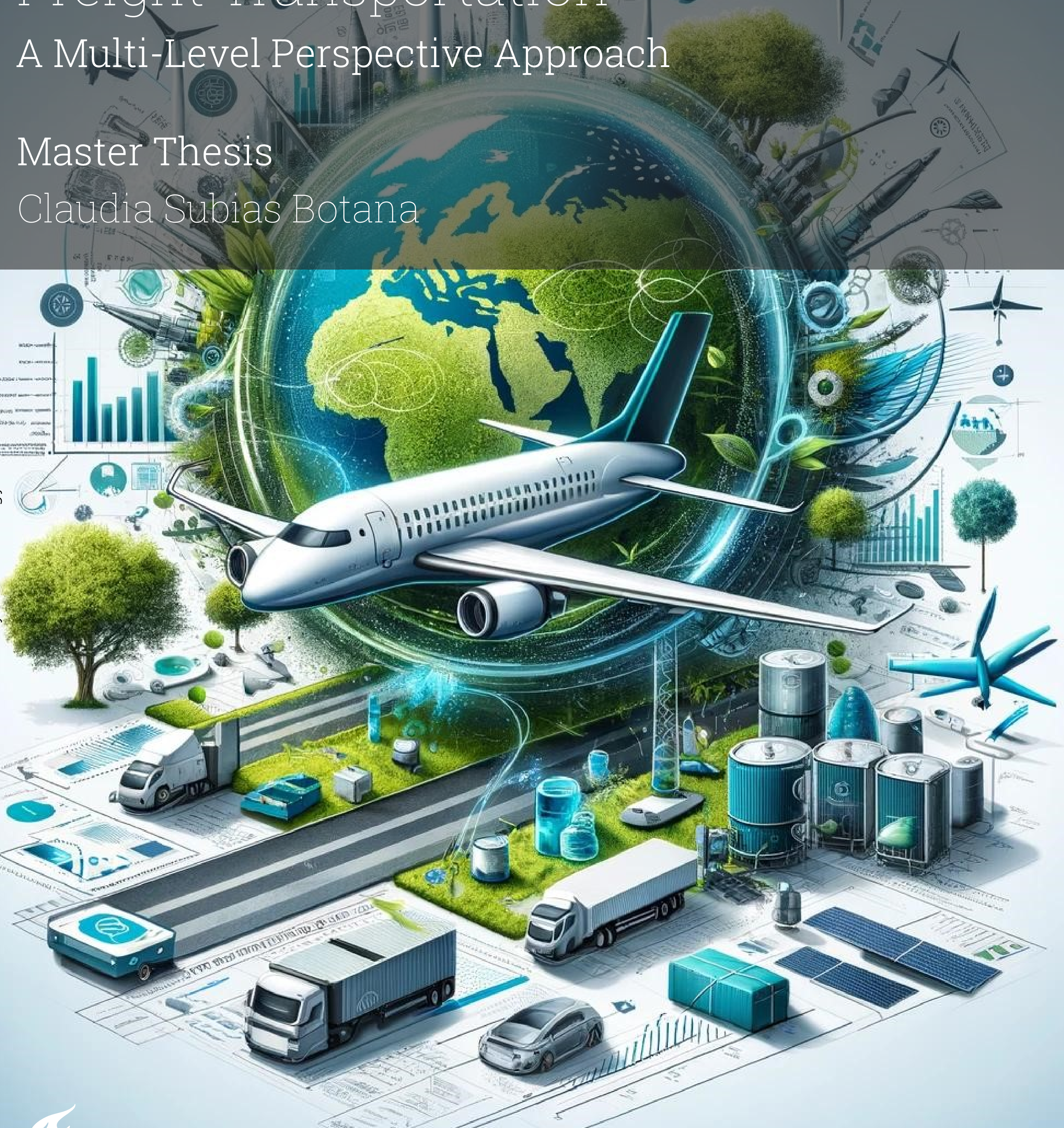
Analyzing the Introduction of Hydrogen-Powered Aircraft in Air Freight Transportation

A Multi-Level Perspective Approach

Master Thesis

Claudia Subias Botana



Delft University of Technology

Analyzing the Introduction of Hydrogen-Powered Aircraft in Air Freight Transportation

A Multi-Level Perspective Approach

by

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Completing this thesis has been a significant milestone, and I am proud of what has been accomplished. As I move forward, I am excited about the new challenges and opportunities that await.

Claudia Subias Botana
Delft, August 2024

Summary

Air transport, encompassing both passenger and cargo airplanes, is the second-largest energy consumer in the transportation sector, following road vehicles. The passenger sector has seen rapid expansion in recent years, with demand expected to double by 2040. Air cargo, which surged during the pandemic, is also experiencing increasing growth due to e-commerce and express logistics. Although frequent flying significantly boosts global connectivity and economic development, it also results in increasing carbon emissions.

Despite technological improvements making current aircraft 80% more fuel-efficient than those from the 1960s, aviation remains a significant environmental concern, responsible for around 4% of global CO2 emissions. The industry's reliance on fossil-based jet fuel poses challenges for decarbonization, especially as carbon emissions at high altitudes have a substantial atmospheric impact. Nevertheless, pressure to mitigate climate change is rising. The European Green Deal aims for climate neutrality by 2050, pushing the aviation industry towards net-zero carbon emissions.

Given that the current kerosene-based propulsion system is the primary source for carbon emissions, a radical change in propulsion technologies is urgently needed to achieve zero-carbon-emission flying by 2050. Among the technologies being explored, hydrogen propulsion is identified as a promising alternative for medium-range flights, making it particularly suitable for European air transport. Therefore, this master thesis focuses on the transition to hydrogen propulsion as a solution to significantly reduce aviation's carbon footprint.

This study aims to understand how hydrogen propulsion can aid in decarbonizing air transport by identifying key factors influencing its adoption and exploring a strategic pathway for implementation. The Multi-Level Perspective (MLP) framework served as the theoretical foundation for analyzing the transition, focusing on a technological niche, the socio-technical regime, and landscape pressures. This framework aids in the understanding that energy transitions often start in niches, highlighting hydrogen propulsion as a potential technological niche to significantly reduce carbon emissions in aviation. Moreover, this study intended to investigate the idea of introducing hydrogen-powered technology in a specific aviation market niche to accelerate the transition. The air freight sector was examined for its potential to be perceived as a safer market for the implementation of a new technology compared to a direct application in passenger aviation. Additionally, the air cargo sector was found to be an underexplored market in the development of sustainable aviation technological solutions, resulting in a significant knowledge gap in both scientific literature and industry applications.

Following a qualitative approach, an extensive literature review and eleven interviews were conducted with aviation experts from academia, industry, and government. The interviews aimed to gather insights on the drivers and barriers for hydrogen adoption in aviation, as well as on the potential of air cargo. The questions for the experts were formulated according to different levels of the MLP framework to drive the discussions. Firstly, at the niche level, technical aspects on hydrogen technology and air cargo were addressed. Secondly, the necessary conditions for hydrogen-regime transition were discussed across five different dimensions. Thirdly, global events in the aviation landscape that influence the adoption of hydrogen were specified. The wide variety of insights provided by the experts led to the classification of drivers and barriers into four main areas: technological, political, economic, and societal. Since hydrogen technology is still in the early experimental phase, a greater number of technological challenges were identified compared to the other areas.

Results showed diverse technological drivers including hydrogen's clean production using renewable sources, its high gravimetric energy density, and its zero-carbon emissions during flight. However, technical barriers such as low volumetric energy density, the need for a complete overhaul of the existing aviation ecosystem, and challenges in hydrogen logistics and storage were noted. Politically, support for hydrogen adoption is driven by climate commitments and the potential for energy independence, but kerosene taxation and new regulations are needed.

Economically, fluctuating fossil fuel prices and job creation are positive factors, but high initial R&D and infrastructure costs pose substantial challenges. Moreover, societal perception plays a crucial role in the adoption of hydrogen technology. Public support is influenced by the environmental benefits of hydrogen-powered aviation, but safety concerns and a lack of understanding about hydrogen technology necessitate extensive public education and transparent communication efforts.

Although the potential of hydrogen in aviation still needs to be proven, targeting the cargo sector is viewed as a smart move to demonstrate feasibility and build acceptance. Advantages of implementing hydrogen in air cargo include greater flexibility in technology integration due to simpler cabin systems and expertise in handling hazardous materials. Cargo aircraft can optimize tank placement without passenger accommodation constraints and benefit from centralized operations at key hubs, requiring less extensive infrastructure. Socially, it offers a low-exposure environment for technology testing, and economically, centralized hubs reduce costs, with potential market opportunities for ”green” military freighters. Nonetheless, the air freight sector may encounter difficulties in adopting hydrogen technology due to less public pressure for sustainable solutions, weaker economic incentives, and the challenge of justifying infrastructure costs, given the lower flight frequency and smaller market size compared to passenger aviation.

This thesis is the first to explore the intersection of hydrogen-powered technology, socio-technical transitions, and the air cargo sector. It provides a comprehensive analysis by integrating technical, political, societal, and economic perspectives, highlighting the air cargo sector as a promising niche for early adoption. The theoretical framework offers insights into the challenges and opportunities in transitioning to hydrogen propulsion, with broader implications for other high-emission sectors seeking sustainable innovations.

Based on the findings of this research, several recommendations were made to facilitate the transition to hydrogen-powered aircraft. Firstly, governments should implement policies and regulations that incentivize the adoption of hydrogen technology, such as kerosene taxation and CO2 restrictions on flights. Secondly, public education campaigns are necessary to improve societal perception and knowledge on hydrogen-powered aviation. Thirdly, collaboration with other industries working on hydrogen is essential to create a supportive ecosystem for hydrogen technology. Finally, focusing on the air freight sector as a testing ground for hydrogen technology will help build acceptance and pave the way for its introduction into passenger aviation.

Future research should focus on several key areas such as incorporating quantitative analyses to assess the economic viability and environmental impact of hydrogen-powered aircraft, expanding the scope of interviews to include diverse geographical regions, and integrating other research methods like case studies and surveys. Additionally, developing policy frameworks to support large-scale adoption and exploring other market niches, such as military and unmanned aircraft systems, are crucial for scaling hydrogen technology in aviation.

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Nomenclature

Abbreviations

Abbreviation	Definition
ACI	Airports Council International
ACTKs	Available Cargo Tonne-Kilometers
AE	Aerospace faculty
ATAG	Air Transport Action Group
ATP	Advanced Turboprop
AZEA	Alliance for Zero-Emission Aviation
CAGR	Compound Annual Growth Rate
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CO2	Carbon dioxide
CTKs	Cargo tonne-kilometers
CoSEM	Complex Systems Engineering and Management
DLR	German Aerospace Center
EASA	European Union Aviation Safety Agency
EEA	European Environment Agency
ETS	Emissions Trading System
EU	European Union
FTK	Freight Ton Kilometers
GMF	Global Market Forecast
GOLIAT	Ground Operations of LIquid hydrogen AircrafT
HIA	Hydrogen in Aviation
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICCT	International Council on Clean Transportation
IDE	Industrial Design Engineering faculty
IEA	International Energy Agency
IFA	International Freight Association
IFC	International Finance Corporation
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Analysis
LH2	Liquid Hydrogen
MLP	Multi-Level Perspective
NGO	Non-Governmental Organization
NLR	Netherlands Aerospace Center
OECD	Organisation for Economic Cooperation and Development
OEM	Original Equipment Manufacturer
PPE	Personal Protective Equipment
R&D	Research and Development
SAF	Sustainable Aviation Fuel
SASI	Strategic Aviation Services International
SMEs	Small and medium-sized enterprises
ST	Socio-Technical
T&E	Transport and Environment
TPM	Technology, Policy, and Management faculty
TRL	Technology Readiness Levels
WTTC	World Travel and Tourism Council

1 Introduction

This chapter serves as the introduction to the research undertaken in this Master's Thesis. It begins with Section 1.1, which introduces the problem being investigated. Following this, Section 1.2 highlights the existing knowledge gap identified in the academic literature, further elaborated in Chapter 2. Following a discussion of the research objectives in Section 1.3, Section 1.4 presents the main research question and the related sub-research questions that the study seeks to address. Section 1.5 outlines the parties involved in the research, conducted as part of a master's thesis internship with Airbus. Section 1.6 determines how the research for this thesis is connected to the CoSEM Master's program. Finally, Section 1.7 provides an overview of the thesis structure.

1.1. Problem Definition

Air transport represents the second-largest energy consumer in the transportation sector, following road vehicles, and encompasses both passenger and cargo airplanes. Aircraft are configured for transporting passengers, freight and mail, connecting people and economies worldwide in a fast and safe manner (Martínez et al., 2019; World Bank, 2023). Over the past few decades, the industry has experienced rapid growth, enhancing connectivity and playing a significant role in economic development (IATA, 2017). The International Air Transport Association (IATA) reported that airlines carried 4.5 billion passengers worldwide in 2019. Additionally, it estimated that air travel demand will double by 2040, resulting in a total of over 8 billion passengers traveling around the globe (Martínez et al., 2019). In the global market for freight, measured in tonne-kilometers, cargo emerged as the leading sector in 2021, being of substantial help during the pandemic (Bouwer et al., 2022). However, its performance has since decreased to just below the levels seen in 2019. Nonetheless, it now accounts for about 20% of total airline revenue, which is twice the average before the pandemic (IATA, 2023c).

Furthermore, airfares are influenced by fuel costs, driving the industry to minimize fuel use through advancements in aircraft design, air traffic management, and airport operations (IPCC, 2010). Reports from the World Bank and the Intergovernmental Panel on Climate Change highlight that technology, including automatic flight systems, has made current aircraft 80% more fuel-efficient than those from the 1960s (ICAO, 2010; World Bank, 2012). However, despite the numerous advantages of air transport and continued enhancements in technology, operations, and infrastructure to further improve fuel efficiency, the aviation industry continues to significantly affect the environment, impacting climate change. Consequently, it is responsible for 3 to 5% of the world's total CO2 emissions and 3.8% in Europe (European Commission, 2021; Kivits et al., 2010; Klöwer et al., 2021).

The key issue relies on the fact that aviation is currently still operating on fossil fuels, mostly kerosene (JET-A1) (IEA, 2023). This high dependence on fossil-based jet fuel, as well as the significant financial investment that a technological change would require, make it a hard-to-decarbonize sector (IFC, 2023). Additionally, aircraft's emissions are being released at much higher altitudes than those from ships or trucks, therefore creating a much larger impact on the atmosphere's chemical composition (Kivits et al., 2010; MIT, 2023).

In fact, air transport is expected to be the last among the primary modes of transport to adjust to a future limited by carbon restrictions (Kivits et al., 2010). Nonetheless, in 2019, the European Union launched the *European Green Deal*, aiming to achieve climate neutrality across the continent by 2050. This sets ambitious goals for the aviation industry, which is expected to achieve net-zero carbon emissions by this deadline. Striving for climate neutrality aligns with the EU's dedication to worldwide climate efforts as stipulated in the *Paris Agreement* (European Commission, 2023; McKinsey & Company, 2020). Moreover, it is expected that the global aviation market will experience significant growth throughout the forecast period from 2023 to 2031 (IEA, 2023). This underscores the urgent need to pursue a sustainable aviation industry transition in Europe through the next decades, requiring substantial large-scale systemic changes.

In Europe, Airbus stands as the leading aircraft original equipment manufacturer (OEM) and is committed to making significant advancements in the development and adoption of hydrogen technology. The company views it as one of the most promising technologies for decarbonizing aviation (Airbus, 2024d). Moreover, it aims to introduce the world's first hydrogen-powered commercial aircraft by 2035. Through its ZEROe project, Airbus is investigating various aircraft configurations and technologies, while also establishing the necessary environment for the production and provision of hydrogen (Airbus, 2024f). Hydrogen can be utilized as a fuel source for aircraft propulsion in two distinct ways, via hybrid hydrogen-electric fuel cells or direct hydrogen combustion. Additionally, it offers the benefits of being produced through various industrial-scale methods in a sustainable way, while also being capable of enabling economically efficient and carbon-free combustion (Petrescu et al., 2020). This makes hydrogen propulsion a promising alternative to fossil-based jet fuel, offering the potential for a substantial reduction in carbon footprint (Yusaf et al., 2022).

Moreover, the shift from current fossil-based jet fuel to hydrogen propulsion represents a socio-technical transition from one socio-technical system to another (Geels, 2004). Such a transition could be described as the complex co-evolution of interconnected technological, social, economic, and institutional transformations, which usually follow a path-dependent trajectory and are unpredictable (Geels, 2019a). Furthermore, analyzing transitions through the perspective of socio-technical systems allows for greater focus on their societal aspect, instead of focusing exclusively on the technology (Geels, 2006). The complexity of sustainable energy transitions involve various actor groups, making it crucial to closely examine their interactions and collaborations (Geels, 2004; Kim et al., 2019). These include airport operators, airlines, aircraft manufacturers, logistics companies, passengers, governmental authorities, as well as energy providers (Kivits et al., 2010). Additionally, the dynamic interplay among technological developments, industrial networks, markets, policy, infrastructure and culture is essential for the successful adoption and integration of a new technology into society (Geels, 2005, 2012).

1.2. Academic Literature Gap

As a socio-technical system, the aviation industry has undergone significant transitions, such as the switch from propeller to turbojet aircraft, which Geels (2006) examined using the Multi-Level Perspective (MLP). This framework, considering niche, regime, and landscape levels, helps to understand how technological innovations emerge and integrate into existing systems. While substantial research exists on historical transitions, like the jet age, recent innovations, especially sustainable ones, are less explored.

Nakamura et al. (2013) highlighted a gap in studies on contemporary aviation transitions, noting the need for research on sustainable technologies beyond jet engines. Sustainable Aviation Fuels (SAF), hydrogen propulsion, and battery-electric systems are among the alternatives being explored, with hydrogen showing promise for medium-range distances, particularly suitable for European air transport. Despite significant advancements, the socio-technical transition to hydrogen in aviation, particularly in the cargo sector, remains under-researched.

This thesis aims to address this gap by applying the MLP framework to analyze hydrogen technology adoption in aviation as a whole and in air cargo. This specific sector, less studied than passenger aviation (Bombelli et al., 2020), presents a valuable niche for deploying hydrogen technology, potentially easing safety concerns and enhancing public acceptance. The globalization of trade, together with the boom of e-commerce and express logistics, have increased demand for sustainable air freight solutions, adding urgency to this transition.

The knowledge gap of this thesis lies in the socio-technical analysis of hydrogen transition in aviation and within the air cargo sector. This research will utilize the MLP framework to explore this emerging area, considering the current socio-technical regime's reliance on fossil fuels and the broader landscape pressures, such as climate change and fossil fuel depletion. Chapter 2 further elaborates on this gap.

1.3. Research Objective

This research aims to employ a socio-technical system perspective to examine the transition from the current fossil-based socio-technical system to a hydrogen-based socio-technical system in aviation, also highlighting a focus on the air freight sector. It seeks to explore how hydrogen propulsion can contribute to the decarbonization of air transport by identifying the key factors that influence its adoption and evaluating strategic implementation pathways.

From an academic standpoint, this master thesis seeks to enhance understanding of how socio-technical transitions towards sustainability can be accelerated, specifically through radical technological innovations like hydrogen-powered aircraft. It aims to offer insights into the introduction of hydrogen in the air cargo sector before the passenger sector, considering the air freight sector as a potential niche market for quicker and easier hydrogen implementation. This niche-first approach is based on the understanding that sustainable transitions often begin within niches.

Furthermore, the research intends to explore the viability and integration challenges of hydrogen technology in aviation, assess necessary infrastructure and policy frameworks, and consider the economic, environmental, and societal implications of such a transition. By examining the interplay between technological innovations, regulatory environments, and societal trends, the research seeks to identify the conditions under which hydrogen can become a long-term sustainable propulsion alternative in aviation. Beyond strategic industry recommendations, these insights can aid in policymaking by addressing challenges in the aviation industry's hydrogen transition.

1.4. Research Questions

Based on the identified knowledge gap, this master thesis study aims to address the following main research question:

To what extent could hydrogen propulsion play a role in the decarbonization of air transport?

To tackle the question presented above, the following two sub-questions will be examined. Each sub-question is formulated to support the research and gather information that aids in answering the main research question.

SQ1: *What are the drivers and barriers for hydrogen transition in air transport from a socio-technical perspective?*

Identifies and analyzes the factors that either facilitate or hinder the adoption of hydrogen as a propulsion technology in air transport, considering both technological, political, economic, and societal aspects. *"Drivers"* refer to the motivating forces or enablers that promote the hydrogen transition. *"Barriers"* are the challenges or obstacles that impede this transition. The socio-technical perspective emphasizes the interaction between society and technology in shaping this transition.

SQ2: *How do aviation stakeholders perceive the introduction of hydrogen-powered technology in the air freight sector prior to the passenger market?*

Explores a potential niche market for hydrogen technology in aviation. It investigates whether stakeholders view it as a feasible starting point for hydrogen implementation before expanding to the passenger market. Moreover, it seeks to understand the reasoning behind prioritizing air freight, identify potential advantages or concerns, and comprehend how this strategy might impact the broader adoption of hydrogen technology in aviation. The focus is on the stakeholders' perspectives and the implications of starting with freight rather than passenger flights.

1.5. Involved Parties

Besides academia, this thesis considers the key role and collaboration of Airbus as a leading stakeholder in the innovation, design, and manufacturing of sustainable aircraft technologies in aviation. Airbus's commitment to exploring and implementing a hydrogen-powered aircraft underscores the industry's readiness to embrace sustainable alternatives to fossil-based jet fuel. The research strives to provide valuable insights and recommendations that could guide Airbus and similar industry stakeholders through the transition towards sustainable aviation practices, emphasizing the critical challenges and considerations for integrating hydrogen technology in aviation. Furthermore, it also offers policymakers important insights for shaping policies and regulatory frameworks that encourage the adoption of hydrogen solutions in aviation. By pinpointing the necessary infrastructural, technological, and societal conditions for hydrogen's integration, it aids in outlining targeted policies that promote sustainability and innovation within the aviation industry, steering it towards a more sustainable future.

1.6. Link of the Research to the CoSEM Master Degree

This research is closely aligned with the CoSEM master program, focusing on a socio-technical system analysis. The goal is to assess the feasibility of implementing hydrogen technology in the air freight sector to facilitate the transition towards carbon emission-free air transport. While the technical aspect, namely hydrogen-powered aircraft, represents the core of the research, the technology alone cannot drive change. It necessitates a collaborative effort involving multiple actor groups within the value chain of aviation to shift the current paradigm. Hence, the research examines how the freight aviation industry's complex interplay of stakeholders, technology, infrastructure, logistics, and regulations influences the adoption of such an innovative technology. This is important for understanding how innovation drives changes in transport, logistics and energy systems, aligning with the program's emphasis on addressing real-world problems through systems thinking.

1.7. Master Thesis Structure

The outline of this master's thesis is structured into six chapters. Chapter 1 introduces the problem, highlighting the academic literature gap, stating the research objective, and framing the research questions. Chapter 2 details the literature review, which covers the state-of-the-art in air transport, sustainable aviation technologies, and socio-technical transitions. Chapter 3 explains the qualitative research approach and provides further elaboration of the research methods, particularly focusing on the interviews. Chapter 4 presents the empirical results extracted from the expert interviews. Chapter 5 shows an overview of the drivers and barriers of hydrogen adoption and of the advantages found in air cargo. Chapter 6 provides an answer to the research questions presented in this study. It also discusses the main contributions and implications, as well as the limitations and recommendations for future research Lastly, Chapter 7 displays the conclusion of the research.

2

Literature Review

In this chapter, the state-of-the-art literature review and the knowledge gap of the study are presented. Section 2.1 outlines the literature search method utilized to identify relevant papers for the research. The article selection resulted in three main categories according to their relevance, displayed in Section 2.2. Thus, the literature review is divided in three parts, namely air transport (Section 2.3), sustainable aviation propulsion technologies (Section 2.4), and socio-technical transitions (Section 2.5). The chapter concludes with the literature knowledge gap (Section 2.6).

2.1. Literature Selection Method

An initial literature review was undertaken to identify the research gap. The purpose was to provide an overview of the current state of scientific knowledge on the important topics relevant to this master thesis research study. The selection of articles will be guided by the PRISMA method, which displays a systematic literature review, commonly used in academic research to aggregate and synthesize existing knowledge on a specific subject matter. It is utilized by researchers to display their selection criteria in a transparent manner (Page et al., 2021). The approach entails a three-step process, namely searching, filtering and selecting. The first step involves identifying databases and open libraries to access pertinent literature according to several search strings. The subsequent step requires filtering the records previously found. Finally, in step three the final articles will be selected based on different criteria. A concise overview of the literature that has been referenced will be the output of this method (Figure 2.1).

Initially, the process begins with the use of multiple search queries across two databases such as Scopus and MDPI. These queries incorporate combinations of specific keywords relevant to the research focus, in this case concerning aspects of aviation, air cargo, environmental impact, sustainable aviation technologies (hydrogen), and socio-technical transition. This comprehensive search resulted in the identification of 13,080 records.

Following this search, a three-step filtering process is applied to refine these results. The first filter screens for document types, restricting the selection to review and research articles, which significantly narrows down the pool of documents. The second filter applies a temporal criterion, including only publications from the years 2002 to 2024 to ensure the timeliness and relevance of the research. The third filter demands the documents to be in English, further reducing the number to 584 records.

The final phase involves applying specific selection criteria to these filtered records to ascertain their direct relevance to the research question. The selection process involves an evaluation based on the title and abstract of each document, ensuring that the content is directly applicable to the research focus. Additionally, the studies must address technical, social, policy, or economic aspects relevant to the topic. This thorough selection criteria reduces the final list to 40 records. These are then included for in-depth analysis and synthesis in the literature review.

