Modeling the Impact of Hydrogen Adaptation Obstacles on Hydrogen-Powered Flights by 2050

In collaboration with Airbus Defence and Space Netherlands

By Stella Wessels - March 2025

TU Delft

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Stella Wessels
Delft, March 2025

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Introduction

This thesis was set up to contribute to the Dutch aviation ecosystem and specifically, its desire to meet sustainability goals. Together with Airbus Defense and Space Netherlands, a topic was defined that could contribute accordingly, and one that could benefit from Stella's knowledge obtained during her studies at Delft University of Technology. With a broader research at a beginning, a research gap was identified. The following research objective was set up to address this gap: to investigate how the obstacles to hydrogen adaptation impact the projected distribution and frequency of hydrogen-powered flights in Europe by 2050.

This thesis report is organized as follows. Part I contains the relevant Literature Study that supports the research presented in the scientific paper. In Part II, the scientific paper is presented.

I

Research Proposal

Research Proposal

The impact of obstacles to hydrogen adaptation to the projected distribution and frequency of hydrogen-powered flights in Europe by 2050

MSc Thesis in collaboration with Airbus

Stella Wessels

Delft University of Technology

TU Delft

Research Proposal

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by

Stella Wessels

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1
Introduction

The aviation industry is undergoing a pivotal transformation toward sustainability. This is driven by the need to meet global climate goals such as the Paris Agreement and the Intergovernmental Panel on Climate Change (IPCC)'s goal to decreasing global carbon pollution by 48 percent from 2019 levels by 2030, and to reach zero carbon emissions by 2050 [1].

Recently, Airbus signed a memorandum of understanding (MoU) with SAS, Avinor, Swedavia, and Vattenfall to explore the feasibility of hydrogen-powered aircraft in Sweden and Norway [2]. This initiative is an example of a ”hydrogen aviation ecosystem”. A system that focuses on the infrastructure and operational requirements for hydrogen aircraft. With their commitment to renewable energy, Sweden and Norway seem like prime candidates for pioneering this transition, reflecting a growing international focus on zero-emission technologies in aviation.

While the adoption of hydrogen technology promises significant environmental benefits, such as reduced carbon emissions, it also introduces complex challenges that are not yet fully understood. One pressing question is how aviation network models, such as Hub & Spoke and Point-to-Point, will adapt to the unique requirements of Liquid Hydrogen (LH2) fuel. Moreover, what is the effect on the network when certain risks concerning LH2 adaptation are actualized at airports, creating obstacles?

By diving into the existing literature, this research proposal will identify a research gap. Accordingly, the methodoloy is formulated that can adress this research gap. This study will provide strategic insights into effectively integrating hydrogen-powered aircraft into the global aviation network by 2050, supporting the broader objectives of achieving net zero aviation.

First of all, a summary of completed research is provided in chapter 2. Accordingly, a research gap is identified in chapter 3 and a research question is set up in chapter 4. Next the expected results are visualized in chapter 5, in order to facilitate the methodology process, elaborated upon in chapter 6. This is followed by a time schedule in chapter 7 and a conclusion in chapter 8.

2
Literature Search Overview

This chapter provides a summary of several relevant topics that were researched in the initial phase of the project. This work provides the background relevant for the identification of the academic research gap and the research question.

2.1. Aviation Emissions

To give context to the scope of thesis, the emissions within the aviation sector are summarized and compared with the emissions that are left with hydrogen-powered aircraft.

In Table 2.1, the different emissions from conventional aircraft are listed.

