Sustainable H_2 Supply Chain Pathways for Local Fossil-Fuel Airports

Master Thesis

M.Sc. Management of Technology

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Xander D. Terpstra

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Executive Summary

As the aviation industry faces pressure to decarbonise, hydrogen (H_2), especially green H_2, emerges as a long-term solution with the potential to reshape the future of aviation. Offering the potential for zero CO_2 emissions and higher energy efficiency, H_2 presents a compelling case for long-term sustainability. However, its adoption demands an overhaul of existing aircraft infrastructure and supply chain networks. The shift to H_2-powered aviation is fraught with challenges; from production and transportation to storage and policy adaptation.

Despite growing interest, there is a critical gap in the current literature, particularly in understanding the uncertainties of integrating H_2 into existing airport operations once H_2 aircraft become operational. This study aims to bridge that gap by exploring sustainable H_2 supply chain pathways for airports currently reliant on fossil fuels. Using a single case study and the 2x2 Scenario-Axes Technique, the research identifies key uncertainties in the hydrogen supply chain and develops future scenarios to guide decision-makers in navigating the transition. The main research question driving this study is: *What are sustainable supply chain pathways to transition a local fossil fuel-based airport to an H_2 airport?*

Before answering the main research question, it is essential to elaborate on the findings and methodology, as they play a crucial role in shaping the H_2 supply chain pathways.

Starting with the uncertainties surrounding the success of H_2 in aviation. This study examined the external environment via a STEEP analysis and found twelve external factors influencing the H_2 supply chain. Figure 1 below shows a matrix of these factors.

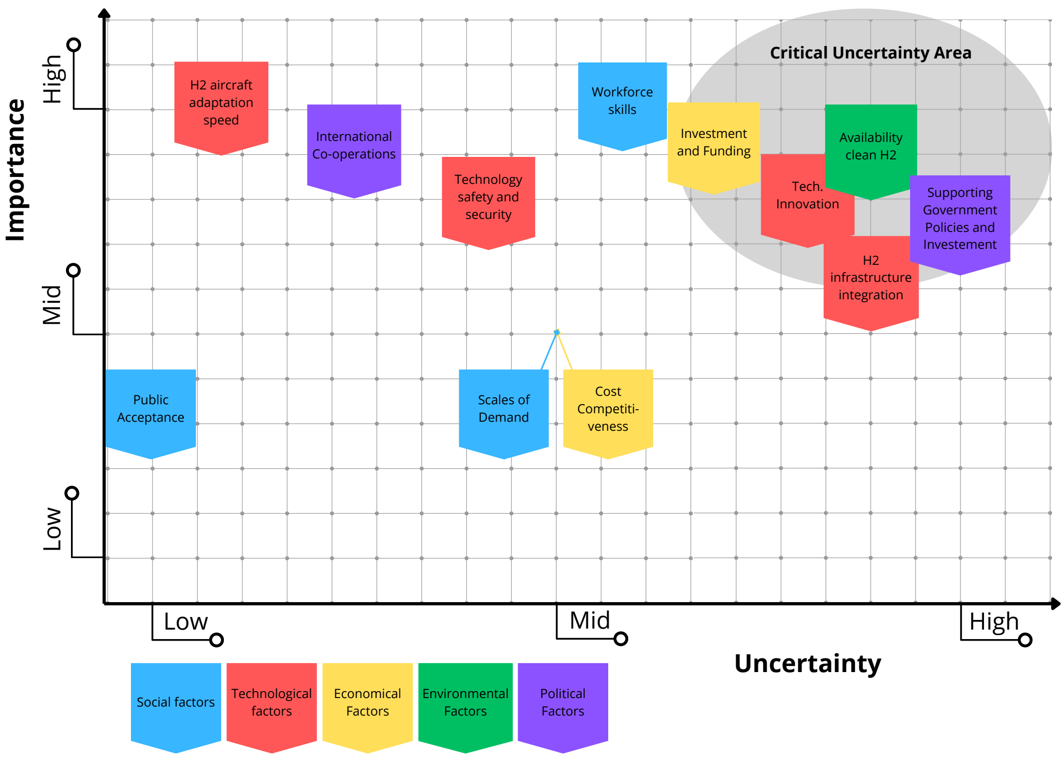

Figure 1: Ranking drivers of change by importance and uncertainty

The scenario analysis shows two key drivers: the availability of clean H_2 and supporting government policies and investments. Both were identified as having the highest levels of uncertainty and near-high importance. These critical factors form the axes of a 2x2 matrix, representing a spectrum from low to high in each category. The matrix presents four distinct scenarios, each representing a potential pathway for H_2 adoption at Lelystad Airport.

The four scenarios and proposed actions for Lelystad Airport mark the initial steps toward developing a sustainable H_2 supply pathway. Each scenario, detailed in Chapter 6, outlines a unique course of action, reflecting diverse stakeholder responses—from substantial investments in infrastructure to exploring alternative options. The significant variation between these scenarios highlights the complexities and uncertainties surrounding the transition, raising crucial questions about the timing and actions that should be taken.

To help navigate these uncertainties, this study introduces key change drivers. Indicators designed to monitor ongoing developments in the hydrogen landscape. By tracking these change drivers, stakeholders can assess when specific scenarios are becoming more probable. Hereby enabling more informed decision-making as the transition unfolds.

Table 1 summarizes these key indicators that track shifts in scenarios. Each ”change driver” is paired with measurable indicators to monitor trends over time. Some indicators overlap with the driving forces from Figure 1, as they also influence the broader environment.

Table 1: H_2 Change-Drivers and Indicators (short)

Change driver	Indicator(s)	Change Direction
Government Policies and Regulation:	Votes in favour of H_2 politicians; H_2 subsidies; H_2 tax incentives.	Higher indicator outcomes result in a more government support and investments
Technology advancements:	H_2 patent filings; H_2 research publications; Assess H_2 TRLs; Breakthrough H_2 innovations.	Higher indicator outcomes result in higher likelihood of more availability of clean H_2.
Market Adoption:	H_2 aircraft deliveries; H_2 take-off and landings; H_2 ready airports.	Outcomes show H_2 transition progress. Higher outcomes could cause a stronger Kaldor-Verdoorn/Demand-Pull effect.
Infrastructure Development:	Overall H_2 distribution; (Sustainable) H_2 production plants; H_2 infrastructure expansion (plans).	Higher outcomes can result in a higher likelihood of government support and a clean H_2 supply.
Economic Drivers:	(Sustainable) H_2 supply; H_2 public and private investments; H_2 R&D Expenditures.	Higher outcomes can result in a higher likelihood of a clean H_2 supply and a stronger Kaldor-Verdoorn/Demand-Pull effect.
Stakeholder Confidence:	Results of H_2 sentiment surveys.	Higher outcomes can result in a higher likelihood of government support and a clean H_2 supply.

These indicators can serve as a basis for analysing the direction of change towards the four scenarios.

Circling back to the main research question *What are sustainable supply chain pathways to transition a local fossil fuel-based airport to an H_2 airport?*

The key takeaway from this study is the recommendation for airports to adopt a cautious yet strategic approach to the transition toward sustainable H_2 operations. Given the current high levels of uncertainty, particularly regarding infrastructure investments, airports are advised to remain flexible, adaptable, and collaborative in the early stages of the H_2 transition. Rather than rushing to invest in permanent supply chain infrastructure, airports should carefully monitor critical change indicators that can signal the viability and success of H_2 in aviation (see Figure 1).

At present, this study emphasises that flexibility and adaptability are important. As H_2 aircraft technology matures, clean H_2 becomes more readily available, and government support and/or technological breakthroughs emerge, airports can adapt their supply chain strategies accordingly. These indicators (see Table 1) provide a framework not only for Lelystad Airport, but for other airports as well. Enabling them to navigate regional government policies, infrastructure readiness, and emerging market trends. This approach ensures that airports are prepared to pivot based on the evolving landscape of H_2 adoption, reducing risks while maximizing opportunities for a sustainable future in aviation.

This study expands on H_2 supply chain for aviation, highlighting the potential for H_2-bonded supply chains and identifying twelve key factors influencing their success through a STEEP analysis. Future scholars and researchers could focus on reducing the uncertainties, enabling more informed policy and strategic decisions for H_2 in aviation. After ranking these factors based on importance and uncertainty, the study developed new scenarios, which then continued towards indicators to measure H_2's success in aviation. Where our research is limited within supply chain from production to airport delivery (in the Netherlands). Further research is needed upstream to determine where and how sustainable H_2 will be produced, if this will be locally or imported, and how it will be distributed within a domestic area. It is also recommended to assess the demand for H_2-powered aircraft. While estimating H_2 needs per flight is a starting point, a detailed analysis is required to understand aircraft range, identify airports within that range, and explore partnerships with those aiming to become H_2 hubs. This will help refine demand estimates and could guide H_2 supply chain development.

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1 Introduction

1.1. Problem Definition

The history of aviation began with the Wright brothers' first powered flight in 1903, igniting a century of rapid advancements. From the early biplanes to the jet age, aviation has transformed global travel and connectivity. However, in 2017, direct emissions from aviation in the EU accounted for 3.8% of total CO_2 emissions [19]. And can go up to 22% by 2050 whilst other industries decarbonize [58, 79]. Therefore, the aviation industry seeks sustainable futures to contribute to limiting climate change by targeting net zero emissions by 2050 [21].

Aviation has seen a dip in passengers during the COVID pandemic, but the global aviation rebound of passenger traffic is projected to recover to pre-COVID demand this year [73]. And Eurocontrol forecasts the European market demand for flying to increase by an average of 44% by 2050 (up about 1.2% per year) [32].

To accommodate the growth and reach the sustainability goals, the aviation industry must undergo various changes, under which sustainable fuels is one of them [63]. Within sustainable fuels, alternative energy carriers already exist. To reach the 2050 climate goals in the short term, Sustainable Aviation Fuels (SAFs) (i.e. bio-fuels, biomass and Synthetic Power-to-Liquid fuels [6]) are promising. These can be used in existing engines as 'drop-in' fuels, which offer the opportunity to reduce aviation emissions in the short term [34]. However, SAFs are not the best long-term solution because they cannot achieve zero CO_2 emissions, require large amounts of land (in case of biofuels), and are costly [4, 17]. This is because SAFs are made via Hydrotreated Esters and Fatty Acids (HEFA) from waste fats, oils and greases (which is limited in supply). Or via Power-to-Liquid (PtL), which requires Hydrogen (H_2) and CO_2. When looking at the conversion in energy efficiency of PtL versus Liquid Hydrogen, Liquid hydrogen is about 20-30% more efficient [35]. So, for long-term CO_2 reduction solutions, H_2 is seen as the most promising decarbonisation technology for aviation [10]. The problem is that changing towards H_2 aviation requires effort and dedication from the stakeholders and policymakers. Because it brings significant changes in the aircraft, infrastructure and global H_2supply chain. In turn, these require substantial investments, accompanied by many uncertainty of the success.

1.2. Knowledge Gap

Currently, the change towards sustainable airports and the future supply chain of H_2 to airports is uncertain. Before the industry can use H_2 on a global scale, there are challenges to solve and uncertainties to figure out. Specifically, since the progress to make H_2 flying aircraft is ongoing. Airbus' new zero-e fleet projects to start operation on H_2 by 2035 [10]. The Hydrogen Aircraft Powertrain and Storage System (HAPSS) program[1] aims to have the first H_2 commercial flight between Amsterdam and London by 2028 [77, 82]. ZeroAvia is working on retrofitting existing aircraft with H_2 as fuel as early as 2025 [88]. If the project(s) succeed, airports should have H_2 readily available to use the aircraft. Although the process of renewing the fleet will span several years if not decades. As this transition occurs, the demand

[1]Hydrogen Aircraft Powertrain and Storage System (HAPSS) is a fully Dutch public-private partnership, set up by Unified International and InnovationQuarter with 17 companies, including Fokker, TU Delft, the Dutch government, the Royal Netherlands Aerospace Centre, and Zepp.solutions. From the National Growth Fund, €383 million has been allocated to the Aviation in Transition program, of which the HAPSS project is the largest part [82].

for H_2 will progressively increase, requiring airports to adjust their supply chain facilities accordingly. Most European airports receive kerosene directly from oil refineries via pipeline and store it in large tanks. REpowerEU plans to have 20 million tons of H_2 available and infrastructure built by 2030 [33]. However, REpowerEU presents no plans for how the infrastructure will look like. Currently, there are barely any papers found regarding the implementation of the supply chain of H_2 for airports. Degirmenci et al. [25] propose a case study for two separate airports, and Hoezelen et al. [41] investigates the H_2 infrastructure, concluding that more research is required. Noting that different geographical locations have different availability and access to low-cost (sustainable) H_2, which influences the design of airline networks [41]. Some airports might access locally produced H_2, while others rely on (international) trade routes. As of today, there is no global trade for green H_2 [16]. Chapter 2 will go over the parts of the H_2 supply chain for airports considered in this study. In addition, because it is a 'transition' and not a 'change', airports preparing to service the new fleet will need to gradually modify and expand their supply chains. This comes with new challenges because H_2 in its pure form is not as easily transported or stored as kerosene due to its physical properties [29].
In conclusion, the transition towards sustainable H_2 airports reveals that there are many uncertainties in its H_2 supply chain within the REpowerEU plan. This presents a knowledge gap in research-specific uncertainties and potential pathways for airport's future (sustainable) H_2 supply chains.

1.3. Collaborating with AIS

This study will be partly executed at AIS, AIS stands for *Aviation Instruction Services* and is based at Lelystad Airport (the Netherlands). AIS started as a sole proprietorship for flight lessons by Arend van der Meer. Over the recent 25 years, AIS has expanded to multiple subsidiaries (of which Mr. van der Meer is still the director): *AIS Airlines* is the airline subsidiary. It's known for offering commercial passenger flights, charter flights and specialized aviation training services. The airline operates a fleet of smaller, regional aircraft, typically serving shorter routes within Europe. Hereby distinguishing it from larger, international carriers. Additionally, *AIS Flight Academy* provides training for pilots, which can be immediately employed at AIS airlines once graduated. And *AIS Development* for innovation, research & development. The company mainly focuses on regional air transportation and pilot training.

Currently, the airline does not require an H_2 supply to operate and achieve its objectives. AIS wants to invest in sustainable aviation technologies, but the investments range in millions of euros and high uncertainty.

One project AIS development is working on is electrifying aircraft engines. Similar to ZeroAvia, they are Looking to replace the turboprops of their fleet (Jetstream 32s) with an all-electric variant. This requires a new energy carrier, which can be H_2 fuel cells. To this point (according to AIS), the practical aspects of using H_2 in aviation are too uncertain. The various forms of H_2 and the lack of infrastructure makes investing difficult. But if H_2 becomes the primary energy carrier for future aircraft, they will need a stable (and sustainable) H_2 supply. Therefore, AIS is interested and willing to provide resources for the research to seek H_2 pathways for their home base; Lelystad Airport.

1.4. Main Research Question

Concluding from the introduction and literature review from Chapter 2, there is a knowledge gap in the research for local airports to transition to H_2. Hence, the research question that this study wants to answer is:
What are sustainable supply chain pathways to transition a local fossil fuel-based airport to an H_2 airport?
Sustainability in the question refers to the practice of conducting business in a way that is environmentally responsible, socially equitable, and economically viable for the airport.

As support to the main research question, the following sub-questions are set up:

1. What are uncertainties in the H_2 supply chain for Lelystad Airport?
2. What indicators can be monitored to track the process for H_2 in aviation?
3. What can Lelystad Airport do to mitigate the H_2 transition uncertainties?

4. How can the results be generalised to other airports that seek to transition towards H_2 airports?

1.5. Relevance

This paper aims to identify the uncertainties and limitations of the H_2 supply chain to airports. This is relevant for the H_2 industry, as for leaders and decision-makers who make (sustainable) investments with less uncertainty. It is also relevant for society since the study contributes to climate change and sheds light on the transition to more sustainable aviation and the viability of H_2 in aviation. Lastly, the study is highly relevant to the Management of Technology (MOT) program, the key elements of the program are Technology, Innovation and Engineering Economics. This study will explore and understand H_2 from a supply chain perspective, and research the innovation towards for H_2 in aviation.

1.6. Report Structure

Following this introduction, this study begins with a literature review covering various aspects of H_2 and the H_2 supply chain for airports. This is followed by the research approach detailed in Chapter 3. Chapter 4 explores the internal dynamics of our case study's selected airport: Lelystad Airport. In Chapter 5, an evaluation of the external macro factors influencing the H_2 supply chain for airports is done, concluding with identifying key uncertain factors that shape the study's scenarios. These scenarios are elaborated in Chapter 6. Chapter 7 explores strategies Lelystad Airport can adopt to stay competitive while striving for sustainability, including indicators that could lead towards a specific scenario. The study ends with a discussion and conclusion in Chapter 8 to circle back and answer the main research question of the study.

To clarify the structure, a Research Flow Diagram (RFD) is created and is available in Appendix A. This RFD outlines the steps followed in the research approach described in Chapter 3.

2

Hydrogen Literature Review

H_2 supply chains have been studied over the recent years. Following up from the introduction, this study will specifically focus on the H_2 supply chain pathways for airports. The goal of the literature study is to get a deeper understanding of the latest knowledge in the H_2 industry and the supply chain in aviation. In addition, this literature study seeks to expand the knowledge gap and the study's relevance.

The main keywords for this literature are "H_2 supply chain" and "uncertainties of H_2". Furthermore, searches are done for: H_2 transition, H_2 forms, H_2 production, H_2 transportation, H_2 storage, sustainable aviation pathways, future H_2 outlook, and H_2 policy in Europe.

The two search engines used are Google and Google Scholar. During the study, papers from 2022 onwards are given priority to have the most recent information regarding the supply chain of H_2, but papers before 2022 were not denied when no post-2022 literature was found. Additionally, the study snowballed through the papers for more relevant literature.

In addition, the study also uses articles from government institutes and H_2 information pages. Adding on to know-how from informal interviews at conferences, seen in Appendix C. And observations from a company visit and panel discussions, seen in Appendix D.