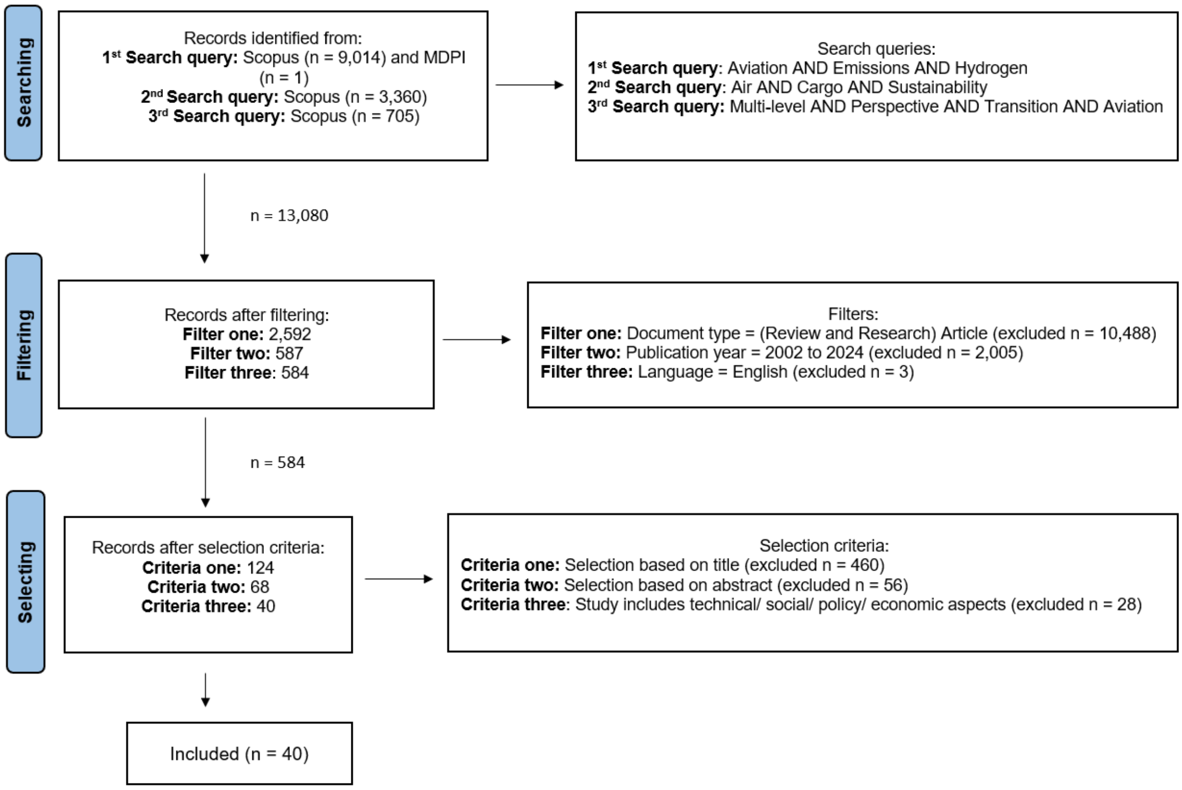

Figure 2.1: Search strategy utilized to find and scope the relevant articles

2.2. Literature Results Overview

The 40 included articles can be seen in Table 2.1, Table 2.2, and Table 2.3. They are distributed in three main categories, namely Air Transport, Sustainable Aviation Propulsion Technologies and Socio-technical Transitions, according to their relevance explained below. This connects directly with the knowledge gap (see Section 1.2), depicting how societal needs and technical capabilities must align and integrate to effectively transition towards new sustainable systems like the implementation of hydrogen-powered aircraft in aviation. Such transitions often require changes not just in technology, but also in people's behaviors, policies, and societal structures.

No.	Article	Relevance
1	Gössling and Humpe (2020)	Analysis on air transport and its sectors
2	Bartle et al. (2021)	Focus on air freight transport
3	Bartulović et al. (2022)	Focus on air freight transport
4	Bombelli et al. (2020)	Focus on air cargo networks
5	Feng et al. (2015)	Focus on air cargo operations
6	Florido-Benítez (2023)	Focus on logistics and e-commerce
7	Popescu et al. (2010)	Focus on air cargo industry
8	Rodbundith et al. (2021)	Focus on e-commerce and air cargo operation challenges
9	Wang et al. (2023)	Focus on opportunities and challenges regarding sustainability in air freight sector

Table 2.1: List of Literature on Air Transport and Air Freight

No.	Article	Relevance
1	Christley et al. (2024)	Analysis on key alternatives to fossil-based jet fuel
2	Kivits et al. (2010)	Analysis of the transition to alternative propulsion technologies in aviation
3	Afonso et al. (2023)	Overview of solutions towards greener aviation
4	Baroutaji et al. (2019)	Focus on hydrogen and fuel cells
5	Cecere et al. (2014)	Focus on hydrogen technology
6	Cremonez et al. (2015)	Focus on biofuels (SAF)
7	Ficca et al. (2023)	Presents a vision for the future of aviation
8	Hoelzen et al. (2022)	Focus on hydrogen-powered aircraft
9	Khandelwal et al. (2013)	Focus on hydrogen-powered aircraft
10	Lei and Khandelwal (2021)	Focus on hydrogen fuel for aviation
11	Najjar (2013)	Focus on hydrogen safety aspects
12	Petrescu et al. (2020)	Focus on hydrogen-powered aircraft
13	Scovell (2022)	Explains hydrogen technology acceptance
14	Su-ungkavatin et al. (2023)	Analysis of alternative propulsion technologies in aviation
15	Yusaf et al. (2022)	Focus on hydrogen fuel for aviation
16	Yusaf et al. (2023)	Focus on hydrogen fuel for aviation
17	Gössling and Humpe (2020)	Analysis on air transport and its sectors

Table 2.2: List of Literature on Sustainable Aviation Propulsion Technologies

No.	Article	Relevance
1	De Haan and Mulder (2002)	Explores the shift to the jet age
2	Geels (2002)	Focus on technology transitions and MLP
3	Geels (2004)	Analysis from sectoral systems of innovation to socio-technical systems
4	Geels (2005)	Technological Transitions and System Innovations
5	Geels (2006)	Explores the shift from propeller to turbojet
6	Geels (2012)	Introduction of the multi-level perspective into transport studies
7	Geels (2019a)	A review of criticisms and elaborations of the Multi-Level Perspective
8	Kim et al. (2019)	Examines key barriers & opportunities for biofuels transition from a socio-technical perspective
9	Kern (2012)	MLP on socio-technical transitions to assess innovation policy
10	Lai et al. (2022)	Socio-Technical System Approach in Prospective Life Cycle Assessment
11	Nakamura et al. (2013)	Explores the shift from propeller to turbojet with MLP and TRL
12	Spinardi and Slayton (2015)	Explores the shift from propeller to turbojet
13	Cohen (2010)	Explores subsequent innovation transitions in aviation
14	El Bilali (2019)	Research on multi-level perspective from other systems than aviation

Table 2.3: List of Literature on Socio-technical Transitions

The subsequent sections Section 2.3, Section 2.4, and Section 2.5, present the literature review conducted across the three aforementioned categories. Section 2.6 identifies the knowledge gap based on the results of the literature review.

2.3. Air Transport

This section starts with a positive view of air transport in Section 2.3.1, Section 2.3.2 and Section 2.3.3. It concludes with an explanation of the negative impact of carbon emissions from increasing air traffic on climate change, which is central to this research topic (Section 2.3.4). Later, Section 2.4 identifies potential technological solutions to decarbonize aviation.

2.3.1. The Economic Benefits of Air Transport

Air transport is crucial for connecting countries and regions, enabling the rapid movement of goods and people. It plays a vital role in global trade, especially for high-value, time-sensitive goods such as pharmaceuticals, electronics, and perishable items (IFA, 2023). This connectivity supports economic growth and development by opening up new markets and facilitating international business and tourism (ATAG, 2020).

Before the impact of the COVID-19 pandemic, the air transport industry was a powerful employment engine, supporting 87.7 million jobs worldwide. This included 11.3 million direct jobs within the airlines, air navigation, airport operations, and aerospace manufacturing sectors. A further 18.1 million jobs were indirectly supported through the industry's procurement from the supply chain. Additionally, the spending of wages by aviation sector employees supported another 13.5 million jobs across various industries, a reflection of the sector's wide economic reach. Moreover, air travel-enabled tourism was a significant contributor to global employment, accounting for around 44.8 million jobs. These figures collectively highlight the aviation industry's crucial role in driving employment and underpinning economic growth on a global scale (ATAG, 2023a).

Furthermore, the development of airport infrastructure requires substantial investment, which can lead to significant economic activity and job creation. Modern and efficient airports enhance a region's attractiveness for business and investment by improving its connectivity and accessibility (PwC, 2014). Moreover, the aviation industry is at the forefront of technological advancement, including the development of more efficient and environmentally friendly aircraft, improved air traffic management systems, and enhanced safety protocols. This drives investment in research and development and promotes innovation across multiple technology sectors (ICAO, 2005).

Additionally, air transport is essential for the tourism industry, which is a major economic driver in many countries. Around 58% of international travelers use air transport (IATA, 2023a). It enables the rapid influx of tourists who contribute to local economies through spending on accommodation, dining, entertainment, and other services. For many island and remote destinations, air travel is the only viable means of large-scale tourist entry (ICAO, 2005). In 2023, the Travel and Tourism sector saw a significant rebound, contributing 9.1% to the global GDP, a 23.2% rise from 2022 and nearing its pre-pandemic economic impact, with just a 4.1% gap from the 2019 figures. This recovery indicates a strong revival in the industry (WTTC, 2023).

Economic resilience is another critical aspect of air transport. During economic downturns or crises, such as the COVID-19 pandemic, the ability to quickly resume air transport is crucial for economic recovery. The rapid distribution of goods and the mobility of personnel via air cargo can help mitigate economic disruptions. In fact, as shown in Figure 2.2, the demand for air cargo services (air cargo airlines and freight forwarders) grew during the pandemic, as air freight became essential for the rapid transportation of medical supplies, including personal protective equipment and vaccines, and for sustaining supply chains amidst global lock-downs (Bouwer et al., 2022).

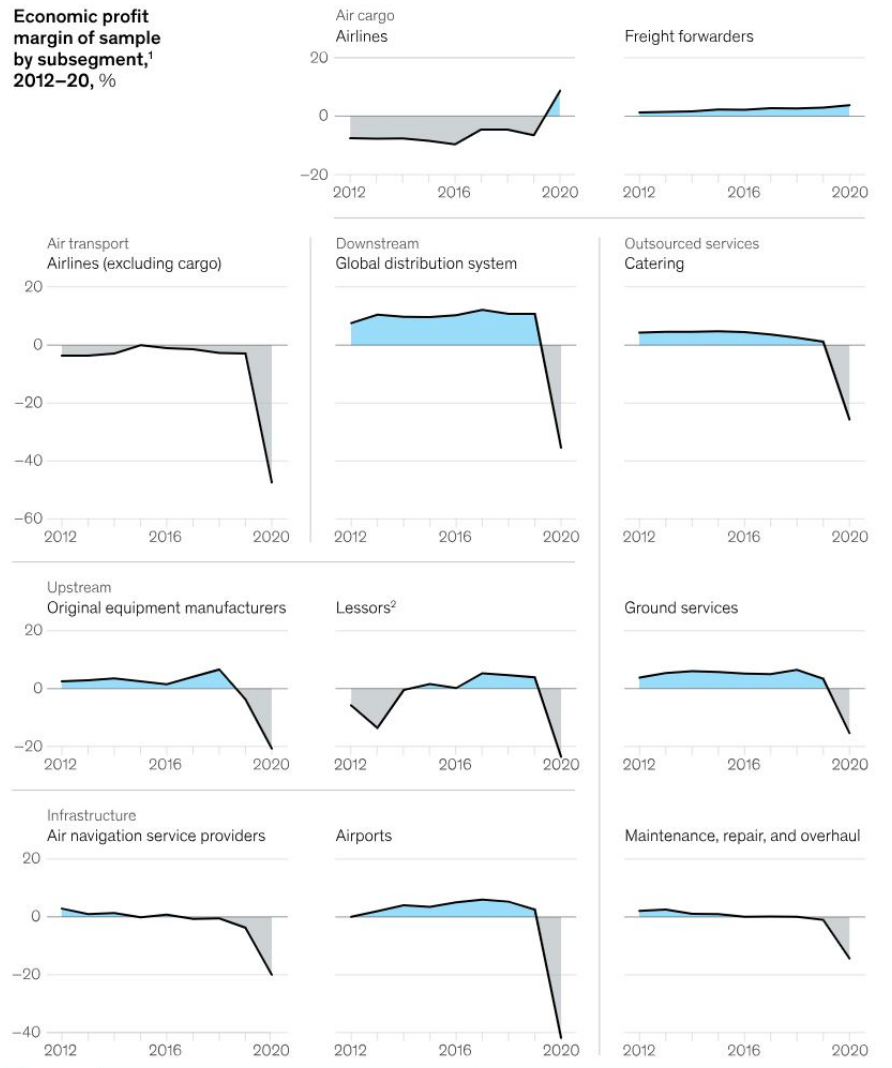

Figure 2.2: Aviation subsectors impact during the pandemic in 2020 (Bouwer et al., 2022)

The economic impact of air transport also includes its multiplier effect on the wider economy, significantly boosting economic output and providing governments with substantial revenue from taxes and duties (OECD, 2008). However, it also faces challenges such as environmental concerns, the need for massive infrastructure investments, and sensitivity to geopolitical and economic instabilities, such as political conflicts that can disrupt air routes, or economic downturns that reduce demand for air travel, which can have substantial negative impacts on the sector's profitability and sustainability (McKinsey & Company, 2023).

2.3.2. Air Traffic Forecast

In 2023, air transport almost reached the activity levels seen before the pandemic (IATA, 2023f). It is forecasted that in 2024, global passenger traffic will surpass 2019 levels for the first time since the COVID-19 pandemic, with an anticipated 9.7 billion passengers, representing a year-on-year growth rate of 12%. This growth is expected to slow down in subsequent years as various markets continue to recover from the pandemic's impact. Moreover, significant risks and uncertainties in these projections arise from macroeconomic factors, including high global inflation, a slowdown in global GDP, low business confidence, and ongoing geopolitical conflicts, such as the war in Ukraine (ACI, 2024). In Europe, passenger traffic reached 2.3 billion in 2023 and it is anticipated to rise to approximately 2.5 billion passengers in 2024 (ACI, 2024).

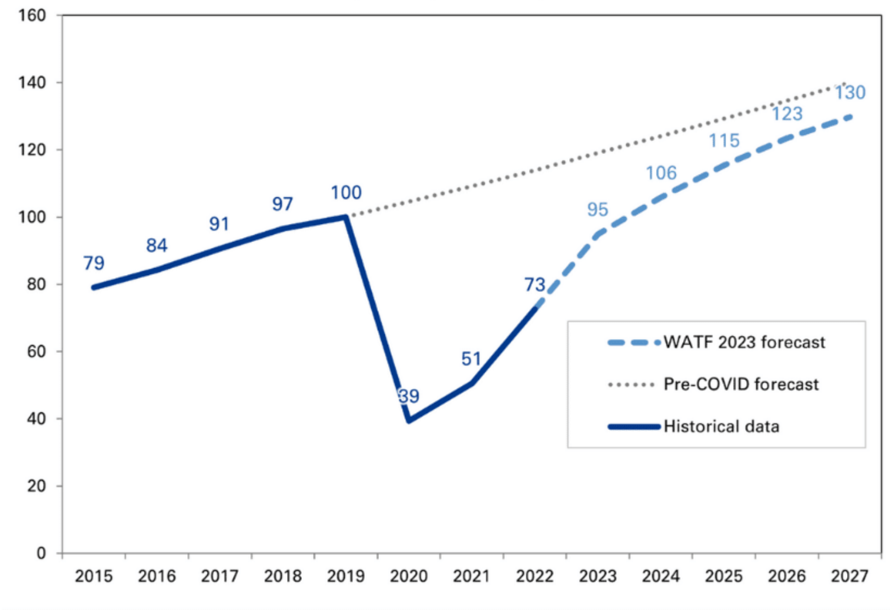

Figure 2.3: Medium-term global total passenger traffic forecast (ACI, 2024)

Furthermore, global air cargo traffic is estimated to grow 4.1% annually through 2041 (Figure 2.4) (Boeing, 2022). At the end of 2023, it experienced a significant year-on-year increase of 10.8% representing the highest annual growth in air cargo tonne-kilometers (CTKs) in two years. Additionally, global air cargo capacity experienced significant growth, with Available Cargo Tonne-Kilometers (ACTKs) increasing by 13.6% year-on-year in December 2023. This rise was driven by the expansion of international passenger belly capacity (Figure 2.5), which resulted in an overall increase of 11.3% in total air cargo capacity when compared to 2022. Moreover, ”preighters” also known as ”cargo in cabin,” refers to an aircraft designed for passenger transport that is temporarily converted to carry cargo in its passenger cabin. This term, a blend of ”passenger” and ”freighter”, was created by Lufthansa’s CEO Carsten Spohr. The concept gained prominence as commercial airlines adapted to the challenges posed by the 2020 COVID-19 pandemic, as shown in the graph during the period from 2020 till the end of 2022 (see Figure 2.5). While converting passenger aircraft into fully dedicated cargo planes can take years, using jets to carry cargo in the passenger cabin allows for much quicker deployment. This became crucial during the health emergency to supply medical equipment (Kingsley-Jones, 2020).

Europe recorded an 8.6% increase in air cargo traffic (CTK) in December 2023 compared to the previous year. The available cargo capacity (ACTK) increased by 7.4% in the same period. This suggests a recovery in air cargo activities, although the growth rates are not as high as in some other areas, like Asia or the Middle East (IATA, 2023e).

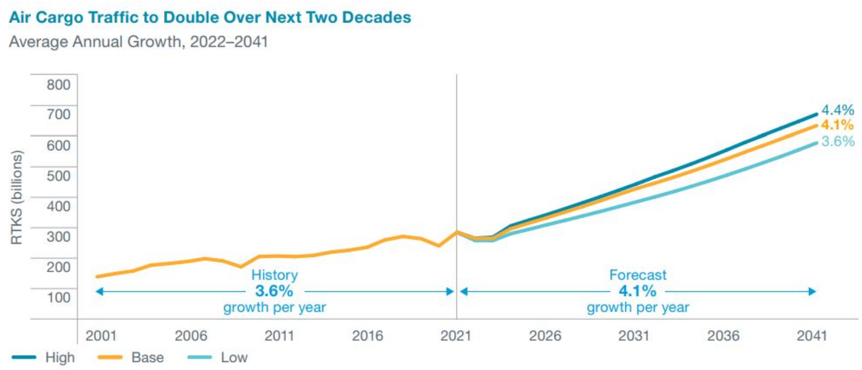

Figure 2.4: World Air Cargo Forecast 2022-2041 (Boeing, 2022)

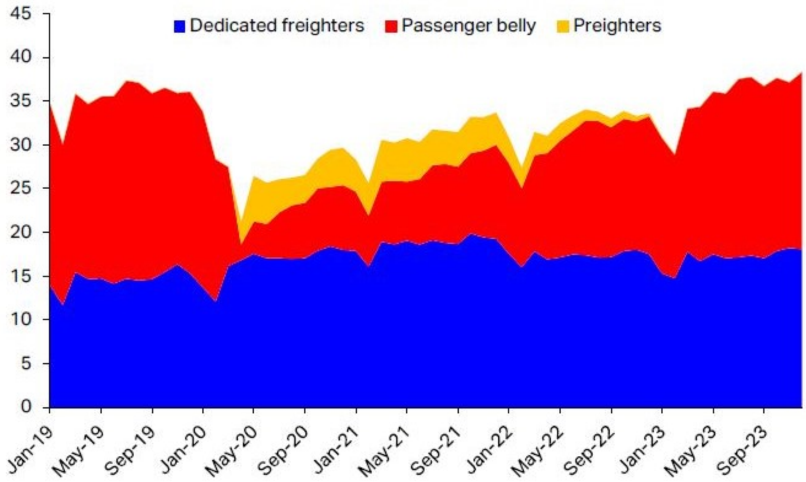

Figure 2.5: International ACTKs by cargo type (billions per month) (IATA, 2023e)

From a company perspective, Airbus' Global Market Forecast (GMF) estimated a demand for 40,850 new passenger and freight aircraft over the next two decades. Approximately 17,170 older and less fuel-efficient aircraft are anticipated to be replaced with newer models. This is part of the industry's move towards more sustainable practices (Airbus, 2024c). It also highlights an anticipated growth in the air cargo sector from 2019 to 2042, with a particular focus on express air cargo. In 2019, express cargo accounted for 17% of the total 250 billion Freight Ton Kilometers (FTK), with general cargo making up the remaining 83%. By 2042, it is projected that express cargo will rise to 25% of an expanded 520 billion FTK due to a Compound Annual Growth Rate (CAGR) of 4.9%, largely driven by the surge in e-commerce. In contrast, general cargo is expected to grow at a slower rate of 2.7% CAGR, although it will still dominate the market in terms of volume (Airbus, 2024c). This shift reflects the high importance of speed and efficiency in global logistics, powered by the e-commerce boom. However, the rise in air cargo flights to meet e-commerce demands directly results in increased fuel consumption and higher carbon dioxide emissions. Thus, there is increasing pressure for the industry to transition to cleaner aircraft technologies.

2.3.3. Air Freight Sector

Air freight, also known as air cargo, refers to the transportation of goods by aircraft (Bartulović et al., 2022). Compared to other transportation modes like shipping, rail, and road vehicles, air cargo is a relatively recent addition to the freight sector (Popescu et al., 2010). It is a crucial component of global logistics networks, offering a fast but often expensive way to ship cargo over long distances (Inbound Logistics, 2023). Air freight services provide connectivity around the world by utilizing the existing infrastructure previously built for air passenger transport. This includes airports and air traffic control systems, which were previously established by public agencies (Popescu et al., 2010). It is also recognized as one of the quickest shipping modes because of its fast delivery times (IFA, 2023). Typically, shipments via air can arrive at their destination in 1 to 5 days, depending on the distance that is needed to reach the final destination (AGI Global Logistics, 2024). This fast reaction time is especially beneficial for businesses that need urgent delivery to be able to meet strict deadlines (Maersk, 2024).

With a market value exceeding US $175 billion, the air cargo sector has emerged as a key player in global trade, representing roughly 35% of its value. Moreover, during the COVID-19 pandemic, air cargo contributed to one-third of the revenue for airlines (IATA, 2023d). Air freight transport is crucial in the e-commerce and express logistics world, being a key component of its daily operations due to its high efficiency and reliability to deliver high-value items such as electronics, luxury products, and popular fashion goods (Rodbundith et al., 2021). According to IATA, e-commerce accounted for 15% of air cargo volumes in December 2019. This figure has been substantially increasing, particularly during and following the COVID-19 pandemic (IATA, 2023b). Air cargo is highly concentrated at a select number of airports and airlines (Florido-Benítez, 2023).

Major cargo airlines, which operate extensive hub-and-spoke networks, are Korean Air, Lufthansa Cargo, Cathay Pacific, and Cargolux (Bryan & O'kelly, 1999). Logistics companies like FedEx, DHL, UPS, and TNT also play a crucial role in the global air cargo industry by managing the entire shipping process from sender to receiver. These companies primarily handle express freight that guarantees highly time-sensitive delivery to meet customer expectations (Florido-Benítez, 2023). At times, air freight is carried on commercial passenger flights, sharing space with passenger luggage. Commercial airlines allocate special cargo holds in their planes for freight shipments (IATA, 2024b). In this way, this shared space enables a cost-effective transport of goods by making use of existing flight routes and schedules (DHL, 2024). For transporting larger volumes of cargo solely, dedicated cargo planes, also known as freighters, are employed. These planes are specifically engineered to maximize cargo space and streamline the loading and unloading procedures (Feng et al., 2015).

However, airlines generally generate higher income from services provided to passengers (Investopedia, 2024). Nevertheless, the air freight sector is projected to experience a higher pace of growth compared to the passenger segment (Popescu et al., 2010). The past two years have shown the considerable importance of freight operations. For airlines that are recovering from the pandemic and aiming to reduce risks and develop new strategies, these findings provide a compelling reason to incorporate cargo operations into their network and fleet planning (Sun et al., 2022).

"Air cargo will be a critical area of resiliency for airlines and airports for the foreseeable future — if managements make it a strategic priority" - Mark Diamond, vice president of SASI (Diamond, 2020)

Furthermore, various industries rely on air freight for its rapid delivery capabilities (AGI Global Logistics, 2024). The manufacturing industry uses air freight to transport essential, time-sensitive components needed for production lines, facilitating just-in-time inventory management (Maersk, 2024). It is also needed for providing humanitarian aid through the delivery of emergency supplies to disaster areas, enabling prompt responses to crises. During the pandemic, pharmaceutical companies used air freight to ship temperature-sensitive vaccines around the world (IFA, 2023). Moreover, the aerospace and defense sectors depend on air freight for delivering crucial items such as avionics, aircraft engines, and military equipment. Additionally, perishables such as produce, seafood, dairy, chemicals, plants, and flowers are also quickly moved to markets to minimize spoilage and maintain freshness (ICAO, 2019).

Nevertheless, there are also disadvantages to the frequent utilization of airplanes as a transport mode. With respect to carbon emissions, airplanes are considered one of the most costly and fuel-intensive transport modes (Bartulović et al., 2022). According to DHL freight, an aircraft produces the highest amount of greenhouse gases per ton kilometer, resulting in the mode with the most significant environmental impact (DHL Freight, 2023). Air freight typically costs 12 to 16 times as much and generates approximately 44 times more $CO2$ emissions than a ship transporting an equal weight over the same distance (CargoFlip, 2023). Compared to road transport, it is 4–5 times more costly (Bartulović et al., 2022). Additionally, aircraft's emissions are being released at much higher altitudes than those from ships or trucks, therefore creating a much larger impact on the atmosphere's chemical composition (MIT, 2023). Since the air freight sector is expected to double in the next years (Boeing, 2022), a considerable increase in carbon emissions from cargo aircraft can be anticipated.

Freighter Aircraft: Airbus A320P2F

Freighters play a crucial role for airlines operating in air cargo markets. Historically, nearly half of global air cargo was transported in the cargo holds of passenger planes. However, freighters provide the tailored scheduling and operational flexibility that many air cargo customers require. Consequently, airlines that have main-deck freighters in their fleets generate 90% of the revenue in the air cargo industry (Boeing, 2022).

Commonly, freighter aircraft are converted from retired passenger planes (CNBC, 2023) .This conversion became especially crucial during the pandemic, when there was a sudden need to distribute vast quantities of vaccines and Personal Protective Equipment (PPE) globally (KPMG, 2022). The existing fleet of dedicated cargo planes was insufficient to handle this surge in demand, making these conversions essential for meeting the challenges of global logistics (Soni, 2022).