Emission Type	Impact Description
CO_2 (Carbon Dioxide)	Long-term atmospheric presence. • Long-lived greenhouse gas; traps heat for centuries.
Water Vapor	Contrail and cirrus cloud formation due to water vapor condensing and freezing into crystals at high altitudes. • Contrails and cirrus clouds enhance greenhouse effects by trapping heat (infrared radiation emitted by Earth's surface) in the atmosphere.
NO_x (Nitrogen Oxides)	Ozone (O_3) formation through reaction with sunlight and methane (CH_4) reduction. • Ozone leads to increased heat trapping (infrared radiation emitted by Earth's surface). • Due to the production of Hydroxyl Radicals (OH), which are crucial for the oxidation of methane, the methane concentration is reduced, leading to a cooling effect.
Soot / Black Carbon	Direct radiative forcing and reduced albedo effect. • Absorbs sunlight and reduces snow/ice reflectivity, leading to direct warming and contributing to further warming by reducing the reflectivity of snow and ice.

Table 2.1: Impacts of Different Emission Types on Climate[3][4]

With hydrogen-powered flight no CO_2 is emitted. The other emission sources remain. However, when comparing NO_x, HC and CO emissions for flight routes, it can be concluded that hydrogen-fueled aircraft emit substantially lower amounts of these substances when compared to conventional kerosine aircraft. This entails lower index values (g/kg of fuel) for the NO_x emissions for example [5]. Figure 2.1 shows the potential impact of LH2 powered aircraft in the future. It is clear that the gross CO2 emissions (where non-CO_2 effects are modelled as such) decrease considerably if LH2 aircraft are introduced.

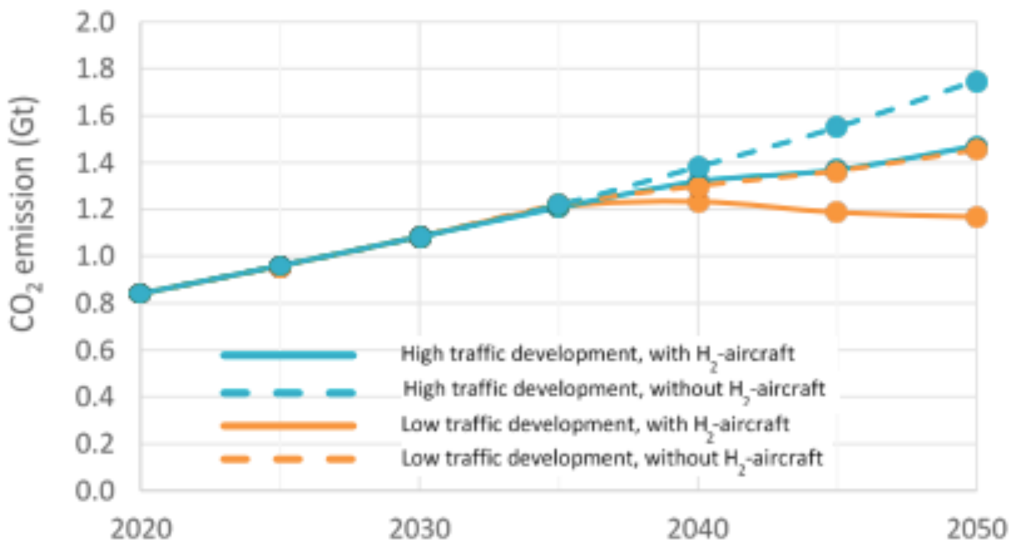


Figure 2.1: Simulated global aircraft gross CO2 emissions under high or low traffic development, and with (solid lines) or without (dashed lines) hydrogen-powered aircraft [6]

2.2. Outlook Hydrogen Aircraft 2050

By 2050, the aviation industry is expected to experience a significant growth in passenger demand, with the International Air Transportation Association (IATA) projecting over 10 billion air passenger journeys and Eurocontrol predicting approximately 16 million flights, a 44% increase from 2019 levels [7] [8].

The question arises what role do hydrogen-powered aircraft could play in this projected scenario. Several commercial design projects are indicating rapid growth of hydrogen aircraft in the upcoming decades. First of all, Airbus's ZEROe project represents a significant step toward future hydrogen-powered aircraft, which they aim to bring to market by 2035 [9]. The multiple aircraft that are being worked on within this project range from turboprop and turbofan designs to a blended-wing body configuration. Additionally, ZeroAvia is currently conducting the HyFlyer II Project, in which they aim to commercialize a 600kW powered aircraft by 2050. They have larger aircraft as a more distant vision [10].

