a technology where hydrogen is a likely substitute for the current system.

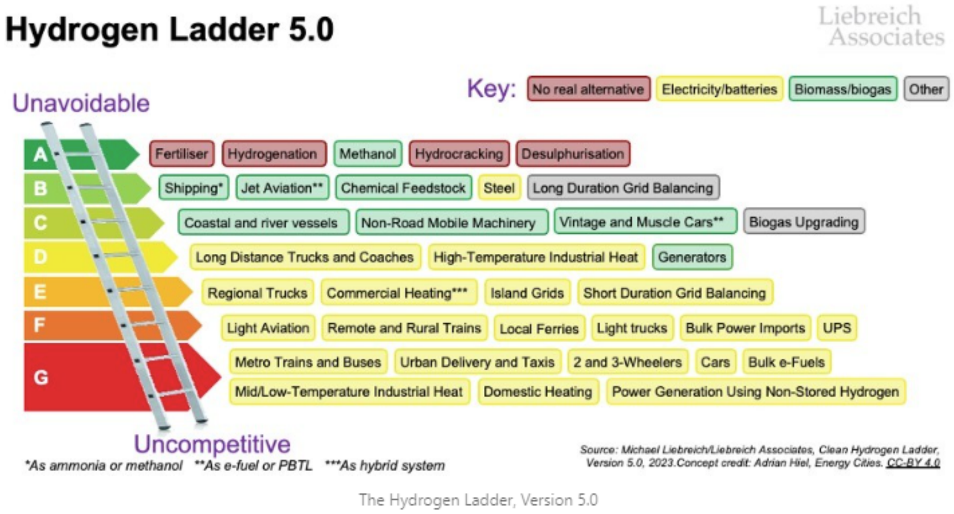

Figure 2.2: "Clean Hydrogen Ladder, Version 5.0" ©Michael Liebreich/Liebreich Associates (Licensed under CC BY 4.0)

2.4 Hydrogen in Aviation

In 1955/1956 the first test of deploying hydrogen as a fuel for an airplane was made. The concept was introduced by NACA (later NASA) and aimed to redesign the aircraft "B-57 medium bomber" to carry LH_2 as fuel and using a pump-fed system (Brewer, 1991). One test with the B-57 was conducted successfully by taking off and reaching test conditions, before initiating the hydrogen system to cruise for 21 minutes and then switching back to the regular fuel. During the tests, the hydrogen was found to be reliable and did not encounter any safety problems. Last year, in 2023, both ZeroAvia and Universal Hydrogen, flew prototype aircraft running on hydrogen-electric powertrains (Doll, 2023; ZeroAvia, 2023). The ZeroAvia plane replaced a turboprop motor with a hydrogen-electric powertrain; the test aircraft has 19 seats. For Universal Hydrogen the testbed was a 40-passenger plane and again, only one of the motors was replaced with a hydrogen-electric powertrain. Even though the future of hydrogen aircraft is unsure, the feasibility of hydrogen aircraft has been tested successfully.

In this chapter are the different types of aircraft in use today, the projected supply chain alternatives, and the current supply path for Göteborg Landvetter Airport presented.

2.4.1 Aircraft types

There are several aircraft types in commercial airlines today that fill different use cases (Mickeviciute, 2023). The main airliner categories are Jumbo jets, cargo airplanes, wide bodies, single-aisle aircraft (narrow bodies), regional jets, and turboprop planes (Mickeviciute, 2023). Of these, turboprop, regional jets, and single-aisle aircraft are projected to be the first aircraft types that are hydrogen-based (Cranfield University et al., 2022; Hoelzen et al., 2022b).

Regional jets and turboprops are often used as regional aircraft, they carry a smaller number of passengers (Mickeviciute, 2023). A turboprop is a propeller driven by a gas turbine. An example of a turboprop aircraft is the ATR 72 which normally carries 72 passengers (ATR, 2024)

The single-aisle aircraft makes up a majority of the aircraft market today (Hoelzen et al., 2022a). They are well-suited for flights of approximately 100 to 240 passengers and work well for short-haul international or regional flights (Mickeviciute, 2023). Common single-aisle types include the Boeing 737 and Airbus A320, two of the most produced aircraft in history (O'Hare, 2022).

2.4.2 Supply chain pathways for hydrogen in aviation

The current supply system cannot be utilized when preparing for a hydrogen supply chain, but in a transitional phase, similar systems may be easier to implement (Degirmenci et al., 2023). Previous studies have concluded that LH_2, due to its increased volumetric density compared to GH_2, is the most effective fuel for aircraft (Busch et al., 2023; Hoelzen et al., 2022a, 2022b; Khandelwal et al., 2013). The hydrogen will therefore have to be liquefied at one time or another within the hydrogen supply chain to support future aviation needs.

Previous studies have investigated the fundamental parts of the hydrogen supply chain for aviation and what options are most beneficial (Hoelzen et al., 2022b; Stiller et al., 2010). The authors both present a solution with a central shared production of hydrogen. In Figure 2.3, from Hoelzen et al. (2022b), the considered pathways are presented. From the central production or import, hydrogen can be transported as either GH_2 or LH_2 to the central processing seen in Figure 2.3. Here the GH_2 may be liquefied to LH_2 for delivery to the airport by truck, train, or ship, or delivered directly to the airport as GH_2 by pipeline or truck, as seen in Figure 2.3. Lastly, airport hydrogen facilities include storage near/on the airport before being used for refueling operations. Stiller et al. (2010) suggests that an LH_2 truck could be used for instant refueling and skipping the storage part, however, this is not displayed as Hoelzen et al. (2022b) requires storage to buffer fluctuations in demand and potential supply chain delays.

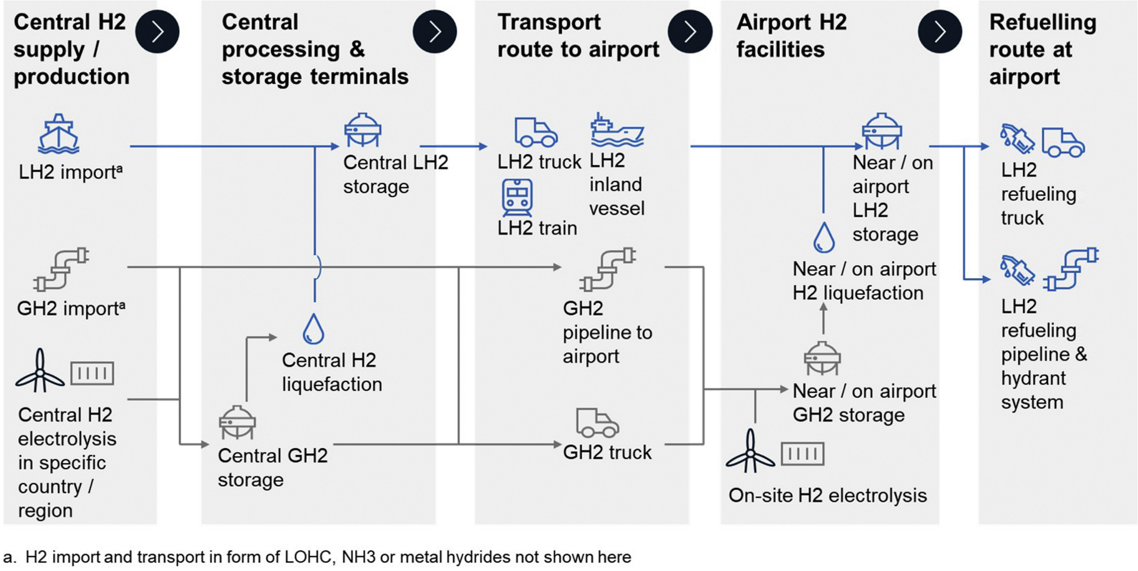

Figure 2.3: LH_2 supply topologies are split into 5 sections, represented by the boxes; not considered is import, storage, conversion, or transportation of hydrogen in the form of LOHC, NH3, or metal hydrides. (Hoelzen et al., 2022b), (Licensed under CC BY-NC-ND 4.0)

2.4.3 Göteborg Landvetter Airport's current supply chain

At Göteborg Landvetter Airport currently, the company Gothenburgh Fuelling Company does the refueling of aircraft (GFC, n.d.). Their operations are currently 3 cisterns with a total capacity of about 2400 m^3 of Jet A-1, which is restocked by truck deliveries. The fuel quality is controlled after storage and supplied to the aircraft by aircraft refueling vehicles. The Jet A-1 is supplied by Air BP, Swedish Shell, and World Fuel Flight Services.

A new railway between Gothenburg and Borås is projected by the Swedish Traffic Agency, and together with Swedavia, a plan to create a train station close to or at Göteborg Landvetter airport is being established ("Järnvägsanslutning - station Landvetter Airport", 2020). However, on 22 December 2022, the planning of the railroad was put on pause and continued first on the 26th of October 2023 (Trafikverket, 2023). There seems to be no intention of moving goods on this railroad. The continued work has not reached any conclusions yet, and Härryda municipality has declined the proposed railway route.

3

Methodology

The research has been conducted abductively, a method commonly used to cover a topic still being explored with qualitative and quantitative data to account for the question (Bell et al., 2019). Abductive research also keeps the possibility of surprising the researcher with the data found during research. The main methods for data collection are semi-structured interviews, a literature review, and a study visit at Göteborg Landvetter Airport.

The semi-structured interviews are analyzed through thematic analysis. The supply chain pathways are identified with help from interviews and the literature review. A model estimating the fuel demand at Göteborg Landvetter Airport is conducted to calculate the costs for the financial analysis and the water withdrawal and consumption for the water demand analysis. The methodological process is displayed in Figure 3.1.

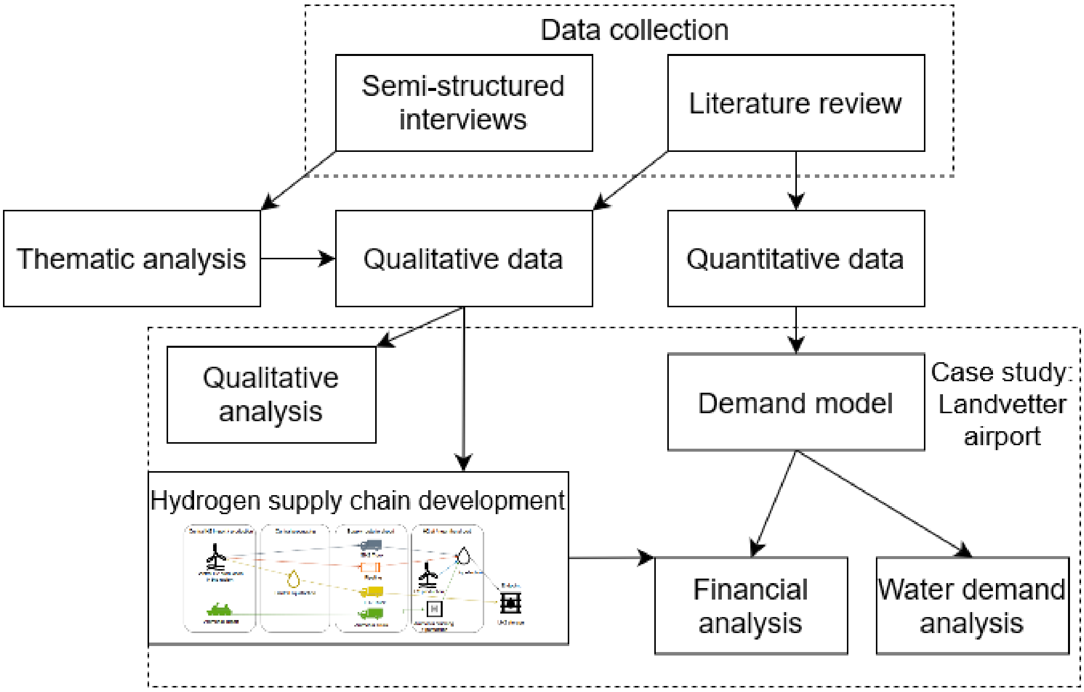

Figure 3.1: Methodological process

3.1 Data collection

The interviews aimed to answer the questions of what supply pathways are viable, how hydrogen projects are influenced by current policies, leakage, and possible synergies and their importance. The literature review was conducted to help answer all the research questions and provide quantitative data for our models. The study visit at Göteborg Landvetter airport gave us insights into how fuel is managed and worked with currently, and what possible obstacles may occur by introducing hydrogen as fuel at the airport. The qualitative and quantitative data complement each other by investigating what is physically possible and what is economically viable, respectively.