This conversion process involves several modifications, including the removal of obsolete passenger equipment like cabin fixtures, adding a large cargo door typically on the left side of the forward fuselage, installing a cargo loading system, reinforcing the main deck floor structure, and equipping the aircraft with additional systems necessary for cargo transport, such as a fire protection system (Engre, 2024). The expense of converting an aircraft depends on the specific modifications a customer needs, but it is generally much cheaper than buying a new cargo plane (Converging, 2023).

One of the most distinguished freighters in the Airbus Freighter Family is the Airbus A320P2F. It is a ”Passenger-to-Freighter” conversion of the standard A320, which has more than 4,200 passenger aircraft currently operating (Airbus, 2024b). This process extends the aircraft's life by modifying the fuselage, adding a large cargo door, and reinforcing the floor for cargo loads. The A320P2F operates efficiently on short- to medium-haul flights, handling main and lower deck cargo. It is valued for its fuel efficiency and capability to operate in smaller airports with limited infrastructure (Airbus, 2024a). Its main aircraft technical characteristics can be seen in Table 2.4 below.

Dimensions	
Length	37.57 m
Height	11.76 m
Wingspan	35.8 m
Capacity	
Max Payload	21 tonnes
Pallets or containers main deck	11
Pallets or containers lower deck	7
Performance	
Max range	3,800 km

Table 2.4: A320P2F Aircraft Characteristics (Airbus, 2024a)

Furthermore, due to the expanding air cargo industry, it is projected that the global fleet of freighter aircraft will double in the next 20 years, with an estimated demand of approximately 1,020 passenger-to-freighter conversions by Airbus (Airbus, 2024a; Boeing, 2022). Together with the increasing pressure to reduce carbon emissions from global air logistics, freighter planes are an increasingly interesting market niche to introduce new innovative solutions, such as hydrogen propulsion systems, before entering the passenger market. In terms of emissions, freighters have different sizes and weight capacities, which leads to significant differences in fuel consumption rates. This means that the heavier the cargo, the more fuel is required, resulting in higher emissions than for passenger planes, which operate under a more standardised set of conditions (CargoAi, 2024; MIT, 2024). Another reason is that passenger risk perceptions towards hydrogen are high due to safety concerns related to highly flammable characteristics. Thus, starting with cargo, could create more acceptance for the passenger market (Scovell, 2022). Additionally, from an economic standpoint, freighters are relatively cheap in price as they are reused from passenger planes.

2.3.4. Air Traffic Impact on Climate Change

As it was seen in the previous sections, air transport, either passenger or cargo, brings substantial benefits to the global economy, including the globalization of trade, the rise of e-commerce, express logistics, and tourism. Nonetheless, the increase in all these activities leads to more frequent air traffic and, thus, an increased consumption of fossil-based fuel in aviation (Bartle et al., 2021). This surge in fuel use not only contributes to higher carbon dioxide emissions and other pollutants but also raises concerns about the sustainability of current aviation practices (Wang et al., 2023). In addition to the environmental issues, using fossil fuels has negative economic effects. The fuel price has increased dramatically due to the fast depletion of fossil fuels. Therefore, to mitigate these environmental impacts as well as to reduce the high dependency on fossil fuels, the aviation industry is exploring different alternative technologies, further elaborated in Section 2.4 (Lei & Khandelwal, 2021).

Propulsion systems are the most prominent contributors to emissions during a flight (ATAG, 2023b; Khandelwal et al., 2013). It is necessary to transition from the current jet turbine engines powered by kerosene-based fuels to alternative propulsion technologies that utilize more sustainable energy sources, like battery-electric and hydrogen-based solutions. A comparison of the innovative technologies can be observed in Figure 2.6.

Sustainable aviation fuel (SAF) also arises as a potential quick alternative to JET A1 (Coykendall et al., 2021). Nevertheless, the ultimate objective is to completely eliminate carbon emissions by 100%, and only electric and hydrogen propulsion have the capability to achieve this goal in the long run (Ficca et al., 2023). While there's growing interest in using rechargeable electric batteries for aircraft, similar to the adoption in electric cars, significant limitations exist due to the inherent weight and low energy density of batteries. Even with advancements in battery technology, the current lithium-ion battery energy storage density is insufficient to power a medium-range flight. As a result, electric planes are likely to be limited to really short-range trips. Besides the energy density and weight issue, considering that batteries occupy a significant amount of space inside the aircraft, it can be impractical for a freighter in which space is key to transporting as much cargo as possible.

This leads to the opportunity to explore liquid hydrogen as a potential energy carrier for the future of aviation. Apart from being a zero-carbon emission fuel, it is suitable to power an aircraft, more precisely the A320 freighter for medium-range flights between 1,500 and 3,000 km. Moreover, since this technology is still in its early stages of development, its prior introduction in a smaller and less risky segment, namely the air freight sector, would make more sense than the passenger segment, where human life on a large scale is at stake. Hence, the A320 freighter aircraft could be particularly suitable as an initial demonstrator model to eliminate carbon emissions from aviation and ultimately reduce the impact on climate change.

<table>
<tr><th>Comparison vs. kerosene</th><th>Biofuels</th><th>Synfuels</th><th>Battery-electric</th><th>Hydrogen</th></tr>
<tr><td>Commuter
<19 PAX</td><td rowspan="5">No limitation of range</td><td rowspan="5">No limitation of range</td><td rowspan="3">Maximum ranges up to 500-1,000 km due to lower battery density</td><td rowspan="3">No limitation of range</td></tr>
<tr><td>Regional
20-80 PAX</td></tr>
<tr><td>Short-range
81-165 PAX</td></tr>
<tr><td>Medium-range
166-250 PAX</td><td rowspan="2">Not applicable</td><td rowspan="2">Revolutionary aircraft designs as efficient option for ranges above 10,000 km</td></tr>
<tr><td>Long-range
>250 PAX</td></tr>
<tr><td>Main advantage ✓</td><td>Drop-in fuel – no change to aircraft or infrastructure</td><td>Drop-in fuel – no change to aircraft or infrastructure</td><td>No climate impact in flight</td><td>High reduction potential of climate impact</td></tr>
<tr><td>Main disadvantage ✕</td><td>Limited reduction of non-CO_2 effects</td><td>Limited reduction of non-CO_2 effects</td><td>Change to infrastructure due to fast charging or battery exchange systems</td><td>Change to infrastructure</td></tr>
</table>

Figure 2.6: Comparison between sustainable aviation propulsion technologies (Clean Aviation, 2024)

2.4. Sustainable Aviation Propulsion Technologies

This section provides an overview of the different technological alternatives that are currently being investigated to potentially substitute conventional petroleum-based jet fuel. It addresses the first sub-question regarding what technological options are available to reduce carbon emissions in aviation. This is the initial step in answering the main research question, as having a broader understanding of the different aspects of each technology is crucial for further research.

Kerosene, also known as JET-A1, is predominantly used across the aviation industry to power the gas turbine engines of an aircraft and it is derived from refined crude oil (Nygren et al., 2009). The aviation industry accounts for 7.8% of total global oil consumption (Planete Energies, 2019). This level of consumption must be reduced, as it contributed to approximately 2% of total carbon emissions from the energy sector in 2022 (IEA, 2023; Ritchie et al., 2020). While substituting fossil fuels is essential, improving energy efficiency is also a key technological driver for reducing fossil fuel usage and thereby decreasing carbon emissions.

The three most explored alternative technologies to kerosene are: Sustainable Aviation Fuel (SAF) which include biofuels and synthetic fuels; battery-electric propulsion; and hydrogen-powered aircraft either through combustion or fuel cells. In other for a new technology to be considered suitable for air transport, it must satisfy several criteria, such as high energy density, low explosion risk, low freezing point, and chemical/physical stability (Cremonez et al., 2015). In addition to the technological feasibility aspect, it also needs to comply with regulations, be financially viable and gain social acceptance.

2.4.1. Sustainable Aviation Fuel (SAF)

One potential option to achieve a nearly 100% decrease in emissions involves modifying the fuel utilized to operate the engines. Sustainable aviation fuels (SAF) are carbon-based and still emit the same amount of CO2 when burned. Nonetheless, the manufacturing process of the fuel throughout its lifespan can compensate for these emissions. The current production price is 3 to 4 times higher than for kerosene fuels and the emissions reduction achieved by using SAF can reach up to 80% (KLM, 2024). However, until SAF's production cost becomes lower so that it can be available on a large scale, the full substitution of kerosene fuels by SAF will still remain challenging (IATA, 2020b).

SAF is "drop-in" fuel that can be utilized in current aircraft without requiring any modifications to the aircraft itself, existing storage, distribution, and fueling systems (Shell, 2024). SAF can be classified into two main categories based on the feedstock used: bio SAF (i.e. biofuels) and synthetic SAF (i.e. synthetic fuels) (Kuehne+Nagel, 2024). Biofuels can be derived from several sources such as cooking oils, fats, plant oils, municipal, agricultural, and forestry waste (Airbus, 2024e). On the other hand, synthetic fuels are produced using a technique that directly collects carbon from the atmosphere (Clean Aviation, 2024; IATA, 2024a).

Furthermore, SAFs can be classified as environmentally sustainable due to their non-competitive nature with food crops or resources, as well as not requiring additional water or land clearance. Moreover, SAF does not contribute to environmental problems like deforestation, soil degradation, or loss of biodiversity (IATA, 2020a). While fossil fuels are heavily responsible for the increase in CO2 levels by releasing carbon that was previously stored, SAF (Sustainable Aviation Fuel) recycles the CO2 that has been absorbed by the biomass utilized in the feedstock throughout its lifespan (Figure 2.7) (IATA, 2024a).

Nevertheless, even if SAF production expands and it is able to compete on price with fossil-based fuels, it will never be able to reach zero-carbon emissions. For that, innovative propulsion technologies are needed such as battery-electric or hydrogen aircraft discussed in the next subsections below (Section 2.4.2 and Section 2.4.3).

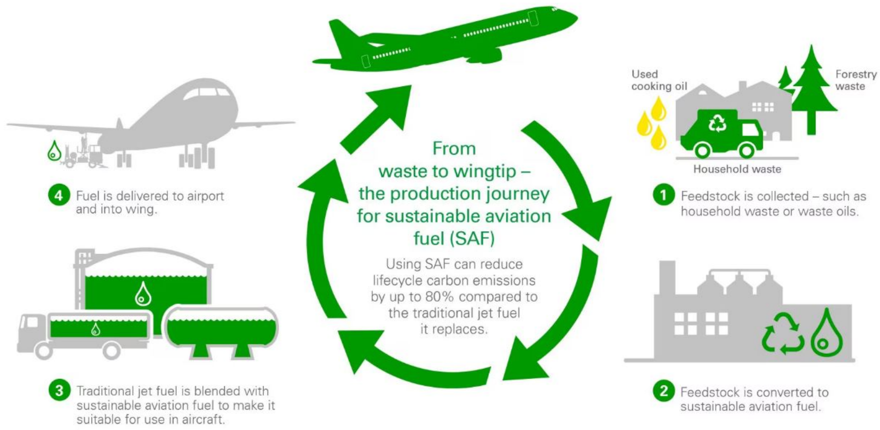

Figure 2.7: SAF Lifecyle Diagram (Air bp, 2022)

2.4.2. Electric-powered aircraft

The electrification of vehicles is rapidly expanding and its environmental benefits are evident across society (Brown et al., 2010). Electric bicycles and scooters are increasingly common in urban areas (Conzade et al., 2021). Public buses, trams and trains are transitioning to electric power (Ajanovic et al., 2021). Car manufacturers are also shifting their focus towards manufacturing more electric vehicles (IEA, 2024). Tesla, for instance, has developed a highly market competitive electric car (Musk, 2013). However, these vehicles are only suitable for relatively limited distances, making them rather impractical to apply in the aviation industry.

Alternatively to jet fuel, electric-powered aircraft are often equipped with rechargeable lithium-ion batteries and electric motors known for being carbon emission free (Becher, 2023). Nonetheless, it is highly improbable that battery technologies will ever achieve an energy density that is adequate for enabling the operation of an electric aircraft for mid-range and long-range flights. Hence, their application is restricted to very short flights (Clean Aviation, 2024). But when it comes to such short distances, high-speed rail is already an available option. So even with considerable technological progress, it will still face increasing competition. Most likely, the only case where electric aircraft might be used, would be for routes where the volume of travel is relatively low for rail or for areas where it would not be feasible to establish a railway system (IEA, 2019).

Furthermore, the viability of electric planes in the future highly depends on advancements in battery technology (Crownhart, 2022). Despite significant advancements in the last 20 years, batteries continue to face challenges due to their low gravimetric energy densities, which range from 0.2 to 0.5 kilowatt-hours per kilogram, as well as their restricted lifetime cycles (Clean Aviation, 2024). Although there have been some improvements in energy density, battery technology would require a significant breakthrough in order to be suitable for longer distances (Eurocontrol, 2024). Additionally, significant aircraft design modifications are needed due to the heavy weight and large space occupied by the batteries (NLR, 2021). Next to this, the implementation of fast charging or battery exchange systems would necessitate substantial modifications to the airport infrastructure (Clean Aviation, 2024).

2.4.3. Hydrogen-powered aircraft

Hydrogen-powered aircraft are a part of an emerging field of sustainable aviation technology that focuses on using hydrogen as a fuel source (NLR, 2021). Hydrogen is the most abundant element in the universe and if generated sustainably, it can be viewed as a zero-carbon fuel since it does not emit CO2 during its usage (European Commission, 2018; IATA, 2020b). In this case, it is known as green hydrogen, which is produced through the electrolysis of water using electricity derived from renewable sources such as solar and wind (TNO, 2024).

When burned, hydrogen produces only water vapor as a by product, because the fuel itself does not contain carbon (IATA, 2020b). Hence, this technology is seen as a potential way to reduce the environmental impact of air transport (Clean Aviation, 2024).

In fact, the concept of hydrogen as an aircraft fuel is well-established and has been demonstrated in flight over a long history of research (NLR, 2021). Its first application in aeronautics was to inflate a gas balloon, known as the Charliére Hydrogen Balloon in 1783. Later in 1893, it was used as fuel for an airship, the Zeppelin. In 1937, hydrogen was implemented to gas turbines with the HeS-1 model (Khandelwal et al., 2013). A couple of decades later in 1956, the hydrogen-powered demonstrator aircraft emerged in the USA as part of the NACA-Lewis liquid hydrogen flight test program, utilizing a modified B-57B Canberra military aircraft. Similarly, in the 1980s in the USSR, the Tupolev Tu-155, a modified version of the Tu-154 civil jetliner, was developed (NLR, 2021). In they year 2000, the European Commission-funded the CRYOPLANE project, led by Airbus Germany, which explored liquid hydrogen's potential further to initiate a large-scale applicability in aviation (Khandelwal et al., 2013). In Figure 2.8 the evolution of hydrogen applications in the aviation industry can be seen.

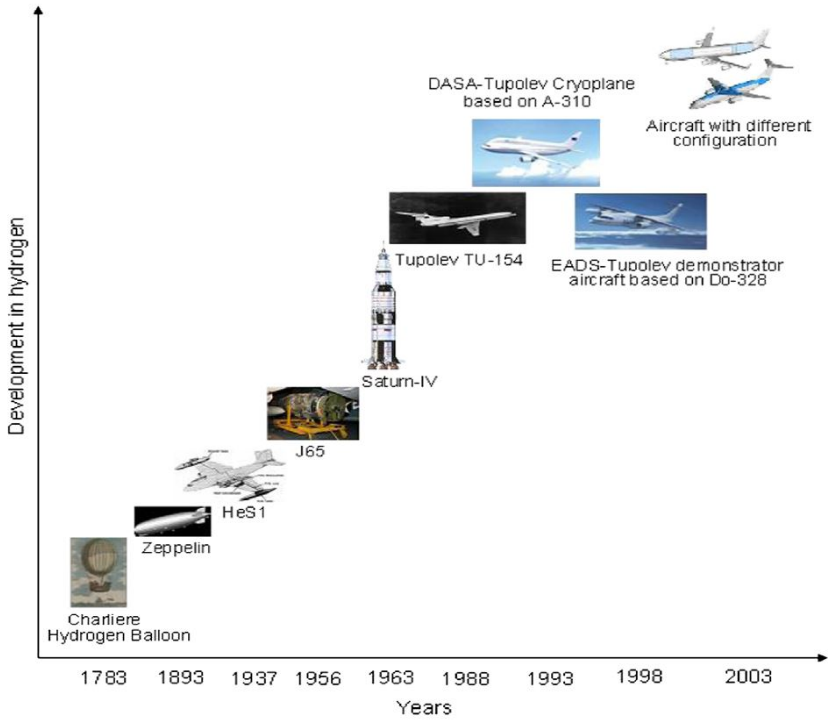

Figure 2.8: Hydrogen evolution in the aviation industry (Khandelwal et al., 2013)

Furthermore, hydrogen can be utilized as an aviation fuel in two ways: directly as a fuel in combustion engines or as a source to generate electricity using fuel cells (Kivits et al., 2010). In the case of hydrogen combustion, liquid or gaseous hydrogen is burned in a modified gas-turbine engine to generate thrust (Airbus, 2020b). This method is the same as conventional internal combustion, but hydrogen, usually employed in its liquid form, is used instead of traditional fossil fuels (Airbus, 2020b; Kivits et al., 2010). On the other hand, fuel cells use a chemical process to convert hydrogen into electricity. Although more efficient than combustion engines it is much more complex and expensive to manufacture (Airbus, 2020a). These two options are still in the early stages of development, yet they continue to gain more and more attention worldwide.

Liquid hydrogen combustion has become increasingly attractive because of its high energy density which is three times higher than for jet fuel (Tashie-Lewis & Nnabuife, 2021). Thus, when fully commercialized, it is expected that it will have lower operational costs compared to an aircraft powered by kerosene, because it will use less fuel to cover the same distance (Cecere et al., 2014). Nevertheless, its initial costs can be large due to the specific cryogenic tanks required to store the liquid hydrogen safely (Burke et al., 2024).

Besides of its high-energy density, endless supply, and cleanliness, liquid hydrogen also gives the opportunity to be independent from foreign control (IATA, 2020b). Moreover, the main advantage of using direct combustion is that it does not emit carbon emissions and it can be achieved with little modifications to existing gas turbine technology, mostly focused on the combustor (TUDelft, 2023). In contrast to a fossil fuel spill, a hydrogen leak would not pose the same environmental risk because hydrogen is an element already present in the atmosphere (IATA, 2020b).

However, several challenges hinder its widespread adoption in the aviation industry. Due to past accidents like the Hindenburg disaster, it has a negative public reputation with regards to safety considerations (Christley et al., 2024). Hydrogen safety concerns mostly revolve on its ignition and combustion properties, including its wide flammability range detonation threshold, low ignition energy, relatively fast flame velocity, and quick diffusion and buoyancy (Najjar, 2013). Furthermore, issues also arise regarding hydrogen storage inside the aircraft. Even when liquefied, it occupies about 4 times the volume of kerosene for the same energy amount (see Figure 2.9) (Khandelwal et al., 2013). Thus, necessitating the use of bigger tanks and aircraft redesign to accommodate these tanks, most likely augmenting the aircraft size (Najjar, 2013). As a direct result, this increases the overall weight of the system, compromising the aerodynamic efficiency (TUDelft, 2023).

Additionally, the size and weight of the tanks could be a problem for long-range flights as higher energy demand is required, thus more fuel consumption (Clean Aviation, 2024). A possible aircraft design was provided by industry experts positioning the tanks along the airplane's longitudinal axis, rather than the traditional placement in the wings (see Figure 2.10) (Yusaf et al., 2023). Moreover, because hydrogen must be liquefied at very low temperatures (minus 253 ºC), specially insulated tanks are required to prevent heat leakage and hydrogen evaporation (Burke et al., 2024). Lastly, the flammable nature of liquid hydrogen can cause the flame to expand towards the tank under specific engine circumstances. This occurrence, known as flame flashback, greatly increases the likelihood of an explosion. Additionally, since hydrogen is odorless and colourless, it can be challenging to find leaks or combat a hydrogen fire that is not visually detectable (IATA, 2020b; TUDelft, 2023).

When LH2 is used with fuel cells, the challenges are quite similar but with additional fuel cell cost and heavier weight on the aircraft (Eurocontrol, 2024). Nonetheless, these safety issues can be overcome with strict safety protocols and certification processes. Therefore, hydrogen-powered aircraft can be made as equally safe as kerosene aircraft with the implementation of thorough research and standardization measures (TUDelft, 2023).

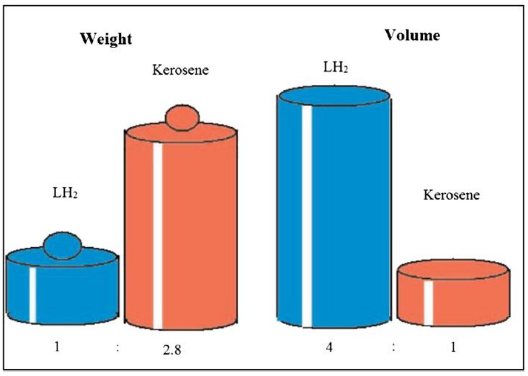

Figure 2.9: Comparison of LH2 and kerosene regarding weight and volume (Khandelwal et al., 2013)

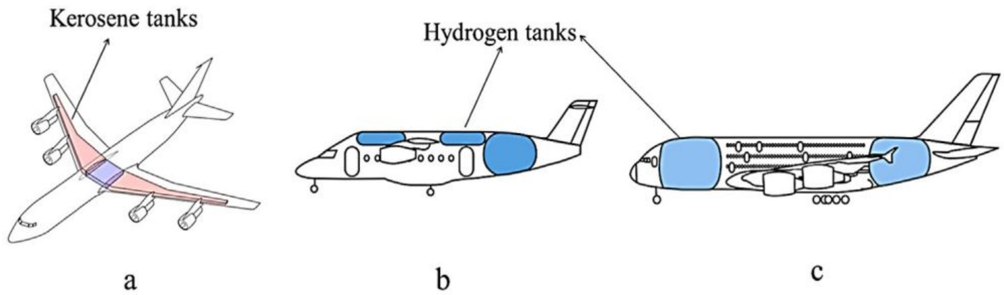

Figure 2.10: Locations of fuel tanks in kerosene-fueled aircrafs (a), medium-range hydrogen-powered aircraft (b), and long-range hydrogen-powered aircraft (c) (Yusaf et al., 2023)

2.5. Socio-technical Transitions

This thesis focuses on the transition of the current aviation industry towards a greener and more sustainable future. Academic literature on this topic arises in the fields of system innovation and transitions. The most relevant literature on system innovation pertains to socio-technical system transitions, under which sustainable aviation is classified (Geels, 2004). The shift from fossil-based jet fuel to a sustainable and innovative propulsion technology represents a transition from one socio-technical system to another, involving a complex and ongoing process (De Haan & Mulder, 2002; Geels, 2012).

Socio-technical transitions refer to the shifts in the interplay between society and technology, encompassing changes in technological innovations, regulations, market structures, cultural norms, and user practices (Geels, 2005). These transitions are not solely technological but involve significant changes in how the society and the economy function and interact with emerging technologies (Geels, 2019a). Technology actors frequently prioritize optimizing the technological side, often overlooking crucial societal considerations (Geels, 2005). Nonetheless, research on sustainable energy transitions should incorporate social perspectives to enable an impactful analysis that addresses the complex interaction between technological advancements, societal needs, behaviors, and values (Geels, 2006; Nielsen & Karlsson, 2018).

In aviation, these transitions involve the evolution of aircraft technologies, operational procedures, and socio-economic implications concerning sustainability (Pereira et al., 2022). Historically, aviation has undergone significant technological transitions, such as the shift from propeller-driven aircraft to jet engines in the mid-20th century, driven by demand for faster, more efficient air travel, and the integration of digital technologies in navigation, communication, and control systems in the late 20th century (Geels, 2006). Current trends in aviation transitions include increased automation and the use of AI for improved safety and efficiency, as well as the development of electric and hydrogen-powered aircraft in response to environmental concerns and rising fuel costs (Kivits et al., 2010).

The industry recognizes that technological alternatives to fossil-based jet fuel will be essential for preserving aviation as a ”rapid worldwide transportation network” while also limiting global temperature rise. Moreover, significantly reducing carbon emissions in the air transport sector requires profound structural changes in the current aviation system, necessitating a radical shift in the propulsion technology. (Geels, 2012). Sustainable aviation propulsion technologies, as discussed in Section 2.4, are part of the broader energy transition from fossil fuels to renewable energy sources. Hydrogen, particularly when produced from renewable sources, represents a clean alternative to traditional jet fuel (European Commission, 2018). A transition to hydrogen technology in aviation involves the participation of multiple actors ranging from civil society to firms, aviation sectors, energy suppliers, policymakers, and public authorities (Christley et al., 2024).

2.5.1. Socio-Technical System of Aviation

The aviation socio-technical system adapted from Geels (2006) can be seen in Figure 2.11. This system is conceptualized as clusters of interconnected elements, including technical artifacts, knowledge, markets, regulation, cultural meaning, laws, and infrastructure (Kern, 2012). Although there has been significant technological advancements, i.e., AI and IoT, and a growing research emphasis on sustainability over the past years, the socio-technical system for aviation has not changed significantly from 2006 perspective till today. Kerosene-based propulsion systems continue to dominate the industry, resulting in a heavily locked-in and path-dependent regime (Geels, 2002). The extensive existing infrastructure for kerosene, long aircraft lifespans, and the substantial investments required for new technologies contribute to a slow and complex transition to more sustainable alternatives.