The World Economic Forum, states under the scenarios modelled by MPP's Aviation Strategy, 24-36% of Schiphol Airport's flights are expected to be hydrogen-powered by 2050. 14-25 hydrogen-powered routes are required to connect to Schiphol. Moreover, for an airport in the context of Asia, it is approximated that 16-32% of flights should be hydrogen-powered, requiring about 3-10 routes to activate the larger hub [11].

2.3. Socio-technical imaginaries of climate aviation

As elaborated upon by C. Meuhlberger et al., there are different visions for achieving sustainable aviation at a future timepoint [12]. Diverse stakeholders shape these visions based on their interests and priorities. As shown in Figure 2.2, the three socio-technical imaginaries identified are: travel innovation, fleet innovation, and fuel innovation. The travel innovation emphasizes demand management and behavioral changes to reduce the climate impact of aviation. Fleet innovation focuses on radical technological advancements, such as the hydrogen-powered aircraft treated in this research, all to maintain the socio-economic benefits of the sector. And lastly, fuel innovation promotes the use of sustainable aviation fuels as the most prominent approach which in its turn provides new challenges. For the duration of this research, a balance should always be made up when taking assumptions from the different stakeholders, seeing the relevance of the statements in the broader scope.

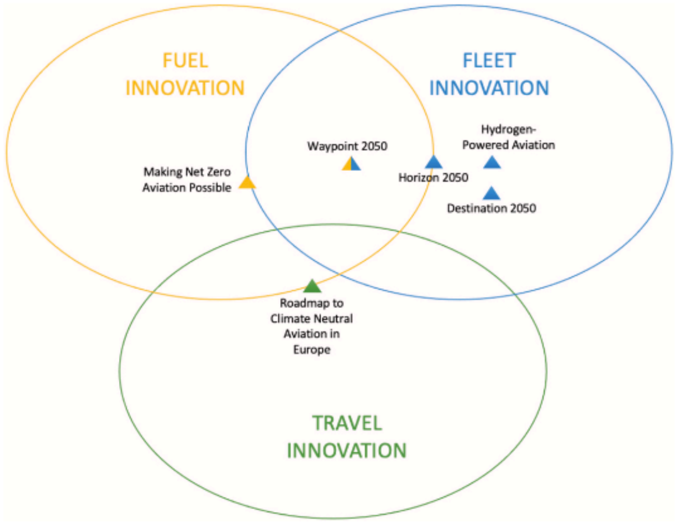


Figure 2.2: Overlapping imaginaries in socio-technical imaginaries for climate aviation [12]

2.4. Key considerations for Liquid Hydrogen adaptation at airports

The transition to LH2 as a fuel for aircraft presents a set of challenges for the airports. This section explores the key considerations necessary for adapting airports to accommodate the future LH2 aircraft, to ensure safe and efficient operations. There are several logistical, infrastructural, safety and economic factors that must be addressed. These are briefly treated in the following subsections. Many of the infrastructure considerations for adapting airports to accommodate hydrogen-powered aircraft are extensively detailed in the report titled 'Integration of Hydrogen Aircraft into the Air Transport System' by the Airport Council International (ACI) and the Air Transport Action Group (ATAG) [13].

2.4.1. Investment requirements

For the complete aviation section, to shift towards alternative propulsion, a capital investment of $700 billion to $1.7 trillion across the value chain is required by 2050, to reach the net-zero goal. About 90% of this amount will be for off-airport infrastructure, with the highest costs for power generation, and hydrogen electrolysis and electrification [11].

When looking at the difference between airport types, this would mean approximately a $3.9 billion investment for an intercontinental hub and a $1.3 billion investment per major regional airport [11].

2.4.2. Supply and delivery

There are differences between the traditional fuels and the hydrogen supply chain, the chain varies based on the route-to-tank method and each airport's infrastructure capabilities. Hydrogen can be supplied via pipelines, trucks, or trains, similar to conventional fuels, as shown in Figure 2.3.