3.1.1 Qualitative data

To gather qualitative data, primarily two methods have been deployed. A literature review has been conducted to understand the current research on the subject, current hydrogen-related policies, and regulations, and identify research gaps within the field. The data was used to form the possible supply chain pathways.

To gather data for the study, and to gain understanding on the subject, semi-structured interviews with stakeholders related to hydrogen production and supply chains have been conducted. The interviewees were chosen as they were active in different hydrogen projects and/or involved in the development of the Swedish West Coast. The interviewees were contacted through:

- Career fair
- Suggestion from our supervisor
- E-mailing author of reports found in literature
- E-mailing organizations with large hydrogen projects

The interviewed participants will be listed in the results. These interviews helped establish a foundation for the supply chain pathway estimations and develop the scope of the study. Semi-structured interviews have the benefit of having the questions formulated beforehand, which allows the interview to stay on topic, and simultaneously opens the possibility for further questioning of the answers to deepen the knowledge (Bell et al., 2019). The prepared questions were partly reoccurring and partly modified to match the interviewee's area of expertise. Some of the more commonly asked questions can be found in Appendix A. In addition to the semi-structured interviews, a study visit at Göteborg Landvetter Airport was conducted as it is a suitable complement to the interviews according to Bell et al. (2019).

3.1.2 Quantitative data

All quantitative data was obtained from the literature review. The data used for the financial modeling is listed in Table 3.1 and Table 3.2. The reference year of the investment cost is based on the source's year of publication.

Table 3.1: Technologies considered with the costs, lifetime, and efficiency connected. LH_{2_i} = yearly demand of LH$_2$ in tons, d = distance in m. Operating costs is a share of the investment cost.

Source	**Technology**	**Investment cost in millions**	**Operating costs**	**Life time**
(Elgowainy & Reddi, 2024)	Hydrogen liquefier	\$ $0.56 \cdot (LH_{2_i}/365)^{0.8}$	2%	40 yrs
(Cesaro et al., 2021)	Ammonia cracker	\$ $18.171 \cdot (LH_{2_i}/(365 \cdot 24))^{0.7451}$	2%	40 yrs
(Elgowainy & Reddi, 2024)	LH$_2$ Storage	\$ $5.6466 + 1.3 \cdot (0.0031 \cdot (((LH_{2_i} \cdot 1000)/70.85)/52))$	2%	15 yrs
(Danish Energy Agency, 2024a)	PEM electrolysis	€ 9.5 per 10MW	2%	25 yrs
(Danish Energy Agency, 2024b)	Pipeline 'Low case'	€ $(1.75 \cdot LH_{2_i} \cdot d)/1,000,000$	2%	40 yrs
(Danish Energy Agency, 2024b)	Pipeline 'Main case'	€ $(0.7 \cdot LH_{2_i} \cdot d)/1,000,000$	2%	40 yrs
(Danish Energy Agency, 2024b)	Pipeline 'High case'	€ $(0.4 \cdot LH_{2_i} \cdot d)/1,000,000$	2%	40 yrs

Table 3.2: Year dependent data

Source	Type of data	2030	2035	2040	2045	2050
(IRENA & AEA, 2022)	Ammonia price, €/ton	656.27	604.21	552.15	500.09	448.04
(Christensen, 2020)	GH_2 price, €/kg	4.94	4.62	4.42	4.24	4.10
(Energimyndigheten, 2016)	Electricity price, €/kWh	0.045	0.049	0.054	0.049	0.045
(Danish Energy Agency, 2024b)	LH_2 Truck Driving cost, €/ton/km	1.10	1.08	1.06	1.03	1.01
(Danish Energy Agency, 2024b)	LH_2 Loading / Unloading cost, €/ton	47.90	45.75	43.60	41,45	39.30
(Danish Energy Agency, 2024b)	GH_2 Truck Driving cost, €/ton/km	1.99	1.90	1.80	1.71	1.61
(Danish Energy Agency, 2024b)	GH_2 Loading / Unloading cost, €/ton	82.90	77.60	72.30	67,00	61.70
(Danish Energy Agency, 2024b)	Ammonia truck Driving cost, €/ton/km	0.12	0.12	0.12	0.12	0.12
(Danish Energy Agency, 2024b)	Ammonia Loading / Unloading cost, €/ton	3.93	3.93	3.93	3.93	3.93
(Elgowainy & Reddi, 2024)	Liquifier efficiency, kWh / kg LH_2	11.90	10.00	9	9	9
(Danish Energy Agency, 2024a)	PEM Electrolysis efficiency, kWh / kg LH_2	56.90	55.23	53.55	51.88	50.20
(Jackson et al., 2020)	Ammonia cracker efficiency, kWh / kg LH_2	14.5	14.5	14.5	14.5	14.5

3.2 Case Study

A case study at Göteborg Landvetter Airport was conducted to explore the possibilities of implementing a hydrogen supply chain. Recommendations were made for the airport in question, on how to structure their hydrogen initiatives based on the research questions and main aspects of the study. A study visit at Göteborg Landvetter Airport was conducted to understand how an airport is structured and to understand the logistics behind it.

3.2.1 Supply chain pathways

The viable supply chain paths that are considered are illustrated in Fig. 3.2. The supply chain alternatives are color-coded accordingly:

- **Green** = Ammonia import and cracking
- **Blue** = On-site production
- **Centrally produced alternatives:**
  - **Yellow** = LH_2 truck delivery
  - **Orange** = GH_2 pipeline delivery
  - **Grey** = GH_2 truck delivery

There is a total of five different supply pathways. Three of these supply pathways are based on central production of hydrogen and then moved by either truck or pipeline. Only one of the supply chains utilizes central processing in this figure – LH_2 moved by truck. Ammonia cracking facilities are assumed to be on/near the airport.

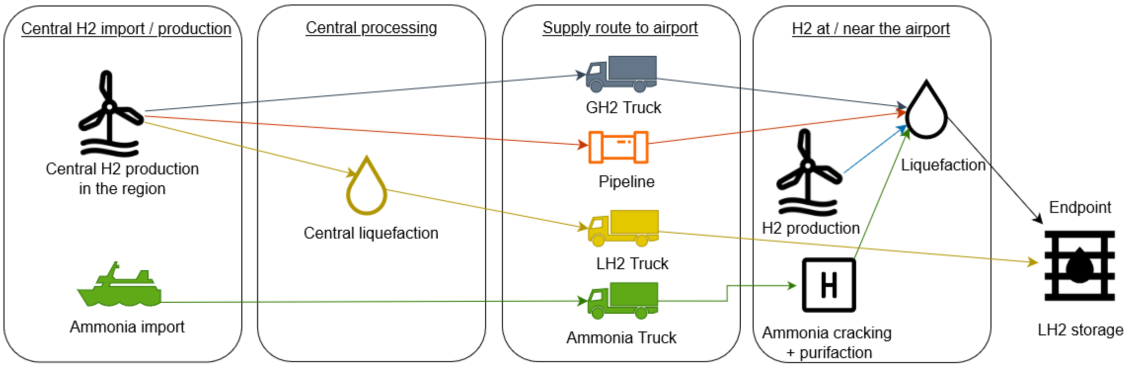

Figure 3.2: Supply chain paths being investigated

3.3 Quantitative modeling

Three different cases will be presented: the *Low case*, *Main case*, and *High case*. The cases represent three different future demand scenarios where the implementation of hydrogen-based aviation is deployed to a low, medium, and high extent, respectively. The financial modeling evaluates the economic viability of the different supply chain paths for each demand case. The quantitative model is conducted to complement the qualitative data and improve the depth of the analysis. The quantitative modeling will investigate the demand, financials, and water withdrawal and consumption.

3.3.1 Demand model

The demand cases apply to Göteborg Landvetter Airport for 2030-2050. Only regional aircraft (less or equal to 750km) and single-aisle aircraft (between 751km and 3000km) were considered for the estimation because these aircraft types are seen as the most prominent for hydrogen-based aviation, discussed in Hoelzen et al. (2022b). To find these, Swedavia's in-going and out-going aircraft statistics were used (Swedavia, 2019). The increase in landings of these aircraft was identified by using Swedavia's longtime projection for departures and passengers (2019-2050) (Thelin, 2019). The projection does not consider hydrogen-powered planes emerging, the global pandemic, or the Russian invasion of Ukraine. The increase is based on the expected increase in passengers.

The main case, presented in Thelin (2019), year-on-year has an expected increase of passengers at 0.0% for domestic travel and 2.3% for international travel. These percentages were applied to landings under the assumption that an increase in passengers would lead to an increase in aircraft landings, domestic flight growth was applied to regional, and international was applied to single-aisle.

To determine the number of hydrogen-based aircraft Hoelzen et al. (2022a)'s calculation model of the global fleet change to hydrogen was used. Hoelzen et al. (2022a) only considers an ambitious case and a base case in their article. Our High- and Main cases are influenced by those. As we also have a Low case is it based on our own restrictive assumptions and Hoelzen et al. (2022a)'s data.

Hoelzen et al. (2022a)'s calculations include a take-rate (the percentage of new aircraft produced that will be hydrogen-powered every year), retirement rate of old aircraft, ramp-up of production, and introduction year. These were set according to Table 3.3. The cases were reworked under our assumptions which changed take-rate, introduction year, and ramp-up time.

Table 3.3: Description of Cases

	High case	**Main case**	**Low case**
Take rate Regional	80%	50%	30%
Take rate Single-aisle	67%	50%	50%
Ramp-up Regional [yrs]	4	10	10
Ramp-up Single-aisle [yrs]	5	10	10
Year of introduction Regional	2030	2030	2040
Year of introduction Single-aisle	2035	2035	2045

The high case reflects a scenario where hydrogen is considered the most viable choice for distances up to 3000 km. Infrastructure is assumed to support hydrogen and a majority of the aircraft will be hydrogen-based. Since the EU considers bio-based SAFs fossil-free, it is assumed that production of older type aircraft will continue to be a part of the market (European Parliament, 2023).