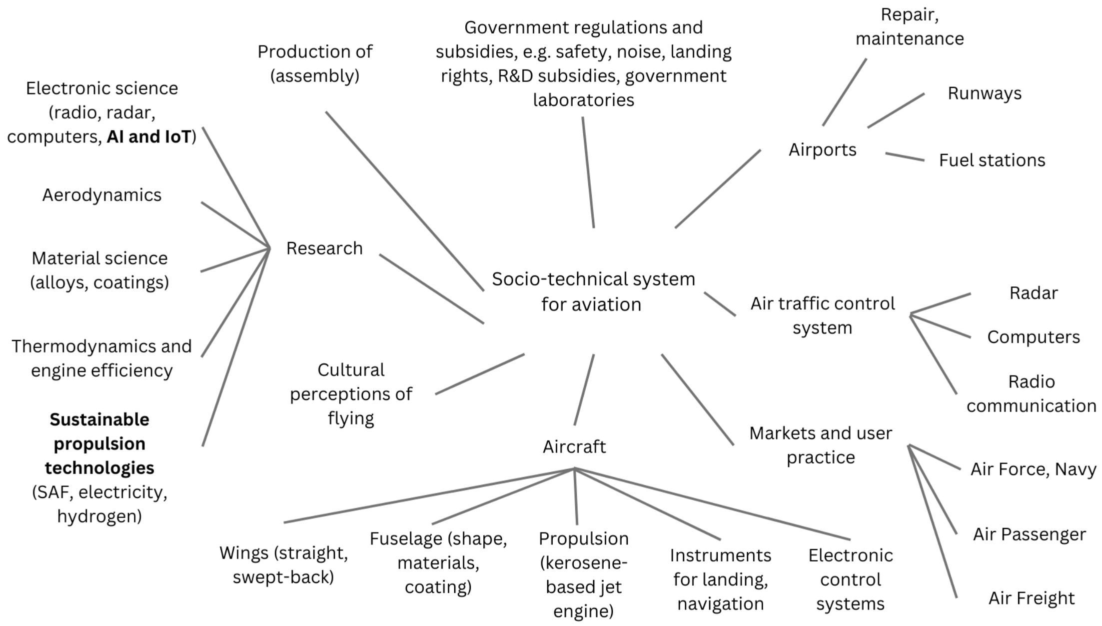

Figure 2.11: Current socio-technical system of aviation (Adapted from Geels, 2006)

2.5.2. Multi-Level Perspective (MLP)

A key framework for analysing socio-technical transitions is the Multi-Level Perspective (MLP). It is used to understand how changes occur in society through the interactions between technology, economy, and culture (Kern, 2012). Moreover, it considers three levels: niche innovations (micro level), socio-technical regime (meso level), and socio-technical landscape (macro level) (see Figure 2.12) (Geels, 2006). In the framework, pressures from landscape-level changes and the internal momentum of niche innovations, supported by a network of actors, destabilize the socio-technical regime, ultimately leading to transitions (Geels & Schot, 2007).

Following a systemic approach, it acknowledges that change is not solely influenced by a single technical advancement but rather by several changes across various dimensions, such as in regulations, user behavior, infrastructure, and society's attitudes that mutually influence one another (Geels, 2002, 2012). The perspective is particularly valuable for analyzing long-term dynamics, transitions from one socio-technical system to another, and the co-evolution of technology and society (Geels, 2006). Additionally, it is widely employed in the socio-technical analysis of low-carbon transitions (Geels, 2012).

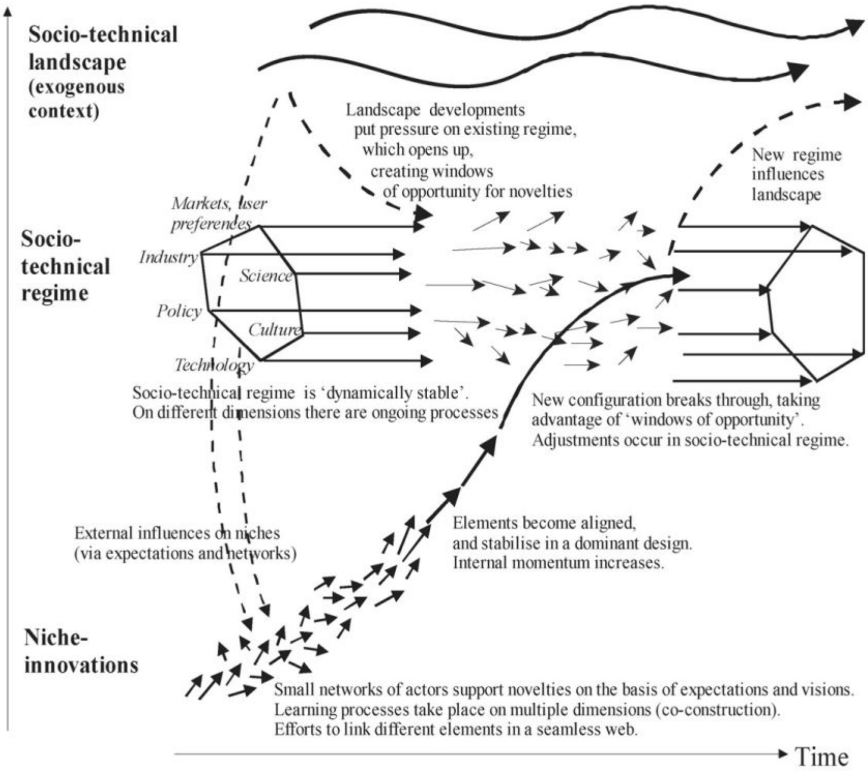

Figure 2.12: Multi-level Perspective on transitions (Geels, 2002; Geels & Schot, 2007)

According to Geels (2006), "Transitions come about when co-evolutionary dynamics at these three levels link up and reinforce each other." The landscape level is characterized by exogenous factors, which are external processes beyond the influence of the actors involved. This macro-level factors can be economic growth, broad political coalitions, cultural and normative values, environmental issues, and resource shortages (Geels, 2006). Moreover, the niche-innovation level includes market or technological niches. Hydrogen is a radical niche innovation that can be implemented in a small market niche sector of aviation.

European key actors working on the development of hydrogen-powered flight are Airbus, Rolls-Royce, and ZeroAvia (Airbus, 2024d; Rolls-Royce, 2024; ZeroAvia, 2024). In addition, there are several alliances involving not only major players like OEMs, but also airlines, airports, and energy companies (H2FLY, 2024; HIA, 2024; Royal Schiphol Group, 2021). These are the Alliance for Zero-Emission Aviation (AZEA), Hydrogen in Aviation (HIA), and H2FLY and Deutsche Aircraft (Airbus, 2024g; Deutsche Aircraft, 2021; European Commission, 2024).

Furthermore, the socio-technical regime level consists of multi-actor involvement and their interrelationships within the ST system of aviation (Geels et al., 2016). Current regime actors comprise a large complex network spread across various segments, including manufacturing, airline operations, and air traffic management (see Figure 2.13). At this level, the alignment between existing technologies, policies, regulations, and infrastructure occurs (Geels, 2011).

In the MLP framework, three phases can be distinguished according to the technological degree of development (Geels, 2005; Rotmans et al., 2001). Since hydrogen-powered aircraft technology is still in the early stages of development, it currently belongs to the first phase of the MLP. In this phase, novel innovations arise in the context of existing socio-technical regime and landscape developments (Geels, 2006). As there is no dominant design for hydrogen-powered technology yet, it competes with other options (i.e., SAF. electric aviation). At this stage, industry actors work and collaborate with each other to bring a technological solution forward that can replace the current regime, which is deeply rooted in various aspects (such as institutions, organizations, economy, and culture).

Nevertheless, in order to move hydrogen technology in aviation to the next phase (Phase 2), it must be introduced in a small niche market that offers resources for technological specialization (Geels, 2006). The next section will elaborate on the identification of a potential market niche for introducing a hydrogen-powered aircraft that could enable a step towards Phase 3, i.e., breakthrough and regime transformation.

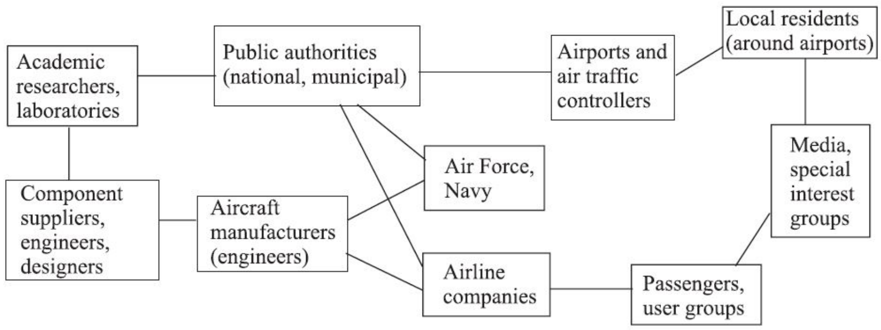

Figure 2.13: Stakeholder network in aviation regime (Geels, 2006)

2.5.3. Market Niche

The air freight sector was identified as a potential market niche to implement hydrogen before the passenger sector (Figure 2.14). Additionally, Figure 2.15 presents a schematic representation of the reasoning behind the market niche identification for hydrogen technology. Although technological aspects, in terms of aircraft and infrastructure at the airport, might not deviate significantly from the passenger market, the perception of safety towards hydrogen in the freight sector is seen more favorably. This is largely because the risks associated with transporting goods are perceived as lower compared to carrying passengers, allowing for earlier adoption and testing of new technologies such as hydrogen propulsion.

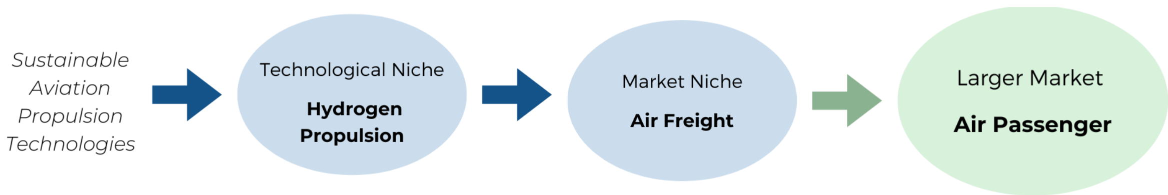

Figure 2.14: Niche trajectory (Adapted from Geels and Schot, 2007)

As mentioned in Section 2.3.3, the air freight sector has an incentive to adopt innovative sustainable technologies to enhance efficiency and reduce costs, as well as carbon emissions. As such, it provides an ideal testing ground for hydrogen technology before scaling up to the passenger sector. This approach would allow stakeholders to address any technological and safety concerns in advance, thereby building public trust and regulatory confidence in hydrogen-powered aviation.

Moreover, the logistical operations of air freight often involve hub-and-spoke models, where centralized refueling infrastructure can be more easily implemented (Sugiyanto et al., 2015). Hydrogen refueling stations and storage facilities can be established at major cargo hubs, facilitating the gradual integration of hydrogen-powered aircraft into the supply chain. This strategic deployment not only supports the technological validation of hydrogen systems but also helps in understanding the economic implications and operational challenges associated with hydrogen propulsion technology.

The positive reception and operational success in the air freight sector are likely to pave the way for broader acceptance in the passenger aviation market. Additionally, if safety and reliability are positively demonstrated during air cargo operations, it could help mitigate public fear regarding hydrogen as a new propulsion system for passenger aircraft in the early implementation stages. This gradual transition is crucial, as it allows for a more controlled and secure implementation of hydrogen technology, ensuring that safety standards are supported and any potential risks are reduced (Geels, 2005).

Furthermore, the environmental benefits of hydrogen as a clean fuel align with the growing demand for sustainable logistics solutions (CargoAi, 2024). Businesses and consumers are increasingly prioritizing green supply chains, and hydrogen-powered freight services can significantly reduce the carbon footprint of air cargo operations (DHL Freight, 2023). This aligns with global sustainability goals and regulatory pressures to lower emissions, thereby accelerating the industry's shift towards cleaner technologies (European Commission, 2018).

Finally, positioning the air freight sector as an early adopter of hydrogen technology represents a strategic and pragmatic approach to advancing sustainable aviation (Feldmann et al., 2023). It leverages the sector's unique characteristics to facilitate the technological and regulatory maturation of hydrogen propulsion, ultimately leading to its broader acceptance and implementation in passenger aviation. Thus, moving towards Phase 3 of the MLP, i.e., breakthrough and regime transformation (Geels, 2006). This stepwise adoption ensures that safety, efficiency, and public confidence are thoroughly established, setting a potential foundation for the future of hydrogen-powered flight.

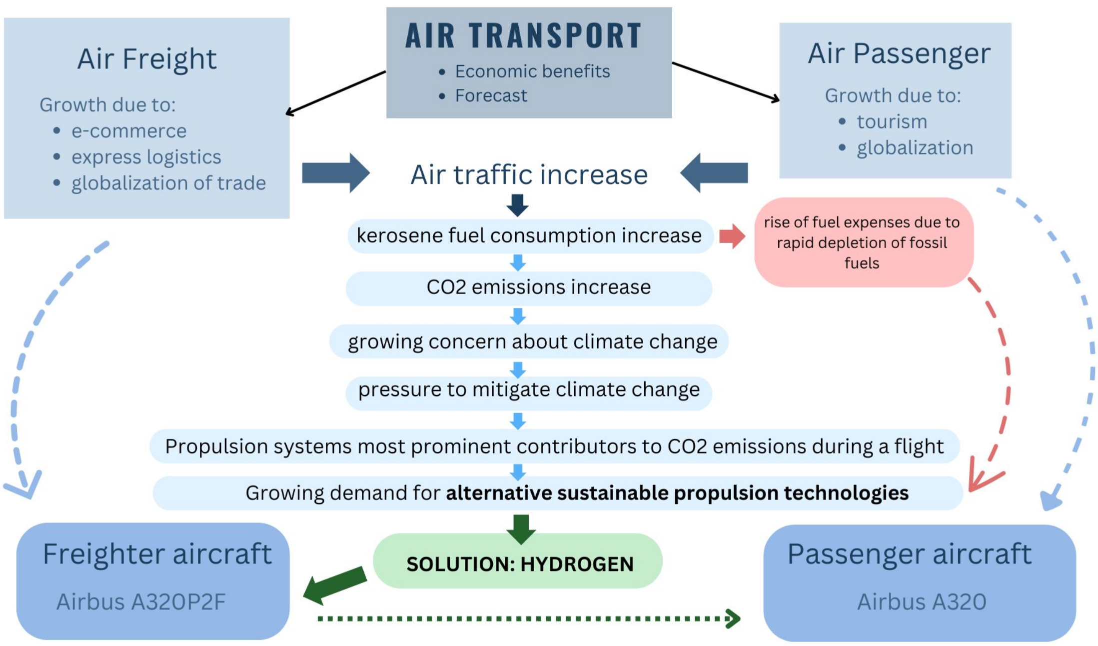

Figure 2.15: Niche identification: Air freight sector

2.6. Knowledge Gap in Literature

As previously noted, aviation is classified as a socio-technical system. While exploring literature on socio-technical transitions within the aviation sector, a key case study emerged, marking a significant milestone in aviation history. Geels (2006) analysed the transition from aviation systems based on propeller-aircraft to aviation systems based on turbojet aircraft (1930–1970). In the paper, Geels examined various co-evolution literature and differentiated between three levels of co-evolutionary processes: new technological breakthroughs, current structures or systems, and the broader societal context. To comprehend transitions, this knowledge is integrated into a multi-level perspective (MLP) that includes niche, regime, and landscape levels. Transitions occur when dynamics at these three levels align and reinforce each other.

The case study illustrates this perspective, showing how co-evolutionary dynamics at different levels interacted to drive the transition. Initially, jet engines emerged as a niche innovation, largely ignored by the established aviation regime focused on propeller-driven aircraft. However, various factors, including war, technological advancements, and strategic rivalries, eventually created windows of opportunity for the new technology. Jet engines broke through in the military domain before being hesitantly introduced into civil aviation, overcoming initial resistance and eventually leading to the replacement of piston engines in commercial aircraft. This transition was not just a technological change but involved adjustments across the broader socio-technical system, including regulations, user practices, and infrastructure.

Later, Nakamura et al. (2013) extended the multi-level perspective (MLP) framework by incorporating Technology Readiness Levels (TRLs) to analyze innovation within the aviation industry, particularly focusing on advanced turboprop (ATP) engines. The paper underscores the need for innovations aimed at addressing environmental challenges, such as climate change mitigation. More importantly, it states a relevant research gap regarding transition periods within the aviation industry.

While earlier studies, such as those by De Haan and Mulder (2002), Spinardi and Slayton (2015) and previously discussed Geels (2006), have explored the shift to the jet age, subsequent innovation transitions have received less attention. Cohen (2010) and Kivits et al. (2010) are among the few studies addressing this gap. Specifically, Kivits et al. (2010) evaluated alternative energy sources for aviation, noting the significant challenges in achieving industry consensus and meeting requirements because of lengthy aircraft life-cycle and substantial investments. Back in 2010, they suggested that to reach further advancements in aviation sustainability, viable technologies need to be explored beyond jet technology. More than a decade later, substantial research has been guided towards sustainable technologies in aviation to mitigate climate change (Afonso et al., 2023; Su-ungkavatin et al., 2023). Thus, a socio-technical analysis from the current aviation perspective towards the transition to alternative fuels and/or propulsion mechanisms can be realized.

As oil production is increasingly constrained by limited resources, the existing fuel technology is finite and prices are expected to rise significantly (Kivits et al., 2010). Incremental adjustments to the current technological system can only advance progress to a certain extent. Therefore, a truly sustainable energy solution must be derived from renewable sources (Healy, 1995). Currently, several alternatives to existing fossil-based jet fuel are being investigated to reduce CO2 emissions. The most explored are: Sustainable Aviation Fuel (SAF) consisting of biofuels and synthetic fuels (or electrofuels), hydrogen via combustion or fuel cell, and battery-electric propulsion (World Fund, 2022).

From a company perspective, Airbus is making substantial investments mainly on SAF and hydrogen (Airbus, 2024d, 2024e). Sustainable Aviation Fuel (SAF) is seen as a key transitional solution for reducing the aviation industry's carbon footprint until other, potentially more sustainable and less carbon-intensive technologies such as hydrogen propulsion can be implemented on a large scale (Coykendall et al., 2021). Additionally, the goal is to ultimately reduce carbon emissions by 100%, and only hydrogen and electric propulsion are able to reach this objective in the long term (Ficca et al., 2023). Nonetheless, battery-electric airplanes are only viable for extremely short distances (Clean Aviation, 2024). Hence, this creates the opportunity of using hydrogen for flights that cover short to medium distances.

From an academic research standpoint, Kim et al. (2019) already examined the key barriers and opportunities for biofuels transition from a socio-technical perspective, highlighting the importance of systemic change and multi-stakeholder collaboration for environmental sustainability in the aviation sector. More recently, Lai et al. (2022) provided a comprehensive analysis of the environmental impacts of various SAF pathways in Sweden, employing a socio-technical system approach and prospective Life cycle analysis (LCA). However, no studies were found to address hydrogen transition in aviation from a socio-technical transition perspective, despite extensive research on hydrogen technology usage in air transport (Hoelzen et al., 2022; Yusaf et al., 2022).

Moreover, as Geels (2006) stated, transitions often start in niches. Similarly to how jet engines were firstly utilized in the military before being adopted in civil aviation, hydrogen technology could be introduced in the cargo aviation sector prior to passenger sector. This approach has not yet been thoroughly examined in academic literature, indicating a significant gap for further research. Additionally, a review of the literature on air cargo reveals a disparity in academic research, with a significantly higher number of studies dedicated to air passenger services compared to those focusing on air cargo (Bombelli et al., 2020). Furthermore, a large number of technical solutions for reducing CO2 get developed in this field, yet under-applied to air cargo (McKinsey & Company, 2023).

Passenger air transport is responsible for 71% of fuel use and emissions, compared to 17% for freight (Gössling & Humpe, 2020). This in combination with a higher visibility and direct impact on the public from passenger flights, can heavily influence where investments and innovations are applied first. Nevertheless, starting with the freight sector could potentially alleviate safety concerns and enhance public acceptance towards hydrogen technology (Baroutaji et al., 2019). Moreover, the COVID-19 pandemic significantly boosted e-commerce and express air cargo demand (IATA, 2023b). Thus, increasing the pressure for faster and more sustainable air freight logistics (IATA, 2023d; Rodbundith et al., 2021). Exploring air cargo as a valuable niche for deploying hydrogen technology could potentially aid in the mission to accelerate the transition towards carbon-free air transport.

The Multi-level perspective is clearly of great relevance for the research topic at hand. This theory has been used to explain transitions in the transport, agro-food and energy sectors (Geels, 2019b). However, it has not been applied yet for such a specific and emerging case in the field of air transport. Following Geels (2006) approach, a potential niche for introducing a new technology (hydrogen) was identified, namely air freight sector. Moreover, the existing aviation industry is heavily locked in to the utilization of fossil-based jet fuel, representing a stable and path dependent socio-technical regime, facing sustainability issues. At the landscape level, several events can destabilize the current regime and create windows of opportunity for niches to emerge. These events include the global concern for climate change, the rapidly depleting fossil resource, and the post-pandemic world. The Multi-level Perspective will be used as the theoretical framework for this thesis to address the knowledge gap.

3
Research Methodology

This chapter examines the research approach and research methods employed in the study. Section 3.1 describes the type of research approach used as well as the advantages and disadvantages of utilizing this approach (Section 3.1.1). The research methods are further elaborated in Section 3.2, comprising a detailed analysis of the data collection methods in Section 3.2.1. The conceptual framework developed for this master thesis is presented in Section 3.3. Lastly, a representation of the research flow diagram is depicted in Section 3.4.

3.1. Research Approach

This master thesis study uses a qualitative research approach to analyse the key barriers and drivers for hydrogen-powered aircraft adoption in European aviation. This approach involved an extensive literature review and interviews with key selected actors in the aviation industry. Conducting a literature review on several topics was crucial to gain a broader picture of the problem and to fully understand the core concepts being investigated. It also addresses areas where quantitative data alone might not capture the full picture. Given the substantial ongoing academic and industry research into sustainable aviation propulsion technologies and low-carbon socio-technical transitions, a thorough literature analysis provides the most recent insights. This information was mainly gathered from white papers, academic articles, technical reports, sustainability reports, company news websites, and publicly available information from Airbus.

Additionally, incorporating both academic and industry expert opinions was essential to ensure a complete analysis of the topic. Interviews with industry professionals provided practical insights and real-world perspectives that complemented and validated the theoretical findings from the literature review. It is important to note that this qualitative approach does not aim to solve the problem of adopting hydrogen technology in aviation. Instead, its goal is to enhance understanding of the field and provide valuable insights as well as recommendations.

3.1.1. Advantages and disadvantages

The main advantage of this research approach is that it allows for an in-depth understanding of complex issues, capturing diverse stakeholder perspectives through literature reviews and interviews. The use of various information sources ensures a well-rounded analysis, while interviews with industry professionals provide a wide range of expert opinions (Rahman, 2020). Regarding the interviewee selection, experts with a positive opinion about hydrogen in aviation were selected. This was done to guarantee that the research is highly oriented towards the hydrogen transition in air transport. Moreover, this approach also incorporates recent research, keeping the study up-to-date and flexible to new developments.

However, qualitative research can be subjective, time-dependent and interviews are restricted to a certain number of samples, limiting generalizability. The transition to hydrogen-powered aircraft is analysed from the experimental phase perspective. The analysis may change once and if hydrogen technology is implemented in aviation.

Additionally, analyzing both literature and interview data can be a complex and time-consuming task (Queirós et al., 2017). Lastly, the quality of insights gained during the interviews depends on the interviewees' knowledge and willingness to share.

3.2. Research Methods

As stated above, this research consists of a qualitative research approach to find the drivers and barriers for hydrogen adoption in aviation. Two main research methods were used to collect the data: a literature review, including a socio-technical transition theory review, and semi-structured interviews with aviation experts.

3.2.1. Data Collection Methods

Literature Review

As previously mentioned, qualitative data was primarily obtained from academic literature. This included studies on air transport, with a specific focus on air freight, papers on socio-technical systems, and transitions, as well as aerospace research reports on the technical aspects of sustainable aviation propulsion technologies, particularly hydrogen. To gain further knowledge on policies regarding hydrogen technology and industry-related projects on hydrogen at airports and hydrogen's supply chain, policy documents, white papers, and grey literature were consulted. The latter comprised firm sustainability reports, environmental reports, technological road maps, and company news websites.

Exploratory Interviews

To gather additional information beyond what is available in scientific literature, interviews were conducted with hydrogen experts at Airbus, academia, and government. These interviews provided valuable insights that complemented and validated the literature findings regarding the potential drivers and barriers to hydrogen adoption. A series of semi-structured interviews were carried out with several aerospace experts, purposely choosing the ones that focus on hydrogen aircraft development. This interview method was chosen because it allows starting with a list of predetermined questions to guide the discussions, while also providing the flexibility to explore additional topics as the conversations progressed.

Before conducting the interviews, a stakeholder analysis was performed using the Quadruple Helix Model (see Figure 3.1) (European Union, 2024). It is important to note that this representation does not include all actors involved in the transition to hydrogen in aviation, but only those directly participating in the experimental phase of hydrogen-powered technologies that are relevant for the research. Hence, for the interviews, most stakeholders belong to the industry and academia sides.

Regarding industry activities, Airbus is central to the research and development of hydrogen-powered aircraft. It also invests significantly in the production of hydrogen-powered technologies, collaborates on innovative projects, and brings new products to the market. Other actors like ZeroAvia are currently testing a hydrogen-electric aircraft and Rolls-Royce is working on the development of a hydrogen combustion engine (Rolls-Royce, 2024; ZeroAvia, 2024). Interested parties in this technology, once fully developed and operational, could be air logistic companies such as DHL, FedEX, UPS, and Amazon, as well as passenger airlines.

From academia, Delft University of Technology plays a significant role in sustainable aviation, together with the Aerospace Innovation Hub. Additionally, it actively participates in innovative hydrogen projects (i.e., GOLIAT), which Airbus is leading in collaboration with other academic partners, airport operators, and hydrogen-industry companies (TUDelft, 2024).

Furthermore, governments play a crucial role in shaping the regulatory and policy environment for hydrogen-powered technologies across the European Union. They set the legal frameworks, provide funding and incentives for research and infrastructure development, and ensure compliance with safety and environmental standards (EASA, 2019). Finally, the community side encompasses the broader society, including non-governmental organizations (NGOs) and the general public (T&E, 2022). This sector plays a crucial role in advocating for sustainable practices, influencing public opinion, engagement, and acceptance, and ensuring that transitions align with societal needs and values.