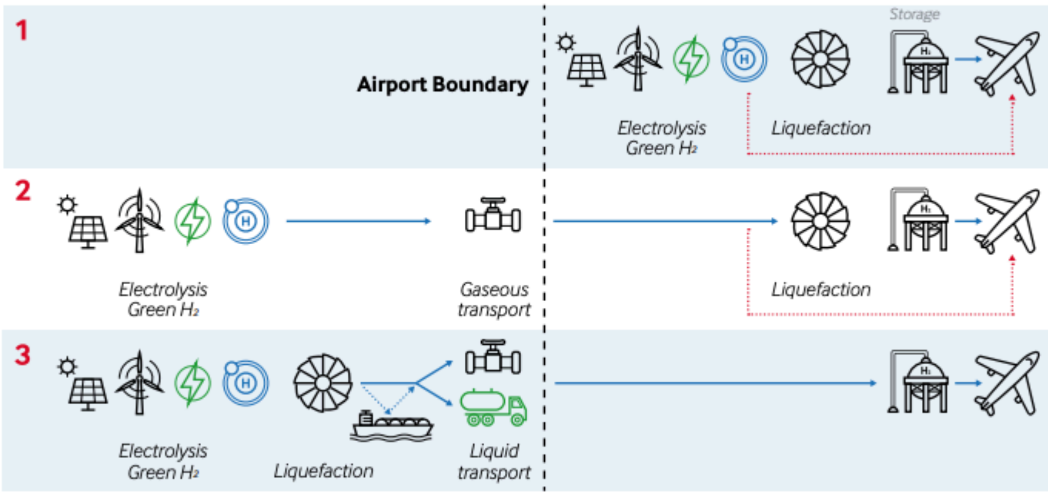


Figure 2.3: Three primary hydrogen supply chain/pathways into the airport [13]

For onsite production (method 1), airports with access to water, renewable electricity, and sufficient land can produce hydrogen directly through electrolysis, reducing the need for transportation of the hydrogen. When onsite production isn't feasible, gaseous hydrogen can be transported via pipelines (method 2), or liquid hydrogen can be delivered over longer distances using pipelines, trucks or trains (method 3) [14]. Specialized H2 pods could also be used to deliver hydrogen directly to aircraft, maximizing storage at the airport.

Alternative large-scale methods, like converting hydrogen into ammonia or using liquid organic hydrogen carriers (LOHCs), may not be suitable for aviation since hydrogen must remain pure [15]. Initially, hydrogen is expected to be delivered primarily in liquid form by trucks, capable of fueling multiple aircraft with minimal infrastructure changes [13].

Ultimately, the choice of hydrogen supply method depends on each airport's resources, infrastructure, and proximity to hydrogen production, with a focus on minimizing environmental and economic costs.

2.4.3. Storage

Storing LH2 at airports requires specialized infrastructure due to the unique physical properties of hydrogen. The International Energy Agency (IEA) estimates that modern liquefied hydrogen storage tanks can achieve an efficiency of about 99%, making them suitable for applications where fuel needs to be readily available, such as at airports [16]. IAE thereby states that hydrogen stored in gaseous form, even when compressed to 700 bar, would occupy nearly seven times the volume of hydrocarbon fuels, rendering large-scale gaseous storage impractical for most airports due to space constraints. Conversely, storing liquid hydrogen is more space-efficient, although it still occupies nearly four times the volume of an equivalent energy amount of Jet A-1 fuel. This necessitates larger storage facilities, which could range significantly in capacity, from 15 tonnes to as much as 1,800 tonnes of liquid hydrogen, depending on the airport's size and anticipated demand.

2.4.4. Footprint estimation LH2 adaptation at airports

Figure 2.4 illustrates the space needed for various hydrogen processing and storage facilities compared to traditional Jet A-1 fuel farms. In the study, several airports were surveyed to assess these requirements, with reported areas ranging from 30,000 square meters for medium-sized airports to 80,000 square meters for large airports [17].