The main case reflects a scenario where the infrastructure supports hydrogen but is not affecting competition with other emerging technologies for sustainable flights (such as other SAFs and Electric). Electric is seen as having a larger portion of the regional flights compared to the high case. Bio-based SAFs are assumed to have a larger share of single-aisle aviation compared to the high case.

The low case is based on assumptions that we would see a smaller percentage of the fleet being changed to hydrogen, as other emerging technologies may get a larger part of the market share. This is related to the late introduction of hydrogen-powered aircraft, which is assumed to decrease the interest in hydrogen power. Therefore, the lower take rate for regional is considered, assuming electric aircraft gain a large market share in the segment. The single-aisle segment is still considered at a 50% take-rate as hydrogen has viable characteristics for this length of flight.

Table 3.4: Estimated aviation fuel (Jet A-1) usage by regional & single-aisle aircraft at Göteborg Landvetter Airport 2023

Aircraft type	**Weight in metric tons**	**Share**
Single-aisle & Regional	57111.45	100%
Single-aisle	51114.75	89.5%
Regional	5996.70	10.5%

To estimate the annual usage of aviation fuel, the Jet A-1 usage at Göteborg Landvetter Airport was the basis. An estimation of the annual tons of Jet A-1 usage by flights between 800 km and 3100 km in the year 2023 was given from Swedavia and is displayed in Table 3.4, which is used for the Single-aisle flights' usage. The shares were found using the in and out-going flights in Swedavia (2019). The Regional Jet A-1 usage for 2018 was found by adding all regional flights (less or equal to 750 km) total flight distance. This was divided by the combined flight distance of regional and single-aisle aircraft (less than 3000km). This resulted in 10.5% of the total flight distance being made by regional flights, displayed in Table 3.4. This was also assumed to be the difference in fuel demand between regional and single-aisle flights. For the years 2024-2050, the fuel demand for each year is calculated with the following formula:

$$x = y \cdot (1 + \alpha + \beta)$$

$$x = \text{Jet A-1 demand for given year}$$

$$y = \text{Jet A-1 demand for previous year}$$

$$\alpha = \text{Annual change of passenger demand}$$

$$\beta = \text{Annual fuel efficiency change factor}$$

The annual efficiency change is based on Hoelzen et al. (2022a)'s data on fuel efficiency change of aircraft year-on-year, decreasing the needed fuel, the exact percentage for each year can be found in Appendix B. With the weight of the demanded Jet A-1 calculated for each aviation type, the corresponding LH_2 weight is calculated by using the energy difference between LH_2's specific energy content and JET A-1, retrieved from Hoelzen et al. (2022a) and displayed in Table 3.5. Lastly, the corresponding LH_2 weight was multiplied by the number of hydrogen-based departures for each aircraft type to receive the demanded LH_2 per aircraft type per year.

The truck delivery frequency is based on the demand per day and the possible carrying load of the trucks. The carrying capacity of trucks are set to 47.5 m^3 per truck, which is based on Danish Energy Agency (2024b) notes. The truck supply

Table 3.5: Energy difference between LH_2 and Jet A-1 (Hoelzen et al., 2022a)

Aircraft type	Difference
Single-aisle	40%
Regional	36%

options are the GH_2 truck, LH_2 truck, and ammonia import and cracking, from the supply chain pathways. The densities of hydrogen and ammonia are based on Aziz et al. (2020) which is displayed in chapter 2.2.3.

3.3.2 Financial model

All costs in the model are converted to the average 2023 level of the euro. The financial models are based on cost estimations listed in Table 3.1 and 3.2. The model is counted at every fifth year from 2030 (projected introduction of regional hydrogen flights in the main and high cases) up to 2050, the model uses the demanded hydrogen of those years as a basis for the equations. The model only considers the annual ton demand for hydrogen, which does not look at peak days or low days but an average across the year. All infrastructure investment costs are covered by the airport as if the airport itself were investing in the infrastructure in each supply chain alternative. All infrastructure investments were depreciated over the full lifetime of the asset.

Some sources did not include estimations on a five-year basis, for those cases linear interpolation was applied. For the sake of consistency, mixing of sources was kept to a minimum, to ensure that the estimates included the same parameters and roughly the same costs.

The total cost per year is calculated by adding the investment cost, operating costs, delivery costs, and electricity costs for that specific year. Note that the cost of water is not included. What infrastructure costs are included in the different supply chain pathways are displayed in Table 3.6. In GH_2 pipeline delivery, LH_2 Truck delivery, and GH_2 truck delivery, hydrogen is bought and does not result in paying for the production infrastructure. Truck deliveries are considered a service, which does not consider the time aspects of each truck unloading and driving. To project the price of buying LH_2, the price from Christensen (2020) was used with the added cost of liquefaction.

Table 3.6: Cost included in different supply chain pathways (costs are displayed in Table3.1)

Supply chain pathway	Storage	Liquefier	Electrolyzer	Ammonia cracker	Truck transport	Pipeline
On-site production	X	X	X			
Ammonia import and cracking	X	X		X	X	
GH_2 Pipeline delivery	X	X				X
LH_2 Truck delivery	X				X	
GH_2 Truck delivery	X	X			X	

The delivery distance was based on the already existing natural gas pipeline on the west coast of Sweden which covers industries between Gothenburg and Stenungsund, however, Edvall et al. (2022) argues that a hydrogen pipeline could be built to include Lysekil as well. The resulting distance, including Lysekil, is 150 km and is used in the calculations for the supply alternatives of GH_2 Truck delivery, GH_2 Pipeline and LH_2 Truck delivery. For ammonia import and cracking the distance is assumed to be between the Port of Gothenburg and Göteborg Landvetter Airport, 30 km. The storage size of the on-site tanks is based on demand for a week, i.e., yearly demand divided by 52.

Electricity uses a projected cost of green electricity rather than the investment of new electricity production to support the production of hydrogen (Energimyndigheten, 2016). As mentioned in subsection 2.1.1 the EU requires additionality, so an increased cost in this could be expected in reality, as the energy must be added with the specific cause of producing green hydrogen.

Electrolyzer
Hydrogen price and electrolyzers are both based on PEM-electrolysis. The choice to consider PEM was reinforced by interviewees within the industry and theory with higher hopes for green hydrogen using PEM rather than alkaline. The electrolyzers for on-site production are assumed to be invested in stacks of 10 MW per electrolyzer. Meaning that if the projected yearly demand needs between one and two electrolyzers, two electrolyzers will be needed.

Pipeline
The pipeline for the GH_2 pipeline delivery is assumed to be built once and is dimensioned to meet the hydrogen demand of the year 2050 in each case. The price difference is displayed in Table 3.1. This results in lower costs for the pipeline as economies of scale give a lower cost on the freighted distance. This is not realistically applicable on early demand as there is a lower limit on the amounts of GH_2 freighted in the large pipes.

Ammonia cracker
For the costs related to the ammonia cracking the "Cracker cost curve" by Cesaro et al. (2021), listed in Table 3.1 has been used. The cracking facility is assumed to be built once and is scaled for 2050 demand in each case. The ammonia is assumed to be bought from a source with a low price of production of ammonia. The Ammonia price displayed in Table 3.2 is calculated by multiplying the production price by 1.3 (assumed marginal of 30%) and adding the transport price to find the price in Gothenburg.

3.3.3 Water withdrawal and consumption

The water withdrawal and consumption are calculated for the three different demand cases on a 5-year basis. Both the withdrawal and consumption intensities are derived from IRENA and Bluerisk (2023) and displayed in Table 3.7. The resulting water withdrawal per year is compared to the total water consumption within the region of Västra Götaland to evaluate if the water withdrawal may have an impact on the regional water availability.

Table 3.7: Water withdrawal and consumption for PEM electrolysis

Source	**Average water withdrawal intensity [L/kGH$_2$]**	**Average water consumption intensity [L/kGH$_2$]**
IRENA and Bluerisk (2023)	25,70	17.52

The total water withdrawal and consumption is calculated by multiplying the total demand for hydrogen for that specific year with the average water withdrawal and consumption intensities.

3.4 Analysis

To understand the qualitative data from the semi-structured interview a thematic analysis was conducted to help sort the information gathered during the study. The thematic analysis was conducted by transcribing all the interviews, with the help of the Microsoft Word tool for transcription. While listening to recordings, all answers from the interviews related to the same subject were color-coded so that they could be categorized. The reason behind listening to the recording and simultaneously highlighting the text was to ensure that the text was correct and that the context was fully understood. The thematic analysis helped structure the transcriptions and allowed more coherent conclusions to be drawn about the results. Interviews were mostly conducted in Swedish, the results are presented in English and we translated.

To compare the cost between the supply chain pathways, the levelized cost of hydrogen (LCOH) was used, which is a variant of the levelized cost of energy, a measure for cost comparisons in energy (Nian et al., 2016). To calculate the LCOH the total cost was divided by the annual demanded kgs of hydrogen, making every calculation based on price per kg hydrogen.

The framework used to compare the scenarios was developed specifically to answer the research questions by comparing the water usage, safety and policies, scalability, and the financial viability of infrastructure including synergies. To compare the viability of the different scenarios, a financial model was conducted to investigate the viability from an economic standpoint.

3.5 Reliability and Validity

As the project is conducted by two project members it is important to ensure high unanimity internally (Bell et al., 2019). This is ensured by developing the method together and not dividing parts between the members. This is done to increase the reliability of the study and through continuous discussion and analysis throughout the project. Measures to ensure ethical sourcing and interviewee safety have been considered so that the information is kept confidential to increase reliability. The answers of the interviewees are compared against each other. Any contradictions between answers that have occurred are mentioned and investigated further. As interviewees are confidential and the case study is unique to the airport in Landvetter, the replicability of the study may be affected negatively. Further, the combination of several sources for financial modeling puts the study at risk of furthering the biases from the previous sources.

4

Result

4.1 Interviews and qualitative analysis

In total, there were 10 interviews conducted. The participants of the interviews are presented anonymized in Table 4.1 below with their respective participant numbers and occupational roles.

Table 4.1: Interviewee's roles and abbreviations

P1	Sustainability Project Manager at Airport company
P2	Professor in Fire Safety
P3	Post-doc in Hydrogen Supply Chains
P4	Product manager at company developing Cryo Tools
P5	Expert in fire safety at a fire protection association
P6	Head of Innovation at a maritime company
P7	Business Developer within fuel company
P8	Business Developer Hydrogen at Energy Infrastructure company
P9	Business Developer Hydrogen at Gas Company
P10	Regional Developer in Energy Systems

The results from the interviews will be presented in the five themes concluded from the thematic analysis, with answers from all the participants grouped for each of the corresponding categories. The themes in the interviews relevant to the study are the following: **Policy and safety regulation, Leakage, Scalability, Synergies, and Supply chain pathways**.