2.1. Hydrogen Supply Chain

The supply chain considered in this study is via a sustainable production method, linked to a transportation method towards the airport where the H_2 is stored and fuelled to the aircraft. Degirmenci et al. and Hoezelen et al. have explored various supply chain pathways for H_2 [25, 41]. Figure 2.1 displays a combined and simplified overview of the potential pathways. These H_2 supply chain pathways are considered the base for this research, where the focus is on the aircraft being the end user, and seeking uncertainties in the path towards distribution.

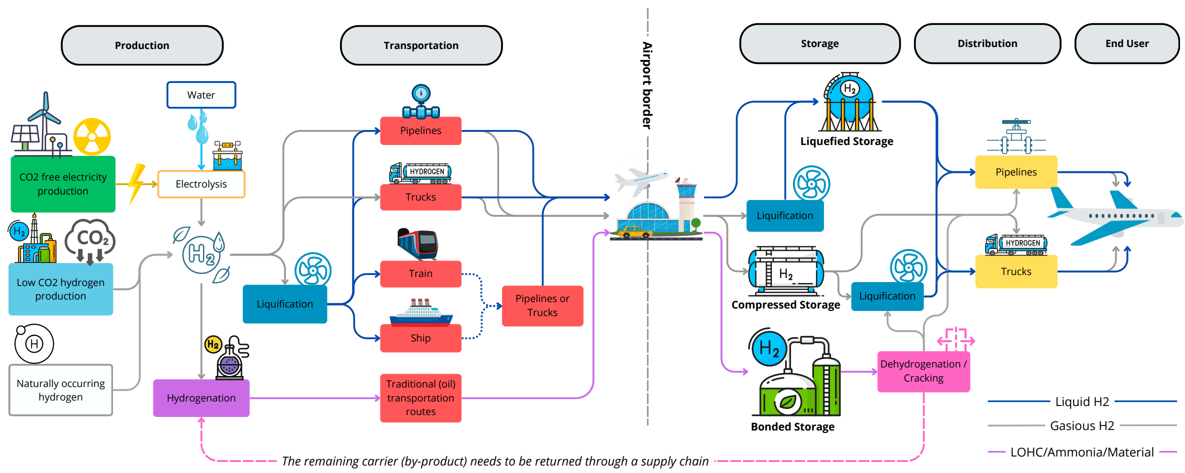

Figure 2.1: Off-site H_2 Production Supply Chain Options for Airports

One observation from both Degirmenci et al. and Hoezelen et al. is that the studies overlook the potential of using a Liquid Organic Hydrogen Carrier (LOHC), ammonia, or any material-bonded H_2 combinations as a means of transport and storage [1]. The benefit of using these combinations in the supply chain is that the H_2 can be transported via the 'traditional (oil) transportation routes'. These transport routes are set up separately they do not require a special (new) type of pipeline, truck, train or ship to transport. A new method of transportation is required for liquid hydrogen and gaseous hydrogen. More about the H_2 forms are discussed in Chapter 2.2.

It is recognised that H_2 could be used for other purposes at the airport. However, we assume that until airplanes are powered by H_2, there will be no supply and storage system at the airport. Hence, the challenge of first getting a H_2 supply chain for any aircraft is the main focus.

Furthermore, it is observed that there will be an insufficient supply of renewable energy (solar and/or wind) at the airport to electrolyse and fuel a plane (more on the production in Chapter 2.3). Therefore, this study assumes that H_2 will be generated elsewhere and transported to the airport. Consequently, this study will not examine the supply chains within the airport for internal H_2 generation.

Finally, this study emphasises that the storage of H_2 is not limited to big tanks at the airport. It acknowledges the option of variable storage through delivery trucks that stay at the airport as a form of storage option (more on H_2 storage in Chapter 2.5).

2.2. Hydrogen Forms

H_2 is the simplest and most abundant element in the universe [29]. The *H_2 form* means the natural state of the H_2, like gas, liquid or mixed with other elements/materials. Several forms of H_2 can be used for transport, storage and refuelling purposes. In Table 2.1, the properties of the H_2 forms considered in the H_2 supply chain are summarized.

Table 2.1: Hydrogen forms and characteristics [13, 57, 59].

Form	Storing pressure and temperature	Density	Energy density
Gaseous Hydrogen (GH_2)	$300 - 700 bar$ and under ambient temperature	42 kg/m^3 $(700 bar)$	$5,6$MJ/L
Liquid Hydrogen (LH_2)	$1,5 bar$ and below $-252,8$°C	71 kg/m^3	$6,4$MJ/L
LOHC-Toluene	Under ambient temperature and pressure, but dehydrogenating process at up to $5 bar$ and around 300°C	867 kg/m^3	$5,4$MJ/L
Ammonia	$10 bar$ and 25°C	$0,73$ kg/m^3	9MJ/L
Material-Bonded	Under ambient temperature and $1 - 20 bar$ pressures depending on material	Current technology: $120 - 400$ kg/m^3	4.95MJ/L

H_2 in pure form exists in two ways: Gaseous Hydrogen (GH_2) and Liquid Hydrogen (LH_2). Each with distinct properties and uses. GH_2 is a colourless and odourless gas at standard conditions, which is used in fuel cells. LH_2 is cooled to extremely low temperatures (below -252.8°C), turning it into a liquid [30]. The process to make LH_2 is called *Liquification* and is about 30-35% efficient [40]. All other forms of H_2 are mixtures or bindings to a different element or product.

A unique form of H_2 storage is LOHC. LOHC is a liquid organic molecule that can carry H_2 and can capture or release H_2 through hydrogenation and de-hydrogenation processes[1] [75]. However, using LOHC requires a reactor in the supply chain for hydrogenation and de-hydrogenation to obtain pure H_2. This process involves an endothermic reaction at 350ºC and 2 bar, where H_2-molecules are released [61]. When H_2 is bonded with Toluene, the most promising LOHC, only 6% of the weight is H_2, leading to significant by-products after de-hydrogenation (see conversation with Hydrogenious LOHC in Appendix C.1.7).

[1] Hydrogenation is a chemical reaction in which a molecule is made 'hydrogen-rich'. De-hydrogenation is a chemical reaction in which hydrogen is removed from a molecule [69].

Additionally, the concept of using ammonia as a carrier for H_2 delivery has similar characteristics to LOHC. Ammonia is easier to liquefy than standard H_2, making it simpler to store and transport [76, 59]. Furthermore, material-bonded technology for H_2 carriers is advancing [30]. This form uses a host material and can be released when required [65]. It has the potential to offer high volumetric energy densities and safety advantages since H_2 is chemically bound at lower pressures [14, 50].

This study acknowledges that each process of combining or releasing H_2 has its own terminology. However, for simplicity, all H_2 combining methods are referred to as 'hydrogenation' and all H_2 releasing methods as 'de-hydrogenation'.

LOHC, ammonia, and material bonded forms can be utilized under more conventional pressure and temperature conditions [57]. However, if future H_2 aircraft, like Airbus's new ZERO-e fleet [9], store pure GH_2 or LH_2, any H_2 bonded with any element requires de-hydrogenation before fueling. Any non-pure form then requires establishing a return supply chain to remain circular (if the airport has no use for the by-products). Although bonding could lower overall transportation and storage costs [59]. Choosing for a non-pure form must be a well-considered decision for the H_2 supply chain, since it requires additional infrastructure.

The forms can play a major role in the supply chain of H_2. Noting that some forms can be transported or stored more easily than others and that binding forms likely need a return supply chain. Today, uncertainty remains about which form is most beneficial for the supply chain of H_2 airports.

2.3. Hydrogen Production

Compared to kerosene, which is refined from extracted oil, H_2 at the present day is barely extracted from the earth [40]. Therefore, the majority of H_2 must be produced. Several production methods exist, categorized by a spectrum of colors. Currently, about 95% of H_2 is produced through carbon dioxide-emitting methods, primarily using natural gas and coal. These methods are known as *black*, *grey*, or *brown* H_2 [71, 86]. While these methods can generate substantial amounts of H_2, they also emit carbon dioxide (CO_2), lacking sustainability. Alternative methods, such as electrolysis[2], can produce H_2 sustainably without emitting CO_2, provided the electricity used comes from a carbon-free source.

The most sustainable H_2 is *green* H_2. This method uses clean energy sources (e.g. solar and wind) either making H_2 via electrolysis or directly.

Pink H_2 is also produced using electrolysers, but the energy for this process comes from a nuclear-powered source, which is CO_2-free, but critics argue it is not 'renewable' because the nuclear waste requires a long time to decay.

Additionally, *blue* H_2 is referred to methods that do emit CO_2 as a by-product, but make use of carbon capture and storage (CCS) to trap and store the carbon.

Recently, it has become evident that naturally occurring H_2, extracted from the earth and known as *white* or sometimes *gold* H_2 [40, 37, 86] also exists. Although it is still early days for natural H_2, scientists do not yet fully understand how it forms, migrates, or accumulates in a commercially exploitable manner [40]. Ultimately, naturally occurring H_2 could have significant impact for the H_2 transition, because, as Prof. G. Eitelberg puts it, "no fuel is cheap when you have to make it yourself."

2.4. Hydrogen Transportation

When the H_2 is produced or extracted, it needs to be transported. Transporting H_2 is not as easy as transporting water or natural gas due to its physical and chemical properties (see Table 2.1). It is important to remember that the overarching goal of the supply chain is not merely to supply H_2. Rather, it's about the transportation of renewable energy from areas where it can be produced at low cost to places where the demand is highest. According to the European H_2 Backbone, it is 2-4 times more cost-effective to transport H_2 via a pipe network, rather than transport electricity and produce the H_2 locally (over a 1000km range) [81].
Still, transporting H_2 requires high pressures or very low temperatures to liquefy, which increases the

[2]Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyzer. Electrolyzers can range in size and capacity and are currently around 70% efficient [43].

energy needed for transportation. Additionally, H_2 can leak through tiny openings and can make metals brittle. Hereby requiring special materials and technologies for safe handling and transport. Therefore, moving H_2 to the airport presents a technical difficulty.

More recently, the International Renewable Energy Agency (IRENA) published three reports on 'GLOBAL HYDROGEN TRADE TO MEET THE 1.5°C CLIMATE GOAL', part one: Trade Outlook for 2050 and Way Forward [2]; part two: Technology Review of Hydrogen Carriers [1]; and part three: Green Hydrogen Cost and Potential [3]. Specifically, part two discusses the most appealing methods for transporting H_2, which introduces different H_2 forms under which H_2 can be transported (short and long distance). The most prominent include ammonia, liquid H_2, and LOHC, which are also discussed in section 2.2. The report mentions that research into the H_2 form will ultimately lead towards a standard, but currently, this remains uncertain.

In addition, the report states that H_2 pipelines offer an alternative for large-scale distribution, particularly in areas with an established natural gas infrastructure [1]. This component could hold significant interest for Lelystad Airport due to the existing gas infrastructure. Although this approach may lower the costs associated with H_2 transportation, uncertainties still remain regarding how H_2 affects infrastructure. Including the integrity of pipeline assets, corrosion, and maintenance requirements [55]. One study suggests that ammonia and (new or existing) pipelines are the best options for initiating the global trade of H_2[16]. However, a single study should not dictate the final decision and further research is needed to explore the options shown in Figure 2.1. Additionally, there is currently no trade system for renewable H_2, highlighting the need for appropriate decisions at the international level [16].

2.5. Hydrogen Storage

As discussed in previous chapters, the form of H_2 used in the supply chain determines transportation requirements and affects the storage infrastructure. Storing pure H_2 necessitates a more complex facility compared to LOHC, ammonia or metal hybrids. For instance, storing gaseous GH_2 typically requires high-pressure tanks (350–700 bar). Storing LH_2 demands cryogenic temperatures. The difference between LH_2 and GH_2 is the storage volume. GH_2 takes up around 2.7 times the volume (when stored at 300 bar) in comparison to LH_2, due to its much lower volumetric energy density [30]. LH_2 storage also has the advantage of being a more mature technology, as it has been implemented at larger scales (hundreds of tonnes of storage per tank) stemming back to 1960s by NASA [24]. Comparing that to LOHC (LOHC-Toluene is stored around 1.5bar, under ambient temperature), Ammonia (stored around 10 bar, $25°$C) and metal hybrids (Under ambient temperature and $1-20bar$ pressures) - *See table 2.1*. Using LOHC, ammonia or metal hybrids can be more advantageous if the energy loss from (de-)hydrogenation, transporting, and storing is more cost-effective than constructing complex infrastructure for cryogenic-temperature (for LH_2) or high-pressure (for GH_2) storage and transport.

Lastly, multiple studies [22, 47] suggest that during the transition to H_2, airports without a H_2 pipeline supply could receive H_2 via trucks. These trucks would also store the H_2. This allows the aircraft to be fueled directly without the need for additional on-site storage infrastructure. As demand increases, the airport could then consider investing in pipeline infrastructure and storage facilities or keep operating via trucks. Today it is unknown how much H_2 is required for a future H_2 aircraft. Since the required amount depends on the H_2 form, the storing capacity, flight efficiency, and flight distance of the H_2 aircraft.

2.6. Hydrogen Policy

Regarding policy plans for the supply chain of (green) H_2, REpowerEU aims to produce and import 10 million tons of renewable H_2 by 2030, with 5% designated for transport [33]. The plan also includes preparing infrastructure for 20 million tons of H_2 by 2030, though specific details are not provided. Consequently, 5% of 20 million tons translates to 1 million tons of H_2 for the transport sector.

The Netherlands has plans to establish a national H_2 network by 2030, connecting the supply and demand of industrial clusters. This network will primarily utilize existing infrastructure, supplemented by new infrastructure still to be built [45, 36]. Currently, this network does not extend to Lelystad Airport, and there is no indication whether it will eventually serve airports. Nevertheless, this initiative represents a significant step towards a H_2 supply chain network.

2.7. Concluding the Literature Review

The literature review of the H_2 supply chain for airports reveals several key observations and insights. Existing studies by Degirmenci et al. and Hoezelen et al. provide a foundational overview of potential H_2 supply chain pathways, though they often overlook the potential of using LOHC or ammonia as transport and storage mediums. These alternatives, supported by IRENA, offer advantages due to their compatibility with traditional oil transportation routes and the reduced need for specialized infrastructure.

H_2 can be transported and stored in various forms, each with unique advantages and challenges. GH_2 and LH_2 are the primary pure forms, while LOHC and ammonia present viable options due to easier storage and transportation. Recent reports by IRENA emphasize the potential of ammonia and existing pipelines for cost-effective H_2 transport, relevant for airports like Lelystad with existing gas infrastructure. However, these require de-hydrogenation before use in aircraft, and a return supply chain for the chosen H_2 carrier, adding complexity to the total supply chain. The production of H_2, especially green H_2 via electrolysis, is critical for sustainability, yet current production methods are predominantly CO2-emitting.

Storage infrastructure must also adapt to the form of H_2 used. While LH_2 storage is more mature, LOHC and ammonia could be more cost-effective if the energy losses and costs of (de-)hydrogenation are managed well. Airports might initially rely on truck deliveries for H_2 supply, transitioning to more permanent infrastructure as demand grows.

Policy initiatives, such as those outlined by REpowerEU and the Netherlands, aim to establish substantial H_2 production and infrastructure by 2030. These efforts, though not explicitly focused on airports, are steps towards integrating H_2 into the transport sector. Airbus's goal of operational H_2 aircraft by 2035 aligns with these policy timelines, indicating a significant shift in aviation fuel sources.

This literature study notes that the H_2 supply chain for airports involves multiple pathways, forms, and logistical considerations. The transition to H_2 fuel in aviation will require coordinated efforts in production, transportation, storage, and policy support to overcome existing uncertainties and infrastructure challenges. During the study, no other study regarding supply chain uncertainties for a sustainable H_2 transition within aviation were found. Therefore, this study will research these uncertainties to seek pathways for fossil fuel airports to mitigate towards a sustainable H_2 supply chain.

3
Research Approach

3.1. Research Method

Because of many uncertainties and the long-term aspect of the transition, the research method for this study selected is a single case study based on the Scenario-Axes Technique. The Scenario-Axes Technique was formalized during the 1990s by the consulting firm Global Business Network (GBN), and later taken by Alun Rhydderch, who explained its use tool for future scenario building. This (qualitative) method can be applied to any situation calling for scenarios but is often used for testing medium-to-long-term policy, because it ensures that policy direction is robust within a range of environments [64]. The approach works by first seeking the two most critical and/or uncertain factors related to the subject being analysed, which will be perceived as the *backbone* of the study and are called the *Critical Uncertainties*. Then the critical uncertainties are positioned on the axes to construct a 2x2 matrix, thereby creating a framework that serves as the foundation for developing potential future scenarios. Figure 3.1 presents a simple sample of the 2x2 matrix.

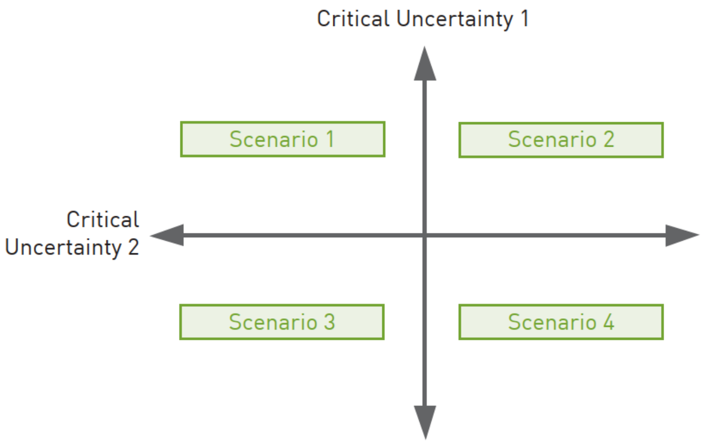

Figure 3.1: Scenario Matrix by Alun Rhydderch [64]

The four scenarios undergo analysis and assessment, leading to the formation of four distinct pathways for the study. Information will be gathered via literature studies, observations and (in)formal interviews.

This method is chosen because the *sustainable supply chain pathways to transition to H_2 airports* for this research is shows significant uncertainty. Via the 2x2 axis method, the study will set out scenarios that can make several pathways for the future, backed by critical factors. Hereby understanding how different factors combined, create different outcomes for the supply chain transition to sustainable H_2 airports. In addition, the H_2 transition is slowly starting and would take 10-20 years to mature if successful, making this medium-to-long-term in the context of aviation. This makes the scenario axis applicable to the study.