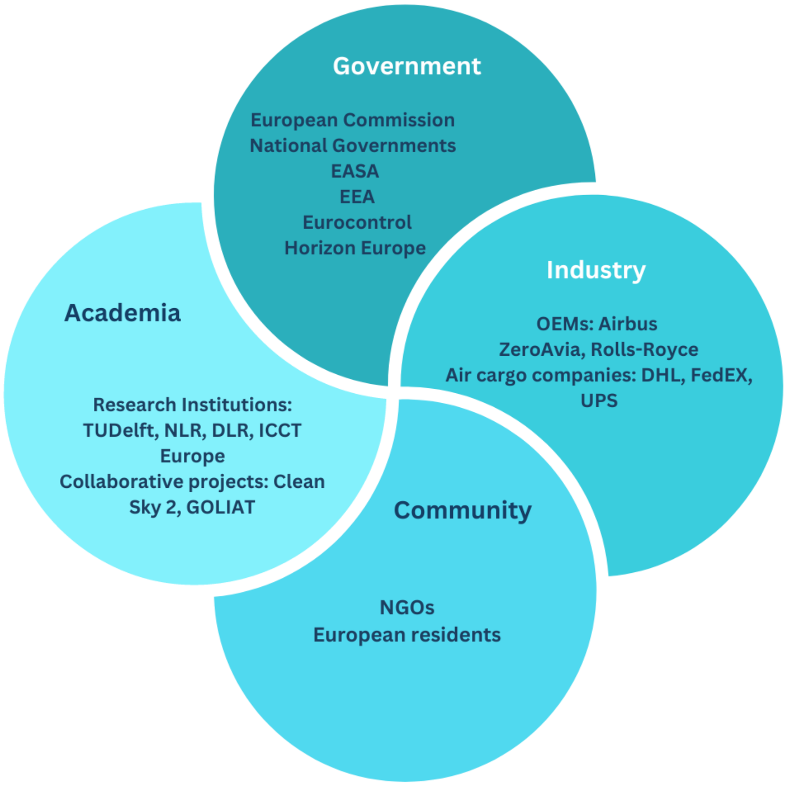

Figure 3.1: Quadruple Helix Model for Stakeholder Analysis (Adapted from Roman et al., 2020)

A list of the respondents that participated in the interview can be seen in Table 3.1. A total of 11 interviews were conducted. The participants correspond to academia, industry, and government clusters. In academia, professors from various faculties at TUDelft, along with experts from the Aerospace Innovation Hub, were selected to provide diverse perspectives. Their expertise covered a wide range of areas, including modeling of socio-technical systems, network design and innovation, strategic business development, and aerospace research. For the industry cluster, hydrogen-propulsion technology experts at Airbus were suggested by the company. Regarding the government cluster, the Ministry of Infrastructure and Water Management in The Netherlands, more precisely the Sustainable Aviation Unit, was contacted to get more insights into the policy aspects of hydrogen in aviation.

The interviews were performed both face-to-face and online via Teams or phone call. Each interview had a duration of 45 to 60 minutes. The interview questions were adapted accordingly for each cluster of participants. A summary of the questions can be seen in appendix A. The questions were formulated based on the three levels, i.e., niche, regime, and landscape, of the Multi-Level Perspective framework previously explained in Section 2.5.2 of Chapter 2. The structure of these questions is designed to cover multiple levels of analysis, from specific technological aspects to broader socio-economic and policy contexts. Each section builds on the previous one, creating a framework to explore the multifaceted nature of transitioning to hydrogen-powered aircraft. In this way, a socio-technical analysis, including technology, markets, user groups, infrastructure, science, culture, and regulation aspects, can be realized to find the potential drivers and barriers of the hydrogen transition in the European air transport system. Moreover, all the interview information was manually processed and analysed to ensure all relevant aspects concerning key drivers and barriers for hydrogen-powered aircraft were taken into account.

Additionally, research ethics were carefully considered by keeping the respondents anonymous throughout the study to minimize the risk of re-identification. This was accomplished by categorizing respondents according to their stakeholder type and their field of expertise (Table 3.1). In addition, participants were requested to sign an informed consent form detailing all relevant aspects of the data management plan approved in advance by TUDelft ethics department. This document can be seen in Appendix B.

Stakeholder type	Field of expertise	Date	Communication channel	Label
Academia (AE)	Air cargo operations (air cargo supply chain)	31/05/2024	Personal communication	A1
Academia (AE)	Air transport & operations (maintenance and network planning)	14/06/2024	Online communication (via Teams)	A2
Academia (AE)	Long-term operations of hydrogen-powered aircraft	14/06/2024	Personal communication	A3
Academia (TPM)	Commercial airline pilot/safety manager/ aircraft standardization & certification (EU)	28/05/2024	Personal communication	A4
Academia (IDE)	Aviation ecosystem (network design and innovation)	03/06/2024	Online communication (via phone call)	A5
Academia (Aerospace Innovation Hub)	Aerospace innovation ecosystem	27/05/2024	Online communication (via Teams)	A6
Industry (Airbus)	Industrilization of hydrogen systems (storage and distribution)	28/05/2024	Online communication (via Teams)	I1
Industry (Airbus)	ZEROe (hydrogen fuel cell systems)	03/06/2024	Online communication (via Teams)	I2
Industry (Airbus)	Technology management (future aircraft concepts)	13/06/2024	Personal communication	I3
Industry (Airbus)	ZEROe (liquid hydrogen department)	29/05/2024	Online communication (via Teams)	I4
Government (Policy officer)	Sustainable aviation department (hydrogen focus)	17/06/2024	Personal communication	G1

Table 3.1: Overview of Interview Respondents

3.3. Conceptual Framework

The conceptual framework depicted below (see Figure 3.2) outlines the five-step approach utilized throughout the study to analyze the transition to hydrogen-powered aircraft in European air transport from a socio-technical perspective. The goal of this framework is to systematically explore and assess the potential of hydrogen-powered aircraft in the air freight sector by involving various stakeholders, gathering expert opinions, and identifying key factors that influence the technology's adoption.

The first phase, *Technological Niche Identification*, focuses on selecting a technological solution at a niche level, exemplified by focusing on hydrogen-powered aircraft (first phase of the MLP). This step aims to identify a specific technology that can be explored and developed within a controlled and limited context before broader implementation in aviation. The research scope was set for a medium-range flight within Europe.

The second phase, *Niche Market Identification*, involves pinpointing a specific market segment where the technology could be implemented, such as the air freight sector (second phase of the MLP). This targeted market segment serves as a testing ground for the technology, ensuring efforts are focused and manageable.

The third phase, *Multi-Actor Analysis*, applies the Quadruple Helix Model for stakeholder analysis involving various actors in the EU aviation ecosystem. The purpose of this step is to understand the roles, interests, and influences of different stakeholders, including industry academia, government, and community, who are directly involved in or affected by the implementation of the new technology.

In the fourth phase, *Expert Opinions*, insights are gathered from participants across various fields through interviews with sustainable aviation experts from industry, academia, government, and community sectors. This phase aims to collect substantial qualitative data, insights, and feedback from knowledgeable individuals to inform the feasibility, challenges, and potential impact of the technology in the next 10 to 20 years.

The final phase, *Key Drivers and Barriers*, identifies the main factors that drive or hinder the implementation of hydrogen technology from a socio-technical perspective. This is illustrated by the results obtained from respondents to the interview questions, which were composed using the MLP framework. The purpose of this phase is to synthesize findings and identify critical drivers and barriers that could either facilitate or obstruct the successful adoption of hydrogen-powered aircraft in the identified niche market and aviation in general.

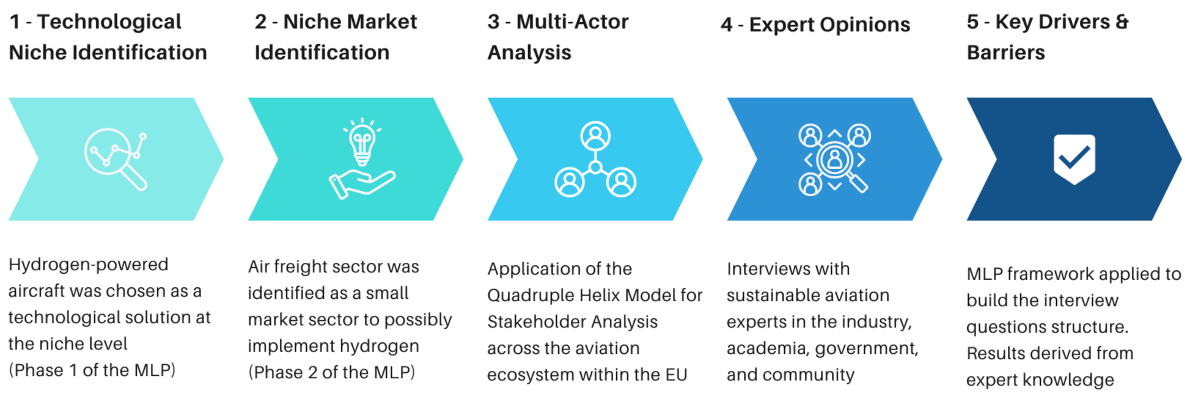

Figure 3.2: Conceptual Framework of the Master Thesis Research

3.4. Research Flow Diagram

The following research flow diagram visually represents how each chapter builds upon the previous one. This leads to a complete understanding of the knowledge flow related to the analysis of hydrogen-powered aircraft through the lens of Multi-Level Perspective theory (Figure 3.3).

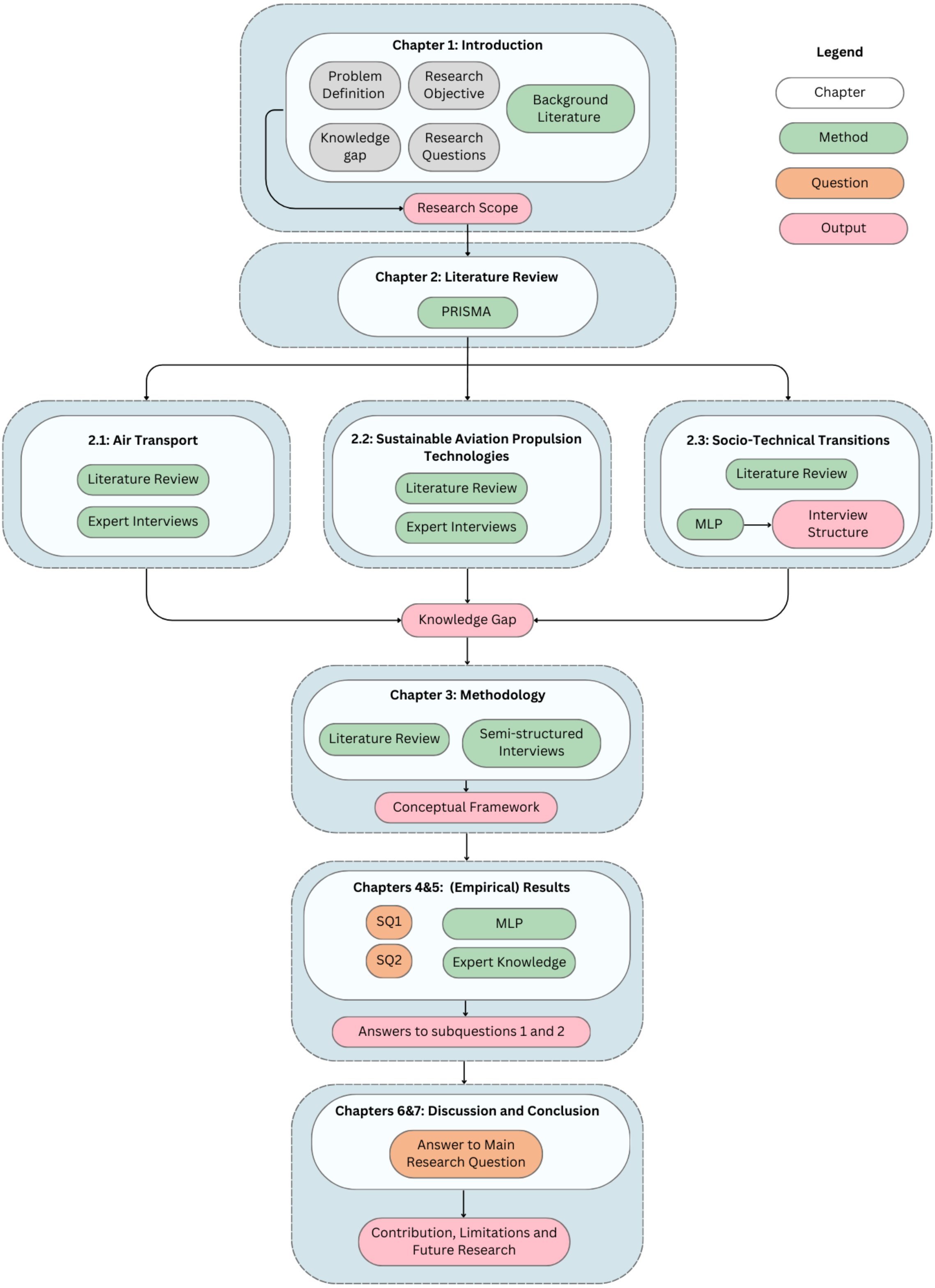

Figure 3.3: Research Flow Chart

4
Empirical Results

This chapter presents the multiple stakeholders' views on the transition to hydrogen-powered technologies in aviation. The 11 semi-structured interviews that were conducted with academia, industry and government actors resulted in a significantly large number of findings. Additionally, the paper by Hennink and Kaiser (2022) argues that qualitative studies reach data saturation with relatively small sample sizes, more specifically with 9 to 17 interviews. Therefore, during the 11 interviews conducted, similarities in the answers were already visible.

Moreover, by interviewing four different clusters of experts, the study aimed to gain insights on the different perspectives that each stakeholder can offer. The interview questions can be found in Appendix A. These questions were already formulated to cover the different levels of the MLP, consisting of niche, regime, and landscape (Section 2.5.2).

4.1. Overview of Topics

In Table 4.2 and Table 4.3, a structured overview of the topics addressed during the interviews can be observed. These topics were classified within major themes and sub-themes. The next sections of this chapter represent each of the sub-themes coloured in blue, followed by an explanation of the topic corresponding to each sub-theme (see Table 4.1).

Sub-Theme	Section
Shift towards hydrogen-powered technology	Section 4.2
Suitability of hydrogen-powered technology	Section 4.3.1
Comparison with alternative propulsion technologies	Section 4.3.2
Introduction in Air Freight	Section 4.3.3
Hydrogen propulsion technology for freighter	Section 4.3.4
Technological Advancements	Section 4.4.1
Infrastructure Challenges	Section 4.4.1
Aircraft Design Alterations	Section 4.4.1
Regulatory Environment	Section 4.4.2
Incentives and Support	Section 4.4.2
Public Perception and Acceptance	Section 4.4.3
Awareness and Community Involvement	Section 4.4.3
Preparation and Collaboration	Section 4.4.4
Economic Considerations	Section 4.4.4
Market Demand and Trends	Section 4.4.5
Customer and Stakeholder Engagement	Section 4.4.5
Global Trends and External Pressures	Section 4.5.1
International Agreements and European Policies	Section 4.5.2

Table 4.1: Sub-Themes and Corresponding Chapter Section

Major Theme	Sub-Theme	Topic
Hydrogen-Powered Aviation	Shift towards hydrogen-powered technology	Initial thoughts on the shift towards hydrogen-powered technology in aviation
Technological Niche Level		
Hydrogen Technology Characteristics	Suitability of hydrogen-powered technology	Characteristics making hydrogen technology a suitable alternative to fossil-based fuels
Hydrogen Technology Characteristics	Comparison with alternative propulsion technologies	Performance comparison of hydrogen technology with electrification and SAF
Hydrogen Technology Characteristics	Introduction in Air Freight	Feasibility of introducing hydrogen technology in air freight operations vs. passenger market
Hydrogen Technology Characteristics	Hydrogen propulsion technology for freighter	Relevant hydrogen-based propulsion technology for freighter aircraft
Socio-Technical Regime Level		
Current state of technology	Technological Advancements	Current technological advancements in hydrogen-powered aircraft
Current state of technology	Infrastructure Challenges	Challenges in implementing hydrogen technology at airports
Current state of technology	Aircraft Design Alterations	Necessary alterations in aircraft designs to accommodate hydrogen technology
Policy	Regulatory Environment	Support and hindrance by European aviation policies
Policy	Regulatory Environment	Necessary regulatory changes for facilitating hydrogen transition
Policy	Incentives and Support	Effective governmental incentives and support
Policy	Incentives and Support	Balancing innovation with safety and environmental concerns
Society and Culture	Public Perception and Acceptance	Public perception of hydrogen as aviation fuel
Society and Culture	Public Perception and Acceptance	Societal and cultural factors influencing hydrogen acceptance
Society and Culture	Awareness and Community Involvement	Initiatives to improve awareness and understanding of hydrogen technology

Table 4.2: Overview of Topics classified per Major Themes and Sub-themes (1)

Major Theme	Sub-Theme	Topic
Socio-Technical Regime Level		
Society and Culture	Awareness and Community Involvement	Importance of community involvement in hydrogen adoption discussions
Industry	Preparation and Collaboration	Industry preparation for hydrogen-powered aircraft
Industry	Preparation and Collaboration	Crucial partnerships and collaborations for the transition
Industry	Preparation and Collaboration	Long-term vision for hydrogen's role in aviation
Industry	Economic Considerations	Economic viability of hydrogen-powered aircraft and comparison with kerosene and other alternatives
Industry	Economic Considerations	Necessary market conditions for significant investment in hydrogen technology
User and Market	Market Demand and Trends	Evolution of demand for hydrogen-powered aircraft in air transport
User and Market	Market Demand and Trends	Key market drivers influencing hydrogen-powered technology demand
User and Market	Customer and Stakeholder Engagement	Motivating stakeholders to adopt hydrogen-powered aircraft
User and Market	Customer and Stakeholder Engagement	Role of customers in driving the market towards hydrogen solutions
Landscape Level		
Global Context and External Factors	Global Trends and External Pressures	Global trends and external pressures influencing hydrogen technology adoption
Global Context and External Factors	Global Trends and External Pressures	Environmental and economic drivers towards sustainable aviation propulsion
Global Context and External Factors	Global Trends and External Pressures	Role of global fuel price fluctuations in considering hydrogen as an alternative
Global Context and External Factors	International Agreements and European Policies	Impact of international policies and agreements on hydrogen technology push

Table 4.3: Overview of Topics classified per Major Themes and Sub-themes (2)

4.2. Shift towards hydrogen-powered technology in aviation

According to stakeholders hydrogen propulsion technology is a promising alternative to fossil-based fuels, yet it is still an emerging technology. The transition to hydrogen in aviation involves multiple technological steps, from research and testing to infrastructure development and aircraft commercialization. While substantial progress is being made, it is not yet widely operational or commercially widespread.

One stakeholder in academia [interview A6] describes the transition process as a ”layered approach”. The interviewee recognized that *”no single solution will fit all needs but rather a combination of different technologies”*. This refers to the idea that different propulsion technologies are suitable for different flight ranges, and these technologies will need to be integrated in a complementary manner to achieve decarbonization in aviation. Thus, combining hydrogen, electrification, and sustainable aviation fuel (SAF) solutions could become essential. Electric propulsion is suitable for short-range aircraft, hydrogen for mid-range flights and, SAF is the only current technology viable for long-range flights. Moreover, this approach emphasizes the complexity and interdependent nature of developing sustainable aviation propulsion technologies. Different technologies will coexist and complement each other, addressing various segments of aviation from short-haul to long-haul flights, rather than competing. Hence, ensuring incremental and strategic progress across the aviation industry.

Nevertheless, the interviewee acknowledges that the right strategy to achieve zero carbon emissions in aviation is still widely unknown and uncertain, as the technologies are still in the early stages of development. Additionally, one industry expert described it as a ”chicken and egg problem”, where the question of *”who decides to go first and takes the hit?”* arises. The expert also suggested a coordinated approach could solve the issue, yet emphasizing it is not an easy fix [interview I4].

Furthermore, an aviation industry expert believes that the transition is challenging due to the lack of prior experience with hydrogen in commercial aviation, and expects a ”bumpy ride” as requirements and solutions are developed over time [interview I1]. An interviewee in academia [interview A4] highlighted that transitioning to hydrogen propulsion is complex, requiring systemic changes in fuel management, pilot training, and airport infrastructure. Moreover, the international nature of aviation increases the difficulty of achieving global coordination. A stakeholder in the industry cluster [interview I4] mentioned that the challenge lies on that fact that it is a new way of developing propulsion systems. Additionally, another expert in the industry [interview I3] concluded that the shift towards hydrogen is seen as disruptive, involving a complete overhaul of the current ecosystem, including aircraft design, operations, certification, and fueling processes.

Another stakeholder in academia [interview A5] argued that while the shift to hydrogen-powered technology is taking extremely long, hydrogen could significantly reduce aviation’s environmental impact and is essential for long-term emission goals by 2050. The same interviewee also stressed the need for interim solutions. Regarding the government’s perspective [interview G1], historically hydrogen research was driven by the oil crisis but was abandoned once the crisis ended because of its inability to compete with kerosene. The current interest is due to hydrogen’s potential to significantly reduce carbon emissions and pollution.

Despite the numerous challenges that still need to be overcome, all interviewees agree upon hydrogen technology having a high potential in aviation, especially for medium-range aircraft.

4.3. Technological Niche Level

4.3.1. Suitability of hydrogen-powered technology

All stakeholders noted that hydrogen can be produced sustainably using renewable energy (green electricity) and that it offers significant advantages in reducing CO2 emissions compared to kerosene. However, challenges remain in terms of hydrogen production, distribution and storage infrastructure.

There are also numerous safety concerns that cannot be fully addressed until hydrogen is more widely implemented. Consequently, the approach to using hydrogen as a power source remains very conservative, leading to heavier first-generation wide-body aircraft and slow innovation [interview I1]. An interviewee in academia believes that *"hydrogen is a proven performance technology but poses challenges in logistics as well as safety due to its explosive nature"* [interview A4].

One industry expert mentioned, *"we must keep improving the kerosene networks over the next decade while ramping up new technologies"*, emphasizing the need to perform both strategies in parallel [interview I1]. Although hydrogen-propulsion technology offers sustainability advantages, it presents feasibility issues, such as requiring more aircraft space for fuel cells and liquid hydrogen tanks, as well as potential aircraft design changes. Additionally, as expressed in the majority of interviews, hydrogen as a molecule has a very high energy content per unit mass. It delivers about 120 megajoules per kilogram (MJ/kg). This means that for a given mass, hydrogen can provide nearly three times more energy than kerosene (44 MJ/kg).

Despite its high energy content per mass, stakeholders also noted that it has a very low energy content per unit volume. In its gaseous state at standard temperature and pressure, hydrogen is poorly dense. Even when compressed or liquefied, it takes up a significantly larger volume compared to kerosene for the same amount of energy. Liquid hydrogen delivers about 8 MJ/L. Kerosene, on the other hand, is much denser as a liquid and thus has a much higher energy content per unit volume, delivering about 32 MJ/L. Consequently, for a given volume, kerosene can store much more energy than hydrogen. However, stakeholders believe this is a potentially solvable technological problem. The industry is already working on cryogenic tanks to store hydrogen in its liquid state, which occupies less volume, by achieving a temperature of about -253°C under very high pressure (700bar) .

Moreover, as one industry expert clarified, *"Hydrogen differs from kerosene in handling, storage, and distribution, requiring cryogenic storage and unique equipment, thus necessitating a completely new way of designing propulsion systems"* [interview I4]. Hydrogen-powered technology can significantly reduce climate impact due to zero-carbon emissions and fewer persistent contrails using hydrogen fuel cells [interview I2 and G1]. It is renewable, produces only water as a byproduct, and has been proven effective in other industries like automotive, as interviewee I2 explained.

The main advantage of hydrogen, quoted by all stakeholders, is its ability to eliminate CO2 emissions during flight. It can also significantly reduce NOx emissions, depending on the type of powertrain used. Additionally, hydrogen-powered technology has overall higher probability of favorable characteristics such as no soot and sulfur, thereby positively impacting climate change and reducing pollution [interview A3]. An expert in the government cluster mentioned, *"it is clean, durable, and potentially cheaper in the long term"* [interview G1].

To conclude, regardless of the generalized uncertainty among different stakeholder clusters concerning the future outlook of hydrogen-powered flight, its potential as an alternative to fossil-based fuels is widely recognized.

4.3.2. Comparison with alternative propulsion technologies

As mentioned earlier, stakeholders view hydrogen as part of a broader solution alongside electrification and SAF. While all three technologies offer benefits, they also present significant drawbacks that need to be addressed during the current experimental phase. Stated by most experts, hydrogen has the potential for significant CO2 reduction, but its implementation is complex. Electrification, for some stakeholders the biggest unknown, is currently limited to smaller aircraft due to battery technology constraints. *"Today, it is still a niche market for smaller aircraft, though this might change tomorrow"*, as reported by interviewee I1.

Moreover, SAF presents limitations in availability and cost. As noted by an industry expert, "SAF made from waste faces the problem of waste depletion, and if produced from CO2, it still requires hydrogen" [interview I1]. The interviewee also added, *"although SAF has easier implementation in current aircraft, securing sufficient amounts remains a challenge"*.

However, an academic expert and former pilot argued that, although a mixed approach seems logical, using different technologies for various flight ranges complicates airport infrastructure development and training programs for ground workers, pilots, and cabin crew: *"Having all three technologies at the same time in an airport is going to complicate things because then you need different tankering solutions, different fueling connections and different trainings"* [interview A4].

Furthermore, hydrogen has several advantages over SAF and electrification. SAF is viewed by one academic stakeholder [interview A5] as a misleading "greenwashing" claim due to ongoing fuel combustion and it is only able to reach up to 80% CO2 reduction [interview G1]. Electrification, although capable of achieving zero-carbon emissions during flight, is heavily hindered by battery weight and energy density concerns [interview A5]. Additionally, *"hydrogen delivers more than 100 times the energy per unit mass compared to lithium-ion batteries, making it highly suitable for powering an aircraft"* [interview I4] .

From the point of view of the industry, *"in aviation, weight is highly significant"* [interview I2]. Hydrogen is seen as having a better balance between weight and energy compared to an electric-powered aircraft, though it is still not as good as kerosene, according to academia expert [interview A2]. Moreover, most stakeholders agree that hydrogen technology offers better climate impact reduction than SAF and electrification, especially for mid-range flights, and could potentially become suitable for long-range applications as the technology develops over time. In addition, hydrogen propulsion can be done in two ways: through combustion or fuel cells. Hydrogen combustion utilizes existing propulsion systems, allowing for easier implementation but resulting in NOx emissions and contrails. In contrast, fuel cells do not produce these emissions and offer high efficiency potential, yet they are currently less developed in aviation [interview I2].