4.1.1 Policy and safety regulation

Every interviewee thought the safety question was relevant, but none considered it a significant problem. All believed there will be some standards and regulations specific to hydrogen presented shortly, at least for GH_2. LH_2 is not as well researched and the regulations and standards for LH_2 may take longer says P2 and P5. These rules must be established and updated regularly as the business will probably grow significantly, P5 continues. P5 remarks that when the solar power market expanded, several companies did not consider safety but were in it for profit. In the case of hydrogen, it is unlikely as hydrogen on this scale is used for industry applications according to P5. According to P5, there is a risk of facing public resistance if there are early incidents while using hydrogen. This would mean a more difficult introduction and less likelihood of major usage, P5 continues, which makes hydrogen-specific regulations important.

P2 remarks that there is vague regulation on hydrogen as of now and that for airport applications, especially "airside", there is another regulatory framework to adhere to. P2 continues, stating that the "airside" of an airport may be under stricter restrictions, and therefore, hydrogen may be placed on the "landside" to make the process less complex and an introduction easier.

Policy and safety regulation - Permits

P6 mentioned their initiative to build electrolyzers to produce hydrogen for heavy-duty vehicle usage. The project has taken them several years with both applications and the approval of permits. P6 stated that they are still applying for certain permits. These processes are slow right now before there is a more standardized method, P6 says. P6 says that they will also need to be able to meet the demand for different types of fuels demanded by their customers, which will put even more administrative strain on their operations as more permits and communication will be needed. P10 discusses that for the pipeline, the region and every affected municipality must agree to the build, a time-consuming process. If one municipality rejects the planned pipeline, you would need to re-think the planned route, which could lead to extra costs and further permit processes. P9 & P6 both note that the concepts of pipelines in Sweden are pretty odd as there is no large established pipeline infrastructure, which may affect the public attitude towards the alternative, making politics in the area harder.

4.1.2 Leakage

Leakage is viewed differently by the interviewees. P4, P7, P8, and P9 do not consider leakage a problem, and the necessary leakage from boil-off should be used to power something else, or worst case, transformed back into electricity on the grid. P4, P7, P8, and P9 have not heard that it has been a big problem in their organization. P3 says there needs to be leakages in the supply chain and that those are needed to clean pipes and vessels to assure purity. P3 also states that the more vessel changes in the supply chain, (for example loading from truck to storage) the higher the number of leakages in the supply chain. Therefore, a solution to minimizing the leaks is to create supply chains with minimized vessel changes, P3 says.

Leakage - Environmental impact

The leakage of hydrogen also has a global warming potential P3 says. The leakage of hydrogen does not have a direct effect, but an indirect warming effect which makes it even more difficult to quantify the effects, and there is still research being conducted in the area according to P3. However, they say that more studies are needed on what leakage can mean for the environmental impact of the supply chain.

Leakage - Safety risks

The safety risks of leakages can mean detonations and can be difficult to detect, says P2. If LH_2 did leak, detonations in the asphalt or the ground could occur, says P2. If there is no build-up of hydrogen, the potential danger of detonation due to leakage decreases, but for a system of underground pipelines, detonations through build-up may occur. One potential incident that P2 exemplifies is the case of leakage underneath the airport platform, which could result in detonation and a significant safety risk.

4.1.3 Scalability

All interviewees expected a growth in hydrogen usage, specifically green hydrogen usage. The interviewees also agreed that large-scale production would have benefits in terms of cost and energy demand and that the highest amount of price reduction would be seen in large-scale production. P4, P8, and P9 all state that the PEM electrolyzers used and produced today are modular, making it possible to stack several 10 MW electrolyzers, which makes them scalable to demand. However, P4 says it is difficult to say if modular builds will be the most optimal solution in the future.

Scalability - Trucks

P1 says that by 2050 there is an expected demand somewhere between 17 and 31 kton of LH_2 annually at Göteborg Landvetter Airport. By that state trucks would probably not be an efficient way to supply hydrogen because of the considerable number of trucks which would be needed, P1 & P3 says. P3 notes that although central production has advantages, moving LH_2 can be an issue as it must be cooled down to -253C °and kept at that temperature.

Scalability - Pipeline

P7 says that the natural gas line used on the Swedish west coast today works well and as the demand for natural gas was known, it was easy to size the pipes. However, considering the unknown demand for hydrogen in the future, P8 & P9 express concern since it is challenging to commit to the investment because of uncertainty. P10 expresses the need for a couple of industries to commit to investing in hydrogen technologies to start developing a cluster to learn.

4.1.4 Synergies

Synergies were categorized into internal and external synergies, based on the answers from the interviewees. Internal synergies are the organization's use of residual products internally in their processes. Residual products in this sense mostly refer to boil-off, residual oxygen, and residual heat from electrolyzers. External synergies are synergies between organizations. In this sense, the supply chain is more relevant, and creating synergetic effects in the supply chain may benefit everyone, but residual products may become important for other organizations too.

P1, P3, P7, P8, P9, and P10 all consider the cost of hydrogen the main problem in transitioning from fossil-based kerosene. If hydrogen is as cheap as Jet A-1 the transition would have already started, P9 says. P10 thinks that political decisions to tax fossil-based fuels or subsidize hydrogen-based fuel will be the main early driver in transitioning from fossil-based aviation fuel. All interviewees discuss central hydrogen production, as it is viewed as a cost-effective solution by leveraging economies of scale and finding synergies. P9 says central production is a good possibility and they can build large-scale central production today, but there are no customers.

Synergies - Knowledge sharing

P1 talks about larger airport cooperation in the industry to support each other and to gain knowledge of hydrogen in aviation. P10 talks about working together regionally throughout the municipalities to build a general knowledge base in the area as many municipalities throughout the Swedish west coast would be affected by increased hydrogen production and demand.

Synergies - Energy demand

P8, P9, and P10 state that electricity availability is central, as much energy is used in hydrogen production. To find synergies in the energy sector, cooperation between industries further away may be needed, says P9. The north of Sweden is good as there is a lot of space, electricity availability, and water. Before cheap energy is available on the West Coast, production may be more favorable in the north of Sweden P9 says.

Synergies - Pipeline

P1, P7, P8 & P9 suggest that if the increased demand they expect meets reality, a regional pipeline on the West Coast will probably be the only reasonable alternative to transport the amounts that the industries on the West Coast would need. The interviewees within the industry and the region seem open to the joint effort of creating a local energy economy based on hydrogen. P10 was positive in joint ventures to create large producers as a start for the pipeline scenario and mentioned that VGR will create incentives for large-scale production. The incentives were not specified. Both P7 and P9 mention that for LH_2 it may be more difficult to find large-scale synergies with the industries since most industries use GH_2. They continue by saying that if future heavy-duty vehicles use hydrogen fuel, the demand for LH_2 will increase significantly and synergies may not be hard to find. P6 says that if they produce excess hydrogen, they would not oppose selling it locally.

Synergies - Internal use of hydrogen

All interviewees agree that internal synergies should be considered a part of every organization's hydrogen strategy. P6 mentions that it would be ideal to use the residual heat and oxygen internally for other applications and P7 & P9 mention that the steelworks in Hofors get full usage of the residual products from their electrolysis. Having heavy-duty vehicles that run on hydrogen at the airport could be one way to handle the boil-off from the hydrogen storage, P1 agrees. P1 considers the snowplows at the airport a possible future hydrogen user as they are not suitable for battery due to the irregular energy demand which is not suitable for battery charging. Another form of synergies that P7 talks about is mixing hydrogen into their products, which may not be as relevant for an airport setting but may have applications in the future.

4.1.5 Supply chain pathways

Every interviewee thought that there may be several possible supply chains early on. But later, with large-scale production and increased demand, there would almost only be the alternative of producing your own hydrogen or pipeline distribution. P9 continues to note that there are investigations into pipelines, but those will not be built in the near future, as there is low demand. P4 and P9 thought train deliveries could help since production could be done in northern Sweden to lower the energy cost for electrolyzers and liquefaction. However, P1 states that there is no current train to Landvetter, and the train projected between Gothenburg and Göteborg Landvetter Airport is mainly for passengers and not goods.

Supply chain pathways - Delivery trucks

P4 discusses the usage of GH_2 truck deliveries today due to the relative simplicity and the low infrastructure investment. As the demand is low this works well and can be transported more freely among customers according to P4. P6 also states that they would buy hydrogen by truck to supply refueling stations if there is a demand in the near future, but the plan is to produce their own hydrogen. P10 states that truck deliveries are easier in terms of logistics, infrastructure, and permits in urban environments than pipelines and that the limiting factor of trucks is the number of trucks needed. The benefit of LH_2 truck delivery is that you move more hydrogen per truck than in compressed GH_2 truck deliveries, P9 states.

Supply chain pathways - LH_2

One of the main problems is that LH_2 needs to remain cooled when distributing it, P3 says. That means regional supply would be ideal, says P4, P3, and P9. On the other hand, P3 talks about prototypes of large-scale liquid hydrogen tanks freighted by ships which could be a possibility in the future, but we are still in the prototyping phase of those being developed. Keeping the hydrogen liquid may become interesting as it is more efficient to move it as a liquid than compressed gas in terms of volume, especially if the hydrogen will be used in its liquid form according to P3.

Supply chain pathways - Combining

P6 & P7 state that a combination of own production and import or buying may be a solution that has more flexibility and can sustain itself better. However, this is only a case if the electrolyzers and production can keep a low cost otherwise investing in own production would render unused as central production would be cheaper, P6 continues.

4.2 Quantitative analysis

In the following chapter, the results derived from the models are presented. Firstly, the percentage of landings from hydrogen-powered aircraft will be displayed. Then the annually demanded tons, the levelized cost of hydrogen, trucks per day, and lastly the water consumption and water withdrawal. All results will be presented from the low-, main-, and high case.

4.2.1 Landings by hydrogen aircraft at Göteborg Landvetter Airport

The hydrogen-based landings are presented in percentage of the total landings of Göteborg Landvetter Airport. The landings are split up into two different categories, single-aisle and regional. As previously discussed in 3.3.1, the total fuel demand is far less affected by regional landings than single-aisle landings.

The percentages of the regional landings can be seen in Figure 4.1. The increase in hydrogen-powered regional aircraft is almost linear and continues to withhold a steady growth in all cases. The total amount of regional landings is not expected to grow at Göteborg Landvetter Airport, discussed in Section 3.3.1. Further, Hoelzen et al. (2022a) data expects a decrease of regional aircraft in the global fleet in the investigated time frame.

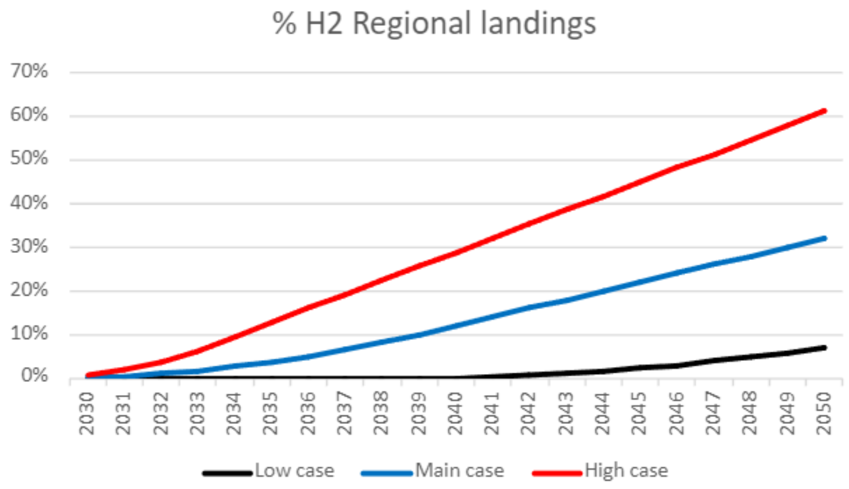

Figure 4.1: Percentage of landings from hydrogen regional aircraft

The percentage of single-aisle landings is displayed in Figure 4.2. The single-aisle segment is growing both in the total amount of single-aisle landings at Göteborg Landvetter Airport, discussed in Section 3.3.1, and in the global fleet data from Hoelzen et al. (2022b).