The goal of constructing scenarios is to make Lelystad Airport and AIS, but also scientists, leaders, and decision-makers aware of the numerous uncontrollable factors that influence the H_2 transition for aviation. This process highlights the importance of flexibility and adaptability. By exploring different potential scenarios, this study can identify which pathways are plausible based on critical uncertainties and potential indicators. These insights are valuable for formulating effective decision-making that can support the H_2 transition strategy.

3.2. Steps of the Research Method

The Scenario-Axes Technique is explained in detail by Alun Rhydderch in his paper *Scenario Building: The 2x2 Matrix Technique* [64]. In his study, the steps are mainly formulated for organisations and he encourages working in groups (although not obligated). Since this study is primarily conducted by one person, the steps from Alun Rhydderch have been adapted and optimized for execution by a single researcher, by including expert opinions and removing group sessions. The re-formalised steps are shown below. Additionally, Appendix A shows a Research Flow Diagram, which includes the steps of the Scenario-Axes Technique.

Step 1: Identify the Focal Issue or Decision
The first phase is designed for setup purposes. It is focused on defining the problem and the knowledge gap by researching existing literature on Google Scholar and Google, including snowballing within papers. This results in the main research question: *What are sustainable supply chain pathways to transition a local fossil fuel-based airport to an H_2 airport?* Followed by sub-questions. This lays the groundwork for scenario development and the contents can be read in Chapter 1 and 2.

Step 2: Observing the Internal Dynamics
Once the key questions are set up, the goal is to research the key *internal dynamics* influencing the study. This step assists in positioning the problem within the context of Lelystad Airport, and creates a deeper understanding of the history and vision of the airport. To gather the internal dynamics, literature on Lelystad Airport is researched on Google, supported by an interview with a manager of Lelystad Airport (see Appendix B). This step can be read in Chapter 4.

Step 3: Identifying the external Driving Forces
To identify the driving forces in the overall environment, which influences the internal factors discussed in step 2, the *Outside-In Thinking* process is executed. This procedure aims to broaden the perspective and examine the external context surrounding the subject of study (the macro environment). Providing a comprehensive overview of the shift towards sustainable aviation and the significance of H_2. While an initial H_2 supply chain exploration began in the literature review outlined in Chapter 2, this step will do a further in-depth investigation of the H_2 aviation macro environment. This is done via a 'STEEP' analysis[1], which looks at Social, Technological, Economic, Environmental and Political perspectives.

Data for this step is collected through literature reviews using Google and Google Scholar, including snowballing from relevant papers. This step is further supported by several informal interviews and observations conducted at two different H_2-related events. The approach and results from these events are detailed in Appendix C and D.

The outcome is an understanding of numerous factors within the external environment of the study. Each factor could influence the long-term perspective of the supply chain of H_2 and sustainable aviation. This part also answers the first sub-question: *What are uncertainties in the H_2 supply chain for Lelystad Airport?*

Step 4: Ranking the Driving Forces by Importance and Uncertainty
The next step is to rank the factors from step 3. With the help of the STEEP analysis and conference visit summaries. The factors are evaluated one by one by the degree of importance and uncertainty towards the success of the H_2 supply chain. This assessment is done through desk research from gathered data, including informal interviews for verification of the results. Once evaluated, the factors are placed on a 'critical uncertainty matrix'. Chapter 5.1 and 5.2 elaborate this step in more detail.

[1] For a more detailed explanation regarding STEEP, visit https://www.infodesk.com/blog/what-is-steep-analysis-5-factors-to-predict-the-future

Step 5: Selecting Scenario Logic
Scenario logic begins with the critical uncertainty matrix from the previous step. The top right corner (highest importance and uncertainty) is referred to as the 'critical uncertainty zone'. The highest-scoring factors are referred to as *critical uncertainties*. Then, the approach selects the two highest-scoring factors from this zone to place on a 2x2 scenario axis. Important is that the drivers of change do not come from the same STEEP category. This is done to avoid interdependence in the scenarios. This step is shown in Chapter 5.3.

Step 6: Fleshing-Out the Scenarios
Step 6 involves crafting a story that aligns with the logic of the designated scenario space. It begins with highlighting the most noticeable, significant, or standout features of each scenario space. Utilising key change drivers identified in the STEEP analysis for support. Each scenario explores potential outcomes unique to its space, establishing the foundation of the narrative. Following this, the narrative investigates the dynamics and interactions among the drivers and ends with the development of a story that leads to the scenario's conclusion. Scenarios strive to be both memorable and believable. The only constraints imposed are: Internal consistency, relevance to the H_2 supply chain, and a connection (either direct or indirect) to the change drivers [64]. In this step, desk research from the results of the previous steps is done. This step is shown in Chapter 6.

Step 7: Scenario Behaviour
This step explores the implications of the scenarios, both generally and more in detail, considering the objectives and decisions as proposed by the European Commission and REPowerEU [33, 21]. The main objective is to examine the decision, plan or strategy in each scenario for Lelystad Airport. This step tries to make a robust strategy so that the outcome can help to envision how Lelystad Airport can behave in each scenario. In addition, Lelystad Airport and AIS' objectives and decisions are to be taken into consideration. This step is solely desk research from previous steps and can be read in Chapter 7.1.

Step 8: Selecting the Leading Indicators of Change
Throughout the scenarios, four pathways emerge, showing how the current situation can progress towards an outcome. This step identifies signs that suggest if a chosen path is followed, it has a probability of leading towards an intended destination. This means that in addition to describing the endpoint of the scenario (as done in step 7), explaining how external changes can impact the direction of sustainable H_2-transition. These elements of change are captured in a set of indicators, which can lead towards the direction of trends. After this final step, the answer the third sub-question: *What can Lelystad Airport do to mitigate the H_2 transition uncertainties?* is given. This step is elaborated in Chapter 7.2.

After the scenario analysis case study, we will conduct a theoretical generalisation to expand the study beyond Lelystad Airport. We seek to interview other Dutch airports and see how they view the scenario analysis. This will answer the fourth sub question: *How can the results be generalised to other airports that seek to transition towards H_2 airports?*.

Finally, the scenarios analysed and the outcome of the study will answer the main research question *What are sustainable supply chain pathways to transition a local fossil fuel-based airport to an H_2 airport?* By combining the findings of the scenarios and generalisation towards a concluding answer.

One additional comment for the Scenario Axis Technique, it does present shortcomings: It does not explicitly consider the interaction between a large number of variables, only the selected and pre-defined ones. Furthermore, it focuses on key uncertainties, therefore it does not integrate stable trends and gradual developments [64].

4 Dynamics of Lelystad Airport

This chapter corresponds to step 2 of the research method and explores the internal dynamics of Lelystad Airport. The analysis contextualizes the problem within the airport's environment. This chapter discusses the history of Lelystad Airport, the delays in its opening to commercial flights, and outlines the airport's vision.

4.1. About Lelystad Airport

Lelystad Airport, located near Flevoland, the Netherlands, has a history that dates to 1973 when it was established. Originally, the airport was used primarily for general aviation and flight training, but in 1993 the airport became part of Royal Schiphol Group. Over the years, it has undergone several expansions and renovations to accommodate growing traffic and to prepare for commercial airline services. The airport's development for commercial flights has been a subject of considerable debate and planning. There were plans to expand Lelystad Airport to relieve Amsterdam's Schiphol Airport, one of Europe's busiest airports, by redirecting some of the low-cost and holiday flights to Lelystad [11]. This expansion was intended to include the lengthening of the runway and the construction of new passenger facilities.

4.2. Commercial Flights

In 2019 the airport finished all necessary upgrades to open for commercial flights, yet the airport was not granted an environmental license. This is due to the Netherlands needing to reduce its carbon and nitrogen emissions. The Dutch government decided to postpone the decision multiple times. At the beginning of 2024, the Dutch government voted 79-71 to accept the motion of Teunissen (Nr. 1348) "Considering that opening Lelystad Airport is undesirable for the climate, public health, and due to the scarce nitrogen space; (...)" (translated from Dutch) [15, 70]. Although the motion has been accepted to not open Lelystad Airport, the motion does not mean that it will never open the Airport for commercial flights [15].

History shows the development of Lelystad Airport and debates around its opening for commercial flights have been influenced by various factors, ranging from environmental concerns to political decision-making. Below is a summary of key moments and reasons [11]:

2014-2015: Expansion Plans

- **June 2014:** The government took a provisional airport decision for expansion, which required advice from the Council of State.
- **March 2015:** Official approval for the expansion of Lelystad Airport was given, with plans to take over approximately 45,000 flight movements from Schiphol by around 2033.

2017-2018: Opposition and Challenges

- **January 2017:** The Council of State decided that expansion was possible without direct danger from birds, despite concerns from Bird Protection (the first delay reason got rejected).
- **2017-2018**: Increasing unrest among residents and politicians over expected noise pollution and

environmental impact. Issues with flight routes and low flying until the airspace reorganization in 2023 raised concerns.

Post 2018: Environmental Objections
Three main reasons why Lelystad Airport has not opened for commercial flights include concerns about climate impact, nitrogen deposition, and noise pollution due to low flying routes:

1. **Climate Impact:** Additional CO2 emissions from more flight movements contradict the Paris Agreement targets.
2. **Nitrogen Deposition:** Harmful to nearby natural areas such as the Veluwe.
3. **Low Flying Routes:** Cause noise pollution and health effects in a large area.

Lelystad Airport did not want to comment on questions regarding the opening for commercial flights.

4.3. Future Vision

The main reason for not opening Lelystad airport has changed over time, with mostly climate reasons. Lelystad Airport's website states it is "prone to working on a sustainable airport, with the ambition to become the most sustainable airport and by having zero-emission and zero-waste for their operations by 2030" (translated from Dutch) [80], potentially working towards a possibility to open commercial flights. In an interview with Lelystad Airport (see Appendix B.1 for a transcript), they said that most of their buildings run solely on green electricity, and in the cases they use gas, green biogas is used. Consequently mentioning that the airport is one of the most environmentally friendly airports in the Netherlands.
Looking forward, Lelystad Airport has its focus on three pillars: 1) 2023 sustainable roadmap; 2) Electrical flying; and 3) H_2 aviation [80]. For electrical flying, the airport currently has an aircraft charging station, since some small plane electrical flying is being tested on the airport. H_2, on the other hand, has no fuelling possibility as of now. On the website, Lelystad Airport gives the following comment: "Lelystad Airport aims to play a significant role in the production, transport, storage, conversion, and application of green H_2. (..) The ambition is to establish a H_2 supply network that, in the future, can provide airplanes with clean fuel." (translated from Dutch) [80]. When asking Lelystad Airport about the airports' H_2 plans, it was said that: "*The idea is to gradually work towards a small-scale application in the coming years that could work, and if there is demand from the market as the technology around H_2 flying starts to mature, we can anticipate that.*" Means that Lelystad Airport is adopting a wait-and-see approach regarding H_2 technology, opting not to actively promote or push for a change, but rather to observe the unfolding developments and technology and proceed accordingly. Later in the interview, the representative mentioned: "*It costs a lot of money and energy to start making progress in that (hydrogen) area, and that is exactly why we are also seeking international collaboration, since a lot of knowledge is needed.*" Recognizing the uncertainties and high costs associated with being a pioneer in the transition.

In the interview, it also became clear that producing H_2 at Lelystad Airport is not within its immediate goals. However, the airport seeks (international) collaboration and is in favour of supporting the local production of green H_2 in the surrounding region. According to the interviewee, the airport's strategy hinges on the progress of the Flevoland Hydrogen Valley (FLHY) project [51]. This project has a focus on establishing H_2 production and transportation within Flevoland. The airport is open to integrating these developments into its infrastructure once H_2 applications at the airport become a reality.

Lelystad Airport is navigating the complex landscape where plans and regulations for the aviation industry are either not yet established or remain restrictive. Despite these challenges, Lelystad Airport is engaged in a collaborative effort to support the H_2 transition for aviation.

5

Driving Forces in the H_2 Supply Chain of Aviation

Now that the internal dynamics of Lelystad Airport have been formulated, the next step aims to examine a broader perspective of the macro environment regarding the supply chain of H_2 for the airport. The approach examines the macro environment is done via a 'STEEP analysis'. This chapter presents steps 4 and 5 of the research approach.

Figure 5.1: Steep Analysis

5.1. STEEP Analysis

STEEP is short for Social, Technological, Economic, Environmental and Political perspectives. For this study, a STEEP analysis is chosen because a broader macro environment is to be analysed. Each of these dimensions is examined and interpreted in the external factors that could impact the operations, strategic decisions, and future opportunities or threats regarding the H_2 supply chain for the airport. This analysis will result in a holistic view of the external factors affecting H_2 supply chain.

5.1.1. Social Factors

Social 1: **Public Acceptance**, For the public to accept a new technological change (like H_2 in aviation), the public will likely base the acceptance on a cost/benefit relation [48]. The production, transport and storage (e.g. H_2 production installations in the neighbourhood) should not 'hinder' the public as much as the public is receiving in return (a cleaner environment). If these end up being misaligned, resistance can occur which can have negative influences on the transition.

Similarly, flight ticket prices can be an acceptance change driver for consumers. It is likely to see a significant price increase for H_2 flights, especially at the beginning of the transition. If the public accepts this (or must accept it due to policy change), it can bring a shift in the overall flight demand. It is also noteworthy that younger generations (Millennials and Gen-Z) show greater interest towards sustainability and adapt more quickly to a 'sustainable lifestyle,' including financial aspects [83]. These younger groups have the potential to propel society towards more sustainable lifestyles [84]. This trend suggests that, in the long-term perspective of H_2 roll-out, such generational shifts could favourably influence public acceptance. More on H_2 prices can be read in economic drivers in section 5.1.3.

Social 2: **Scales of (consumer) demand**. Demand is a crucial component to direct the trajectory towards the right economic venues [27]. Where the transition to H_2 energy is a gradual process of demand, rather than an immediate shift [41]. Depending on other industries and the adaptations of H_2 (and/or the adaption of SAF alternatives), the future demand can vary. Timely deployment of infrastructure across the whole supply chain is expected to be needed to meet clean H_2 demand [39]. It is to be noted that the H_2 industry is beyond aviation. Overall advances in technology, coupled with the growing adoption of H_2-powered technologies within the global economy, all

have the potential to significantly boost demand. This, in turn, could lead to more investments and reduced costs through the benefits of economies of scale. In the end, it can be argued that the new investments leading to new (cheaper) technology, which decreases the costs of H_2, can be seen as the 'chicken and egg' situation. This is also what Lelystad Airport described when asking about the H_2 plans for the airport: "I find that very difficult to determine, and it's always a bit of a chicken-and-egg situation." Demand will increase once cheaper technology is available and high demand drives investments.
Following up with Policy implementation and plans (like REPowerEU [33]), these plans can perceive as less uncertainty, which can increase investment and increase supply, leading to a demand-pull situation that also affects the demand. More about demand-pull in Economical Factor 2.
When talking to a representative at HyGear (see Appendix D.1), it was mentioned that there should be a distribution network for sustainable H_2 to meet supply and demand on an international scale. Especially for green H_2. For them, this is uncertain how the future will unfold and if H_2 will break through its innovation phase.

Returning to the topic of airports, the demand for H_2 is also influenced by the availability of H_2 aircraft. The greater the number of operational H_2 aircraft, the higher the demand for H_2 to maintain their flight operations.

Social 3: **Workforce Skills.** Any production, infrastructure development, maintenance and safety aspects of H_2 require workers with specialised knowledge. Since 2014, incentives for certification have started. Currently, the European Commission is collaborating with CertifHy to accelerate the certification of H_2 whilst taking Europe-wide green and low carbon H_2 certification to the next level [60]. Certification is not avoidable, but it is essential to have a workforce to apply for these certifications. Already back in 2021, the Dutch workforce had an estimated a 20.000 professional deficit for the work required to balance climate change, like placing heat pumps and windmills [52]. A new technology like H_2 that is launched on a larger scale requires an increased workforce. In the Netherlands, there is a 'national H_2 workforce program' for 2022-2025. The work plan emphasizes the entire H_2 value chain, covering necessary activities, investments, coordination issues, coherence between various activities, and monitoring [28]. However, there appears to be limited information available on the H_2 workforce data and how the plan is evolving.

5.1.2. Technological Factors

Tech. 1: **Technological innovations** could significantly influence the future role of H_2 and may be needed to ensure the uptake of H_2 within aviation [39]. Innovative approaches that make the production, transportation, or storage more efficient and/or faster, can result in cheaper and faster adoption of H_2. Economies of scale (in the H_2 economy) can (and are expected to) decrease the cost of sustainable H_2 production in the long run [49]. See economic factors in Section 5.1.3.
Innovation within the supply chain of H_2 can advance significantly even before the launch of an H_2 aircraft, but this is rather uncertain how this will evolve according to Royal Haskoning DHV, Petroac and Air Products. See Hydrogen Aircraft Adaptation Speed in Tech. 3. Lelystad Airport mentions that technological innovations heavily influence Lelystad Airport's transition and that they wait for the maturation of necessary technologies (see Appendix B). Yet, when looking at the available technologies to set up the supply chain, they all exist already (clean energy, electrolysers, purifiers, transportation trucks, storage), suggesting 'innovation' is not mandatory to transition. In a talk with Fluor (see Appendix C.2.1), they mention that while the technology is already available, the investments needed for scaling up are still lagging behind.