Most experts stated that hydrogen-powered flight shows great potential compared to other alternatives. As expressed by one industry expert *"no one has proven it unfeasible so far. Therefore, let's assume it is viable and continue development"* [interview I3].

However, they also acknowledge that since the technology is still in the early stages of development with very low Technology Readiness Levels (TRLs) [interview G1], the future is somewhat unclear.

4.3.3. Introduction in the Air Freight sector

This section connects to the previously mentioned idea of introducing a niche technology, such as hydrogen-powered aircraft, in a specific aviation market niche. As identified in Section 2.5, the air freight sector may offer a less risky and easier implementation compared to the passenger market, thus potentially accelerating the transition to more sustainable aviation technologies.

Furthermore, introducing hydrogen-powered technology in the air freight sector prior to the air passenger sector presents several considerations and challenges. All stakeholders inside academia, industry, and government clusters admitted to never having thought about this possibility before and confirmed that most technological solutions in aviation are focused on and get developed within the passenger market. Therefore, this question gave stakeholders the opportunity to think of the potential advantages of introducing hydrogen in the air cargo sector before the passenger one.

Preliminary results showed a disparity of opinions and ideas, ranging from seeing no significant difference in the quickness or ease of implementation between cargo and passenger aircraft to believing that it could be a more straightforward way to demonstrate hydrogen's potential in aviation.

This section identifies several categories derived from stakeholders' answers regarding the different aspects to consider for the introduction of hydrogen technology in the air freight sector.

Aircraft Certification

An academic expert in cargo aviation explained that approximately half of the cargo transported daily, weekly, or yearly is carried in the lower deck of a passenger aircraft. Nevertheless, older passenger aircraft that would require a lot of maintenance are often converted to freighters to extend their useful lives. Additionally, some aircraft are designed as full freighters from the start, i.e., dedicated freighters, such as the Boeing 747-800 freighter and the Airbus A-350 freighter [interview A1].

Concerning the certification process of freighters, including both converted versions and fully dedicated freighters, most stakeholders agreed that certification is not easier because it carries cargo and not passengers. It is important to note that there are still two pilots and sometimes passengers (up to six people) who opt to travel with their highly valuable goods on the aircraft's main deck [interviews A1 and A4].

More specifically, when conversion from passenger aircraft occurs, the aircraft has already undergone passenger aircraft certification and might still require additional modifications, like changing the nose for loading cargo, adding a large door, and removing seats. For dedicated freighters, most stakeholders believe that the certification process is the same as if it was a passenger aircraft.

As stated by an academic expert as well as former pilot and aircraft certification expert, *"It is never the case that a cargo aircraft has a lower degree of safety or gets more margin or less restrictive regulation. Aviation is seemingly an equal playing field for all types of aircraft"* [interview A4]. This ensures that all aircraft, regardless of their specific use (passenger or freight), are held to the same high standards to ensure safety and reliability, both crucial aspects for aviation.

From the industry part, an expert explained that *"certification for freight aircraft is not easier than for passenger aircraft. Both types must adhere to the same standards and safety measures, particularly for propulsion systems and backup systems"* [interview I4], and emphasized that there is no significant difference in safety precautions between cargo and passenger aircraft.

Therefore, in terms of the certification process, no fundamental difference was found between cargo aircraft and passenger aircraft.

Technical aspects inside the aircraft

Industry experts, more precisely expert [I2], highlighted several technical advantages of implementing hydrogen technology in freighter aircraft compared to passenger aircraft. Freight aircraft are equipped with oxygen supplies in the cockpit, ensuring that in an emergency situation, such as a loss of cabin pressure, both the pilot and co-pilot have access to an alternative source of oxygen. In cases where there are passengers on board (a maximum of six) who choose to travel with their goods, they can also be provided with an additional oxygen supply. This backup oxygen supply allows pilots to have more time to find a suitable place to land safely, which is crucial during emergencies like a hydrogen leak or other serious issues. In contrast, in passenger aircraft, it is impractical to equip every passenger with an alternative oxygen supply due to the large number of people (a minimum of 200) and the logistical challenges involved. In such scenarios, passenger aircraft need to land immediately to ensure the safety of everyone on board. Moreover, in the early stages of hydrogen flight implementation, it is anticipated that emergencies may occur more frequently, which increases the risk for passengers during this initial period.

Furthermore, in passenger aircraft, maintaining a constant and effective passenger cabin ventilation system is crucial for passenger comfort and safety. This system is less critical in cargo aircraft, thus potentially simplifying the design and integration of new technologies like hydrogen. Additionally, air freight has experience transporting various unusual and potentially hazardous items, such as live animals (e.g., horses) and batteries that can catch fire. This existing expertise in handling potentially dangerous goods makes it easier to accommodate hydrogen tanks in the aircraft, which also have specific safety requirements.

A more common statement among stakeholders was that cargo aircraft have more flexibility in terms of where hydrogen tanks can be placed because they do not have to accommodate passengers. This allows for safer and more efficient tank configurations that would not be feasible in a passenger aircraft. One industry stakeholder [interview I2] mentioned the possibility of a modular fuel storage system to adjust the cargo space based on specific freight requirements and flight duration. For instance, a shorter flight might require less fuel, allowing for smaller tanks or fewer tanks to be installed, thereby freeing up more cargo space. Conversely, a longer flight would need larger or more tanks to carry sufficient fuel for the journey. In this way, the payload-to-fuel ratio is maximized.

Emergency venting protocols for hydrogen in both passenger and cargo aircraft involve safely releasing hydrogen gas into the air in the event of an overpressure situation. This is essential to prevent pressure buildup in the tank, which could lead to hazardous conditions. One significant advantage of cargo aircraft is that hydrogen tanks can be centrally placed, which is strategically beneficial for venting. By positioning the tanks in the middle of the aircraft, any overpressure hydrogen can be vented directly upwards, away from critical areas and personnel. In contrast, passenger aircraft cannot have hydrogen tanks below the passenger cabin, as venting hydrogen upwards from below would pose a safety risk to passengers. This limitation is not a concern in cargo aircraft, where there are no large numbers of passengers to consider, allowing for greater flexibility in tank placement. In the exceptional case where there are a few passengers (up to six) traveling with their cargo, they can be accommodated in a special compartment near the cockpit, away from the hydrogen tanks, and equipped with its own ventilation system.

In summary, the ability to provide pilots and additional passengers with an alternative oxygen supply in freight aircraft allows for a longer window to manage emergencies and find a safe landing spot. Other advantages include greater flexibility in tank placement within cargo aircraft, a less complex cabin ventilation system, existing experience with unusual cargo, possibility for a modular fuel storage system, and the ability to safely vent hydrogen by positioning tanks centrally and venting upwards. These characteristics make hydrogen technology more adaptable and potentially easier to implement in the air freight sector than in passenger aviation.

Technical aspects in aircraft operations

In the air cargo sector, network operations are often centralized around large hubs, whereas passenger networks need to adjust to certain destinations driven by passenger demand. This makes air cargo operations less limited by the ecosystem. *"With two large hubs equipped with hydrogen infrastructure, air cargo operations can already commence"* [interview I2]. This centralized approach allows for a more concentrated and manageable deployment of hydrogen technology at the early stages of implementation. Cargo operations can begin using hydrogen at a few strategically chosen hubs without needing widespread infrastructure immediately. In contrast, passenger airlines require extensive infrastructure across numerous airports, complicating initial implementation. *"No passenger airline is going to invest in hydrogen-powered aircraft if they can only operate in (for instance) five airports around the world"*, emphasized an industry expert [interview I2].

Moreover, an academia expert in air transport operations [A3] mentioned that airports with freight activities often have established synergies with other transport modes such as trucks, rail, or ports. Hence, these connections could be leveraged to facilitate the establishment of hydrogen infrastructure. *"Hydrogen hubs would not only support aviation but also other transport modes, utilizing existing infrastructure and connections"* [interview A3]. This integration could enhance the efficiency and sustainability of various transportation systems by centralizing hydrogen resources and technology.

Furthermore, regarding ground operations at airports, passenger airlines prioritize minimizing turnaround times to keep airplanes available and maintain consistent schedules. Frequent maintenance or extended downtimes for hydrogen systems could pose a significant drawback for their business operations. Conversely, cargo flights typically operate less continuously than passenger flights, giving cargo airlines more flexibility with their turnaround process.

Therefore, the air cargo market could be better suited for the initial adoption of hydrogen technology, as cargo planes can potentially accommodate the initially more intensive maintenance requirements of hydrogen systems with less disruption.

> **To conclude**, the main benefits identified by stakeholders for the air cargo sector are that cargo operations can efficiently adopt hydrogen technology by centralizing it at key hubs and leveraging existing transport synergies. Additionally, there is a greater tolerance for extended turnaround times than passenger airlines, and there is less reliance on extensive infrastructure, allowing for a phased implementation of hydrogen technology.

Technical aspects in hydrogen infrastructure at the airport

Most stakeholders indicated that the infrastructure required for hydrogen deployment at airports, including refueling, storage, and transport systems, will be the same regardless of whether it is for cargo or passenger activities.

Nonetheless, one expert in academia [interview A3] pointed out that passenger aircraft typically need to be refueled at the gates of the terminal where passengers board and disembark. *"This proximity to large numbers of people adds an extra layer of complexity and raises safety concerns when dealing with hydrogen due to the lack of previous experience in aviation"* [interview A3]. Thus, ensuring the safe transport and handling of hydrogen to these refueling points at large and busy airports (like Schiphol, Amsterdam) is particularly challenging. The same expert added, *"the infrastructure must account for potential new risks and hazards associated with hydrogen"*.

In contrast, freight aircraft refueling, as well as loading and unloading of cargo, often occur in more remote areas of the airport, usually away from passenger terminals. This remote location for freight operations might simplify the infrastructure challenges for hydrogen refueling. The reduced proximity to the main passenger areas can alleviate some safety concerns, allowing for potentially easier and quicker implementation of hydrogen infrastructure for freight aircraft.

> **In conclusion**, the interviewee suggests that while there are significant challenges in establishing hydrogen refueling infrastructure for passenger aircraft due to safety concerns and the need to refuel at busy terminals, the situation could be somewhat easier for freight aircraft because their operations occur in more isolated areas of the airport.

Societal aspects

One stakeholder in the industry [I3] claimed that introducing hydrogen in air freight could be a smart strategic move, targeting a niche market with less public scrutiny compared to passenger aviation. *"It gives a protected environment to develop, test and refine the technology"* [interview I3]. Consequently, in the event of issues or failures, these can be managed with less public and media exposure and without directly affecting passengers. Moreover, the same expert added that successfully implementing hydrogen technology in freighter aircraft can serve as "proof of concept" to demonstrate the technology's viability and safety. Thereby potentially building public confidence and paving the way for its adoption in passenger aircraft.

By starting with freight, the industry can address and mitigate any perceived risks of hydrogen-powered aircraft. This gradual approach can help in gaining public trust, as the technology would have already been proven in a less sensitive and lower-stake environment. An academic expert [A2] supports the idea by highlighting that social acceptance and potential risks associated with passenger flights might make it easier to begin with freight. This suggests that the public might be more comfortable with hydrogen technology once it has been demonstrated in freight operations, reducing resistance to its later introduction in passenger aviation.

To summarize, introducing hydrogen technology in air freight first from a societal perspective is seen as a strategic move to develop, test, and prove the technology in a less scrutinized environment, thereby easing its future adoption in passenger flights and increasing public trust in hydrogen-powered aircraft.

Economic aspects

Implementing hydrogen technology in the air cargo sector presents unique economic challenges and opportunities when compared to the passenger sector. Significant disparity in stakeholder opinions was observed concerning economic aspects. One industry expert believes that the decision-making processes and cost structures in the passenger and cargo sectors are inherently different [interview I1]. The same expert also suggested that regulatory changes and cost-benefit analyses will drive hydrogen technology adoption, but admitted not being a specialist in market dynamics.

An academia expert in the cargo sector mentioned that the cargo market, while growing due to fast fashion e-commerce, is still not as large as the passenger market. This together with the high costs associated with developing and certifying a hydrogen-powered cargo aircraft, involving extensive testing hours, could make it economically challenging [interview A1]. This opinion was supported by an industry expert [I3] emphasizing that the air freight sector is extremely price-sensitive and less influenced by intangible benefits such as environmental concerns or the desire to ”fly green”. Adding that *”the economic justification for hydrogen adoption must be very strong, focusing on long-term cost savings and efficiency improvements rather than environmental benefits alone”* [interview I3].

Nevertheless, another industry expert [I2] saw one potential economic advantage for air freight. Since cargo operations can be initially centralized in a few strategically chosen hubs, initial hydrogen infrastructure investment and complexity could be mitigated, as opposed to the extensive network needed for passenger flights.

All stakeholders agreed that, as of now, there are no significant initiatives focused on hydrogen technology in the cargo sector. The approach is not widely adopted, and awareness of its potential is limited. An expert in the government believes that *”since the potential of hydrogen technology still needs to be fully proven, it is too early to develop a business case for cargo flights”*, suggesting it might take a few more years [interview G1]. However, despite the current lack of initiatives, there is a belief among some experts that hydrogen implementation in the cargo sector could make sense and hold potential in the future. One industry stakeholder also suggested that the military could be be interested in a green freighter aircraft [interview I1].

Lastly, while the cargo sector presents economic challenges for hydrogen implementation, strategic approaches such as focusing on initial hubs and demonstrating clear cost-benefit analyses could pave the way for future adoption. The current market dynamics and regulatory environment will play crucial roles in determining the feasibility and timeline of this transition.

4.3.4. Hydrogen propulsion technology for freighter aircraft

Considerable opinion differences arose among stakeholders regarding which hydrogen-propulsion technology, combustion or fuel cell, could work better for a freighter aircraft. Some experts expressed no clear preference and emphasized the importance of certification, regulations and cost considerations [interviews A6 and I1]. Nevertheless, these experts claimed that if the freighter element is eliminated from the decision-making process, both technologies have pros and cons, and the choice depends on various factors such as size and range of the aircraft.

Most stakeholders who opted to chose one of the technologies agreed that freighter aircraft often perform longer flights. Thus, they believe hydrogen combustion is more relevant due to its suitability for long-range flights (over 2000 nautical miles) and its foundation in existing technology. In contrast, fuel cells are hybrid systems that often require additional components like batteries, making them better suited for short to mid-range flights.

4.4. Socio-Technical Regime

At the moment the socio-technical regime is still heavily dominated by fossil-based fuels (Section 2.5.1), yet the aviation industry is gradually transitioning towards a more sustainable future, that will eventually result in a new regime. The following sections will focus on the current experimental stage of hydrogen technology (see Figure 4.1). The transition awaits necessary developments across five key dimensions: technical, regulatory, societal, industry, and user and market aspects to reach a new socio-technical regime. By exploring these dimensions, an overview of the potential drivers and barriers for hydrogen transition in air transport can be achieved.

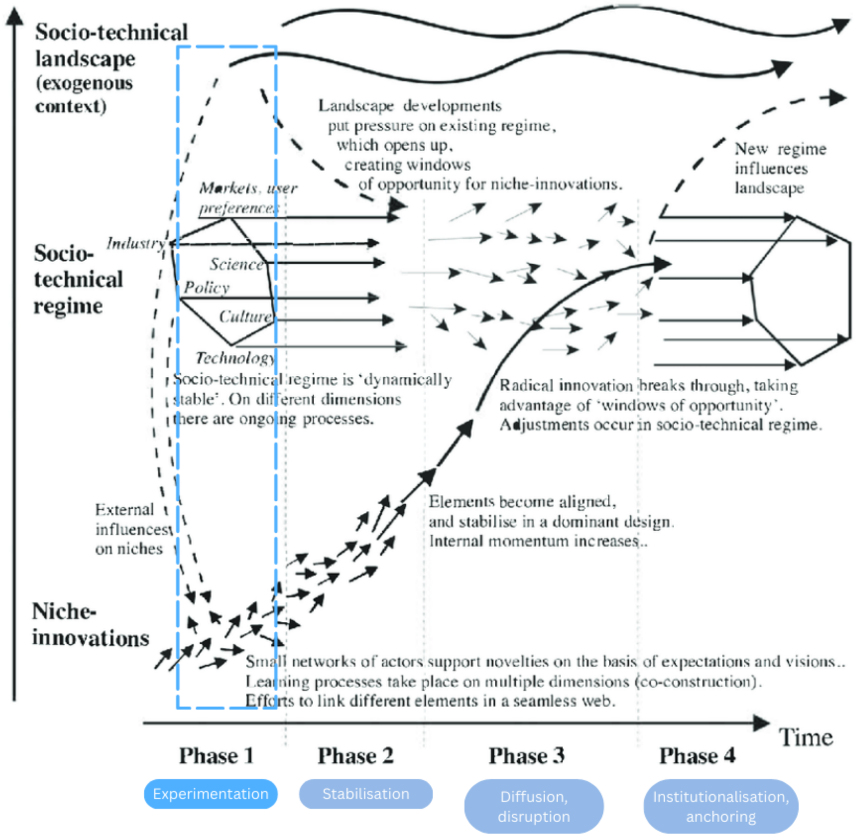

Figure 4.1: Visualization of the current experimental stage of hydrogen-powered technology in aviation in the MLP (Adapted from Geels (2018))

4.4.1. Current State of Technology

Technological advancements in hydrogen-powered aircraft

Currently, the technology is transitioning from conceptual designs to demonstration phases, with integrated demonstrators expected in the future. However, it is still in the early stages and not yet a fully integrated product [interview I3]. An industry expert pointed out that *"there is a noticeable overshoot in hydrogen expectations, placing us at the peak of the hype curve"* [interview I3] (see Figure 4.2).

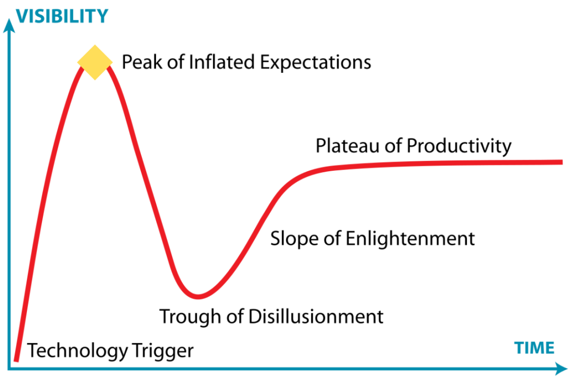

Figure 4.2: Gartner Hype Cycle: Hydrogen-powered technology positioned at the Peak of Inflated Expectations (Diamandis, 2017)

Recent technological advancements in hydrogen-powered aircraft have led to significant improvements in propulsion efficiency and sustainability. Environmentally, hydrogen's carbon footprint is minimal if produced from renewable energy sources. However, technological challenges remain, particularly in hydrogen storage, temperature management, and integrating hydrogen subsystems into the aircraft design [interview A6].

An industry expert explained that "hydrogen technology is not new, but its application in aviation requires further development". OEMs like Airbus are at the forefront of technological development, exploring both hydrogen combustion and fuel cell technologies with a focus on safety and efficiency [interview I1]. Additionally, companies like ZeroAvia and Universal Hydrogen are developing concepts for hydrogen-powered aircraft, and research universities are conducting smaller-scale hydrogen combustion experiments [interview A3]. Concerning fuel cell development, advances in high-temperature proton exchange membrane fuel cells and thermal management systems to manage the significant heat produced by fuel cells, are noteworthy [interview I2]. Other work currently being undertaken involves the entire fuel cell powertrain, focusing on the correct order and arrangement of subsystems, tank placement, and gearbox development. High-power fuel cells are also being developed to accommodate larger passenger capacities [interview G1].

The shift to hydrogen-powered aircraft involves adapting existing aerospace technologies to accommodate hydrogen use, such as creating tanks to store liquid hydrogen. An expert in the industry clarified that *"unlike kerosene, hydrogen is non-toxic, thus mitigating risks if a leak occurs. But it requires cryogenic tanks for storage"*. The same expert mentioned that Airbus is involved in the ASCEND project, which focuses on developments in cryogenic superconductivity [interview I4].

Furthermore, several stakeholders highlighted that learning from the automotive industry, particularly companies like Toyota and Nissan, is crucial. *"The hydrogen combustion market in cars and trucks offers valuable insights"* [interviews A5 and I2].

Hydrogen infrastructure challenges

Current infrastructure for kerosene is well-established and integrated with existing pipelines and refueling systems. Kerosene can be easily transported and stored, and airports are already equipped to handle it efficiently. Unlike kerosene, hydrogen requires entirely new infrastructure. One industry expert mentioned that *"airports are not currently equipped with the necessary systems to handle hydrogen, whether it be in liquid or gaseous form"* [interview A3]. According to another stakeholder, the industry faces a dilemma: *"aircraft manufacturers may hesitate to develop hydrogen-powered aircraft without hydrogen infrastructure, while infrastructure developers may wait for the aircraft to be built first"* [interview I3].

The integration of hydrogen as an aviation propulsion technology poses significant technological infrastructure challenges, varying with the size and operational demands of airports [interview A6]. An academic expert [A6] mentioned "small airports have an advantage due to their lower hydrogen demand, while large airports face substantial logistical and infrastructural hurdles".

The same expert added that key challenges at the airport include storage, operational safety, and ensuring a sufficient supply of green hydrogen. Another stakeholder in academia supported this by stating that *"constant availability of hydrogen at airports is crucial for efficiency, as lacking it significantly reduces performance"* [interview A4]. On the industry side an expert highlighted that *"transitioning from kerosene to hydrogen will not happen abruptly. Both systems will coexist for some time, necessitating dual infrastructures"* [interview I1]. Moreover, introducing hydrogen at the airport requires considerable investment in new facilities, specialized refueling equipment, and training programs for airport personnel.

Furthermore, hydrogen infrastructure must be integrated with existing systems without disrupting current operations. This includes maintaining stringent safety standards and managing the unique challenges of storing and handling hydrogen [interview A5]. When it comes to hydrogen storage, large tanks are needed to store liquid hydrogen, which must be kept at extremely low cryogenic temperatures (around −253°C). Alternatively, gaseous hydrogen requires even larger storage tanks due to its lower volumetric energy density compared to liquid hydrogen. Both storage types come with significant safety concerns, including risks of leaks and explosions, as well as the need for specialized handling equipment [interview A3].

Regarding production and supply chain, generating hydrogen on-site at the airport can ensure a consistent supply but necessitates significant investment in production facilities and technology, such as electrolyzers. Alternatively, hydrogen can be produced off-site and transported to the airport via gas pipelines or trucks carrying liquid hydrogen. This approach requires additional logistics and infrastructure, including liquefiers at the airport, for safe and efficient delivery [interview I4]. The best infrastructure solution may vary depending on the airport's location, considering factors such as proximity to ports, availability of renewable energy sources, and existing transport connections like rail and road [interview A3]. A stakeholder in academia [A3] pointed out that there is no "one-size-fits-all" solution. Each airport may need to be accommodated according to its specific circumstances and logistical considerations.

Nonetheless, an academic expert and former pilot explained that airports need globally standardized infrastructure to handle non-standard operations like emergency landings and maintain performance during contingencies [interview A4]. According to the expert, having standardized facilities, equipment, and procedures across airports worldwide ensures that these non-routine situations are managed effectively and safely. The expert highlighted that mixed-methods complicate procedures for pilots, who would otherwise need to adapt to different systems and protocols at various airports, increasing the risk of errors. Additionally, this lack of standardization adds to the infrastructural complexity, leading to inefficiencies and potential safety hazards.

Moreover, an expert in the industry remarked that safety measures are extremely important, as hydrogen, while not inherently less safe than kerosene, requires rethinking safety protocols due to its different properties to kerosene and sensitivity to leaks [interview I2]. The same expert added that *"the aviation world needs a comprehensive hydrogen ecosystem, including mature subsystem innovation and clear safety protocols, to support hydrogen-powered commercial aircraft"* [interview I2].

> **In summary**, the transition to hydrogen in aviation involves extensive and diverse challenges, encompassing production, distribution, storage, refueling, and safety considerations at every stage (Figure 4.3). It is a complex and multifaceted process requiring significant technological and financial investments while ensuring global infrastructural standardization.

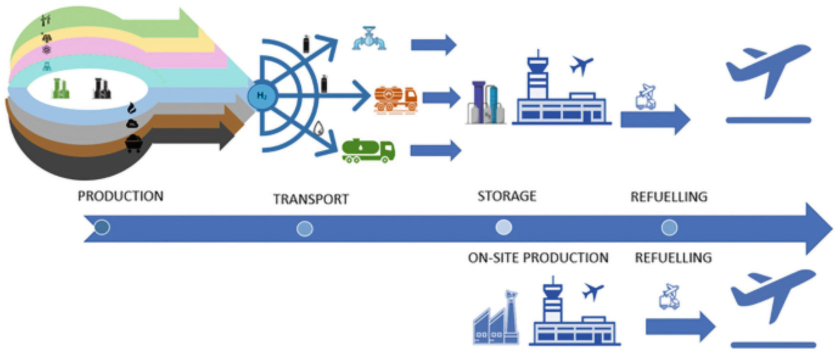

Figure 4.3: Hydrogen infrastructure and logistics at the airport (Marksel et al., 2022)

Aircraft design alterations

Necessary alterations in aircraft designs to accommodate hydrogen-powered technology involve several key modifications and considerations. Traditional tube-and-wing aircraft designs are required to accommodate hydrogen tanks, impacting the aircraft's balance and center of gravity [interview I1]. Additionally, both passenger and cargo airplanes must ensure adequate separation between people, cargo, and hydrogen tanks to mitigate risks [interview A4]. Hydrogen, whether in liquid or gaseous form, requires more volume than kerosene and cannot be stored in the wing tanks. Instead, it must be kept in heavier insulated cryogenic tanks. Possible configurations for hydrogen tank placement include tanks within the fuselage, most likely in the rear of the aircraft. Additionally, the tank location must consider safe venting strategies to prevent overpressure inside the tank [interview I4]. However, an academic expert clarified that these tube-and-wing designs configurations need still thorough research to ensure the tanks and storage systems fit within the aircraft's aerodynamic capabilities, while maintaining the space required for cargo or passengers [interview A5].

Furthermore, most stakeholders suggested considering new aircraft designs, such as flying wings, to improve volume and weight distribution. This design, with its larger internal volume, could more effectively accommodate hydrogen tanks. However, stakeholders also expressed caution, noting that a flying wing design would represent a significant departure from traditional aircraft configurations and require additional infrastructure alterations. One interviewee remarked, *"I would be surprised if the industry immediately embraced such an extreme change"* [interview G1].