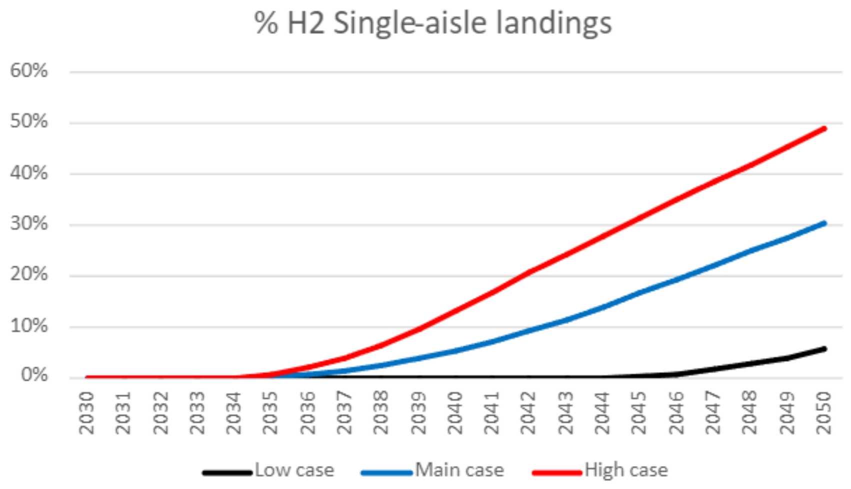

Figure 4.2: Percentage of landings from hydrogen single-aisle aircraft

4.2.2 Demanded LH_2 annually

The annual demand for LH_2 is based on how many of the landings are hydrogen-based. The demand is displayed in tons LH_2/year.

The projected demand for LH_2 is illustrated in Figure 4.3. The introduction year has a large impact on the demand. With late introduction the demand's cumulative growth is impacted and results in lower demand. The low case reflects this as seen in Figure 4.3. The impact of hydrogen aircraft adoption is also reflected. This can be seen as the high case has a significantly higher demand in 2050 than the main case, due to higher take-rate and faster ramp-up time.

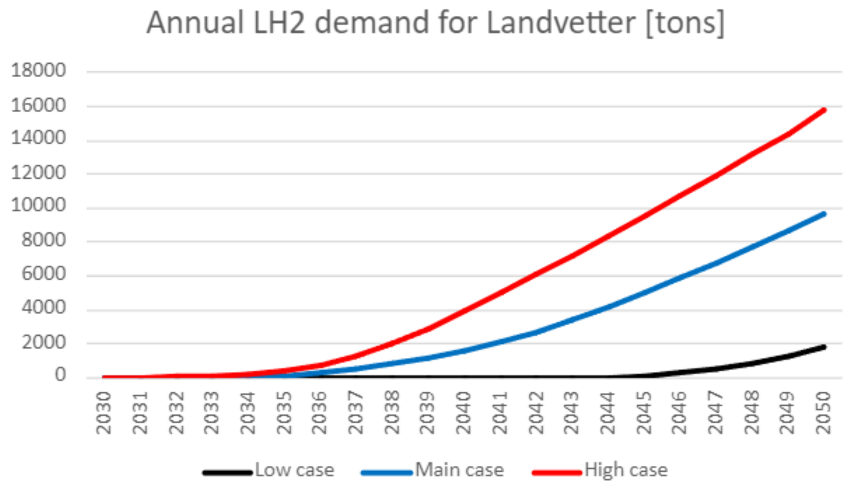

Figure 4.3: Annual LH_2 demand for Landvetter in tons

4.2.3 Levelized cost of the supply chain

In this section, the supply chain pathways' LCOH are discussed. The supply chain pathways are discussed in section 3.2.1. The costs are based on the total cost, found in Appendix C, and then divided by the demanded LH_2, which is discussed in depth in Section 3.4. The levelized cost is displayed in euro/kgH_2. All cases begin at a high rate because the storage has a high static cost, which offsets the LCOH because of the low start demand and high initial cost. Since all supply chain options are affected, the comparison is still relevant.

High Case

Figure 4.4 displays the levelized cost of the high case. All the centrally produced hydrogen options (GH_2 pipeline, LH_2 truck, and GH_2 truck in Figure 4.4) with different delivery alternatives, come close to each other as the cheapest pathways in the beginning. The only difference between the three supply chain pathways is the method of transport, which makes their price similar. In addition, buying hydrogen makes up 81% of the GH_2 pipeline cost, 93% of the LH_2 truck cost, and 78% of the GH_2 truck cost in 2050.

By the end of 2034, at 373 tons of annual demand, on-site production becomes the cheapest alternative and stays that way until 2050. However, investing in on-site production in 2035 would still mean that the LCOH is doubled compared to investing in production in 2050. Before 2040 only one electrolyzer is needed, so investing in an electrolyzer early does not utilize the full potential. The results indicate that ammonia import and cracking will be cheaper than the centrally produced alternatives (GH_2 pipeline, GH_2 Truck, LH_2 truck) by mid-2039.

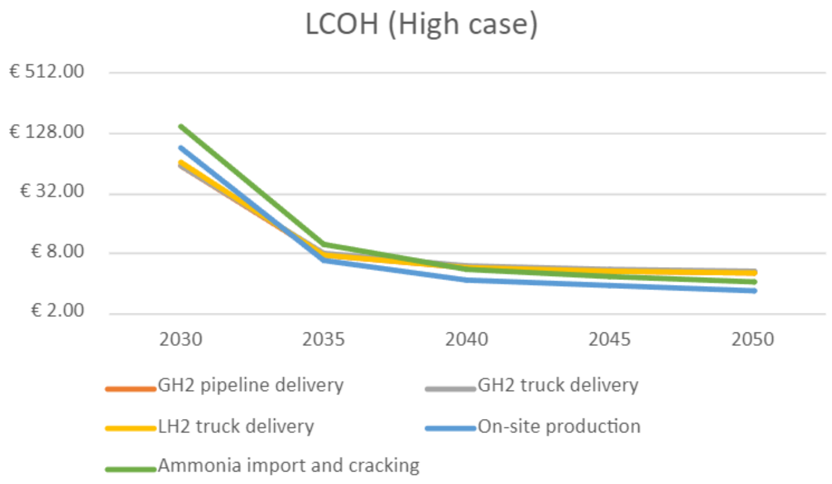

Figure 4.4: Levelized cost of the high case

Main Case

In Figure 4.5 the LCOH of the main case is displayed. The same pattern as viewed in the high case is displayed in the main case. The GH_2 pipeline delivery and LH_2 follow each other's cost between 2030-2050. In the main case, on-site production becomes the cheapest alternative in mid-2037, at 597 tons of annual demand.

Ammonia import and cracking becomes cheaper than the centrally produced alternatives at the end of 2039. Notably, the on-site production takes 2.5 years longer to become the cheapest alternative than in the high case, while ammonia is only offset by about half a year.

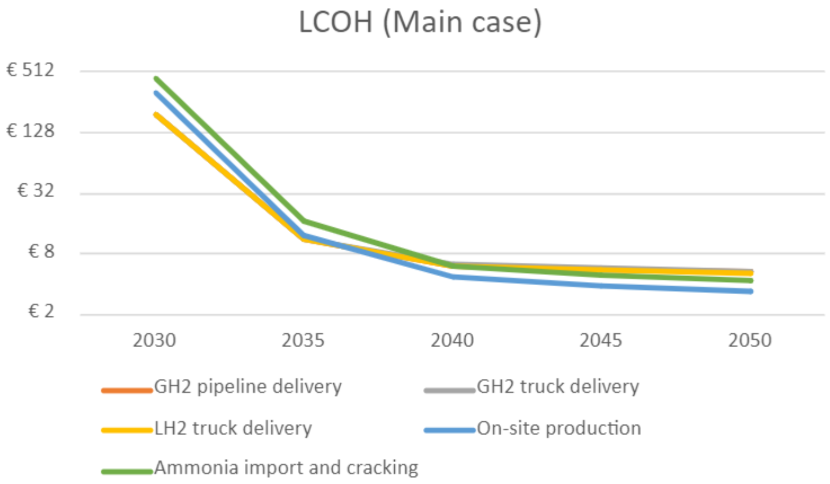

Figure 4.5: Levelized cost of the main case

Low Case

Figure 4.6 displays LCOH for the low case. In the low case, the centrally produced pathways start as the cheapest alternative as well, but there is a bigger difference between them. Pipeline on a smaller scale, as in this low case, does become significantly more expensive than in the other cases. In 2050, the GH_2 pipeline sticks out with almost twice the LCOH than the other transport methods of the centrally produced pathway, as shown in Figure 4.6. The pipeline price behaves differently than in the main and high case because the smaller pipes are less affected by economies of scale effects.

About halfway through 2047, on-site production emerges as the cheapest alternative, at 680 tons of annual demand, and holds the position until 2050. Ammonia becomes cheaper than GH_2 truck delivery halfway through 2048. The low case is the only case where only one electrolyzer is needed for the on-site production.

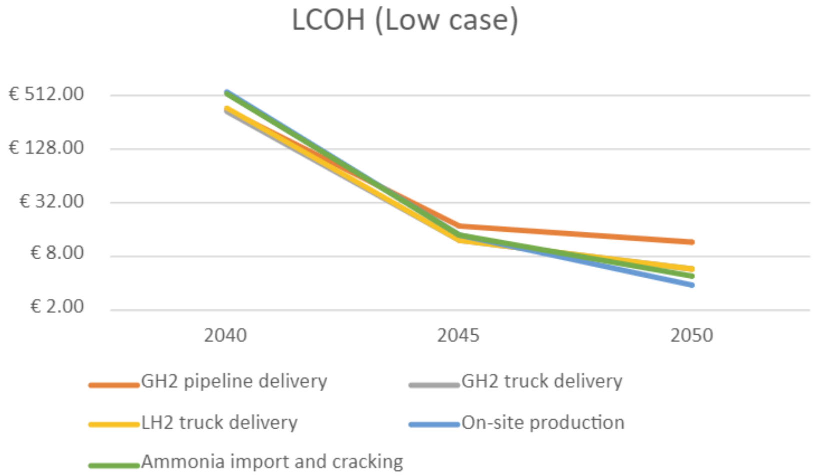

Figure 4.6: Levelized cost of the low case

4.2.4 Trucks needed for delivery of hydrogen

In this section, trucks needed for delivery are displayed. The relevant supply chain pathways are ammonia import and cracking, LH_2 truck delivery, and GH_2 truck delivery. Ammonia requires the least number of trucks and GH_2 requires the largest. The carrying capacity of the trucks is based on (Danish Energy Agency, 2024b), and discussed in Section 3.3.1.