Tech. 2: **Hydrogen infrastructure integration**. The different availability and access to low-cost, green H_2, might influence the design of airline networks [41]. H_2 can be delivered to the airport through pipelines, ships, trucks or trains [85]. Mirroring the distribution methods used for traditional fuel. All airports have different availability for H_2 deliveries as noted in the Literature Review in Chapter 2, so infrastructure should be considered per geographic location.
Pure H_2 is the smallest element on earth [29] and can arrive at the airport in liquid-, gaseous- or combined form. The latter includes converting H_2 with other elements such as those existing for ammonia or natural gas. LOHC are also showing promise in some regions around the world for transporting H_2 with other molecules [47]. These could capitalise on well-established supply

chains and infrastructure, which could make these forms cheaper to transport (see Chapter 2.2). Looking beyond aviation, the H_2 adaptation for other sectors can benefit the airport's supply chain. Hynetwork, a subsidiary of Gasunie, is planning a H_2 network across the Netherlands, from Rotterdam to the North Sea Canal Area and up to Northern Netherlands [45]. Airports along this route could gain from convenient access to H_2, which would lower infrastructure costs and potentially boost demand in those easily accessible areas.
As of now, the Dutch pipeline infrastructure scheduled up to 2050, does not pass close by Lelystad Airport [46]. This means that flights on Lelystad Airport will need (local) truck transport if it wishes to supply H_2 to planes until 2050, unless the airport invests in H_2 infrastructure themselves. One benefit of supplying by trucks is the ability to store and fuel planes in the same delivery trucks, which would eliminate the need for airport storage infrastructure. This supply method has low upfront investment costs and high modularity [22]. When asking Gasunie about their plans for airport supply, they do not think the infrastructure will become a limiting factor in the transition towards H_2 because the infrastructure will be built wherever H_2 is demanded to a significance that it is worth building an infrastructure for.

Tech. 3: **Hydrogen Aircraft Adaptation Speed.** Before the aviation industry can switch to H_2, H_2 aircraft need to be ready and operational. Airbus schedules to have H_2 aircraft ready by 2035 [10]. The Hydrogen Aircraft Powertrain and Storage System (HAPSS), set up by Unified International and InnovationQuarter with 17 companies, aims to have the first H_2 commercial flight between Amsterdam and London by 2028 [77, 82]. Even sooner is ZeroAvia, with the development of H_2-electric power-trains, planning to have a 9-19 seat commercial offering by 2025 and 40-80 seater aircraft by 2027 [88, 87].
As of today it is not made public what the price of a new H_2 aircraft will be and if it will be profitable. But as the adaptation increases and airports get more demand for H_2, the logical outcome is that the price of the supply of H_2 will decrease.
Similarly, it is uncertain when airlines will adapt to fly on H_2. In an article of the World Economic Forum, EasyJet states it aims to reach net zero by 2050. And from the article it is noticed that for short-haul airlines, H_2 appears to be the best solution to de-carbonise [42]. Truly sustainable aviation requires moving from combustion engines to electric and H_2-electric propulsion [42]. Transforming aviation to H_2 will be a challenging and lengthy process, likely spanning decades, yet it should be done both efficiently and effectively to reach climate goals.

Tech. 4: **Hydrogen Technology Safety and Security.** As mentioned by Hygreen Energy, Petrofac and Air Products, safety and security seem rather uncertain at the moment. Yet safety (and the standards) evolve with new technologies. Since H_2 is recently getting significant traction, safety knowledge is limited and must be learned and/or developed. Companies working on cutting-edge and new technologies like H_2 must commit to the safe use and handling of the technology. To comply, or at least practice safety with the development of H_2, companies have open portals available like H2tools[1]. This portal is set up to support implementation of the practices and procedures to ensure the safety of H_2. It also has a page dedicated to 'Best Practices [53]' and 'Lessons learned [54]'.

5.1.3. Economical Factors

Econ. 1: **Cost Competitiveness** of H_2 for airports plays a significant role in their transition. H_2 does not only compete with Sustainable Aviation Fuel (SAF) in terms of cost, but also faces competition within its own production methods. For instance, the cost of solar-powered H_2 production systems is slightly under \$10 per kg, while coal gasification and steam reforming methods can produce H_2 at costs below \$3.05 per kg [7]. The International Council for Clean Transport (ICCT) is expecting the price of (green) $H_2$to decrease over the upcoming years due to a decrease in electricity grid prices [18]. The ICCT also assessed multiple studies of median H_2 prices between 2020-2050 in Europe and the USA, based on three scenarios. Where the median H_2 price in Europe from grid-connected electricity can decrease from \$13.11/kg to \$7.69/kg; the minimum price could decrease from \$4.83/kg to \$3.21/kg. A direct connection to a renewable electricity generator could decrease the median price from \$19.23/kg to \$10.02/kg; with a minimum price decrease of \$4.06/kg to \$2.23/kg. And curtailed electricity for H_2 production could decrease from \$10.85/kg

[1] See `http://www.h2tools.org`

to \$6.08/kg; with a minimum price decrease of \$5.97/kg to \$4.67/kg [18].

The price of H_2 (produced using renewable electricity) also varies greatly based on geographic location, with significantly lower production costs in some favourable areas [18]. While the aim is to prioritise the use of H_2 produced sustainably during this transition, the intense competition over prices means that systems based on renewable energy should become more cost-effective. The feasibility and manner of this cost reduction are part of the market dynamics. The change will probably necessitate a coordinated effort involving industry, investors, and national- & local governments [5]. Additionally, CO_2 prices (or sustainable TAX credits) and subsidies can help to facilitate the decarbonisation of existing H_2 demand, as the switch will likely not be attractive based on economics alone [39].

Econ. 2: **Investment and Funding**. Investing in H_2 today signifies a long-term investment with high uncertainties. Although government policy can reduce market uncertainties (see political factors), the technical risks can still hinder investments. Yet investments and funding in the overall H_2 industry are essential to support and stimulate the H_2 transition. The 2021 H_2 Insights Updates from the Hydrogen Council and McKinsey & Company highlight accelerated H_2 deployment; Showing 131 new large-scale projects announced globally since February 2021, totaling 359 projects, and an estimated \$500 billion investment by 2030 [68] (in comparison, the GPD of the Netherlands was little over \$1009 billion in 2022 [38]). This indicates a significant increase in investment and funding, driven by more countries committing to de-carbonisation targets and the announcement of large-scale clean H_2 projects.

In an informal interview with Fluor, a company experienced in multiple H_2 installations (see Appendix C.2.1), Fluor expressed concern that investments are not gaining sufficient traction. The perspective is that although the technology to build H_2 infrastructure is fully developed, investments are lagging due to the perceived technology risks and uncertain prospects.

The investment and innovation loop can be related to the 'Kaldor-Verdoorn Effect'. This effect is an economic principle that explains the relationship between the growth of output and growth of productivity [78]. As the H_2 transition can be referred to as an 'H_2 economy'. One of the primary mechanisms behind this effect is economies of scale. As production increases, the average cost per unit of output decreases, leading to higher productivity. Fostering conditions that support higher output growth allows economies to achieve sustained increases in productivity. In turn, leading to higher standards and economic development.

In addition to the Kaldor-Verdoorn effect, the economic principle of 'demand-pull innovation,' as formulated by Jacob Schmookler, is also relevant. This principle suggests that increased demand drives greater innovation activity. In a growing market, it becomes financially easier and less risky to introduce new products or adjust production processes, further enhancing innovation [66].

Followed from these principles, in Figure 5.2 below, a simplified graphical representation of the effect of Kaldor-Verdoorn and Demand-Pull innovation is shown.

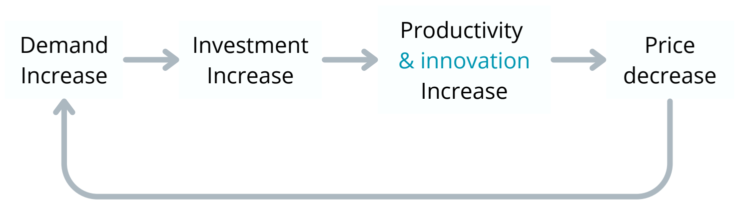

Figure 5.2: Kaldor-Verdoorn and Demand-Pull effect [78, 66]

5.1.4. Environmental Factor

Env. 1: Availability Clean Hydrogen. Most H_2 used today is not produced via a sustainable (clean) method. The cleanness of any H_2 is determined by the cleanness of the production pathway. Therefore, a guarantee of H_2 origin is important in assessing any H_2 energy cleanness [23]. In Chapter 2.3 it shows that about 95% of production is via CO_2 emitting methods (mostly gas and coal). Yet it is recognized that the H_2 transition in aviation is meant to be environmentally friendly. Meaning new H_2 transition industries should have H_2 from a clean source, preferably clean energy. Production of H_2 via CO_2-emitting methods is considered sustainable if the CO_2 is captured, called *blue* H_2. Other non-CO_2 production methods use electricity. Theses are considered *green* H_2 (if the energy source is renewable energy) and *purple* (if the energy source is nuclear energy). Mckinsey and company define the entire net-zero aviation dependent on the availability of renewable energy, with an optimistic scenario for 2050 CO_2eq. Where the impact for H_2 significantly increases when renewable electricity becomes more widely available [31]. The availability of clean H_2 was also mentioned by Fabrum, Royal Haskoning and Gasunie, who see this as uncertain for the future.

Similarly, White H_2 is referred to as the natural occurring H_2 within the earth. More recently, by coincidence, a big discovery in Lorraine, France, shows that a significant amount of H_2 is stored at approximately 1250 meters deep. the Lorraine deposit could contain up to 46 million tonnes of white H_2 which is to say more than half of the world's current annual production of grey H_2 [62]. The discovery of white H_2 in commercial quantities could lead to more affordable and environmentally sustainable H_2 energy, offering a viable alternative to other renewable energy forms. Despite its potential to become the cheapest H_2 source, there is limited published research on its occurrence, sources, accumulation, generation processes, and recovery methods [8]. As a result, the understanding of white H_2 sources, accumulation, and extraction remains limited, which makes the future of white H_2 uncertain.

Looking deeper into the REpowerEU plan to have 20 million tons of clean H_2 available by 2030 (10 million imported and 10 million self-produced) [33]. In turn, this means that around 120 GW of electrolyser capacity will be needed to reach the goal of producing 10 million tons of renewable H_2 in the EU by 2030 [72]. Although it seems like there is a significant gap between the capacity of the clean H_2 projects that have been announced, and the capacity of projects which have reached the final investment decision (FID) or construction phase [72]. It is questionable whether enough clean electricity is available for 120 GW of electrolysers, as it is one of the major barriers to progress in building up clean H_2 production capacity [72]. Together with the question of whether it will one day be clear how we can extract white H_2, it generates substantial uncertainty around the availability of clean H_2.

5.1.5. Political Factors

Pol. 1: Supporting Government Policies and Investments. Azadnia (2023) poses the development of policies and regulations as highly uncertain and risky [12]. When asking companies at the World Hydrogen Summit event (see Appendix C.1), nearly all mentioned that policies and public investments are a big uncertainty in the development of H_2. Wood Mackenzie sees this as a loop where investment and funding need to be stimulated by policy support to create more off-takers. In turn, it will make it more favourable for private (but also public) investors who invest in innovations. Here the loop continues to a higher likelihood of faster/reliable/safer technological innovations for the H_2 supply chain that decreases the price, which in turn creates more off-takers (comparable to the Kaldor-Verdoorn and Demand Pull effect from Figure 5.2). Similarly, Strategy& sees the number one change required in the European H_2 landscape to decrease risk for investments is: 'More financial support to bring down cost' [72].

It is proven that government agencies providing grants or subsidies for innovation and developing policies in favour of research and development of innovation can significantly help with R&D [26] (if they are given). Future environmental regulations, ESG-compliant investments, and the associated "green premiums" will influence customers' and investors' decisions [68]. Incorporating H_2 into long-term energy plans, with national, regional, and city governments shaping future outlooks (as presented by REpowerEU [33]), could decrease the risk for investors, which increases the likelihood of investments. However, the lack of clarity in government support brings up uncertainties surrounding the demand and emerging applications and hinders the decarbonizing of aviation [39].

Pol. 2: **International Co-operations**. Besides local (green) H_2 production and distribution, global agreements and (private) partnerships can facilitate the development of international H_2 markets and supply chains [39]. Hyde notably noticed that "*Pursuing net zero won't happen overnight, and it can't be accomplished alone. It requires partnerships among different stakeholders in and beyond aviation. We must come together and drive real change to ensure a sustainable future for the aviation industry*" [42]. Noting that a global industry like aviation needs collaboration to work. The European Commission set twenty key actions of the EU H_2 strategy, under which five key action points aim for international dimensions like 'promoting cooperation with Southern and Eastern Neighbourhood partners and energy community countries (..)' and 'Set out a cooperation process on renewable H_2 with the African Union (..)'. According to the European Union, by 2022 all points were implemented and delivered [20]. Yet the collaboration does not end here, it requires continuous improvements and events like the Hydrogen Summit and Sustainable Aviation Futures to strengthen the new co-operations and knowledge across the sustainability of aviation. A panel regarding 'the global appeal of SAF' at the Sustainable Aviation Futures Congress (see Appendix D.2.2) firmly noticed that: '*If we as an industry do not drive the sustainable transition, other policies will be set to de-grow the aviation industry in order to de-carbonise*'. Showing the importance of coordination that is required across the aviation sector and the government.

The results from the STEEP analysis show the overall factors in the macro environment of the H_2 supply chain for Lelystad Airport. In the next chapter, these factors will be analysed to get to the 'Critical Uncertainties'.

5.2. Critical Uncertainties

The multiple factors identified in the previous chapter will be assessed individually for their significance to the success of the H_2 supply chain for airports. The assessment is done by identifying the importance and uncertainty of every factor. It will use the data from previous chapters, including the results of informal interviews and observations.

5.2.1. Evaluating the Driving Forces

On the following pages, the evaluation of all factors is done. All factors are separated in the STEEP divisions once again, starting with the Social-Cultural factors in Table 5.1, to Technological Factors in Table 5.2, Environmental Factors in Table 5.3, Environmental Factors in Table 5.4 and closing with Political Factors in Table 5.5.

Table 5.1: Social-Cultural Factors involved in the supply chain of H_2

Social-Cultural Factors		**Importance scale**	**Uncertainty scale**
Item	**Public acceptance**	The public may need to accept the transition and its consequences depending on future policy. This is significant because too much resistance can negatively affect developments. Although newer generations tend to lean more towards sustainability, they can still be hindered. Therefore, this factor is given a low to mid level of importance.	Younger generations are increasingly focused on sustainability. Although the transition will take time, public awareness of the necessary changes is growing and can still be enhanced. Therefore, public acceptance is considered to have low uncertainty.
Mentioned by	Air Products		
Sources	Wood; Kaneko	**Low-Mid**	**Low**
Item	**Scales of (consumer) demand**	The scale of consumer demand is connected to many factors. The main point is that higher demand leads to more investments, which in turn increases the likelihood of innovation and efficiency through economies of scale. This results in lower prices and/or higher returns on investment. However, it can also be seen as a chicken-and-egg problem. In conclusion, demand is required for adaptation, making it of medium importance.	At first glance, demand can span across all industries, but the overall H_2 demand remains unclear. The EU's REpowerEU plans exist, but the timing and extent of company and industry adaptation are uncertain. For the aviation and airport supply chain, the transition is expected to be gradual and relatively certain, thus rated as medium in uncertainty.
Mentioned by	Air Products		
Sources	Hoezelen et al; Airport Council International (ACI); Cornel; HyGear; Lelystad Airport	**Medium**	**Medium**
Item	**Workforce Skills**	Without a workforce, achieving the transition will be challenging. Skilled individuals are needed to build the necessary infrastructure and supply chain. Both Fabrum and Chart/Howden recognize this as a significant uncertainty, thus it is considered highly important.	The workforce appears unprepared, with the Netherlands lacking 20,000 workers in 2021 (Kuys). However, there are plans in place, though their outcomes remain uncertain. This factor is therefore rated slightly higher than medium.
Mentioned by	Fabrum; Chart/Howden		
Sources	European commission; Kuys, Ministerie van economische zaken en klimaat	**High**	**Medium+**

Table 5.2: Technological Factors involved in the supply chain of H_2

Technological Factors		**Importance scale**	**Uncertainty scale**
Item	**Technological Innovations**	The importance of innovation is frequently emphasized by companies because current technology is both limited and expensive. Investments are risky, and adaptation may lag behind. An upward cycle can be envisioned: Innovation leads to decreased costs, which increases adaptation, enhances the H_2 economy (towards economies of scale), boosts investments, and in turn, fuels further innovation. Lelystad Airport is awaiting maturity and does not make any investments on its own, allowing the industry to lead with incoming innovations. Yet, it is not mandatory to innovate, since necessary technology already exists. Therefore, technological innovation that is assigned a mid-high importance.	Innovations, particularly in the long term, are unknown how they will evolve. Projects are inherently risky, leading to uncertainty. This is even more pronounced for airports, as current infrastructure planning in the Netherlands does not yet focus on airports (as higher demand is projected further into the future). Multiple companies mention this factor's importance in demonstrating and stimulating cost reductions, yet innovations are being worked on. Hence the uncertainty is rated mid-high.
Mentioned by	Royal Haskoning DHV; Petrofac; Air Products		
Sources	Interview Lelystad Airport; Gulli et all, icct;		
		Mid-High	**Mid-High**
Item	**Hydrogen Infrastructure Integration**	H_2 infrastructure integration could be a necessary factor in enabling the supply chain for airports. If industries ultimately do not use H_2, its implementation in aviation will likely not occur. Conversely, the more industries that adapt, the more likely they will integrate H_2 into airports. Since Gasunie is already constructing infrastructure for H_2, they anticipate that industries will connect once H_2 becomes available. Easy access could also enable a higher demand for H_2 (if enough clean H_2 is available). Yet a scale-able option is to supply H_2 with trucks, suggesting no need for costly infrastructure. Consequently, this factor is rated mid+ in importance.	The uncertainty regarding H_2 integration is present. The capabilities of H_2 and its integration over time are not fully known, both for airports and other industries aiming to reduce carbon emissions. If other industries do not transition, it could affect demand scales and hinder innovation. Conversely, if they transition quickly, the aviation sector's implementation ease will be high, but it remains uncertain which industries will adapt. Therefore, this uncertainty is rated high-.
Mentioned by	HyGear, Gasunie (not a problem)		
Sources	Hoezelen et al; HyGear; ACI; Inframap; Cornel; Gasunie		
		Mid+	**High-**
Item	**Hydrogen Aircraft Adaptation Speed**	H_2 aircraft are currently being built, but they must be purchased and utilized. Although multiple companies are constructing these aircraft, the results are yet to demonstrate their potential, and no (public) official orders have been placed. For H_2 to be supplied to the airport, it is vital to have a H_2 flying aircraft, thus the importance is rated high.	For companies to adopt new technology, it generally needs to become cheaper over time. The WEF believes that H_2 aircraft are essential for achieving true sustainability in aviation. Airlines, including EasyJet, aim for net-zero emissions by 2050, making the uncertainty for adaptation low+.
Mentioned by	*Not mentioned*		
Sources	Airbus; Wendling; Veenstra; Icct; World Economic Forum		
		High	**Low+**
Item	**Technology Safety and Security**	Safety remains a predominant concern, as noted by multiple companies. Though mistakes typically occur during development, the supply chain must be safe and secure. H2tools provides an open portal to learn from accidents, enabling companies to benefit from each other's experiences. Hence, the importance of safety is rated mid-high.	Concerns about H_2 safety are evident among companies. However, research shows that there is an open platform to aid in safety and security. Technologies will be tested and should be secure, and lessons will be learned from any mistakes or incidents. Therefore, this uncertainty is rated medium-
Mentioned by	Hygreen Energy; Petrofac; Air Products		
Sources	H2tools; Hygreen Energy; Petrofac; Air Products		
		Mid-High	**Medium-**