> Therefore, most stakeholders recommended a more incremental approach, integrating hydrogen technology into existing designs without drastically altering the aircraft configuration, as a more practical short-term solution.

4.4.2. Policy

Regulatory Environment

According to most stakeholders, European aviation policies are increasingly focused on significant investments in technology development and CO2 reduction to meet ambitious climate goals. The EU aims to be the first climate-neutral continent by 2050, with detailed targets set in the European Climate Law and the 'Fit for 55' package, which includes a 55% reduction in emissions by 2030 compared to 1990 levels. Achieving these goals requires coordinated efforts, including the implementation of aviation fuel taxes across Europe to level the playing field with rail travel. One stakeholder in academia mentioned that the current absence of such taxes creates "false competition", making flying artificially cheaper and less environmentally sustainable than rail [interview A6]. Introducing and gradually increasing these taxes can help balance the true costs of different transportation modes and promote the use of sustainable options like trains.

To support the hydrogen transition in aviation, several regulatory updates and collaborative efforts are essential. From the point of view of an industry stakeholder, regulations need to evolve alongside OEMs' development efforts, with current policies adapting to new technical standards for hydrogen-powered technology [interview I1]. An expert in academia and former pilot believes that *"current policies are preparing for new technologies, but there is a need to balance safety margins and avoid overly flexible regulations due to economic pressures"* [interview A4].

Therefore, governments and regulatory bodies like EASA must provide stable and clear regulations, as frequent changes can hinder technological development and lead to financial losses. Moreover, stakeholders in the industry emphasized that proactive cooperation with authorities is crucial to avoid designing an aircraft against moving targets [interview I3].

> The same expert suggested that jointly developing regulatory frameworks with specific directives for the safe supply chain, handling, and storage of hydrogen, can ensure that new technologies meet safety and operational standards without compromising on efficiency or cost savings [interview I3].

Incentives and Support

Most stakeholders agreed that the transition to hydrogen-powered aircraft needs both financial incentives and regulatory measures. An expert in academia mentioned that while carbon taxes could make hydrogen more attractive by increasing the cost of fossil fuels, their effectiveness alone is limited [interview A3]. Instead, the interviewee suggests financial incentives like subsidies to encourage adoption, along with early involvement of regulatory bodies like EASA to ensure new technologies meet safety and certification standards. *"It should be more of an incentive than a taxation to switch to new technologies"* [interview A3].

Transitioning to hydrogen-powered technology in aviation involves significant initial costs, necessitating substantial government financial support during the early stages. This support can be provided through subsidies, grants, or other financial incentives to alleviate the financial burden on companies. Additionally, governments should cultivate an environment that encourages innovation by backing research and development (R&D) efforts and providing a "no rule zone" where feasibility tests can be realized [interview I2].

One industry expert highlighted the critical need for early incentives and support in R&D, particularly for small and medium-sized enterprises (SMEs) involved in developing subsystems for larger original equipment manufacturers (OEMs) like Airbus. This expert pointed out that SMEs often do not benefit from public funding to the same extent as larger companies [interview I4]. An academic expert emphasized that governments should serve as the initial catalyst, providing a significant initial push to overcome the "chicken and egg" dilemma, where companies are reluctant to invest due to high risks and uncertainties [interview 3].

> Another academic stakeholder supported this statement, suggesting that governments could act as the launching customer for hydrogen-powered planes to demonstrate feasibility [interview A5].

4.4.3. Society and Culture

Public Perception and Acceptance

Experts believe that hydrogen-powered technology is generally perceived positively as an innovative solution, particularly due to its clean technology characteristics, which include reducing emissions and eliminating kerosene odors and particles [interview G1]. They also noted that the public currently views hydrogen in aviation as an experimental technology and therefore does not yet feel concerned about its risks.

Additionally, one stakeholder in the industry mentioned that *"people are generally indifferent to the technology behind being environmentally friendly. They only care about having a sticker on their ticket indicating that it is environmentally friendly"* [interview I1]. Despite the optimism, experts also noted that safety concerns can emerge as the technology gains visibility [interview A6].

Furthermore, lack of understanding and initial perceptions of hydrogen as a risky technology can hinder acceptance. One stakeholder in the industry mentioned that there is a historical association of hydrogen with explosions due to the Hindenburg disaster [interview I2]. Moreover, most stakeholders emphasized that accidents in aviation have a large public repercussion, as exemplified by the current situation with Boeing [interview I4]. Therefore, initial successful demonstrations of hydrogen-powered aircraft are crucial to build public trust and acceptance [interview I2].

Additionally, the influence of regulatory policies and societal pressure to mitigate climate change further drives the need for sustainable aviation solutions. Generational differences may also play a role, with younger people being more open to environmentally friendly technologies [interview A2]. Lastly, an expert in academia expressed that European companies tend to have a more long-term perspective, while North American companies remain focused on short-term profits [interview A3].

Awareness and Community Involvement

Ultimately, the public's evolving perception of hydrogen-powered technology will be influenced by ongoing communication from governments and manufacturers on environmental advantages to increase awareness. A government expert emphasized that communicating the potential for job creation and broader economic benefits is crucial for gaining support from both industry stakeholders and the public. The expert believes that showcasing how hydrogen technology can drive economic prosperity, alongside its environmental advantages, makes a stronger case for its adoption [interview G1].

Moreover, community education plays a critical role, particularly in bridging the gap between technical specifics and public understanding. One academic stakeholder suggested, *"perhaps in the next generations, we can begin teaching children in school about new energy carriers like hydrogen and other alternatives"* and added that *"instead of steering societal views in a single direction, we should encourage a more open-minded and critical perspective on these new possibilities"* [interview A3].

> Additionally, effective and transparent communication addressing noise and emissions concerns will be essential in shaping a positive and informed public perception of hydrogen-powered aviation in the future [interview G1].

4.4.4. Industry

Preparation and Collaboration

Currently, the industry is more focused on SAF as it is seen as a short term solution to reduce carbon emissions [interview I4]. Nevertheless, the industry acknowledges the limitations of SAF in the long term, so in parallel they are engaging in European research projects funded by the European Union or the European Commission. These projects bring together various stakeholders to advance hydrogen technology, ranging from those interested on developing specific subsystems to those who adopt a more neutral standpoint and conduct techno-economic assessments [interview A3].

Furthermore, key stakeholders including OEMs, hydrogen producers, research institutes, airlines, and airports are working together to tackle the complex challenges involved in the transition. These collaborations span the entire hydrogen ecosystem, from production and logistics to certification and regulatory policies, critical for ensuring safety and compliance. From the industry perspective, interviewees expressed particular interest in closely engaging with universities and research institutes, *"we are in close contact with researchers to make sure that we are in the right path to obtain the most beneficial breakthroughs and achieve higher technology readiness levels"* [interview I2].

Significant advancements are envisioned in the next few years. By 2035, Airbus plans to release its first-generation hydrogen-powered aircraft. An industry expert highlighted that in approximately 20 years from now, in 2045, considerable reductions in overall fuel consumption should be observed in order to reach the goal of zero-carbon emissions during flight by 2050.

Additionally, the same expert estimates that by 2045 there will be significant modifications to the first-generation aircraft to improve efficiency, though not yet a second-generation aircraft but rather an improved version of the first [interview I1]. Moreover, the academia foresees the technology progressing from TRL 1, i.e., basic technology research, to a maximum of TRL 4/5 close to technology demonstration in the next 15 years, stating that it will not be ready for market implementation within this timeframe [interview A5].

Economic Considerations

Many experts agreed that hydrogen is currently not economically viable compared to kerosene. However, a stakeholder in the government emphasized that with the right policies and incentives, the technology could be economically feasible in a few years [interview G1]. If kerosene is taxed appropriately and CO2 emissions pricing increases, hydrogen-powered technology could become more competitive, especially in medium range markets. Additionally, most stakeholders explained that in order to avoid regional disparities in kerosene prices, coordinated global efforts are needed [interview I4]. For instance, if the Netherlands implements a higher tax than Germany, ticket prices will rise, leading passengers to choose flights from Frankfurt Airport over Schiphol Airport.

Furthermore, both industry and academic experts recognized that achieving economic feasibility in aviation also requires broader industrial adoption of hydrogen in other industries to achieve scale and cost reductions. The interviewee emphasized that relying solely on the aviation sector to drive this shift may make regulating prices considerably challenging [interview I1].

Hence, a transition to hydrogen economy is crucial to reduce hydrogen production costs significantly, thus transforming the overall sustainable aviation mindset.

4.4.5. User and Market

Market Demand and Trends

According to the interviewees, the market demand for hydrogen is expected to grow in the upcoming years, primarily driven by regulatory change, environmental awareness, technological maturity and the economic viability of hydrogen as an alternative solution to fossil-based fuels. An academia stakeholder expressed that while initial demand may focus on short- to medium-range flights, long-term assessments could see hydrogen being used for long-range flights, which have higher CO2 impact [interview A2].

Moreover, an expert in the government noted that with airports in the Netherlands imposing CO2 restrictions on flights, the importance of developing hydrogen-powered technology rises. This trend is supported by investments in hydrogen production and infrastructure at key locations like Eemshaven in Groningen and the Port of Rotterdam [interview G1].

Nevertheless, the expert also pointed out that governmental involvement is essential to guarantee sufficient allocation of hydrogen for the aviation industry. This is especially important as the automotive and marine industries are also pursuing hydrogen solutions [interview G1].

Customer and Stakeholder Engagement

According to one expert in academia, airlines and logistics companies, can be motivated by a ”carrot and stick” approach [interview A6]. The ”stick” involves regulatory restrictions. If an airline's aircraft fleet does not meet the required emissions standards, the airport authorities may prohibit their aircraft from landing at the airport. On the contrary the ”carrot” symbolizes a reward for adhering to environmental regulations, allowing business operations at airports for airlines adopting cleaner technologies.

Industry experts noted that airlines and logistics companies might be driven to adopt sustainable solutions to avoid financial penalties for CO2 emissions and enhance their public image. However, profitability remains crucial for these companies, necessitating both affordable purchasing costs and low costs in aircraft operations and maintenance [interview I2].

On the other hand, passengers mainly prioritize reaching their destinations safely and affordably. Although environmental awareness regarding emissions and noise has grown in recent years, there is still uncertainty about passengers' willingness to pay for more sustainable air travel options [interview G1]. Two academic experts believe that customers must be convinced of the environmental benefits and provided with safety assurances to accept potential higher costs.

> *"Education and marketing strategies will be crucial in shaping customer perceptions and acceptance", they stated* [interviews A2 and A4].

4.5. Landscape Level

4.5.1. Global Trends and External Pressures

The global push towards sustainability and greening trends is moving the hydrogen economy forward, driven by the urgent need to address climate change and reduce greenhouse gas emissions. Aviation, a particularly challenging industry to decarbonize due to its existing aircraft design and infrastructure favoring kerosene fuel, exemplifies the pressing need for innovation in hydrogen-powered technology. As fossil fuel resources are finite and becoming expensive, the demand for sustainable propulsion alternatives is growing over the next decades.

Furthermore, an industry expert emphasized that climate change effects, such as heat waves, flooding, and other environmental disasters, are motivating some regions more than others to take action. Areas experiencing severe events are more likely to implement aggressive policies and measures to mitigate and adapt to these changes [interview I2].

Moreover, several experts pointed out that political and economic instability created by war conflicts contributes to uncertainty in global fuel supplies and prices. This instability drives countries to seek greater energy independence. Hydrogen offers a pathway to energy independence because it can be produced domestically in almost any country. In Europe, northern countries can benefit from wind energy and in the south from solar energy.

> Unlike oil, which is concentrated in specific regions in Middle East, hydrogen can be produced locally using electrolysis powered by renewable energy sources [interview G1].

4.5.2. International Agreements and European Policies

At a global level, all experts mentioned that the Paris Agreement, which seeks to limit global warming from increasing 2°C, is driving countries to reduce carbon emissions across all sectors, including aviation. Similarly, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) aims to stabilize CO2 emissions from international aviation at 2020 levels [interview A2].

Furthermore, at the European level, a government stakeholder noted that the European Green Deal, which aims for EU climate neutrality by 2050, promotes clean aviation technologies through initiatives like the Clean Aviation Joint Undertaking, including Clean Sky 2 program. Additionally, the EU Emissions Trading System (EU ETS) covers CO2 emissions from flights within the European economic area. Under this system, airlines must acquire allowances to cover their emissions, incentivizing them to reduce their carbon footprint [interview G1].

5
Results

In this chapter, a summary of the drivers and barriers for hydrogen adoption identified during the discussions with the experts is displayed (Section 5.1). The section delves into the key factors that promote the use of hydrogen technology as well as the challenges that hinder its widespread implementation. These insights are crucial for understanding the current landscape and future prospects of hydrogen adoption. The drivers include technological advancements, environmental benefits, and policy support, while the barriers encompass issues related to cost, infrastructure, and market readiness.

Moreover, an overview of the potential advantages of introducing hydrogen in air cargo is presented (Section 5.2). The air freight sector can play a crucial role in the early adoption and demonstration of hydrogen technology, paving the way for its broader implementation in passenger transport and significantly contributing to global sustainability efforts.

5.1. Overview of Drivers and Barriers for hydrogen adoption

This section presents a list of drivers and barriers for the adoption of hydrogen-powered technology in aviation, based on the perspectives from various stakeholders. Each driver and barrier has been categorized into four main areas: technological, political, economic, and societal. Additionally, the section in Chapter 4 where each aspect was identified is noted in brackets.

Aspect	**Tables**
Technical	Table 5.2 and Table 5.3
Political	Table 5.4
Economic	Table 5.5
Societal	Table 5.6

Table 5.1: Summary of Tables by Aspect

Drivers	Barriers
• Promising clean alternative to fossil-based fuels (Section 4.3.1) • It can be produced sustainably using renewable energy (green hydrogen) (Section 4.3.1) • It is a disruptive technology that allows for a complete transformation of the propulsion system (Section 4.2) • Produces only water as a byproduct (Section 4.3.1) • Unlike kerosene, hydrogen is non-toxic (Section 4.4.1) • It has zero-carbon emissions in flight (Section 4.3.1) • It can be used directly in a gas turbine for propulsion (i.e., hydrogen combustion) or converted in a fuel cell to generate electricity for an electric motor (Section 4.3.2) • Hydrogen combustion can effectively eliminate CO2 and reduce the majority of soot and sulfur emissions (Section 4.3.1 and Section 4.3.2) • Hydrogen fuel cells also have potential to reduce contrails and NOx emissions (Section 4.3.1 and Section 4.3.2) • Layered approach: hydrogen has potential for medium-range flights (Section 4.2) • Higher gravimetric energy density than kerosene (Section 4.3.1) • Proven performance in other industries (e.g., automotive, maritime) (Section 4.3.1, Section 4.4.1 and Section 4.4.5)	• Still an emerging technology, not yet operational and commercialized (Section 4.2) • Early stages of technology with low Technology Readiness Levels (TRLs) Section 4.3.2 and Section 4.4.4) • Competition with other alternatives (SAF, electricity) (Section 4.3.2) • Lack of sufficient previous experience with hydrogen in commercial aviation (Section 4.2) • New way of developing propulsion systems (Section 4.2 and Section 4.3.1) • Disruptive technological shift involving a complete overhaul of the current ecosystem (Section 4.2 and Section 4.4.1) • Complex logistics and handling to the airport (Section 4.4.1) • Heavy and voluminous hydrogen storage at the airport compared to kerosene (Section 4.4.1) • Lower volumetric energy density than kerosene (Section 4.3.1) • Inflated expectations for hydrogen-powered aircraft (Section 4.4.1) • Current infrastructure for kerosene is well-established and integrated (Section 4.4.1) • Need for dual infrastructures during the transition period (Section 4.4.1)

Table 5.2: Technological Drivers and Barriers (1)

Drivers	Barriers
• Scarcity of supply and high costs for SAF boost hydrogen innovation (Section 4.3.2) • Large battery weight and low gravimetric energy density for electric aircraft boost hydrogen innovation (Section 4.3.2) • Increasing development of cryogenic tanks and high-power fuel cells (Section 4.4.1) • Concepts for hydrogen-powered aircraft are being undertaken (ZeroAvia and Universal Hydrogen) (Section 4.4.1) • Smaller-scale hydrogen combustion experiments are being conducted by research universities (Section 4.4.1) • Potential for new aircraft designs like flying wings (Section 4.4.1)	• Aviation safety standards remain very conservative, resulting in slow innovation (Section 4.3.1) • Potential extensive changes in pilot training (Section 4.3.2 and Section 4.4.1) • Specialized refueling equipment and training programs for airport personnel (Section 4.4.1) • Complex integration of hydrogen subsystems into the aircraft design (Section 4.4.1) • Temperature management of hydrogen fuel cells (Section 4.4.1) • Hydrogen infrastructure implementation for large airports (Section 4.4.1) • Securing constant availability of hydrogen at the airport (Section 4.4.1) • Hydrogen infrastructure integration with existing systems without disrupting current operations (Section 4.4.1) • Global infrastructural and procedure standardization (Section 4.4.1) • Storage of hydrogen in the tube-and-wing aircraft design (Section 4.4.1) • Liquid hydrogen cannot be stored in the wing tanks but rather in cryogenic tanks within the aircraft's fuselage occupying significant space (Section 4.3.1 and Section 4.4.1) • Liquid hydrogen which must be kept at extremely low cryogenic temperatures (around −253°C) and stored in heavier insulated cryogenic tanks (Section 4.3.1, Section 4.4.1) • Gaseous hydrogen necessitates even larger storage tanks because it has a lower volumetric energy density compared to liquid hydrogen (Section 4.4.1) • Hydrogen is not less safe than kerosene but requires rethinking of safety protocols (Section 4.4.1)

Table 5.3: Technological Drivers and Barriers (2)

Drivers	Barriers
• Climate Change and Paris Agreement (Section 4.5.1 and Section 4.5.2) • Environmental disasters caused by global warming (Section 4.5.1) • Zero-carbon emission goals by 2050 (Section 4.4.2 and Section 4.5.2) • Opportunity for energy independence (Section 4.5.1) • Oil is finite resource, requires complex refinement and has limited extraction sites (Section 4.5.1) • Unlike fossil jet fuel, hydrogen can be generated close to its consumption point, removing the need for long-distance transport (Section 4.5.1) • Kerosene taxation (Section 4.4.2) • CO2 restrictions on flights (Section 4.4.5) • Increasing regulatory support and financial incentives by the EU (Section 4.4.2) • Collaboration and partnerships between industry and research actors (Section 4.4.4) • Opportunity for joint development of new regulatory frameworks (Section 4.4.2) • Government as a potential launching customer for hydrogen-power aircraft (Section 4.4.2) • Research projects funded by the European Union or European Commission (Section 4.4.4) • Europe's potential in renewable energy sources (Section 4.5.1)	• High fossil fuels dependency (Section 4.5.1) • International nature of aviation increases the difficulty of achieving global coordination (Section 4.2) • Risk of overly flexible regulations due to economic pressures (Section 4.4.2) • Current regulations are not viable for hydrogen-powered technology (Section 4.4.2) • Provision of "no rule zone" for testing is non-existent (Section 4.4.2) • Early incentives and support in R&D for SMEs is lacking (Section 4.4.2) • Regional disparities on kerosene taxation (Section 4.4.4) • Guarantee sufficient allocation of hydrogen to aviation (Section 4.4.5)

Table 5.4: Political Drivers and Barriers

Drivers	Barriers
• Fossil fuel price fluctuations (Section 4.5.1) • Potential for job creation leading to economic prosperity (Section 4.4.3) • Broader industrial adoption of hydrogen to achieve economies of scale in hydrogen production (Section 4.4.3) • Potential of hydrogen being cheaper in the long-term than kerosene (Section 4.4.3) • European companies have a long-term profit perspective compared to US companies (Section 4.4.3)	• High initial costs for R&D and infrastructure development (Section 4.4.2) • Hydrogen is currently not economically viable compared to kerosene (Section 4.4.4) • Passenger willingness to pay for more sustainable air travel (Section 4.4.5) • Initial operational and maintenance costs for hydrogen-powered aircraft (Section 4.4.5)

Table 5.5: Economic Drivers and Barriers

Drivers	Barriers
• Positive public perception of hydrogen as an environmentally friendly technology (Section 4.4.3) • Public demand for sustainable aviation solutions (Section 4.4.3) • The public does not yet feel concerned about the risks (Section 4.4.3) • Young generations pushing for sustainability (Section 4.4.3) • Ongoing communication from governments and aircraft manufacturers to influence public perception (Section 4.4.3)	• Public safety concerns and historical associations of hydrogen with explosions (Section 4.4.3) • Generational differences in the acceptance of new technologies (Section 4.4.3) • Lack of understanding about hydrogen-powered technology among the public (Section 4.4.3) • High public repercussions of aviation accidents (Section 4.4.3)

Table 5.6: Societal Drivers and Barriers

5.2. Hydrogen in Air Freight: Advantages and Disadvantages

This study also aimed to analyse whether introducing hydrogen-powered technology in the air freight sector could have advantages compared to the air passenger sector (see Section 4.3.3). According to stakeholders' opinions during the interviews, several advantages were identified and classified into technical, social, and economic categories (Section 5.2.1). Although the main focus of this section was to investigate potential advantages, a few societal and economic disadvantages were also identified during the discussions with experts (Section 5.2.2). These points will be further detailed in Chapter 6.

5.2.1. Advantages

TECHNICAL
Aircraft
• Cargo aircraft are equipped with alternative oxygen supplies for pilots or any additional passengers, providing them with an extended timeframe to handle emergencies and locate a safe landing site. • Greater flexibility in hydrogen tank placement within cargo aircraft, allowing for safer and more efficient tank configurations. • Less complex cabin ventilation system, which simplifies the design and integration of new technologies like hydrogen. • Air cargo's expertise in handling potentially dangerous goods facilitates the accommodation of hydrogen tanks in aircraft, which also have specific safety requirements. • Cargo aircraft offer the possibility for a modular fuel storage system, which allows for the adjustment of cargo space according to specific freight requirements and flight duration. • Cargo planes could safely vent hydrogen by positioning the tanks centrally and venting upwards.
Air cargo operations
• Air cargo is less limited by the ecosystem. • Cargo operations can efficiently adopt hydrogen technology by centralizing it at key hubs and leveraging existing transportation synergies. • Greater tolerance for extended turnaround times.
Airport infrastructure
• Less reliance on extensive infrastructure enables a phased implementation of hydrogen technology. • Ability to refuel in more isolated areas of the airport, which alleviates safety concerns and simplifies the implementation of hydrogen infrastructure.

Table 5.7: Technical Advantages

SOCIETAL
• Air freight can act as a "protected environment" to develop, test, and refine new technologies. • In case of issues or failures, these can be managed with less public exposure and without directly affecting passengers. • Starting with air freight helps address and mitigate initial perceived risks associated with hydrogen-powered aircraft, creating a gradual path towards public acceptance. • Successfully implementing hydrogen technology in freighter aircraft can demonstrate its viability and safety, serving as proof of concept and potentially building public trust. • Public comfort with hydrogen technology is more likely once it has been demonstrated in freight operations, reducing resistance to its later introduction in passenger aviation.

Table 5.8: Societal Advantages

ECONOMIC
• Centralizing cargo operations in a few strategically chosen hubs can mitigate the initial investment in hydrogen infrastructure, unlike the extensive network required for passenger flights. • Market opportunity in the military for a green freighter aircraft.

Table 5.9: Economic Advantages

5.2.2. Disadvantages

Societal
• Lower public visibility reduces societal and market pressure to adopt hydrogen technologies. • Less urgency and motivation to innovate compared to the passenger aviation sector.
Economic
• Weaker economic incentives due to the smaller size and higher price sensitivity of the air freight sector. • High investment costs are less justifiable with lower traffic compared to passenger airports.

Table 5.10: Societal and Economic Disadvantages

6 Discussion

This research aimed to investigate the potential of hydrogen propulsion in decarbonizing air transport, evaluate the feasibility and benefits of transitioning from kerosene to hydrogen-powered technology, and identify the associated challenges. The purpose of this study was not only to identify drivers and barriers for hydrogen adoption in aviation, but to explore a potential market niche, namely the air freight sector, in which hydrogen could be first introduced to minimize the perceived risks linked to adopting a new technology. Previous studies have shown that a considerable amount of research has focused on air passenger traffic, while comparatively less attention has been given to air cargo, despite its growing impact on CO2 emissions. Moreover, there is extensive literature on hydrogen technology for aviation, yet an analysis from a socio-technical perspective is missing. Therefore, this research addresses this gap by examining the transition using a multi-level perspective approach that considers technical, political, economic, and societal dimensions. This chapter summarizes the findings across the three levels of the MLP, provides answers to the research questions and outlines the key contributions and implications of the research. Additionally, it examines its limitations, and offers suggestions for future studies.

6.1. Theoretical discussion

The theoretical framework, namely Multi-Level Perspective (Section 2.5.2), was utilized to formulate the interview questions for the experts (Appendix A). In this way, insights were obtained across the three levels of the MLP (Chapter 4). At the technological niche level, findings indicated that hydrogen, although still in its early stages of development, holds promise for application in medium-range aviation to significantly reduce CO2 emissions. However, it faces challenges in production, storage, and safety that must be overcome to disrupt the current dominance of the kerosene-based regime. Moreover, its introduction in the air freight sector led to a disparity in opinions, ranging from the believe that this niche could be a more straightforward way to demonstrate hydrogen's potential compared to passenger transport, to others considering the implementation equally challenging.

At the regime level, results revealed that hydrogen technology requires significant development in technical, regulatory, societal, industry, and user and market aspects to establish a new socio-technical regime. *Technical* challenges remain, especially in hydrogen storage and handling, temperature management, and the integration of hydrogen subsystems into aircraft design. *Policy* and regulatory aspects are also crucial, with the European Union setting ambitious climate goals that necessitate significant investments in technology and policy adjustments. This includes the need for stable and clear regulations to support the development and certification of hydrogen technologies, while balancing safety and environmental concerns. *Society and culture* play a role in the public's perception and acceptance of hydrogen as a viable aviation fuel, which can be influenced by awareness campaigns and community involvement. The *industry* faces the challenge of preparing the ecosystem for hydrogen adoption, requiring collaboration and partnerships across sectors to facilitate this transition. *Economic* viability considerations are critical, with concerns about the current feasibility of hydrogen-powered aircraft compared to kerosene-based fuel.