In Figure 4.7 the trucks needed in all the cases can be seen. In the high case, all supply chain options need at least 9 trucks per day in 2050. The GH_2 trucks have a total of around 23 trucks needed per day in 2050.

In the main case, GH_2 trucks will have around 14 deliveries per day in 2050. In the low case, GH_2 trucks reach 2.6 trucks per day and all pathways reach at least one truck per day in 2050.

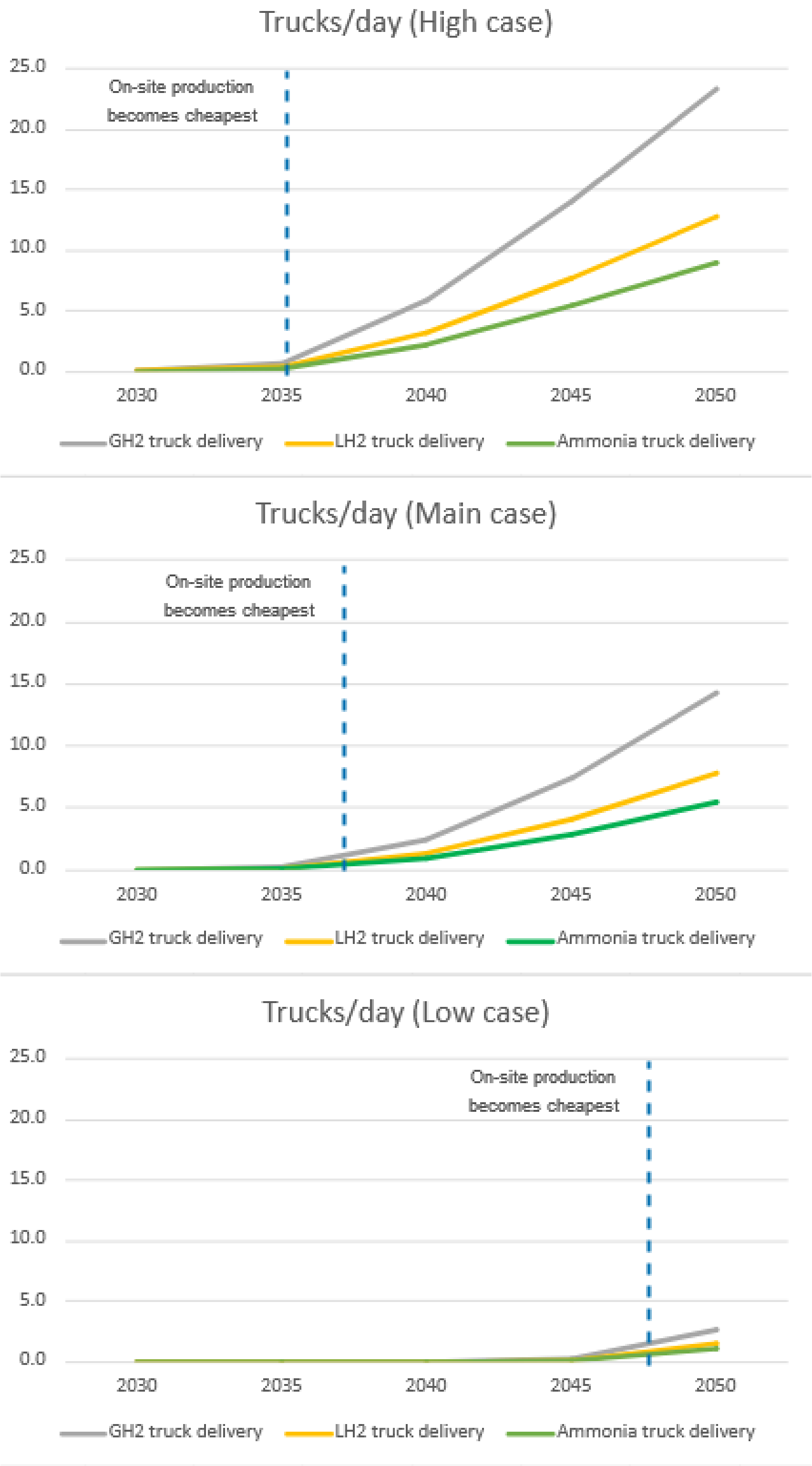

Figure 4.7: Trucks per day for the cases

4.2.5 Water consumption and withdrawal

Figure 4.8 shows the direct water consumption of the electrolysis process to fulfill the demand for hydrogen at Göteborg Landvetter Airport. The second graph, Figure 4.9, shows the water withdrawal for the electrolysis. The difference is discussed in Section 2.1.1. The consumption and withdrawal are only relevant to the on-site production pathway, as that is when Göteborg Landvetter Airport would need the water itself. Looking at the water withdrawal from Figure 4.9, the high case with 400,000 m^3, amounts to about 0.3% of the total usage in VGR. From Figure 4.8 we can see that the water consumption amounts to about 276,000 m^3 for the high case. The difference between the withdrawal and consumption is about 124,000 m^3 of water, which could be re-introduced on a local level. However, considering on-site production, the water usage in proximity to the airport may be more relevant than the regional water usage. The bedrock groundwater capacity underneath and around Landvetter airport is 600-2000 l/h, or 14.4-48 m^3/day (Sveriges Geologiska Undersökning, 2024). The high case reaches the limit of groundwater capacity by 2035, main case by the end of 2036, and the low case by mid-2046 in terms of water withdrawal.

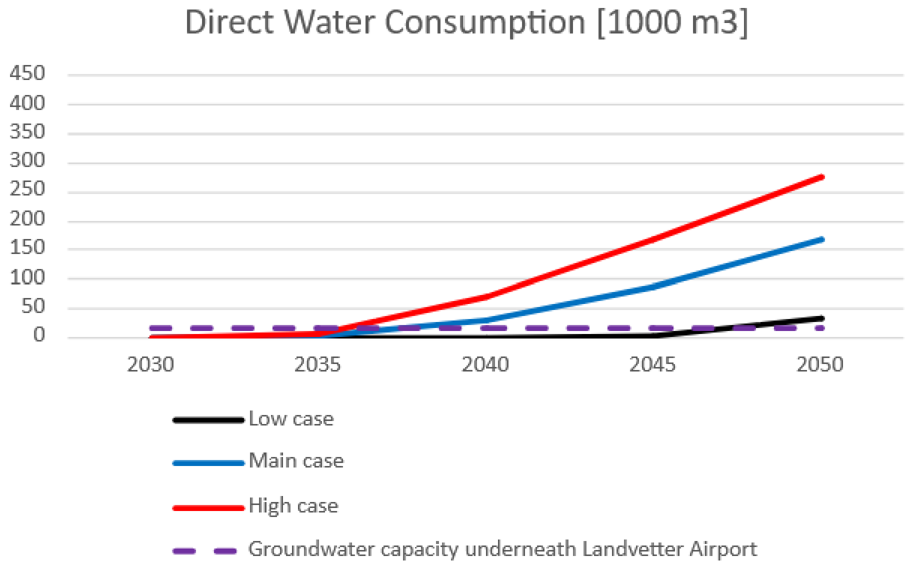

Figure 4.8: Direct Water Consumption [$1000m^3$]

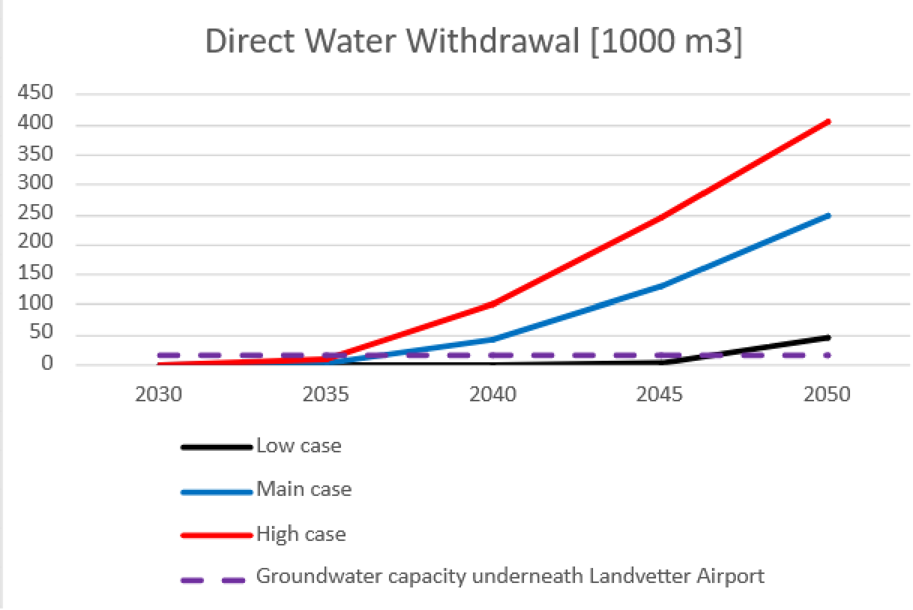

Figure 4.9: Direct Water Withdrawal [$1000m^3$]

5

Discussion

This study shows that different supply chain pathways are optimal based on the demand for hydrogen at the airport. In the early introduction, centrally produced alternatives are the cheapest. As demand grows, there is a transition where on-site becomes the most cost-effective alternative in all projected cases.

This chapter will discuss possibilities and challenges with every supply chain pathway, connected to the research questions. It will also present two strategy recommendations to Göteborg Landvetter Airport depending on expected demand.

GH_2 Pipeline

Pipelines are a larger infrastructure investment, with building times and permit applications, which may increase costs over time. As mentioned in the interviews, a rejection in one municipality could mean re-routing, which is the case for the suggested railroad (Trafikverket, 2023). The pipeline's cost-effectiveness is largely tied to the scale of the pipes. Small pipes perform badly, which is shown in the low case LCOH.

On the other hand, larger pipelines are the cheapest of the centrally produced alternatives, which correlates with Danish Energy Agency (2024b) and Hoelzen et al. (2022a) findings. Constructing large pipelines for only one organization requires a minimum flow of GH_2, which needs a stable demand before construction starts. This makes the scalability of the pipeline limited and often tied to the possibility of synergies. The results show that synergies and large-scale production to supply several industries are expected by stakeholders, but pipelines in Sweden are uncommon and will probably not be constructed soon. If the synergies and demand for hydrogen are not properly identified beforehand, it is difficult to justify the investment in pipelines.

LH_2 Truck delivery

The results indicate that LH_2 delivery trucks are a viable supply alternative in low to mid-demand cases. As results and theory indicated LH_2 trucks can carry larger amounts of hydrogen than GH_2 trucks less transport is needed (Tashie-Lewis & Nnabuife, 2021). Delivering it as LH_2 requires no transformation on-site, which makes the scalability less complex than the other supply chain pathways, as the only infrastructure needed in our model is storage, as shown in Section 3.3.2. This results in a simpler regulatory process, especially in urban areas, than the other supply chain pathways. From an operational perspective, there would be a minimal transition as fuel delivery trucks are used today (GFC, n.d.). Additionally, the results show that LH_2 truck delivery can be beneficial in terms of leakage if fewer vessel changes are involved. However, logistical challenges may arise as the number of LH_2 truck deliveries increases.