Table 5.3: Economic Factors involved in the supply chain of H_2

Economic Factors		Importance scale	Uncertainty scale
Item	**Cost Competitiveness**	H_2's role in sustainable aviation could depend on competition with non-sustainable H_2 production. In the long run, the ICCT foresees cost reductions in sustainable energy for electrolysers. However, Gulli believes that government incentives are essential for economic feasibility. Ultimately, the supply chain does not require sustainable production to function, although it is crucial for sustainability. Therefore, the importance is rated as medium.	Cost competition for sustainable fuel is expected to decrease over time due to technological innovation and economies of scale. However, the degree of affordability and the timeframe remain uncertain, so this factor is rated medium in uncertainty.
Mentioned by	Royal Haskoning DHV		
Sources	Azadnia et al; Ahmed; Gulli; icct		
		Medium	**Medium**
Item	**Investment and Funding**	Investment and funding is necessary to build infrastructure, foster new innovation, and drive the transition forward. Globally, an estimated 500 billion USD is spend on H_2. Yet, Fluor believes H_2 investments are not gaining enough traction. A loop can be defined from the Kaldor-Verdoorn and the Demand-Pull effect, where investment increase plays a role. Because of these reasons, the importance is set to high-.	Political Policies can decrease risk, which can increase private investment. But these are highly uncertain. Today, about 500 billion USD is invested in H_2 project globally, but Fluor believes it is not enough. It is questionable how much can be defined as 'enough', therefore the uncertainty is set to medium+.
Mentioned by	Wood Mackenzie; Fluor		
Sources	McKinsey & Company; World Bank Group; Fluor		
		High-	**Medium+**

Table 5.4: Environmental Factors involved in the supply chain of H_2

Environmental Factors		Importance scale	Uncertainty scale
Item	**Availability of Clean Hydrogen**	An airport can transition to H_2 without clean H_2, but the primary goal is to decarbonize aviation. If the H_2 is not clean, there is little reason to switch in the first place. McKinsey and Company consider this vital for the transition, and Strategy& - PwC also view this as a major barrier to scaling up clean H_2 production. White H_2 can significantly impact the transition by eliminating the need to produce H_2. Since cost is a critical driver in the shift to H_2, large-scale extraction could accelerate the availability of H_2. Consequently, this factor is rated as high- in importance.	There are plans under REpowerEU to obtain H_2, but the transition for aviation and airports is too distant to determine specific requirements. Multiple H_2 companies highlight this as a significant uncertainty, with plans likely falling short of targets. The availability of white H_2 has only recently been discovered and there is limited knowledge about the extraction and to how much H_2 can be extracted from the earth. Hence, the availability of clean H_2's uncertainty is high-.
Mentioned by	Fabrum; Royal Haskoning DHV; Gasunie		
Sources	Aimikhe; Pironon and Donato; Mckinsey; Dawood; WEF; REpowerEU; Strategy& - PwC		
		High-	**High-**

Table 5.5: Political Factors involved in the supply chain of H_2

Political Factors		**Importance scale**	**Uncertainty scale**
Item	**Supporting government policies and Investments**	government investment can significantly stimulate the H_2 transition, but they are not mandatory to make the transition happen. On the other hand the policies are important for the transition, the lack of clarity brings uncertainties in investments, which are important (as seen at Investment and Funding), hence the combined importance is set to mid-high.	Azadnia et al. identify policy development as a high-risk area, with companies also perceiving significant uncertainty. Government subsidies and supporting policies for the transition are not yet adequately in place according to surveyed companies. Gulli also points out that uncertainty around government support hinders the transition. Therefore, this uncertainty is rated high-.
Mentioned by	Rein; Wood Mackenzie; Plug Power; Royal Haskoning DHV; Chart/Howden; Air Products		
Sources	Strategy& - PwC; Azadnia et al; Gulli; European Commission; Sparkedadmin		
		Mid-High	**High-**
Item	**International Co-operations**	Companies and governments need to collaborate, as no single airport or H_2 producer can independently transition to a new fuel. If the industry does not take the initiative, the policy will eventually mandate a sustainability change. Therefore, cooperation to address the challenges is of high- importance.	Uncertainty is somewhat present, but global conferences and (mandated) policies foster cooperation. Thus, the uncertainty regarding international cooperation is rated as low to mid.
Mentioned by	SAF conference; Strategy& - PwC		
Sources	Gulli et al.; Hyde; European Union;		
		High-	**Low-Mid**

Now that the factors have been ranked, they will be placed on a matrix to visualise the outcome.

5.2.2. Critical Uncertainty Matrix

The tables in the previous section give the following Critical Uncertainty matrix, shown in Figure 5.3 below.

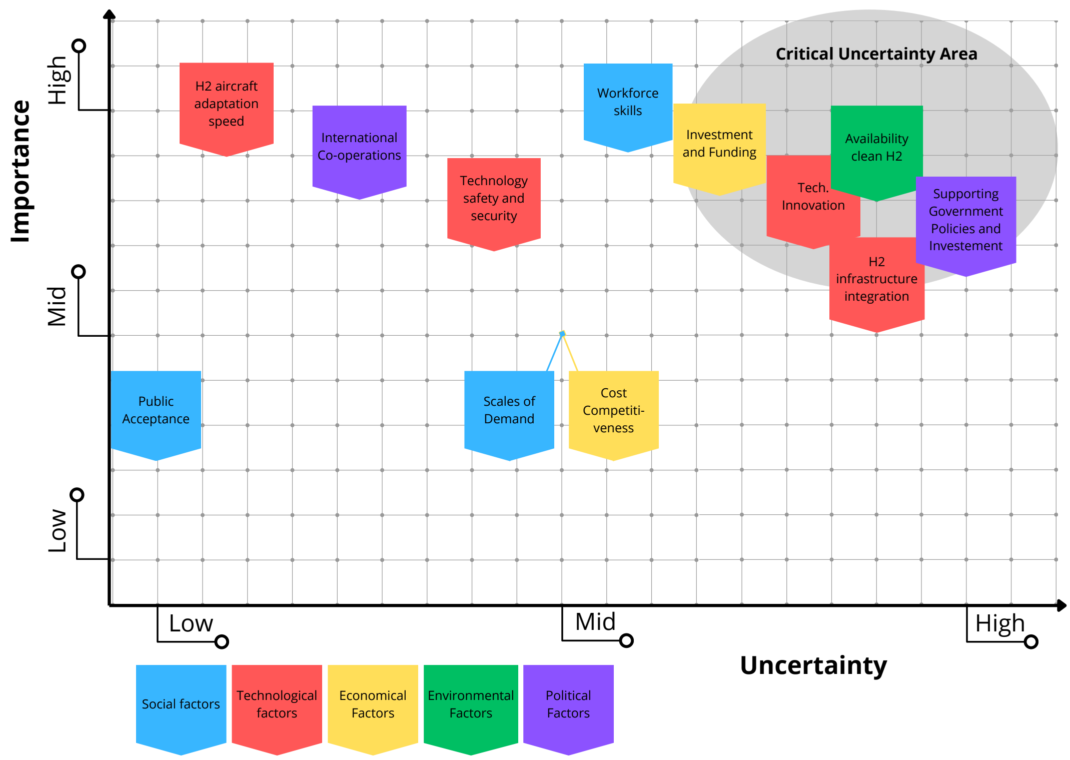

Figure 5.3: Ranking drivers of change by importance and uncertainty

Based on the matrix in Figure 5.3, it is evident that most of the factors (9 out of 13) have a higher than medium importance. Technological factors, in particular, score high on the vertical axis. On the horizontal axis, there is more diversity, but it is noteworthy that all environmental and economic factors have medium or higher uncertainty.

This matrix forms the basis of the change drivers surrounding the H_2 supply chain of aviation. In the next chapter, this matrix is used to define the scenarios for further analysis.

5.3. Scenario Axes

The upper right section of Figure 5.3 (shaded in grey) highlights the area of critical uncertainties. Two of these uncertainties are to be positioned within the 2x2 scenario framework as presented in Chapter 3.1.

From the critical uncertainty area, the availability clean electricity for H_2 and supporting government policies & investments are the most uncertain factors which also have significant importance. Therefore, these two factors are chosen for the scenario framework. Setting both the factors on a scale from low to high, results in the framework as presented in Figure 5.4 on the next page.

In the following Chapter, the four scenarios presented in the axes will be examined and the scenarios will be fleshed out.

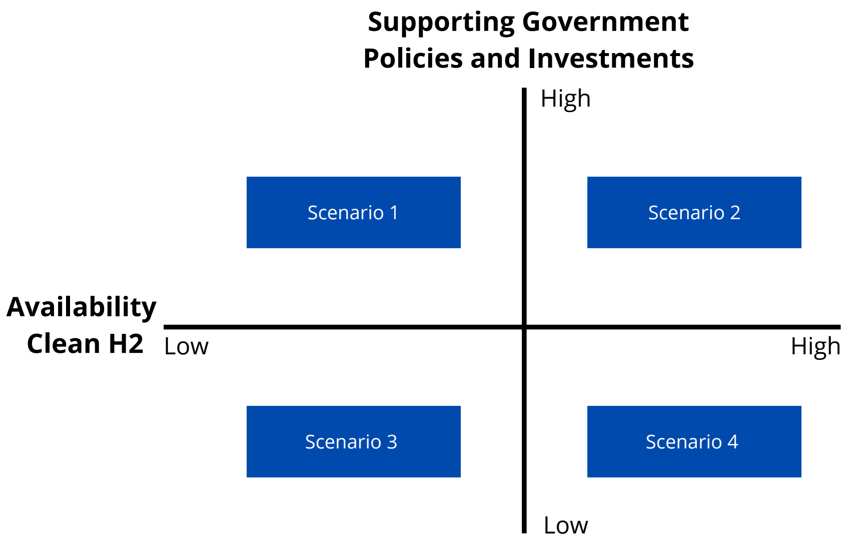

Figure 5.4: Scenarios followed from Scenario Logic

6

The Four Scenarios

This chapter involves fleshing out the scenarios by building a story that aligns with the scenario space's logic (step 6). The scenarios start by highlighting significant features of each scenario and using key change drivers from the STEEP analysis. Each scenario explores unique outcomes, establishing the narrative's foundation. The narrative then examines driver dynamics and develops a story leading to the scenario's conclusion. Scenarios should be memorable, believable, internally consistent, relevant to the central issue, and connected to the change drivers from previous chapters.

For every scenario, the key actors in the scenario are (the government, Lelystad Airport and the H_2 industry) evaluated. Note that the Netherlands has a democracy, in which the public votes for the government. Hence, it is assumed that the government support decisions are voted for by the general public.

In addition, it is assumed that the workforce skills grow with the H_2 technology and availability of H_2, staying in equilibrium. Also, it is believed that companies will successfully develop an operational H_2 aircraft, otherwise, no supply chain would be required. This can also be viewed as a pivotal event; once H_2 flights become operational, it becomes logical to establish a supply chain for H_2.

The area of focus is the Netherlands, specifically Lelystad Airport, which is presumed to open as a commercial airport and has the aspirations to become a sustainable hub in aviation during the scenarios.

Finally, this study believes the Kaldor-Verdoorn/Demand-Pull effect (see Figure 5.2) has a strong impact on the success of the H_2 industry. As a positive loop can increase demand, investment, productivity and innovation, leading to a price decrease and a higher success rate of the H_2 supply chain.

6.1. Scenario 1: Policy-Driven Transition

Key Features

The key features of *Policy-driven Transition* is high government support and low availability of clean H_2. It can be defined as a slow H_2 transition, with weak input from the industry. In this scenario, the overall infrastructure might already be made because of government support, but no clean H_2 is available for the aviation demand. In turn, it means that clean electricity is not available for aviation H_2, which could result in unused infrastructure. It can also be that non-sustainable production technologies are being used in the supply chain to transition, so that a start of H_2 in aviation can be done.

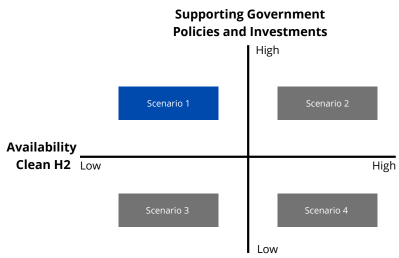

Figure 6.1: Scenario 1

The Narrative
In this scenario, despite strong government support, the transition to H_2 powered aviation faces significant challenges due to limited availability of clean H_2. Technological and resource constraints prevent the market from keeping pace with the government's ambitions. This low availability of clean H_2 undermines the transition, potentially causing stakeholders to lose confidence in its feasibility.

Lelystad Airport may encounter H_2 demand from customers wanting to use H_2 powered aircraft. However, with limited clean H_2, prices are likely to remain high, making flights expensive unless subsidized. Alternatively, to meet demand at a lower cost, the airport might resort to using non-sustainable H_2. This likely impacts the environment negatively.

Government efforts likely include funding pilot projects and demonstration plants, but widespread supply chain development lags behind. The limited supply and reliance on less sustainable production methods keep H_2 prices high. H_2 transportation is likely facing challenges, and airport refuelling stations remain sparse. Consequently, airlines are cautious about adopting H_2 powered aircraft due to high costs and supply reliability concerns. Technological advancements and breakthroughs might be necessary to increase clean H_2 supply.

As a result, the aviation sector sees only a gradual reduction in emissions, falling short of desired sustainability goals. Government investments stimulate some economic activity, but the low availability limits the widespread adoption of H_2.

Nevertheless, there is potential for the industry to catch up through scaling up and innovative solutions. Government support continues to drive the transition forward, although private investment likely remains low. Because of the medium investments, the Kaldor-Verdoorn/Demand-Push effect might not end up in a positive spiral depending on investments and innovation breakthroughs.

Conclusion
In conclusion, while strong government support drives the push for H_2 powered aviation, the limited availability of clean H_2 presents substantial challenges. High costs, potentially slow technological progress, and fragmented infrastructure hinder the transition, causing uncertainty among stakeholders. Lelystad Airport likely faces high H_2 prices and the potential need to resort to non-sustainable alternatives. Despite these obstacles, continued government backing, and future innovations could help to overcome current limitations and achieve a sustainable H_2 economy in aviation.

6.2. Scenario 2: Green Skies

Key Features
The key features of the *Green Skies* scenario are high government support and high availability of clean H_2. Likely resulting in a succeeding H_2 transition. Both the government and the industry work collaboratively to reach sustainability in aviation, and the positive sentiment of the government helps the industry. The supply chains are likely set up and in use in this scenario and a growing number of aircraft are flying on clean H_2.

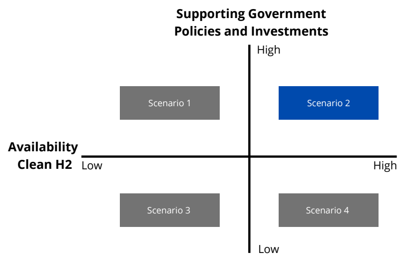

Figure 6.2: Scenario 2

The Narrative
In this scenario, both the government and the market are aligned in promoting a robust H_2 economy. Strong government support comes in the form of subsidies, tax incentives, and investments in infrastructure development. Regulations favor green technologies, and strict carbon emission limits might already be in place. The aviation's H_2 transition is likely successful, with an abundance of clean H_2 available. This abundance ensures that the price of clean H_2 remains competitive, yet affordable, due to economies of scale (see Cost Competitiveness in Chapter 5.1.3). This will likely make H_2 powered flights cost-effective.

With a positive consensus around H_2 in aviation, Lelystad Airport will efficiently serve the demands of H_2 aircraft. H_2 infrastructure, including production facilities, pipelines, and refueling stations at airports, ensures reliable supply and availability. Additionally, rapid advancements in H_2 production and storage technologies, particularly through the widespread adoption of electrolysis powered by renewable energy sources, drive technological progress.

In the efficient and reliable supply chain, airlines are rapidly adopting H_2 powered aircraft due to favorable policies and economic incentives. This leads to a significant reduction in aviation-related emissions. The ongoing H_2 transition will likely attract more investments and innovation, creating an upwind spiral of growth via the Kaldor-Verdoorn/Demand-Push effect. This dynamic will contribute positively to achieving the 2050 sustainability goals.

In this scenario, the aviation sector experiences a significant reduction in greenhouse gas emissions, especially CO_2. This likely leads to a boost in green jobs and industries related to H_2 technology and infrastructure. Consequently, countries with strong government support in H_2 technology can become global leaders in sustainable H_2 aviation.

Conclusion
In conclusion, this scenario highlights how coordinated governments and market efforts can foster a thriving H_2 economy. The alignment results in affordable clean H_2, robust infrastructure, increasing technological advancements, and a reliable supply chain. All contributing to significant environmental benefits and strong economic growth in the H_2 sector.

6.3. Scenario 3: Stalled Progress

Key Features
The scenario of low government support and low availability of clean H_2 is referred to as *Stalled Progress*. This scenario suggests a failing transition for H_2 in aviation. Because there are low incentives given by the government, and the industry did not manage to secure a clean H_2 supply. H_2 supply chains and infrastructure for airports is probably barely-to-not present in this scenario.