These concerns include the high initial costs of hydrogen production and storage infrastructure, as well as the necessary *market* conditions, such as kerosene taxation and CO2 restrictions, required to support the widespread adoption of hydrogen technology in aviation.

At the landscape level there is a strong global push towards sustainability and reducing greenhouse gas emissions, particularly in industries like aviation that are challenging to decarbonize. Climate change impacts, such as severe weather events, are prompting more aggressive policy actions in affected regions. Additionally, political and economic instability, particularly from war conflicts, creates uncertainty in fossil fuel supplies, motivating a shift towards energy independence through domestically produced hydrogen. Moreover, international agreements like the Paris Agreement and CORSIA, along with European initiatives such as the Green Deal and the EU ETS, are critical in setting emissions targets and incentivizing cleaner aviation technologies. These measures collectively support the transition to hydrogen-powered aviation as a sustainable alternative.

6.2. Answers to the research questions

To answer the main research question of this study, *"To what extent could hydrogen propulsion play a role in the decarbonization of air transport?"*, two sub-questions were proposed.

The first one, *"What are the drivers and barriers for hydrogen transition in air transport from a socio-technical perspective?"* aimed to cover a broader view of the possibility for hydrogen transition in aviation and resulted in an elaborated list of drivers and barriers for hydrogen adoption classified according to four main categories, technological, political, economic, and societal.

The main technological drivers for hydrogen adoption include its potential as a clean alternative that can be sustainably produced using renewable energy sources, known as green hydrogen. Additionally, hydrogen emits zero- carbon emissions during flight and has a higher gravimetric energy density than kerosene. It can also be utilized directly in gas turbines, i.e., hydrogen combustion, or through hybrid hydrogen-electric fuel cells. Nevertheless, hydrogen technology faces numerous technological challenges that create barriers to its adoption. It is still an emerging technology, with low TRLs and not yet operational. Moreover, the need for a complete ecosystem overhaul highly complicates immediate implementation. Despite its high energy content per mass, hydrogen has a very low energy content per unit volume, creating significant challenges for transport and storage both at the airport and within the aircraft.

Political support for hydrogen is driven by climate change commitments and zero-carbon emission goals by 2050. Hydrogen could offer energy independence as oil resources deplete. Regulatory measures like kerosene taxation and CO2 restrictions, along with EU financial incentives and collaboration between industry and research parties, could further support hydrogen adoption. Additionally, growing government backing and EU-funded research projects highlight Europe's commitment to hydrogen-powered technology. However, there is still a high dependency on fossil fuels. Current regulations do not support hydrogen technology and disparities in kerosene taxation may arise. Moreover, ensuring sufficient hydrogen allocation for aviation requires robust political coordination.

Economic drivers involve fluctuating fossil fuel prices, job creation potential, and economies of scale in hydrogen production, making it potentially cheaper than kerosene in the long run. Moreover, European companies' long-term profit perspectives favor hydrogen's adoption. Nonetheless, high initial R&D and infrastructure costs, coupled with hydrogen's current economic non-viability compared to kerosene, represent major barriers for adoption. Additionally, uncertainty in passenger willingness to pay for sustainable air travel, as well as high initial operational and maintenance costs for hydrogen-powered aircraft further complicate the current economic prospect.

Public perception of hydrogen as an environmentally friendly technology and demand for sustainable aviation drive societal support. Moreover, younger generations' advocate for sustainability, and additional ongoing government and industry communication can influence broader public acceptance of hydrogen technology. Nevertheless, public safety concerns and historical associations with hydrogen explosions lead to distrust in the new technology. Moreover, generational differences in technology acceptance and a general lack of understanding about hydrogen-powered aviation hinder societal acceptance. Large public repercussions of aviation accidents amplify these concerns, necessitating education and transparent communication to build trust.

The second sub-question, *"How do aviation stakeholders perceive the introduction of hydrogen-powered technology in the air freight sector prior to the passenger market?"*, intended to explore a specific market niche in air transport that could serve as a starting point for hydrogen implementation in aviation. It aimed to analyze the potential advantages and disadvantages of focusing on air cargo compared to directly implementing this technology in the passenger market.

Results revealed a common belief that the potential of hydrogen technology in aviation still needs to be proven, making it premature to develop a business case for cargo flights. However, the concept was viewed as a potential strategic move. By targeting a market niche with less public scrutiny than passenger aviation, this approach was seen as a smart and forward-thinking strategy. Moreover, when comparing the introduction of hydrogen technology in passenger and freight aviation, there are notable differences, including specific advantages and disadvantages for air cargo.

In addition to the previously discussed challenges for hydrogen adoption in both passenger and freight markets, the air freight sector faces particular difficulties, mostly economic, compared to passenger aviation when considering the adoption of hydrogen-powered aircraft. While reduced public scrutiny may also be seen as an advantage, lower public visibility means there is less societal and market pressure to adopt and showcase new technologies, such as hydrogen-powered aircraft. As a result, there is less urgency and motivation for the air freight sector to invest in this innovation compared to the passenger aviation sector, where public demand for sustainability is more pronounced. Additionally, the economic incentives are weaker in the air freight sector due to its smaller size and higher price sensitivity, making the substantial investment required for hydrogen technology less justifiable. Another significant challenge is the justification for infrastructure investment. With fewer daily flights the cost of developing hydrogen infrastructure at cargo hubs may not be justified by the lower frequency of use compared to passenger airports, which have higher daily traffic and could spread infrastructure costs more broadly.

Despite these disadvantages, experts highlighted several significant benefits for cargo aviation. While the certification process remains the same for passenger and cargo aircraft, air cargo offers potential advantages over passenger transport. These encompass technical, social, and economic aspects. Technically, a cargo aircraft could incorporate hydrogen technology more flexibly due to backup oxygen supplies, simpler cabin ventilation systems, and expertise in handling dangerous goods. Additionally, since it does not need to accommodate passengers, tank placement configurations can be more efficient and allow for safer venting. Moreover, air cargo benefits from centralized operations at key hubs, requiring less extensive infrastructure implementation. There is also greater tolerance for extended turnaround times than passenger airlines. Additionally, as air cargo is less limited by the ecosystem, it allows for refueling in more remote areas of the airport, away from passenger terminals. Socially, air freight can serve as a protected environment to develop and test hydrogen technologies with less public exposure, facilitating gradual public acceptance. Economically, centralizing cargo operations at strategic hubs reduces initial investment costs, and there is potential market opportunity for "green" military freighter aircraft.

Going back to the main research question presented above and reflecting on the different expert opinions, it becomes evident that hydrogen propulsion has the potential to significantly contribute to the decarbonization of air transport, but its role will likely evolve over time rather than being an immediate solution. While hydrogen offers a clean energy alternative, the required infrastructure is costly and underdeveloped. Additionally, current regulations and financial incentives do not fully support its adoption, and public concerns about safety persist. Despite these challenges, there has been no conclusive evidence proving the infeasibility of hydrogen propulsion in aviation.

The air freight sector presents a more manageable starting point due to lower public scrutiny and centralized operations. However, it also faces challenges, such as economic constraints and less societal pressure for sustainability compared to passenger aviation. Despite these hurdles, introducing hydrogen technology in air freight could pave the way for broader adoption in the industry, gradually overcoming the barriers to its widespread use in passenger transport. Success in this niche could help expand knowledge of the technology, build confidence, and increase public acceptance, all while minimizing risks to human life compared to passenger aviation. Thus, hydrogen propulsion's role in decarbonizing air transport will likely grow over time, beginning with a strategic and phased integration.

In conclusion, while hydrogen propulsion has significant long-term potential for decarbonizing air transport, its immediate role is constrained by technological, economic, political and societal barriers. A phased approach, starting with air freight, may be the most practical path forward, allowing the industry to gradually overcome these challenges and build towards a more sustainable future in aviation.

6.3. Scientific Contribution

Knowledge Gap Reflection

This thesis contributes to the academic field by addressing several critical knowledge gaps in the existing literature. Firstly, while substantial research exists on historical transitions, such as the jet age, recent contemporary aviation transitions, particularly those related to sustainability innovation, are less explored. This knowledge gap is addressed by focusing on the socio-technical transition analysis of one sustainable technology innovation, namely hydrogen-powered aircraft. Secondly, although many scientific papers focus solely on the technical aspects of hydrogen-powered aircraft, this study aims to provide insights beyond the technical elements by also addressing political, societal and economic drivers and barriers influencing hydrogen adoption in aviation. Thirdly, many studies are primarily centered on passenger aviation, overlooking other potential markets for initial technological implementation. This gap was examined by exploring the potential of the air cargo sector, a less researched market compared to passenger aviation, as a valuable niche for deploying hydrogen technology and identifying its advantages over passenger aviation.

Scientific Relevance

This thesis contributes significantly to the scientific understanding of sustainable aviation technologies, specifically focusing on hydrogen-powered technology. The use of a Multi-Level Perspective framework provides a comprehensive socio-technical analysis, exploring the interplay between technological, economic, political, and societal dimensions in the transition towards hydrogen propulsion in aviation. This approach enriches the existing body of knowledge by integrating technical feasibility with socio-economic and policy considerations, offering a holistic view of the potential and challenges of hydrogen technology in air transport.

One of the key scientific contributions is the detailed exploration of hydrogen as a technological niche within the aviation sector. The research identifies critical drivers and barriers to hydrogen adoption, including technological advancements, infrastructure requirements, regulatory frameworks, and societal acceptance. This nuanced understanding is crucial for stakeholders aiming to facilitate the transition towards zero-emission aviation, providing direction of the multi-faceted challenges associated with hydrogen technology.

Beyond the specific case of hydrogen-powered aircraft, the findings of this thesis offer broader, generalizable insights into sustainable transitions in other high-emission sectors. The use of the MLP framework can be applied to other industries seeking to adopt disruptive technologies for sustainability. The research demonstrates the importance of considering technological innovation in conjunction with socio-political and economic factors, underscoring the necessity of a supportive policy environment, public acceptance, and cross-sectoral collaboration and communication.

Moreover, the thesis highlights the strategic value of targeting market niches, such as air freight, as early adopters of emerging technologies. This approach can serve as a model for introducing innovative solutions in other sectors, where niche applications can help to mitigate initial risks, build market acceptance, and pave the way for broader adoption. The insights into stakeholder perspectives and the identified advantages of starting with cargo applications can inform strategies in other industries facing similar technological and societal challenges.

6.4. Practical Implications and Recommendations

This thesis is the first to explore the intersection of hydrogen-powered technology, socio-technical transitions, and air cargo. In addition to its academic contribution, the findings suggest several practical implications and recommended actions for different stakeholders, which can facilitate the transition to hydrogen-powered aviation.

Government and Regulatory Bodies

Governments and regulatory authorities play a crucial role in fostering an environment favorable for hydrogen technology adoption. The study underscores the need for financial incentives such as subsidies and grants, which can alleviate the significant initial costs associated with developing and deploying hydrogen-powered aircraft. Additionally, regulatory support is essential. This includes establishing clear and stable regulations that facilitate the certification and operational safety of hydrogen technologies. Governments should also consider implementing policies that promote hydrogen as a viable alternative by, for instance, applying carbon taxes to kerosene fuels, thereby making hydrogen more economically attractive .

Industry Stakeholders

The findings highlight the importance of collaborative efforts between OEMs, research institutes, and SMEs. The latter, in particular, require greater support to participate in the innovation process, as they often lack the resources available for larger companies. The industry should also focus on integrating hydrogen technologies incrementally, starting with air freight operations, which are perceived to have lower safety risks compared to passenger flights. This approach allows for the gradual testing and validation of hydrogen systems in a less publicly sensitive context. Moreover, further collaboration with other industries outside aviation, such as automotive and maritime, which are also exploring hydrogen can be beneficial for aviation. These partnerships can help develop well-established hydrogen infrastructure, share technological advancements, and create economies of scale in hydrogen production, supporting broader adoption of hydrogen technology across transportation modes.

Public and Educational Institutions

Public perception and acceptance of hydrogen technology are critical for its successful adoption. Educational initiatives should be aimed at increasing public awareness of the environmental benefits and safety measures associated with hydrogen-powered aviation. Schools and universities can incorporate curricula on sustainable technologies and hydrogen energy systems to foster a new generation of informed citizens and professionals. Public communication strategies should also emphasize the economic and job creation potential of the hydrogen economy, thereby encouraging wider societal support.

International Organizations and Policy Makers

International organizations and policy makers should work towards standardizing safety and operational protocols for hydrogen technologies in aviation. This standardization is crucial to ensure uniformity in handling, storage, and emergency response procedures across different regions and airports. Such efforts would not only enhance safety but also facilitate smoother international operations and cooperation.

6.5. Limitations

The study acknowledges several limitations. First, the analysis is primarily qualitative, relying on literature reviews and eleven stakeholder interviews. This research approach, while providing valuable insights, lacks the ability to capture the quantitative economic and emission aspects of the hydrogen transition.

Second, the systematic literature review revealed a significant gap in research focused on air cargo compared to the extensive studies on air passenger traffic. Moreover, as no studies were found addressing hydrogen-powered technology in the air cargo sector, the insights were mainly extracted from the interviews with experts.

Third, although multiple experts from academia and industry were interviewed, enhancing the reliability and validity of the data collected for these two clusters, only one stakeholder from the government cluster could be contacted within the 5-month research timeframe. Regarding the community cluster, it was assumed that since all interviewees were also European residents, this cluster was simultaneously covered.

On the other hand, the notable dominance of academia and industry experts on hydrogen propulsion in this study may result in a bias towards emphasizing the benefits and feasibility of hydrogen technology. This is due to their roles and interests in advancing innovation and commercial applications.

Fourth, the research is framed within a European context, particularly concerning policy aspects from the perspective of European stakeholders. This geographic focus reflects the regulatory environment and infrastructure considerations prevalent in Europe, which may not be directly applicable to other regions with different regulatory frameworks, economic conditions, and technological capabilities. As a result, the findings may have limited generalizability to other global contexts, where the adoption of hydrogen technology could face different challenges and opportunities.

Lastly, the study primarily focused on the airport environment, including the aircraft. Technical challenges across the hydrogen supply chain, such as production, storage, and distribution logistics, were only briefly mentioned.

6.6. Recommendations for future research

Building on the findings and limitations of this study, future research should focus on several key areas. Firstly, later studies could incorporate a quantitative analysis to assess the economic viability and environmental impact of hydrogen-powered aircraft. This should include detailed cost-benefit analyses to compare hydrogen technology with current fossil fuel-based systems, as well as life cycle assessments to understand the total environmental impact from production to disposal. Scenario modeling can be used to project future adoption rates under various policy and market conditions, while choice experiments can help determine customer willingness to pay for hydrogen-powered flights, providing valuable insights into market acceptance and potential pricing strategies.

Secondly, there is a need to conduct in-depth interviews with a larger and more diverse group of participants, encompassing various geographical regions. This approach would provide a broader perspective on the challenges and opportunities associated with hydrogen technology in different regulatory and infrastructural environments. Expanding the scope of interviews can also capture regional variations in stakeholder perceptions, policy support, and technological readiness.

Thirdly, integrating interviews with other research methods, such as case studies and surveys, could enhance future studies. Case studies of specific regions or startups that are pioneering hydrogen technology in aviation could provide practical insights and lessons learned. Surveys can complement qualitative interviews by quantifying stakeholder opinions and preferences, offering a more balanced view of the potential drivers and barriers for hydrogen adoption.

Fourthly, further studies should explore the development of policy frameworks that can support the large-scale adoption of hydrogen technology in aviation. This involves examining best practices from other industries and regions. Comparative studies can identify effective regulatory measures, financial incentives, and collaborative models that could be adapted for the aviation sector. Such research would provide policymakers with actionable recommendations to create a favorable environment for hydrogen adoption.

Finally, following studies could investigate other potential market niches for implementing hydrogen technology in aviation beyond the air freight sector. For instance, the military could benefit from the strategic advantages of hydrogen-powered aircraft, such as reduced emissions in operational areas and an enhanced public image due to the adoption of environmentally friendly technologies. Unmanned aircraft systems (UAS) represent another promising niche where hydrogen technology can be tested and refined without involving human life. Exploring these niches could reveal new opportunities for scaling hydrogen technology and achieving broader impacts across the aviation industry.

7 Conclusion

This thesis investigates the potential of hydrogen-powered technology as a sustainable alternative to conventional kerosene-based aviation. The study emphasizes the urgent need to reduce the aviation industry's carbon footprint, which is a significant contributor to global greenhouse gas emissions. Hydrogen propulsion technology emerges as a promising solution, offering the potential for zero-carbon emission flights, thus contributing to the broader goals of environmental sustainability.

The research employs a Multi-Level Perspective framework to explore the socio-technical transition required for the adoption of hydrogen technology in aviation. This approach reveals the intricate interplay between technological advancements, market dynamics, regulatory frameworks, and societal behaviour. The analysis highlights several key drivers for the adoption of hydrogen-powered aircraft, including technological innovations in fuel cells and hydrogen storage, increasing regulatory pressure to reduce emissions, and growing societal awareness and demand for sustainable travel options.

However, the research also identifies substantial barriers that must be addressed to facilitate this transition. The high initial costs associated with hydrogen infrastructure development, including refueling stations and production facilities, pose significant technical and economic challenges. Additionally, the current lack of a comprehensive regulatory framework for hydrogen-powered aviation creates uncertainty, potentially slowing the adoption process. Societal acceptance remains another critical barrier, with concerns over the safety of hydrogen as a fuel and the broader implications for air transport.

Furthermore, the air cargo sector is proposed as an initial testing ground for hydrogen technology, providing a lower-risk environment compared to passenger transport. This sector's relative flexibility and centralized operations make it an ideal candidate for early adoption, allowing for the refinement of technology and operational protocols. Moreover, successful implementation in air cargo could pave the way for broader acceptance and integration of hydrogen propulsion in passenger aviation.

The study provides strategic recommendations for industry stakeholders, policymakers, and researchers. It emphasizes the importance of creating a supportive regulatory environment that includes incentives for early adopters and clear safety standards for hydrogen technology. Public-private partnerships are crucial to share the financial risks and benefits of developing the necessary infrastructure. Additionally, the study highlights the need for public education campaigns to address misconceptions about hydrogen safety and to build public trust in this emerging technology.

From an academic perspective, this research contributes to the literature on sustainable aviation technologies and socio-technical transitions. It offers understanding of the challenges and opportunities of adopting hydrogen propulsion in aviation, exploring a potential niche for its implementation. The insights gained from this study can inform future research and guide policy development, helping to align technological innovation with broader societal and environmental goals.

In conclusion, while the path to hydrogen-powered aviation presents numerous challenges, it also offers significant opportunities for reducing the industry's environmental impact. The successful transition to hydrogen propulsion will require substantial efforts across multiple sectors, including technology development, regulatory frameworks, economic investment, and public engagement. The pursuit of hydrogen technology in aviation is not just a technological challenge but a societal one, requiring a holistic approach to achieve the goal of a zero-carbon emission aviation by 2050.

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A
Interview Questions

A.1. Opening Questions

A.1.1. For company

1. Could you briefly tell me about your role in the firm?
2. How long have you been working at the company?

A.1.2. For university

1. Could you briefly describe the main focus of your current research?
2. What projects are you currently working on?

A.2. General Questions

A.2.1. For company

1. How does your role relate to hydrogen-powered aircraft and/or the air freight sector and/or sustainable aviation?
2. What are your initial thoughts on the shift towards hydrogen-powered technology in aviation?
3. How does your firm contribute to the transition to hydrogen-powered aircraft?

A.2.2. For university

1. How does your research relate to hydrogen-powered aircraft and/or the air freight sector and/or sustainable aviation?
2. What are your initial thoughts on the shift towards hydrogen-powered technology in aviation?
3. How does your research contribute to the transition to hydrogen-powered aircraft?

A.3. Technological Niche Level: Hydrogen-powered technology

1. What characteristics make hydrogen technology a suitable alternative to fossil-based fuels?
2. From your perspective, how does hydrogen technology perform compared to other potential alternatives, such as electrification or SAF?
3. What do you think of introducing hydrogen technology in the air freight sector? Do you think it is easier and quicker to realize than for the passenger market? Why?
4. Which hydrogen-based propulsion technology could be more relevant for a (freighter) aircraft?

A.4. Socio-Technical Regime Level

A.4.1. Technology

Current state and Challenges

1. What are the current technological advancements in hydrogen-powered aircraft that you are aware of?
2. What are the major technological infrastructure challenges currently facing the implementation of hydrogen-powered aircraft at the airport?
3. How do current (freighter) aircraft designs need to be altered to accommodate hydrogen technology?

A.4.2. Policy

Regulatory Environment

1. How do current European aviation policies support or hinder the transition to hydrogen-powered aircraft?
2. What changes in regulation do you think are necessary to facilitate this transition?

Incentives and Support

1. What types of governmental incentives or support would most effectively promote the adoption of hydrogen technology in aviation?
2. How can policymakers balance the need for innovation with safety and environmental concerns?

A.4.3. Society and Culture

Public Perception and Acceptance

1. How do you think the public perceives hydrogen as a fuel for aviation (especially in the context of air freight)?
2. What societal or cultural factors might influence the acceptance of hydrogen-powered aircraft?

Awareness

1. What initiatives could help improve awareness and understanding of hydrogen technology among stakeholders and the public?
2. How important is it to involve the community in discussions about hydrogen adoption in aviation?

A.4.4. Industry

Industry Dynamics and Collaboration

1. How is the aviation industry (particularly the air freight sector) preparing for the potential shift to hydrogen-powered aircraft?
2. What partnerships or collaborations are crucial for this transition?
3. Looking 10-20 years into the future, how do you envision the role of hydrogen in the aviation industry evolving?

Economic Considerations

1. How do you see the economic viability of hydrogen-powered aircraft compared to conventional or other alternative fuels?
2. What market conditions are necessary for the industry to invest significantly in hydrogen technology?

A.4.5. User and Market

Market Demand and Trends

1. How do you anticipate the demand for hydrogen-powered aircraft evolving (in the air freight sector)?
2. What are the key market drivers that could influence this demand?

Customer and Stakeholder Engagement

1. How can stakeholders (e.g., airlines, logistics companies) be motivated to adopt hydrogen-powered aircraft?
2. What role do customers play in driving the market towards hydrogen solutions, and how can their needs be addressed?

A.5. Socio-Technical Landscape Level

A.5.1. General Context

1. What global trends and external pressures do you believe are most influencing the adoption of hydrogen technology in aviation? And how do these factors impact the industry?
2. What are the major environmental and economic drivers influencing the shift towards sustainable aviation propulsion technologies?

A.5.2. External Factors

1. What international and European policies and agreements impact the push for hydrogen-powered aircraft?
2. What role do global fuel price fluctuations play in considering hydrogen as an alternative?

B

Informed Consent Form

B.1. Study Information

You are being invited to participate in a research study titled *"Analyzing the Introduction of Hydrogen-Powered Aircraft in Air Freight Transportation"*. This study is being done by Claudia Subias Botana, MSc student in Complex Systems Engineering (Transport & Logistics) at TU Delft, as part of her master´s thesis project (period February 2024 – August 2024) in collaboration with Airbus Netherlands. Both TU Delft and Airbus are providing supervisory support for this study.

The purpose of this research study is to explore the potential transition from kerosene-based fuel to hydrogen-powered aircraft in the air cargo industry. It acknowledges the significant contribution of the air freight sector to global CO2 emissions and analyses hydrogen propulsion as a more sustainable alternative. The interviews aim to gather further insights on potential drivers and barriers to adopting hydrogen technology in air freight from an industry perspective. Airbus experts in sustainable aviation will be consulted. Each interview will take approximately 45 minutes to complete.

From this information, insights will be gathered from key stakeholders in the aviation socio-technical system, specifically aiming at validating information. An analysis on the hydrogen transition followed by academic and company recommendations, will be the result of the master's thesis research project. The knowledge gathered through this interview will be thus serve as inspiration for introducing hydrogen technology in air transportation. The audio and transcript of the interview are securely stored on TU Delft OneDrive for the project's duration, accessible only to my first supervisor, Jan Anne Annema, Guido Schwartz, and myself. The data will be anonymized for inclusion in the master's thesis report, which will be publicly available in the TU Delft educational repository. Interviewees may contact either me or my first supervisor, Jan Anne Annema, to request the interview transcript in the thesis report at any time before its publication in the TU Delft educational repository (before the end of August 2024). They are welcome to suggest modifications or request the removal of any information deemed incorrect or confidential. Once prepared, a summary of the interview will be provided to the interviewee for review.

Despite the inherent risks of online activity, we commit to maintaining the confidentiality of your responses to the best of our abilities, safeguarding all data with personal information through secure storage on TU Delft OneDrive. Access will be limited to project members (myself and the supervisors mentioned). All personal data obtained during the interview will be erased no later than one month post-project completion.

Should the graduation committee decide to publish a research paper based on this thesis project, the data (including interview transcripts and summaries) will be securely stored in TU Delft's institutional storage until the end of the study. Anonymized interview summaries may be included in the paper's appendix or cited within the text.

Your participation in this study is completely voluntary, with the freedom to skip any questions or withdraw at any time. Should you choose to withdraw, any data collected, including recordings or data submitted by you, will be deleted within a week of your withdrawal request. You are also invited to review the interview summary before the project's conclusion.

B.2. Explicit Consent Points

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICIPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I willingly give my permission for this interview to be recorded to facilitate its transcription (Note: The interview will not be recorded without consent).	☐	☐
2. I freely agree to allow the student Claudia Subias Botana to take notes during my interview.	☐	☐
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
3. I acknowledge that my identifiable personal information, including my name, signature, current organization, and email address, will be kept confidential and only shared with the student Claudia Subias Botana and her first supervisor, Jan Anne Annema.	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
4. I am aware that following the research study, the anonymous summary I contribute will be utilized in the Appendix section of Claudia Subias Botana's master thesis report.	☐	☐
D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE		
5. I consent to the anonymous summary I have provided being stored in the TU Delft repository, where it may be accessed for future research and educational purposes.	☐	☐
6. I am aware that the TU Delft repository is accessible to the public.	☐	☐

I confirm that I have read and understood the form, and I voluntarily agree to participate in the research and to the processing of my personal data as outlined in this document.

Signatures

__________________________ __________________________ ________

Name of the participant [printed] Signature Date

Study contact details for further information:
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