In terms of regulation, LH_2 is lacking compared to GH_2. According to the interviews, the synergies in LH_2 may also be limited depending on the development of heavy-duty vehicles. Based on Liebreich (2023)'s hydrogen ladder shipping is the most likely other form of heavy-duty vehicle to be hydrogen-based, long-distance trucks and coaches are also listed but not as likely as aviation and shipping.

GH_2 Truck delivery

GH_2 truck delivery is the cheapest alternative in the introductory years of the low case. In all the other cases, GH_2 truck delivery is sub-optimal in terms of cost and number of trucks needed because of the volume, which aligns with the findings of IEA (2019). However, as stated in Section 2.2.1, compressing GH_2 is already used today to move GH_2. Compressing GH_2 is the least energy-demanding alternative of the pathways explored, as seen in Section 2.2. The interviews also show that the regulatory framework is further in its development for GH_2 compared to LH_2, which is beneficial for the supply pathway.

On-site production

On-site production emerges as the cheapest supply chain pathway when the demand increases in all explored cases. The interviews reinforce the viability of the supply chain pathway by considering it one of the few pathways that could support the high demand for hydrogen from a logistical standpoint, and the large scale of production needed is deemed feasible by P9. Further, on-site production can be scaled up with modular electrolyzers to meet future demand. However, interviews and theory underline the need for a comprehensive hydrogen strategy for on-site production, as synergistic effects are deemed necessary for full utilization of production. The results indicate that, in regulation and policies, on-site production may be a time-consuming process that differs vastly from the operations today.

With on-site production, the water withdrawal would only increase slightly compared to total water withdrawal regionally today. Looking at the bedrock groundwater capacity underneath Göteborg Landvetter Airport, the results indicate that the water withdrawal would see significant constraints, which aligns with IRENA and Bluerisk (2023) findings. All cases exceed the maximum bedrock groundwater capacity gathered from Sveriges Geologiska Undersökning (2024), and in the main and high cases, the limit is reached before 2040. The difference between water consumption and water withdrawal is relatively high, so a strategy for managing wastewater would be needed.

Ammonia import and cracking

Ammonia import and cracking is the second-cheapest alternative in 2050 in all explored cases, according to the model. Even though interview data on ammonia is limited, section 2.2.3 discusses ammonia as a substance that is in use today at a large scale which indicates benefits for regulatory processes. The scalability of ammonia cracking is considered somewhat limited, as the cracking facility is not modular for the model. There are modular concepts for ammonia cracking, shown by Jackson et al. (2020). However, the projected demand would need a significant number of cracking modules. Cesaro et al. (2021) argues that economics of scale benefits can be gained using one large-scale cracking facility.

As seen in Section 2.2, converting hydrogen into ammonia and back demands a significant amount of energy. Therefore, the pathway would only be realistically viable if ammonia (and green hydrogen) could be produced at a significantly lower price far away. This is still being explored, and projections of green ammonia production cost are speculative (IRENA & AEA, 2022). As discussed by P3, prototypes of large-scale LH_2 tanks are explored, which could mean that transforming the hydrogen to ammonia no longer fills a purpose in distribution.

Strengths & Weaknesses of the study

The study benefits from input provided by multiple stakeholders within the industry, each possessing knowledge and experience of working with hydrogen. This input allows the study to present a nuanced analysis, identifying potential issues throughout the entire supply chain.

Focusing specifically on Göteborg Landvetter Airport, the case study investigates local synergistic effects, which have proven to be important in practical implementation. This also allows for a real-world scenario to be analyzed and give recommendations to an existing airport.

A significant limitation of the study is the absence of interviews with local municipalities, which are often critical in the development of local infrastructure. No interviews were conducted with aircraft producers either, which could have benefitted the demand model. The study does not account for peak days and seasonal variations in demand, potentially leading to overestimating supply chain feasibility and underestimating infrastructure costs. The model is simplified and does not reflect all costs included. An example is the cost of water and processing of water, which is not included in the model.

The assumed delivery distance of 150 km (Lysekil to Landvetter) for a pipeline, GH_2 truck, and LH_2 truck may not reflect a realistic scenario, as hydrogen might be supplied from a closer location, such as Gothenburg.

It is important to note that the recommendations may only apply to the case-studied airport with its geographical placement, local industries, and flight pattern allowing for an interesting case in terms of hydrogen. A large percentage of the flights from Landvetter are inter-European or regional, which is where most think that hydrogen will become an energy carrier. Its geographical location has a lot of local industries using hydrogen as feedstock and a large port nearby. As part of projects like the "Fossilfritt Flyg 2045" initiative, Swedavia, the owner of Göteborg

Landvetter Airport, demonstrates a commitment to sustainable development and positions itself as an early mover in the aviation industry, which may not be reflective of other airport organizations (Al-Ghussein Norrman & Talalasova, 2021).

5.1 Recommendations for hydrogen at Göteborg Landvetter Airport

Depending on the expected demand, two different strategies will be presented. One for lower demand and one for mid to high demand.

Strategy 1: Lower demand
This strategy is recommended if lower demand is expected. The hydrogen should be bought as LH_2 from central production, supplied with LH_2 trucks, and stored on-site. LH_2 truck deliveries start as one of the cheapest alternatives in every case and are reinforced by interviews to be a good alternative if LH_2 is going to be used. This strategy offers low infrastructure investment costs. The trucks are flexible, and fuel that the airport does not demand can be shipped elsewhere. The results of our models show that the number of trucks should be manageable at low demand and this strategy resembles the current fuel supply operations, which can make a transition to hydrogen-based fuel easier operationally.

The negative side of this strategy is that it may be difficult to find a supplier of LH_2 if demand is low and, according to the model, it comes at a higher cost. However, practically, this may be more efficient and less costly because of the added flexibility and lower operational strain.

Strategy 2: Mid to high demand
Strategy 2 is recommended if mid to high demand is expected. A suggested timeline based on our results is presented in Figure 5.1. The strategy includes an introduction phase, a transitional phase, and then on-site production.

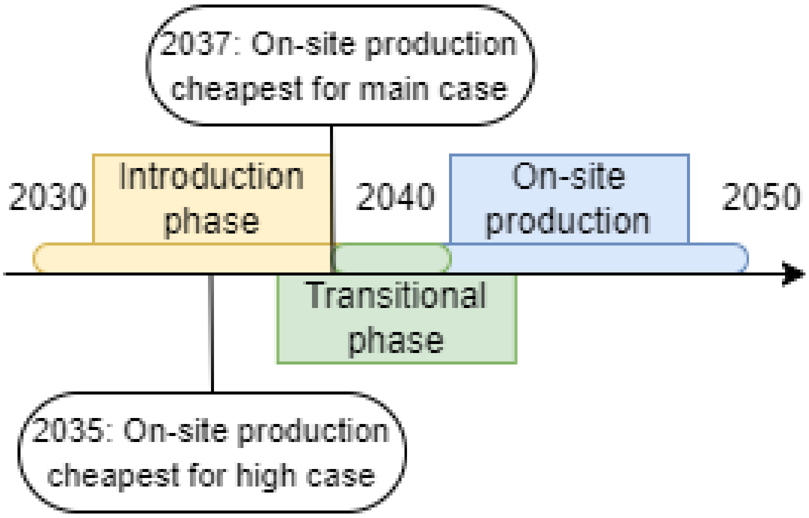

Figure 5.1: Timeline for Strategy 2

1. **Introduction Phase:**
    - Utilize Centrally Produced Hydrogen: Initially, should centrally produced hydrogen be preferred due to its lower cost compared to on-site production and ammonia import and cracking. This phase allows for a gradual increase in hydrogen demand while minimizing operational re-shaping.
    - LH_2 Truck Delivery: Delivering hydrogen as LH_2 via trucks is a viable early option, as the method does not require large infrastructure investments. Buying LH_2 avoids the needed on-site transformation of hydrogen as well. However, logistical challenges arise as the number of truck deliveries increases which must be managed.
    - Analyze growth: Analyze the demand growth and possible synergies during this time to project the hydrogen market's future. Start contacting municipalities and the region to understand their needs and projections they make.

2. **Transitional Phase:**
    - Transition to On-Site Production: As hydrogen demand increases, on-site production will become the most cost-effective solution, according to our model. The transition is recommended when an electrolyzer can be fully utilized to meet the demand.
    - Mixing of Supply Chain Pathways: To ensure that hydrogen can be supplied before the on-site production is fully developed it can be beneficial to continue using LH_2 truck delivery.
    - Understanding the Implications: Learn and create standards from the practical deployment of on-site production. Use the knowledge from previous hydrogen projects and share the knowledge with other stakeholders.

3. **On-site Production:**
    - Fully deploy on-site production: Full commitment to on-site production is deployed when the supply can be guaranteed. The operations of on-site production have had some time to become standardized and an understanding of

the practical implications has been gained.
- Leverage Local Synergies: On-site production allows for greater control over supply and can be scaled up by stacking electrolyzers in 10 MW modules. Leverage local synergies by collaborating with nearby industries that already utilize hydrogen, enhancing the overall feasibility and cost-effectiveness of the supply chain.
- Manage water withdrawal: Ensure that local water withdrawal is managed and regulated to avoid potential conflicts with municipal water usage. A comprehensive hydrogen strategy should be developed to streamline regulatory processes and address any time-consuming aspects.

Drawbacks of on-site production

- Permit Applications: Permit times have been stated as a problem, hopefully, these can be managed if early collaborations between VGR and the municipalities affected are explored. However, it may still face uncertainty and scaling up, and building new infrastructure may be more time-consuming than projected.
- Safety regulations: The safety aspect is still under investigation. Even though the interviewees expect standards and regulations to develop in the coming years it is difficult to say what consequences those will bring to the viability of on-site production.
- New operational challenges: Producing LH_2 would mean a new type of operation for the airport. Further, the acquisition and usage of water would need to be managed. This includes new jobs and logistics at the airport, which may lead to administrative and operational strain.

In both strategies, it is important to continuously monitor advancements in hydrogen technology and market trends, particularly in the heavy-duty vehicle and aviation sectors. This will help in making informed decisions about future investments and infrastructure developments. Stay informed about the evolving regulatory landscape to ensure compliance and utilize new incentives or support mechanisms.

6

Conclusion

This thesis employs an abductive method to analyze how demand for hydrogen may increase at Göteborg Landvetter Airport. It uses quantitative and qualitative data to consider the viability of different supply chain alternatives to meet the projected demand cases. This thesis provides an example of what parameters may be important for airports when considering supplying hydrogen as a fuel. These parameters include infrastructural investments, opportunities for local and regional synergy, and the regulatory landscape.

All studied supply chain pathways are viable for supplying liquid hydrogen to airports. Centrally produced truck deliveries (GH_2 and LH_2) are promising in low-demand scenarios with benefits in synergies with local industries and less policy and regulatory administration. GH_2 Truck deliveries and Pipeline are challenging in terms of future scalability. On-site production has the benefit of being able to use excess hydrogen and residual product within the own organization and appears promising for future scalability and meeting high demand, however, local water availability may constrain the hydrogen production. All supply chain pathways are affected by leakages, but keeping the vessel changes to a minimum benefits the supply chain.