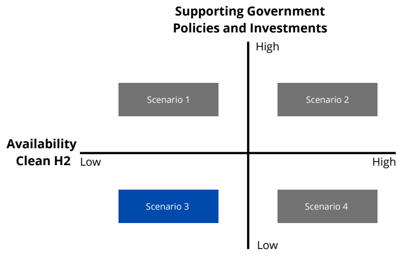

Figure 6.3: Scenario 3

The Narrative
In a scenario with minimal government support and limited availability of clean H_2, the transition to H_2powered aviation struggles to gain traction due to high technological and economic barriers. The likelihood of Lelystad Airport being able to supply sustainable H_2 is low. Consequently, fueling H_2 at Lelystad Airport is unlikely without a sustainable supply chain. Any H_2 flights that do fly are likely to be expensive or potentially unsustainable. High H_2 prices also result from inefficient production methods and a lack of economies of scale. This scenario leads to a high likelihood of insecurity in the H_2 transition, with stakeholders potentially losing faith in H_2 feasibility.

However, other sustainable aviation innovations may excel. Advancements in Sustainable Aviation Fuel (SAF) production or battery technology could make aviation turn away from H_2 altogether. The infrastructure for H_2 remains sparse and underdeveloped, with likely only a few isolated projects and very limited refueling stations. Technological progress around H_2 is slow, with few breakthroughs and limited investment in research and development. The supply chain might be inefficient and unreliable, facing significant logistical challenges and high transportation costs. Airlines probably do not adopt H_2 technology, or adopt very slowly, preferring conventional fuels due to high costs and uncertainties around H_2.

As a result, the Kaldor-Verdoorn/Demand-Push effect does not pick up a positive spiral, and the aviation sector sees minimal reduction in emissions. Potentially hampering progress toward sustainability goals. Economic growth in the H_2 sector is limited, with a likelihood of continued reliance on traditional energy sources.

Conclusion
In conclusion, the scenario of minimal government support and limited availability of clean H_2 signifi-

cantly hampers the transition to H_2 powered aviation. With high technological and economic barriers, sparse infrastructure, and high costs, airports like Lelystad likely struggle to adopt H_2 fueling. Leading to slow progress in reducing emissions. Stakeholders may lose confidence in H_2 potential, turning instead to other sustainable innovations such as SAF and battery technologies.

6.4. Scenario 4: Market-Driven Transition

Key Features
The *Market Driven Transition* scenario's key features are high availability of clean H_2 and low government support. In this scenario, the industry did find its way towards sustainable H_2 supply with minimal government support. This suggests that H_2 has picked up traction over the years and is available for the aviation sector. Additionally, this scenario suggests that the supply chain and infrastructure are set up, and flying on H_2 can be profitable without subsidies.

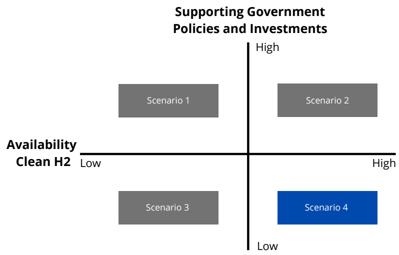

Figure 6.4: Scenario 4

The Narrative
In this scenario, the availability of clean H_2 is high, likely due to significant private sector investment and technological advancements, despite minimal government support. With few incentives or regulatory frameworks to promote H_2 adoption in aviation, the industry has independently driven the H_2 market.

The low government support suggests that either heavy industry investments and/or breakthrough innovations have made clean H_2 production much easier and more cost-effective. Consequently, H_2 in aviation might become profitable through market dynamics alone. For Lelystad Airport, this scenario means they may have funded their clean H_2 supply chain without relying on government subsidies. In this case, the H_2 supply chain likely depends solely on trucks, trains, or ships, as there might be no government support for pipeline infrastructure.

Alternatively, the government could have mandated the aviation sector to become more sustainable through CO_2 output caps or higher taxes on kerosene, indirectly accelerating clean H_2 production. Lelystad Airport would then follow the industry's demand for clean H_2. In this scenario, clean H_2 prices are likely to be competitive, falling into the mid or lower end of expected outcomes.

Key characteristics of this scenario include a supply chain developed primarily through private investment and market demand. Likely with key H_2 hubs and refuelling stations at major airports. H_2 prices are competitive due to technological efficiencies and abundant supply, and the Kaldor-Verdoorn/Demand-Push effect is likely in a positive loop. Innovation driven by private sector initiatives leads to cost-effective H_2 production and distribution. The supply chain is probably robust and market-driven, with efficient logistics and high reliability. Airlines adopt H_2 technology driven by market advantages and customer demand for sustainable options.

The impact of this scenario includes a significant reduction in greenhouse gas emissions and other pollutants from the aviation sector. There likely is a boost in green jobs and industries related to H_2 technology and infrastructure.

Conclusion
In conclusion, despite minimal government support, the high availability of clean H_2 driven by private sector investment and technological innovation most likely makes H_2-powered aviation profitable. This market-driven transition likely leads to competitive H_2 prices, efficient supply chains, and widespread adoption by airlines. With a high chance of resulting in significant environmental benefits and economic growth in the H_2 sector.

6.5. Key Scenario Takeaways

These four scenarios highlight the role of coordinated efforts between government policies, technological innovation, and market dynamics in shaping the future of H_2-powered aviation. The scenarios also show that the success of the H_2 supply chain involves factors that Lelystad Airport has limited control over. Public or private investments are eventually required to set up production, transport and storage of H_2. This study also recognises that the market dynamics might lean towards SAF alternatives if H_2 does not develop or gain support over time. The next chapter will explore the decisions, plans, and strategies that Lelystad Airport, and potentially other airports, could adopt to stay competitive and aim for sustainability. Including a customer (AIS Airlines) in the decision-making process.

7 Scenario Behaviour & Indicators

This chapter will execute steps 7 and 8 of the research approach. It will examine how decisions, plans, and strategies can evolve within each scenario space and get to a list of indicators leading towards a scenario. The goal is to develop strategies for the scenario's direction, aligning with Lelystad Airport's sustainability mission.

7.1. Scenario Behaviour

This section will evaluate each scenario. Analyzing how an airport might be able to operate in each of the scenarios. The evaluation is done from both Lelystad Airport's perspective, a competitor's perspective, as well as a customer of Lelystad Airport (AIS Airlines).

7.1.1. Policy-Driven Transition

In this scenario, Lelystad Airport faces a challenging environment where strong government support contrasts with the limited availability of clean H_2. Lelystad Airport could invest selectively in H_2 infrastructure, focusing on pilot projects and demonstration plants to showcase potential benefits. Despite these efforts, the low availability of clean H_2 keeps prices high, making widespread adoption difficult. To manage these challenges, Lelystad Airport can advocate for increased government investment in H_2 production and infrastructure, potentially securing pilot projects. Additionally, exploring alternative sustainable technologies to complement the H_2 initiatives and keep the sustainable mission going. Cost management strategies, such as long-term supplier contracts, can help to maintain operations.

Competitors are likely also cautious, investing in high-potential projects and diversifying their sustainability efforts to avoid over-reliance on H_2. Airlines are likely to be slow to adopt H_2 technology, carefully weighing the high costs and supply reliability issues. Passengers might continue to demand sustainable options, but the limited and expensive H_2 flights restrict their choices, potentially moving to other sustainable options. Despite gradual reductions in emissions, the desired sustainability goals may not be met. Government investments could be looking into some economic activity, but without clean H_2 supply, the aviation sector struggles to achieve significant environmental and economic benefits from H_2. Other airports striving for greater sustainability might consider adopting a similar approach. Excelling in this effort compared to other airports can distinguish Lelystad Airport and foster sustainable flight growth. Creating a more robust plan for sustainable growth in this scenario.

For AIS Airlines, a customer of Lelystad Airport, it is recommended to keep focus on its electrification project. Potentially pushing for a reliable H_2 supply from the airports when their electric aircraft is testable with H_2. Yet with limited availability, chances are that H_2 might not become the energy carrier for their electric fleet. Staying aware of energy-carrying technology over time is recommended to utilize their electric engines and grow in sustainability.

7.1.2. Green Skies

In the second scenario, Lelystad Airport could strive to adapt sustainable H_2, as both government and market forces converge to promote a robust H_2 economy. The airport can invest in H_2 infrastructure, installing H_2 refuelling stations and storage facilities, as a robust supply chain is likely to be set up. Partnering closely with H_2 suppliers and leveraging substantial government subsidies and tax incentives, Lelystad Airport can position itself as a leading green airport. Continuing to take the facilitating role and grow seamlessly with the growth of aviation demand and the H_2 transition. All Staff should undergo training to handle the new H_2 technology, ensuring safety and efficiency in the transition. The airport's branding highlights its commitment to sustainability, attracting airlines that look forward to adopting H_2 aircraft and passengers.

Meanwhile, competitors are likely to use similar strategies. Investing in similar infrastructure to stay competitive, forming strategic alliances with H_2 suppliers and technology firms. Airlines might be quick to transition to H_2 aircraft, encouraged by supportive policies and economic incentives. Passengers likely choose H_2-fueled flights, driven by a growing awareness of sustainability.

In this scenario, customers like AIS Airlines should have the innovative capacity to adapt to the H_2 transition. Doing so by continuing to develop the electric engines and H_2 energy carrier. With the availability of the first H_2 planes and an established supply chain, the AIS flight school can also be motivated to go into new H_2 flight training and prepare its pilot students for H_2 aircraft.

7.1.3. Stalled Progress

In the third scenario, Lelystad Airport faces minimal government support and limited availability of clean H_2, severely hampering the transition to H_2 powered aviation. With high technological and economic barriers, the airport should make minimal investments in H_2 infrastructure. It is recommended to keep focus on maintaining existing operations and managing risks. By storing H_2 in trucks, the aircraft can fuel H_2aircraft on the go, if there is some demand. On the other hand, the airport should seek alternative sustainable fuels and technologies, like SAF, to mitigate the impact of H_2 limitations and keep the sustainable mission going. Competitors likely adopt a conservative approach, avoiding heavy investments in H_2 and diversifying their sustainability efforts. Airlines remain hesitant to adopt H_2 technology. Likely to stick to conventional fuels unless economic conditions improve, as stable sustainable H_2 supply is scarce. Passengers see limited impact on their choices, as H_2 powered flights remain limited and probably on the high price.

Customers like AIS Airlines are likely not adopting many H_2 aircraft. AIS specifically should hold back on adapting H_2 as the carrier for its electrification project. Potentially seeking alternative energy carrier options for the project, if not already done.

In this scenario, the aviation sector sees only a gradual reduction in emissions, likely to be short of the desired sustainability goals set by the government. This scenario would probably need coordinated efforts by airports and airlines, to overcome current limitations and achieve (meaningful) progress in sustainable aviation.

7.1.4. Market-Driven Transition

In the fourth scenario low government support and high availability of H_2, Lelystad airport should have a good time supplying H_2 to the customers in need. As a facilitator, it might be able to provide sustainable H_2 to the customers without government support.

In this scenario, Lelystad Airport can capitalise on the high availability of clean H_2. Likely driven by significant private sector investment and technological advancements, despite minimal government support. The airport could secure private funding to develop extensive H_2infrastructure, including key hubs and refuelling stations. Hereby ensuring a reliable supply. The market dynamics likely make H_2 in aviation profitable, with competitive pricing due to technological efficiencies and high H_2 supply. Lelystad Airport can position itself strategically in the market, attracting airlines and passengers interested in sustainable travel. Operational efficiencies can also be prioritized to maintain cost competitiveness. In addition, partnerships with innovative technology companies could drive further advancements in H_2 technology.

Competitors are likely seeking private investments to enhance their H_2 capabilities and position themselves as leaders in sustainable aviation. Airlines, driven by market advantages and customer demand, will likely adopt H_2 technology. When influenced by competitive pricing and environmental benefits, passengers can increasingly opt for H_2 fueled flights. In this scenario, the aviation sector experiences a significant reduction in greenhouse gas emissions, assisting the green jobs and industries related to

H_2 technology. This market-driven approach highlights the potential for private sector initiatives to lead the way in sustainable aviation, even without strong government support.

Customers like AIS Airlines could be at the front of using H_2 in their electric aircraft and should be able to adapt the project to H_2as an energy carrier. Without government support, carefully select investment projects. Potentially collaborating with other H_2 companies and airlines to keep sustainable aviation growing. In this scenario, the AIS flight school can also be motivated to go into new H_2 flight training and prepare its pilot students for the new H_2 aircraft.

7.1.5. Behaviour Conclusion

This chapter presented the scenarios and associated stakeholder behaviours for Lelystad Airport and the customer AIS Airlines. These scenarios show significant variation, resulting in diverse stakeholder responses, ranging from high levels of investment to seeking alternative solutions. This raises the question of the appropriate timing and course of action in response to these scenarios. To manage this variability and uncertainty, the next chapter introduces indicators of change. These indicators monitor the current situation and signal when a particular scenario becomes more probable.

7.2. Indicators of Change

The indicators in this chapter provide a systematic approach to understanding and measuring shifts along the scenario axes. Key overarching indicators, which capture essential change elements, are evaluated and summarised in Table 7.1.

The Table indicates a core 'change driver' that can influence the change direction, followed by indicators that could measure the direction over time, using quantifiable indicators when possible. Some indicators are similar to the driving forces discussed in Chapter 5, as they also impact the macro environment.

Table 7.1: H_2 Change-Drivers and Indicators

Change driver	Indicators
Government Policies and Regulation First, the fluctuation in government support around H_2 serves as a key indicator and source of uncertainty. This involves monitoring the implementation of new laws, subsidies, tax incentives, and regulations aimed at promoting H_2 adoption and reducing carbon emissions. If the government continues to support this transition and the public votes for parties that favour H_2 technologies. The industry is likely to position itself in the upper part of the 2x2 scenario matrix (and vice versa). However, uncertainty regarding changes in the regulations will remain. This indicator is to follow the general trend. Keep an eye out for tax incentives and regulations that can favour H_2 transition.	Votes in favour of H_2 politicians; H_2 subsidies; H_2 tax incentives.
Technology Advancements Second, the innovation rate in H_2 serves as a valuable measure. The frequency and impact of breakthroughs in H_2 production, storage, and utilization can indicate the increasing viability of H_2. Additionally, the number of patent filings related to H_2 reflects ongoing research and development efforts, combined with the Technology Readiness Levels (TRLs) of H_2 innovations. When technological advancements are increasing, the Kaldor-Verdoorn/Demand-Pull effect tells us that price decreases, demand increases and investment increases, creating a positive loop. Ultimately, the likelihood of achieving higher availability of clean H_2 (positioned on the right side of the 2x2 matrix) is significantly greater (and vice versa).	H_2 Patent filings; H_2 Research publications; TRLs on H_2 innovations; Breakthrough H_2 innovations

Table continues on the next page.

Change driver	Indicators
Market Adoption: Specifically, the number of airlines adopting H_2-powered aircraft and the frequency of H_2 powered flights are key indicators. Although it is assumed there will be H_2 aircraft ready; monitoring developments, deliveries, and flights will provide insights into the adoption rate. Additionally, monitor the locations where H_2 flights take off, land, and refuel. This information does not directly indicate a specific scenario but demonstrates the progress of H_2 transitions. It could also foster demand-driven innovation and enhance the Kaldor-Verdoorn/Demand-Pull effect in the sustainable H_2 supply chain.	H_2 aircraft deliveries; H_2 take-off and landings; H_2 ready airports
Infrastructure Development: Infrastructure growth in the capacity of H_2 production facilities, especially sustainable production (See Chapter 2.3), can measure future sustainable H_2 infrastructure. Monitoring the percentage of sustainable H_2 used worldwide is crucial, especially given that currently, 95% of H_2 production is unsustainable (see Chapter 5.1.4). Additionally, tracking the H_2 distribution in other industries, like refuelling stations for road transport can indicate infrastructure expansion. For instance, Gasunie is currently constructing H_2 infrastructure and plans to supply the industry with H_2 from Rotterdam to Groningen (see Chapter 5.1.2). Monitoring the expansion and development of new infrastructure both locally and globally is a valuable measure of progress.	Overall H_2 distribution; (Sustainable) H_2 production facilities; H_2 infrastructure expansion (plans)
Economic Drivers: Sustainable H_2 prices can serve as a leading indicator. Trends in the cost of H_2, particularly sustainable H_2, can show the level of (sustainable) H_2 supply. Additionally, the investment amount from both public and private sectors into H_2 related projects and companies is an important metric. Increased investments can create an upward demand and innovation spiral, as discussed in Chapter 5.1.3. This can lead to higher availability of clean H_2 and enhance public sentiment towards H_2, potentially resulting in greater support for H_2 favourable political parties and increased government support.	(Sustainable) H_2 supply; H_2 public and private investments; H_2 R&D expenditures
Stakeholder Confidence: Finally, the industry sentiment and public perception of a H_2 economy can be seen as an indicator. Increased positive sentiment and public acceptance of the H_2 economy can stimulate more investment, innovation, and government support. This can lead to a higher supply of sustainable H_2 and votes towards H_2 supporting politicians. It can be monitored through surveys and feedback from industry stakeholders, including (but not limited to) airlines, flight schools, H_2 producers, and suppliers, regarding their confidence in the H_2 transition.	Results of H_2 sentiment surveys

One mention is that the indicators are not limited to the local environment. Worldwide technology advancements, market adoption, infrastructure development or economic drivers can impact the direction of change both locally and globally. More local indicators are the government policies and regulations and stakeholder confidence, still, those decisions can have an impact around the world (e.g. when a more dominant country favours the H_2 transition).

This Chapter answers the second sub-question: *What indicators can be monitored to track the process for H_2 in aviation?* Where the indicators listed in Table 7.1 can provide a start for identifying trends in the H_2 industry transition for Lelystad Airport.

7.3. Ending the Scenarios

Across all scenarios, Lelystad Airport faces a complex interplay of H_2 availability and Government support. For Lelystad Airport it is recommended to adopt a caution strategy from today onwards. In an interview with Lelystad Airport, it is mentioned that rather than actively pursuing innovations, they already prefer a wait-and-see approach. By adding the active monitoring of the indicators, Lelystad Airport can keep track of sustainable pathways and opportunities.

Since the scenario-specific behaviours and the indicators of change are known, the answer to the third sub-question: *What can Lelystad Airport do to mitigate the H_2 transition uncertainties?* can be given.

It is strongly recommended to monitor the indicators regularly as the H_2 transition in aviation progresses. Furthermore, when the indicators appear to be moving in a particular direction of the scenarios, this study suggests following the scenario behaviour suggestions from Chapter 7.1. The indicators are also related to the driving forces from Chapter 5, as they circle back to the input of the STEEP analysis. This can change the outcome of the critical uncertainties, potentially resulting in different scenario axes and different change drivers. For this case study on Lelystad Airport, the following is suggested:

- **Policy Driven Transition:** Since the government continues to support pilot projects, Lelystad Airport could secure a pilot for a H_2 supply chain. Meanwhile keep exploring other sustainable aviation technologies and keeping cost management strategies for resource optimization.
- **Green Skies:** Lelystad Airport should invest in the necessary H_2 supply chain infrastructure, train staff for safety and efficiency in handling H_2, and attract airlines that support H_2-powered flying.
- **Stalled Progress:** Lelystad Airport should adopt a 'wait and see' approach, avoiding infrastructure investments and using readily available solutions like trucks to fuel aircraft with H_2 as needed.
- **Market-Driven Transition:** Proposes that Lelystad Airport adapt to H_2 infrastructure by securing private funding and investments, forming strategic partnerships with innovative companies for the H_2 supply chain, and attracting airlines that operate H_2-powered flights.

8 Conclusion and Discussion

8.1. Final conclusion

To answer the main research question: *What are sustainable supply chain pathways to transition a local fossil fuel-based airport to an H_2 airport?*

This study has demonstrated that the transition to H_2 in aviation is filled with many uncertainties. Making incorrect decisions could result in substantial resource waste and lead to less sustainable outcomes, potentially yielding sub-optimal delivery or less sustainable solutions. To ensure a sustainable H_2 pathway for airports, it is recommended to take a cautious approach while closely monitoring the relevant indicators and aligning actions with the projected scenarios. At this stage, the study shows that investing in permanent infrastructure is not justified, as no H_2 aircraft are currently operational. When demand for H_2 at airports emerges, flexible supply chain solutions, such as trucks, can meet the need. Accelerating the process through collaboration with airlines, and aircraft manufacturers, or by positioning the airport as an H_2 early adopter could help generate demand for H_2 in aviation. Airports could continuously monitor key indicators. As H_2-powered aircraft become operational and clean H_2 becomes more accessible, along with increased government support or promising technological advancements, airports could adjust their strategies to accommodate the development of more permanent H_2 infrastructure.

8.2. Discussion

H_2 in aviation is currently very immature and uncertain. While H_2 in aviation has the potential to significantly impact de-carbonisation, our study highlights the limitations and uncertainties of the H_2 supply chain for stakeholders and decision-makers.

The initial objective of this study was to explore the development of a sustainable H_2 supply chain for airports, even with significant uncertainty. Initially, I assumed that Lelystad Airport's 'wait and see' strategy was unsustainable, based on my perspective of the H_2 transition. However, as the study progressed, I realized that given the current high level of uncertainty, it seems not justified for an airport to invest in such a supply chain today. It may become viable in the future if we end up leaning towards the positive scenarios and when uncertainties decrease.

Additionally, we aimed to assess cost efficiency and identify a positive business case for obtaining H_2 at an airport. However, we found that as of today, maintaining flexibility (e.g. via truck deliveries) proved to be more sustainable, rather than investing in infrastructure that might not be utilized due to the prevailing uncertainties.

8.2.1. Generalisability

While the study has been done at Lelystad Airport, we see no reason why the result of the study cannot be used at other airports. Although the indicators given are focused on the Netherlands, most indicators are similar in other areas. Every airport should assess its local environment, especially around government support and regulation. For example; a less (or non) democratic country might not be able to vote in favour of H_2 regulation. Hence the indicator might not be valid. Therefore, based on the limitation of clean H_2 availability and government support and policy, we see no reason for other airports to follow the same indicators in their local environment to define their H_2 transition and supply chain investments.

8.2.2. Practical Contributions

In this study, we investigated the different elements of an H_2 supply chain and the specific dynamics of Lelystad Airport. We followed the study by identifying the thirteen driving forces of the H_2 supply chain for airports via a STEEP analysis (see Chapter 5). These driving forces were ranked on importance and uncertainty to get to the critical uncertainty matrix as shown in Figure 5.3.

We noticed that multiple driving forces are higher than medium in uncertainty, and even more are above medium in importance. The combination of both led to critical uncertainties, of which the 'availability of clean H_2' and 'supporting government policies and investments' ranked the highest according to the literature, informal interviews and observations. We note here that although the informal interviews were prepared, and the spokespersons were selected to meet specific requirements. There is still a possibility that talking to a different company and/or representative could have led to different ratings and outcomes because of opinions and biases. Yet we believe the impact would be minimal since representatives repeated similar uncertainties.

With the two highest scoring critical uncertainties, a 2x2 scenario axes was set up with a scale of low-high for each axis (as seen in Figure 5.4). For the scenarios, we assumed the following:

- H_2 aircraft will become operational.
- Lelystad Airport is presumed to be open for commercial flights and continues its mission towards sustainability.
- Because the Netherlands has a democracy, the general public votes for government decisions.
- Workforce skills stay in equilibrium with H_2 technology
- The Kaldor-Verdoorn/Demand-Pull effect has a significant impact on the H_2 economy.

Based on these assumptions, we developed four scenarios. Outlining their key features, narratives, and conclusions. We discovered that Lelystad Airport has limited control over the factors driving the success of a sustainable H_2 supply chain. But depending on the scenario, airports can act differently. Higher government support and regulation can seek for pilot projects or subsidies towards a supply chain. Conversely, high availability of clean electricity for H_2 indicates that the industry found a way to make sustainable H_2 available. Hereby potentially willing to invest and collaborate with airports to set up a H_2 supply chain.

When both factors lean towards the high side, the likelihood of success of H_2 in aviation is greater. This can make investments worthwhile, being from the government, the industry or an airport. On the contrary, when both are leaning towards the low side, there is a low likelihood of having a potential sustainable H_2 supply chain at the airport.

From the scenarios and factors, we found seventeen indicators in six categories that can measure the direction of change for a H_2 supply chain. These can be seen in Chapter 7. Following the indicators and aligning with a direction's actions can increase the likelihood of a sustainable H_2 transition for Lelystad Airport.

Reflecting on the interview with Lelystad Airport, it was noted that they currently adopt a 'wait-and-see' approach rather than actively pursuing innovations. For now, this approach appears reasonable. As the transition progresses, staying engaged with the indicators and considering actions for each potential scenario direction is recommended. Mainly because there are too many uncertainties and uncontrollable factors. Today, there is no operational plane flying on H_2; there is no standard for the H_2 supply chain today; a variety of H_2 supply options are available; no government plans for Lelystad Airport and H_2 (or even if it will eventually open for commercial flights). Combining this with the literature, it becomes clear that in the early stages of the transition, using trucks that store H_2 at the airport and can fuel the aircraft is the most sustainable supply method. As more H_2 aircraft begin to operate, it is crucial to analyse the environment using indicators of change. Potentially seeking partnerships with H_2 aircraft manufacturers like Airbus and ZeroAvia. Until the indicators show there is greater certainty around a sustainable H_2 supply and government support.

8.2.3. Scientific Contributions

From a scientific standpoint, this study adds to Demirmenci and Hoezelen's H_2 supply chain for aviation, where we see the potential for H_2-bonded supply chains as an option. In addition, we found the driving forces in the H_2 supply chain for airports via a STEEP analysis. Where we found thirteen factors influencing the success of a H_2 supply chain. Based on the literature and informal interviews with industry experts at two separate events, we ranked the factors of importance and uncertainty. These factors are crucial for future research regarding H_2 supply chains for airports. Especially the high importance and uncertain factors. Following from the scenarios, new indicators have been developed to provide a metric for the success of H_2 in aviation.

Adding to this, we see that as of today, it is recommended to take a step back in the development of H_2 supply chains for airports. There are many uncertain factors involved in the success of a H_2 supply chain, and the indicators have yet to show a clear indication of the direction the aviation sector is heading. We recommend looking into the individual factors to decrease uncertainty. This advancement enables more effective policy formulation and strategic decision-making for H_2 in aviation.

8.2.4. Limitations

It is important to recognize that the scenarios presented are limited by the current critical uncertainties, which are likely to evolve over the coming years or as the transition progresses. Should these uncertainties change, the 2x2 scenario axes and the indicators used for assessment may lose relevance, and some factors may no longer be as important or uncertain. Consequently, this study indicates the uncertainty surrounding the progress of H_2 in aviation, highlighting the need for further research on the factors mentioned and how this uncertainty can be reduced.

One notable limitation is the assumption that H_2 aircraft will eventually be deployed. Companies like ZeroAvia and Airbus have plans to release H_2 aircraft, and while we believe they will succeed, we also recognise that an H_2 supply chain would have limited utility if aircraft do not ultimately operate on H_2. Furthermore, our focus is restricted to the use of H_2 and its supply chain only when H_2 aircraft become operational. However, it is possible that other airport services, such as heating, may adapt to H_2 during the transition. Both limitations underscore the enabling role of an H_2 supply chain for airports as they begin to incorporate H_2 technology.

We also limit this study to the general generation of H_2 and do not dive into the specifics of its sustainable production. While we believe that H_2 should be produced sustainably, this study does not address whether production occurs locally in the Netherlands via solar and wind farms or is imported from other parts of the world. Similarly, we restrict our focus on the production methods of H_2 to CO_2-free categories: green, purple, blue, and white (as discussed in Chapter 2.3). While these methods are CO_2-free, they may still be considered 'unsustainable.' For instance, some argue that nuclear energy is unsustainable due to the long decay time, despite its ability to generate large amounts of energy with minimal waste. We remain neutral on this issue, recognizing that the H_2 industry requires significant quantities of H_2, and nuclear energy offers a way to produce large amounts of H_2 in a CO_2-free manner. Additionally, there is limited knowledge about white H_2 (extracted from the earth), and future studies may reveal that it is not sustainable in the long term

Lastly, reflecting on the approach used for the case study (the 2x2 Scenario Axes Technique developed by Alun Rhydderch), we believe it is the most suitable method for a scenario study with a high degree of outcome uncertainty. However, after applying it, I found that it is not an easy approach to execute when conducted by a single researcher (as Rhydderch notes, the method is intended for use by a group or organization). In particular, formulating the external environment and conducting the STEEP analysis is more effective when done by a group of subject matter experts. Unfortunately, I did not have access to such a group. My only opportunity to interact with multiple experts came through brief encounters during company and event visits, which limited my time with them. As a result, completing the STEEP analysis in a scientifically robust manner was a time-consuming process. Having a dedicated group of experts available would make this part of the process faster and more efficient, and this should be considered when planning to use the 2x2 Scenario Axes Technique.

8.3. Future Research

Upon reviewing the conclusion, we note that further research into the financial implications of a supply chain is essential. Each airport presents unique infrastructure challenges that the supply chain must adapt to. While monitoring trends is important, it is equally crucial to actively evaluate the success of transitions and explore cost-effective supply chain options.

We also recommend future studies on the macro-environmental factors identified as 'critical uncertainties.' These studies should focus on reducing uncertainty, thereby potentially improving the outlook for H_2 in aviation.

Our research is limited to the specific supply chain within the country, from production to delivery at the airport. It is advisable to extend this research further up the supply chain to determine where and how sustainable H_2 will be produced. Key questions include whether H_2 will be produced locally or imported, as well as the methods and forms in which it will be transported. This inquiry is crucial for the overall success of a sustainable H_2 supply chain.

Additionally, it is recommended to investigate the demand requirements for aircraft operating on H_2. Estimating the H_2 needed per flight is a good starting point, but a detailed analysis is required to understand the range an aircraft can achieve with H_2. Hereby identifying which airports fall within this range, and seek partnerships with airports aiming to become sustainable H_2 hubs. This approach will help establish a demand estimate, enabling H_2 supply chains to develop accordingly.

8.4. Usage of AI

During the writing of the thesis, a few AI tools have been used. Namely tools as Grammarly[1] and ChatGPT[2] for rephrasing, grammar and spelling purposes. Additionally DALL-E[3] is used for image generation (front page).

[1] See https://www.grammarly.com/
[2] See https://openai.com/chatgpt/
[3] See https://openai.com/index/dall-e-3/

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A

Research Flow Diagram

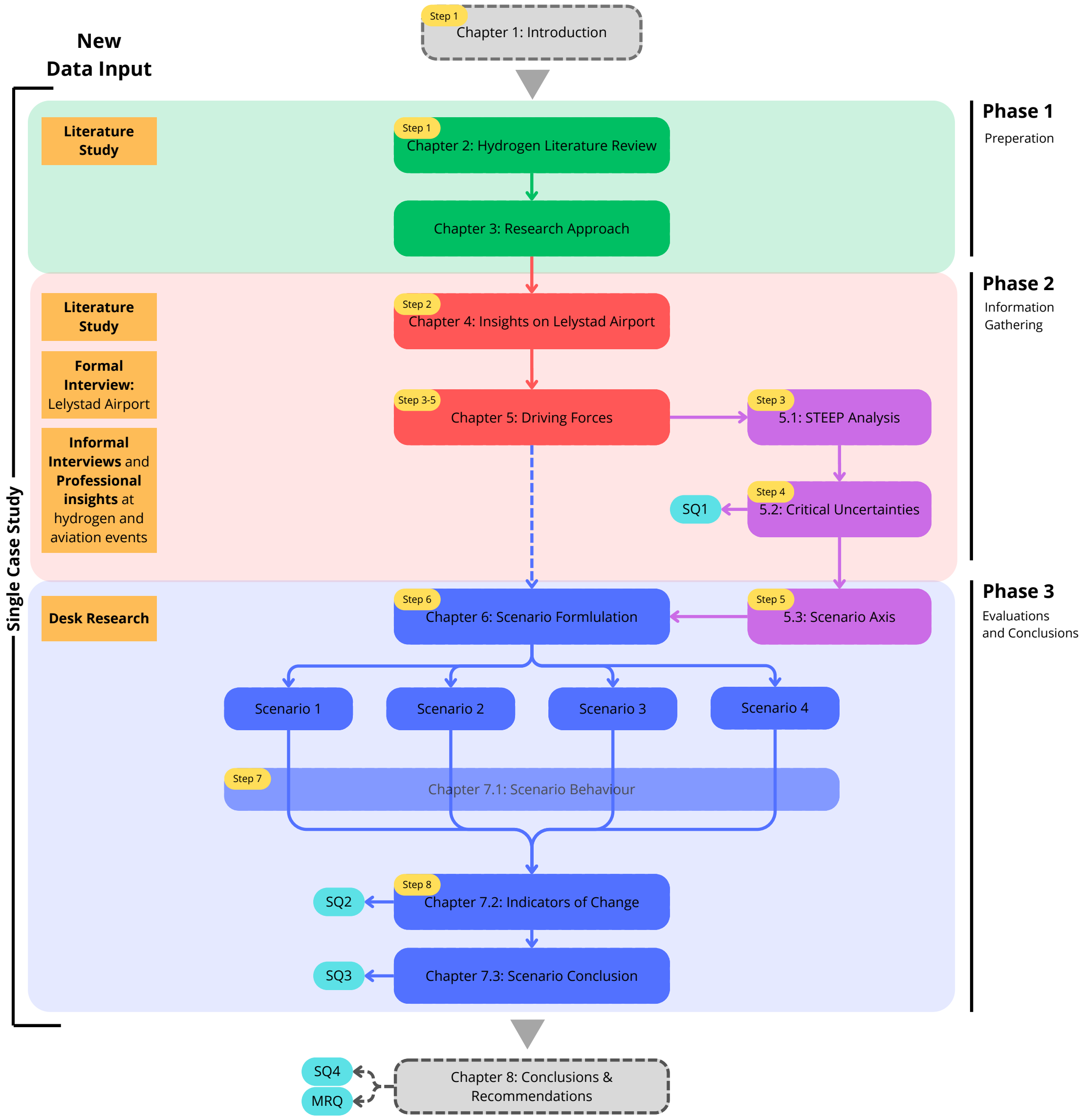

Figure A.1: Research Flow Diagram

B

Formal Interviews

B.1. Lelystad Airport

B.1.1. Interview Question Guide

Topic: Hydrogen Supply Flow at Lelystad Airport (LA) Objective: To gain insight into the internal dynamics (the situation) within the airport for the sustainability transition, particularly towards hydrogen and the supply chain for Chapter 4.

Introduction Questions

- Zou u uzelf kunnen introduceren en wat u doet bij LA?
- Hoe bent u in deze positie terecht gekomen?
- Wat zijn uw verantwoordelijkheden bij Lelystad Airport?

Sustainable developments withing LA

- Aan welke duurzame ontwikkelingen werkt LA?
- *Vraag naar de genoemde ontwikkelingen.*
- Welke interne factoren spelen een rol bij de transitie naar waterstof? (i.e. constraints; facilities; bottlenecks, finance, infrastructure, legislation binnen LA.)
- Hoe ziet u deze factoren in de toekomst (5-15 jaar) veranderen?
- Op de Lelystad Airport website staat: "LA wil graag een belangrijke rol spelen in productie, transport, opslag, conversie en toepassing van groene waterstof."
- Kunt u iets meer over wat en hoe LA van plan is deze rol te vervullen?
- Welke rol kan LA spelen in de plannen voor de productie van waterstof?
- Meer vragen over stroom en opslag, afhankelijk van het antwoord.
- Welke transportmethoden van waterstof worden overwogen voor de transitie (en waarom)?
- Wat ziet u als uitdagingen bij het transport van waterstof?
- Welk (tijds)schema zou u geven voor deze transitie voor LA?
- Wat ziet u als de grootste onzekerheden met betrekking tot de levering van waterstof voor LA?
- Zijn er nog andere opmerkingen die u zou willen maken over waterstof voor LA?

Closing Questions

- Zijn er nog punten waar u op terug wilt komen of die u wilt vermelden?
- Zijn er andere collega's met wie ik eventueel zou kunnen spreken?
- Heeft u nog een afsluitende opmerking of vraag aan mij?