One of the key findings of the thesis is that a transition may be needed from centrally produced alternatives to on-site production when considering the hydrogen supply chain. Further, the study shows a need to create a long-term plan on how organizations acquire and use hydrogen, which considers local water-consumption and withdrawal effects, synergies, and understands the logistical needs of a hydrogen supply chain. The thesis is based on a simplified model of reality, and the costs and estimations are used more as a guideline or as a foundation for further in-depth analysis of each supply chain pathway.

Future studies are recommended to explore the local effects of water consumption with each supply chain option and analyze the effects of freshwater relocation. Analyzing peak demand scenarios could also give a more accurate assessment of supply chain feasibility. By building on the insight provided by this thesis, we hope that future studies can build a general understanding of how a hydrogen supply chain to airports may look.

Hopefully, the thesis will be used to make more informed decisions and to act as a foundation for the planning process of hydrogen at airport initiatives.

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A

Appendix

Interview guides

Reoccurring questions for the interviews

- Hur arbetar ni med vätgas just nu och vad är era framtidsvisioner?
  (How are you currently working with hydrogen and what are your future visions?)

- Vad tror ni om synergier utefter västkusten och vätgas?
  (What do you think about the synergies along the west coast and hydrogen?)

- Vad ser ni som möjliga vätgas distributionsvägar till flygplatser?
  (What do you see as possible hydrogen distribution pathways to airports?)

- Hur tror ni att behovet efter vätgas kommer förändras?
  (How do you think the demand for hydrogen will change?)

- Vad tror ni det finns för utmaningar med vätgas som bränsle till flygplan?
  (What challenges do you think exist with using hydrogen as aircraft fuel?)

- Hur arbetar ni med säkerheten, finns inget i pränt i Sverige ännu?
  (How are you addressing safety, given that there are no established regulations in Sweden yet?)

B

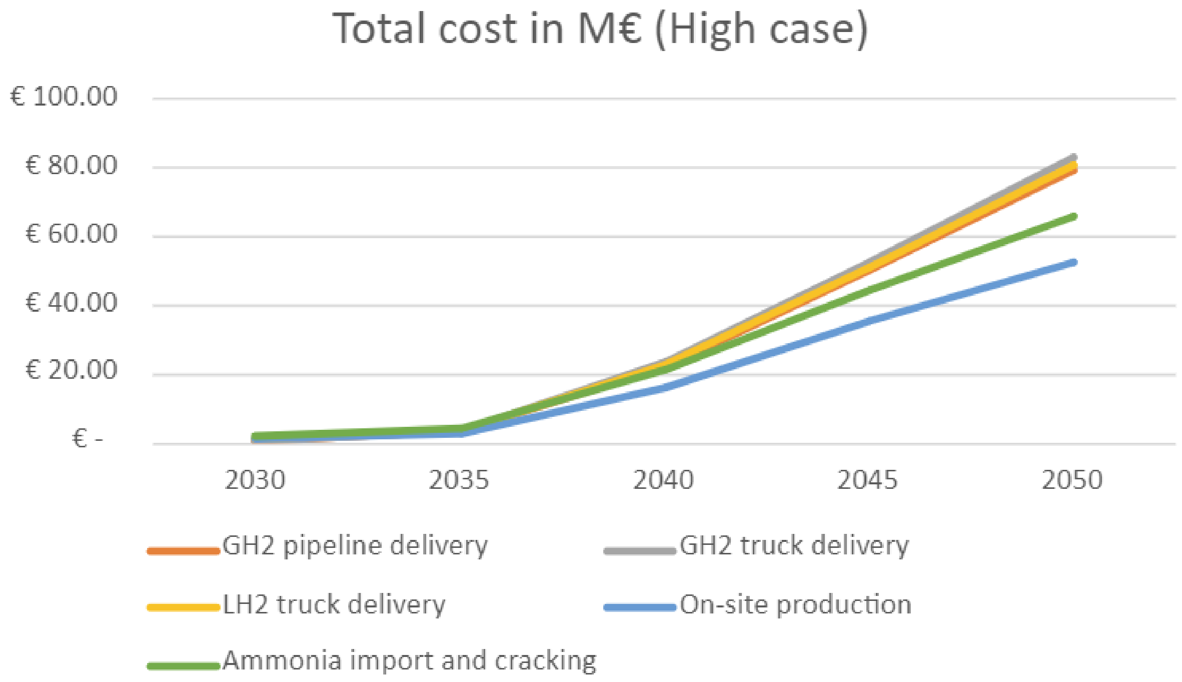
Appendix

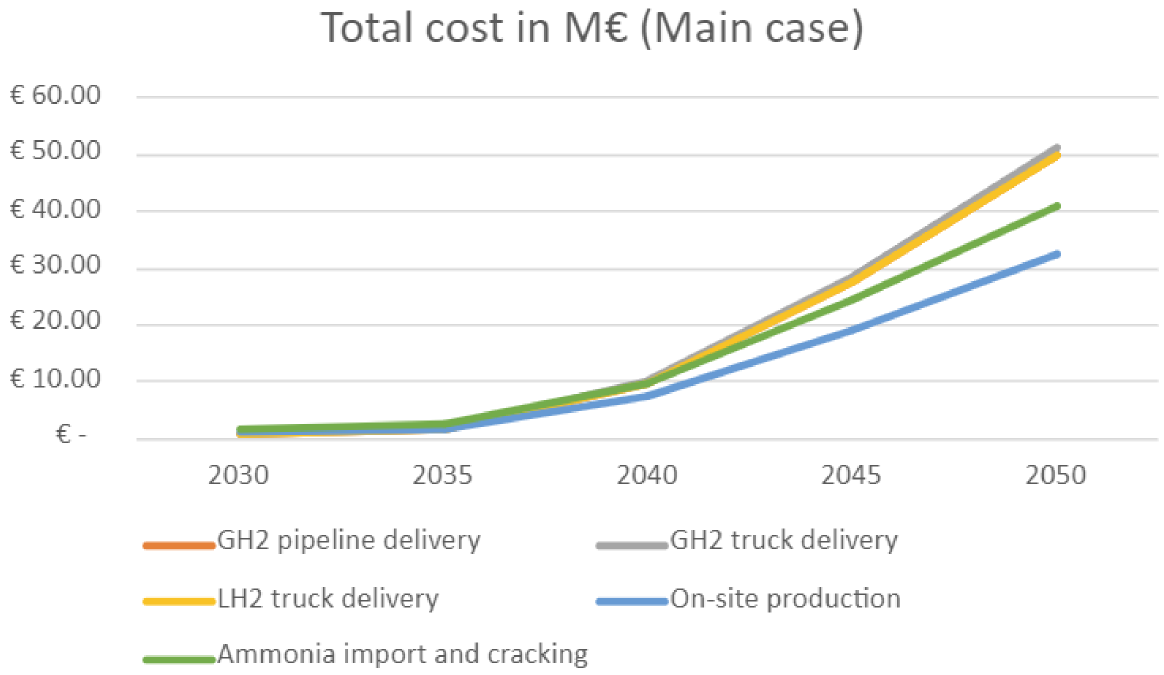
Year	Annual efficiency change %
2030	0.89
2031	0.88
2032	0.87
2033	0.86
2034	0.85
2035	0.84
2036	0.84
2037	0.83
2038	0.82
2039	0.81
2040	0.80
2041	0.79
2042	0.78
2043	0.77
2044	0.76
2045	0.75
2046	0.74
2047	0.73
2048	0.73
2049	0.72
2050	0.71

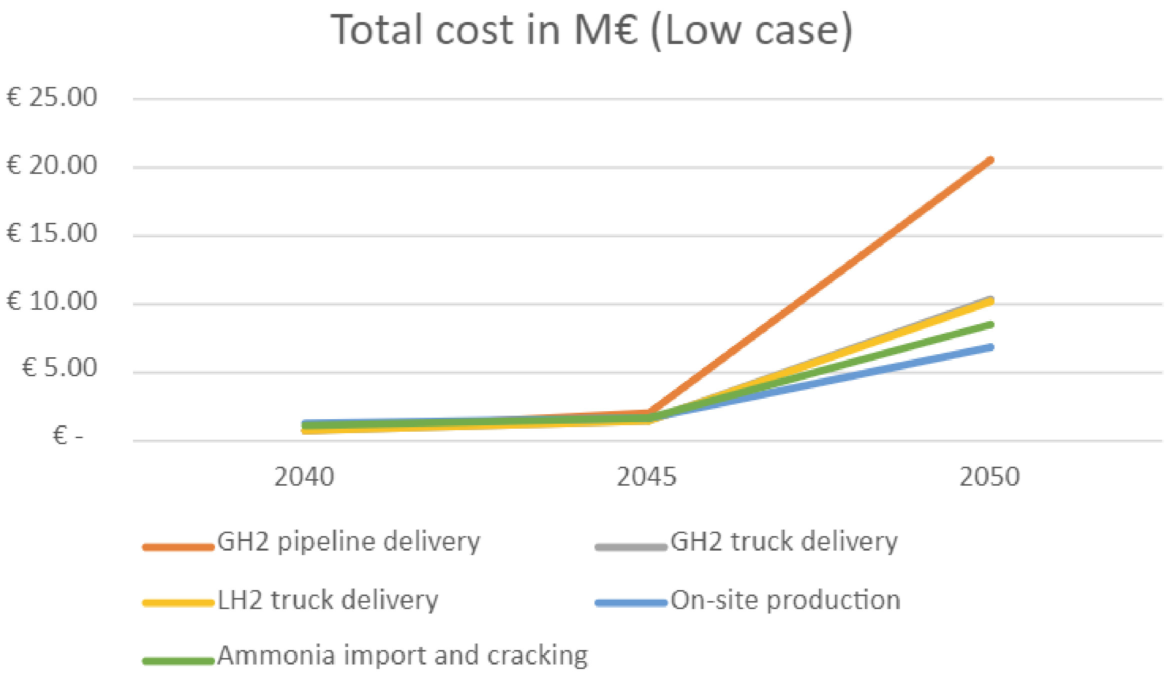
Table B.1: Caption

C

Appendix


Total cost in M€ (High case)
€ 100.00
€ 80.00
€ 60.00
€ 40.00
€ 20.00
€ -
2030
2035
2040
2045
2050
GH2 pipeline delivery
GH2 truck delivery
LH2 truck delivery
On-site production
Ammonia import and cracking


Total cost in M€ (Main case)
€ 60.00
€ 50.00
€ 40.00
€ 30.00
€ 20.00
€ 10.00
€ -
2030
2035
2040
2045
2050
GH2 pipeline delivery
GH2 truck delivery
LH2 truck delivery
On-site production
Ammonia import and cracking


Total cost in M€ (Low case)
€ 25.00
€ 20.00
€ 15.00
€ 10.00
€ 5.00
€ -
2040
2045
2050
GH2 pipeline delivery
GH2 truck delivery
LH2 truck delivery
On-site production
Ammonia import and cracking