B.1.2. Summary of interview Lelystad Airport

On March 20, 2024, an interview was conducted with a development manager Lelystad Airport.

Lelystad Airport is heavily focused on sustainability and innovation, with a particular emphasis on promoting electric and hydrogen flying. Including developing Dutch e-mobility hubs, ensuring sustainable fuel supply, and managing ground handling for business flights. The airport's energy consumption strategies have led to the use of 100% green electricity and gas, with ongoing efforts to reduce further energy consumption and transition from gas to electric options.

Lelystad Airport has established a charging station for electric planes and vehicles, recognizing the significance of electric flying, especially for training schools that constitute a large portion of the airport's traffic. In terms of hydrogen initiatives, When asking Lelystad Airport about their H_2 plans, they mention: *"I find that very difficult to determine, and it's always a bit of a chicken-and-egg situation"*. The chicken and egg are the H_2 planes and H_2 supply chain. Today, the airport is involved in the FLHY project, a hydrogen consortium in Flevoland that aims to create an infrastructure for hydrogen production, transport, storage, conversion, and usage across various sectors, including aviation. The project is still in its early stages, facing challenges related to regulatory frameworks and the need for extensive knowledge and technological development.

Network congestion and electricity capacity issues have posed significant challenges, but the airport has managed to set up the necessary infrastructure for electric flying. Lelystad Airport highlighted the importance of waiting for market demand and technological advancements before fully committing to hydrogen infrastructure, quoting: *"The idea is to gradually work towards a small-scale application in the coming years that could work, and if there is demand from the market as the technology around hydrogen flying starts to mature, we can anticipate that".*

The airport is collaborating with other airports and international partners to share knowledge and implement sustainable solutions effectively. As Lelystad mentioned: *"It costs a lot of money and energy to start making progress in that area (hydrogen), and that is exactly why we are also seeking international collaboration, since a lot of knowledge is needed".*

Currently, the airport primarily handles training flights, business jets, and private flights, totalling approximately 80,000 flight movements annually. Despite the emphasis on electric flying, the airport remains up to date with developments in hydrogen technology, with the Fly Consortium playing a crucial role in the establishment of the Hydrogen Valley in Flevoland.

C
Informal Interviews

This Appendix presents the informal interviews given at two different conferences: ”World Hydrogen Summit” and ”Sustainable Aviation Futures”.

C.1. World Hydrogen Summit - Visit Summary

Date: May 14, 2024

The plan involved speaking with several companies from different areas of the supply chain to gather their perspectives on the uncertainties in the H_2 supply chain.

In short, I spoke to several companies regarding the macro factors of the supply chain (or value chain) of H_2 and in specific to airports. The main opening question asked at the conference was ”**Which uncertainties in the supply chain are you noticing that are limiting the H_2 transition?**” If time and interest continued for both parties, the conversation continued towards aviation.

Below are the companies interviewed, along with their backgrounds and responses.

C.1.1. Rein Hytec Co.

Rein is a hydrogen leader in clean energy storage and transportation equipment with 12,000 jumbo cylinders production in 2023.
A business developer at Rein Hytec noticed that supporting policy is the main part of the supply chain evolution.

C.1.2. Hygreen Energy

Hygiene is a world-leading electrolyzer manufacturer that offers comprehensive solutions to green hydrogen production.
An account manager at Hygreen thinks the safety and security regarding production, transport and storage H_2 is very uncertain and needs certification to make it more clear what to build towards.

C.1.3. Wood Mackenzie

Wood Mackenzie is the leading global data and analytics solutions provider for renewables, energy and natural resources.
A research analyst at Wood Mackenzie sees the development of new technology that can decrease the cost of production and storage as the main uncertainty. It also feels the transition is driven by policy, which means it needs proper support to make investments worthwhile. They see the circle as ’strong policy support –> More offtakes –> more investment –> more policy support’

C.1.4. Plug Power

Plug is building an end-to-end green hydrogen ecosystem, from green hydrogen production, storage and delivery to energy generation through mobile or stationary applications.
An engineer at Plug Power mainly see the uncertainty regarding regulation development and awaits standardization.

C.1.5. Fabrum

Fabrum is a New Zealand-based company that provides onsite liquid Nitrogen, Oxygen, and Air production, as well as green hydrogen and cryogenic engineering services.
A chair member of Fabrum believes that specialized skills will be the main uncertainty. They noticed that a lot of companies at the event proudly say that 'they can do it'. While they see there is a bigger picture of workers who are not being trained and that companies need to learn along the way of the transition (lots of mistakes are going to be made if we are not careful).
They also see the availability of sustainable H_2 (green, white or low CO_2) as an uncerainty.

C.1.6. Royal Haskoning DHV

Royal HaskoningDHV is an independent consultancy which integrates 140 years of engineering expertise with digital technologies and software solutions.
Although Royal Haskoning has not had project for airports yet, an energy consultant thinks the aviation innovations are going to be the uncertainty (are we going to switch to H_2 and will it be worth it or will we stay with SAF?). Where the uncertainty for aviation is 'if it will take off'.
In addition to the overall H_2 supply chain, the price will be a huge limiting factor (hence an uncertainty), they wonder how the supply of green hydrogen will be scaled up enough (they acknowledge that the industry needs a lot more), and that policy can play a significant role in this transition if it is properly in place (hence an uncertainty)

C.1.7. Hydrogenious LOHC

Hydrogenious LOHC Technologies purpose is to unleash the potential of clean H_2 and make a common global vision come true: "A climate-neutral economy and society by carrying the new energy world Handling H_2 as an oil" [74]. As a midstream player, Hydrogenious LOHC is an enabler and accelerator for the energy transition. "We make sustainable H_2 available in a safe, efficient and economical way."
Hydrogenious LOHC is one of the only companies at the event that promotes the use of LOHC, although the content is only 6% (6kg out of 100kg LOHC is H_2), a development manager thinks for long distances and trade, the LOHC will become much cheaper since it can be treated like oil products.
The development manager says the company is looking to reuse infrastructure, but is unclear about their thoughts on uncertainties.

C.1.8. Petrofac

Petrofac is a global company that designs, builds, and operates energy facilities with low emissions. Learn about its projects, services, investors, and careers in the energy sector.
An engineer at Petrofac thinks storage costs and safety will be the biggest uncertainties of the supply chain of H_2.

C.1.9. Chart/Howden

Chart and Howden shared a stand as close partners.
Hart's vision is to be the global leader in the design, engineering and manufacturing of cryogenic process technologies and equipment, and Howden provides mission-critical air and gas handling products and services.
When speaking to both company representatives, their main concern was the availability of knowledgeable engineers in regards to H_2. They also see the lack of standardization and miss the policies/regulations that can support the transition.

C.1.10. Air Products

Air Products is a world-leading industrial gas company in operation for over 80 years focused on serving energy, environmental, and emerging markets.
A project manager at Air Products sees multiple uncertainties for the future, their main points were security and regulation, technology innovations, social acceptance and scale-up to get to economies of scale.

C.1.11. Gasunie

Gasunie manages and maintains the infrastructure for gas transportation, storage, heat, and CO_2. The company contributes to the energy transition to green gas, hydrogen, and sustainable energy [36].
Multiple representatives of Gasunie mentioned they did not have a clear future of the supply chain towards airports (when requested, they will work on it), but gave the main uncertainty to be the availability of green and white H_2, where they do not see a viable option of white H_2.
the infrastructure is what they see as 'not a problem' in the supply chain.

Finally, a speaker at the event finished the presentation with the collaboration between companies, universities and governments around the globe to be vital in the change.

C.2. Sustainable Aviation Futures - Summary of Experts

Date: May 22-23, 2024

At the Sustainable Aviation Futures (SAF) event, I engaged with various company representatives regarding sustainability in aviation. Since the conference was not exclusively focused on H_2, I first asked the companies and representatives about their vision and contributions concerning H_2 in aviation. If the representatives had relevant insights on H_2 in aviation, I then inquired about the importance/uncertainty matrix and requested their feedback.

Below is a summary of all the relevant companies spoken to at the event.

C.2.1. Fluor

A brief discussion with the process director of Fluor. Since Fluor worked on multiple H_2 installations, the matrix was shown, where the director mentioned that technology developments should be set lower towards somewhere in the middle (was set to high-). The reason is that we have the technology, maybe not the perfect technology, but there certainly is technology that can make the H_2 supply chain towards airports a reality. Only investments have to come in, which are uncertain, hence the investments and funding should have a higher uncertainty (was set to low).

C.2.2. Honeywell

Honeywell had multiple representatives, under which the Chief Technology Officer. In summary, the talk mentioned there is no 'magic bullet' to clean aviation, and they were against carbon credits, since it only stimulate 'creative accounting' and does not really decarbonize the sector. The CTO believes the H_2 is currently in the 'valley of death[1]', where we have the H_2 technology, but no investments (or resources) to make the technology a reality, because the uncertainty is too high to calculate returns.
Furthermore, Honeywell gave pros and cons for several options to fully decarbonize aviation (see Table C.1 on the next page). Honeywell is also working on a 1MW H_2 Fuel Cell, approaching TRL6 (referring to the NASA Technology Readiness Level [56]) by 2026.

C.2.3. Freshfields Bruckhaus Deringer

Talked to a Lawyer from Freshfields Bruckhaus Deringer regarding H_2. The lawyer advises on rules and regulations regarding environment and climate investment. This is one of the factors mentioned in the critical uncertainty matrix, I showed him the matrix, under which the lawyer was very confident that investment is much more uncertain than 'low', the lawyer suggested around mid to mid-high.

C.2.4. Strategy& - PwC

Talked to the Director at Strategy&, as part of the PwC network, he was representing the Clean Hydrogen and Alternative Fuels Solutions for PwC, both collaborated on a recently published report called 'Navigating the hydrogen ecosystem [72]'. The director's insights are mainly regarding the integration and implementation uncertainty. The H_2 production industry is significantly behind on projects, and the director sees this as a 'chicken and egg' problem. We need production to generate more off-takers, but recently the off-takers demand is way more than the production capacity, still acknowledging that most investors perceive investments as uncertain if they will reach profitability.

[1]The Valley of Death refers to the decision-making zone that lies between available research resources and the resources needed for the commercialization of a product or technology.

Table C.1: Options for Decarbonizing aviation, pros & cons (from Appendix C.2.2)

Approach	**Benefits**	**Drawbacks**
Turbofan + SAF	Drop-in or modified drop-in: No change to aircraft or engine	Cost & availability of SAF; potential regional land-use/water-use constraints
Full electric	True zero operational emissions	Batteries are approx. 30X the mass of JetA for same stored energy; impractical for long-range flight
Turbofan H_2	Eliminates CO_2, particulates, carbon monoxide, & unburned hydrocarbons	Volume of H_2 is prohibitive
Fuel cell H_2 (for propulsion)	Eliminates CO_2, NOx, particulates, carbon monoxide, & unburned hydrocarbons; FCs are approx. 2X the efficiency of a small turbine engines	FC & BoP weight is 3− to- 5X compared to a turbofan; 50% of FC power is heat that must be dissipated; volume of H_2 is prohibitive for long range (> 1000 nm) flights
Hybrid turbine/-electric	Reduces turbine engine size and optimizes for cruise	Trades battery weight vs improved fuel consumption (< 10% SFC benefit); higher system complexity

D
Professional Insights

This appendix provides supplementary notes capturing insights gathered during company visits or events. The summaries include significant findings that are relevant to the thesis.

D.1. HyGear - Visit Summary

Visit to HyGear on March 21st 2024, HyGear is a pioneer in hydrogen technology and a worldwide market leader in on-site hydrogen generation and purification, based in Arnhem, the Netherlands [44]. The afternoon started with an introduction about HyGear, its technologies and future goals.
Some interesting observations from the presentation:

- The most efficient (and thus sustainable) H_2 production is actually using steam methane reforming (their HY.GEN system) either by using waste heat or biomethane with carbon capture (= carbon negative), in the second case they call the product 'biohydrogen'.
- European Unions H_2 production is mostly steam reforming (usually grey) because the electricity grid is not ready.
- SAF is made with green hydrogen
- LOHC H_2 form is great for transport, but takes a lot of energy to transform.
- Pipeline distribution plans make their H_2 production product obsolete, but in the Netherlands, these will be between 97-98% H_2 purity, which is usually not enough for the industry, hence HyGear can still sell their H_2 purifiers. This is an interesting note because aviation H_2 also needs to be very pure, so having a pipeline connection will still need purification infrastructure.
- Close to the source is also a note which determines the price of H_2, since the transport is not easy/cheap as of now.
- Within aviation, NOx will still be emitted because of combustion, only CO_2 is reduced.
- The Biggest step for H_2 to take off is to make a (global) distribution network operational. (chicken and egg problem)

The afternoon continued with a presentation of the mother company 'HoSt BioEnergy Group' that acquired HyGear in 2023.

After the presentation, we got a tour around their facility, where they showed us their working H_2 production technologies.

D.2. Sustainable Aviation Futures - Panel Summary

This part of the SAF conference visit is regarding the observations during the panels and presentations (for the discussion notes, see Appendix C.2). Below is a summary of all the relevant panels attended.

D.2.1. Panel: Analysing the clean H_2 landscape

A brief discussion about 'what is clean H_2?'. Acknowledged that everything non or low CO_2 is referred as 'clean' (renewable energy, carbon capture and nuclear). To scale up H_2 off-takers should work

together and build trust to increase H_2 production. Barriers to scale-up are the regulations.
Most companies wait and try to see what will happen, but there is no time for increased technology advancements, we have to go to market with what we have. Noting that policy can significantly help to go to market. There were several viewpoints: One mentioned we should only implement H_2 on a small scale and implement where essential with current technology and wait until advancements improve to scale up; another sees it as 'the way' to decarbonize, where we should start making airports ready to store H_2; another was in favour of keeping H_2 in its first form, do not start mass production to PtL, since this results in significant losses in energy; the latter mentioned that the aviation sector should be included in the mass distribution of H_2 around the EU.
Hearing all these viewpoints made me realise the H_2 for aviation is highly uncertain.

D.2.2. Panel: The Global Appeal of SAF

This panel is mainly regarding SAF, but the outcomes can also be drawn towards H_2. Most importantly; 'if we as industry, do not drive the transition, other policies will be set to de-grow the aviation industry to decarbonize.' Making global warming a coordinated problem within the aviation industry. In addition, the panel referred to the overall policy as 'uncertain and in-perfect', which will always be the same, concluding that policy should not let these limit your investments, so scale up production of what we have (referring to SAF and H_2).

D.2.3. Panel: Airline Sustainability Roundtable - Pathways to aviation decarbonization

A panel dedicated to airlines and their view on decarbonization. In summary, the panel agreed that regulatory and policy help significantly. Currently purchasing SAF without the requirement can become unfair in the future with other airlines that do not. They also see the demand of sustainable fuel as supply and efficiency-driven.
One note regarding self-production was also mentioned. As Delta announced its LAX project, where Delta, in collaboration with Shell, will produce SAF themselves to sustainably fuel their own fleet [67]. The panel viewed this as a courageous first-mover step, but all do not see airlines becoming a sustainable fuel producers in the future (SAF or H_2).

D.2.4. Panel: Sustainable Airport Masterplanning

This panel discussed the airport planning strategies for sustainable fuels, SAF and H_2. They all say they plan for H_2, where the airport of Rome representative believes self-production of H_2 can become a key change-maker for the airport, to not only stay as a 'facilitator' role, but also a producer role. On this comment, the Brussels airport representative did not agree, since there is no space in and around the airport to produce H_2. Acknowledging this is not set for every airport. In my view, it seems like the airports do not take into account the energy requirement, they see the demand as drivers which, if there is demand for H_2, they have no problem in supplying, which is easier said then done.
In all cases, the panel acknowledge that there is a need for a leveled playing field for everyone, as Europe seeks on different regulations compared to other areas in the world. Additionally, a long-term strategy for investments and collaboration are important, hence they include H_2 in their 'masterplan'.

D.2.5. Panel: Future Fueling Infrastructure

This panel made clear that infrastructure and planes are required to fly on H_2. The notion of electric flying was also pointed out, but the heavy weight of both solid-state and fuel cells compared to their energy capacity is too little, LH_2 more prominent. There seems to be a real mix in the sustainability transition, where H_2 is the main driver, also for feedstock for SAF (eFuels). All panel members pointed out that regulation can shift the direction of sustainability enormously. The example of Italy is given, where there is high regulation, and the development goes fast, compared to Portugal where there barely is any regulation, and sustainable developments go slow (Companies like to be guided in the right direction). In the end, it comes down to safety. When following regulations, a company cannot be held responsible when accidents happen, while if there are none and accidents happen, the company is fully liable for the damages.

At the end, a question to all panel members was asked: "What if we have an H_2 aircraft tomorrow, how soon will you be able to fly this with passengers?" The responses were mixed, The UK Civil Aviation

Authority thinks that the first flight can happen in 2027. Catalunya Airport thinks no sooner than 2035. Ikigai Capital thinks by the time regulation and supply chains are set up, it will be no sooner than 2030. Milan Airport thinks the first plane might be able to fly within a year, but start slow and when available the acceleration will start soon.

D.2.6. Company Presentation: Ikigai - Glasgow Airport H_2 innovation hub

Ikigai presented a feasibility study on H_2 as an enabler of multi-modal airports. In summary, their study was a 'back-2-base' approach for Glasgow Airport. They control the fuel at Glasgow and fly to the nearby island airports and airports in London, then back to base to refuel only at Glasgow (<230km one way). They presented a feasible case for Glasgow when H_2 planes become widely available, concluding with the mention that the H_2 in aviation will come faster than you think, and airports should make supply chains a certainty in their plans. Their main limitation was that they were uncertain where to liquefy the H_2. It is an energy-intensive process. Ending with the notion that H_2 production close to usage is key for cheapening. The study concludes that hydrogen on-site production (when possible), storing H_2 in compressed form, and distributing to planes via tube trailers is the best option.
This brings much hope to the future of H_2 and other feasible studies. Ikigai mentioned that multiple partners, including Rotterdam/Den Hague airport, are heavily involved in the project. Yet many uncertainties, under which fueling equipment and H_2 handling procedure/requirements are still questioned and need more clarity.