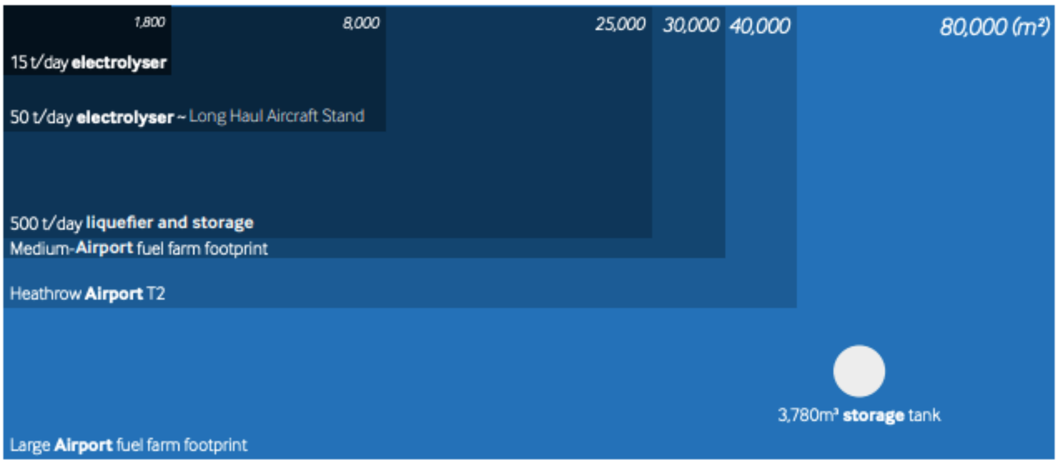


Figure 2.4: Visual comparison of land requirements for some hydrogen infrastructure elements, referenced to the footprint of existing infrastrucrure [13]

2.4.5. Network of airports requirement

The adoption of liquid hydrogen by one airport necessitates a network wide commitment. Origin-destination pairs need to be possible. Moreover, to ensure a reliable and efficient hydrogen supply chain, multiple airports should collaborate to develop a compatible infrastructure and fueling systems for example. These combined and coordinated efforts will also reduce the risk of disruptions [11].

2.4.6. Hazards and safety

Despite advancements since the Hindenburg disaster, public perception of hydrogen-powered vehicles remains a hurdle, which means building confidence in hydrogen is necessary [18].

Currently, risks remain when it comes to hazards and safety. Hydrogen has a broad flammability range and low ignition energy, making it more prone to fire hazards. Additionally, hydrogen's properties such as a rapid dispersion and high burn rate require specialized storage and handling protocols to mitigate risks. This includes scenarios involving spills or leaks [19].

2.4.7. Infrastructure compatibility

The adoption of LH2 at airports also requires compatibility of airport infrastructure with the new aircraft designs. This is highlighted in the ICAO Aerodrome Design Manual and Airport Planning Manual [20] [21]. Modification will be necessary for runways, taxiways and parking stands for example to accommodate potentially longer aircraft and increased wingspans. Moreover, refueling operations will need specialized equipment and procedures.

2.5. Optimization models for aviation networks

Three primary models are often discussed in aviation network analysis: Hub & Spoke (H&S), Point-to-Point (P2P), and the Fleet & Network model [22] [23]. The Hub & Spoke model centralizes operations at key hub airports, routing flights from smaller airports (spokes) to a central hub where passengers can transfer to their final destinations. In contrast, the Point-to-Point model offers direct flights between Origin and Destination (OD) airports. The Fleet & Network model integrates aspects of both the H&S and P2P models, focusing on optimizing both the network design and fleet composition. This model allows airlines to strategically deploy a diverse range of aircraft based on specific route characteristics and operational needs, potentially including the use of Liquid Hydrogen (LH2)-powered aircraft. These three primary models are discussed in subsection 2.5.1. In addition to these models, there is the Fleet Assignment in the Global Air Transportation System (ATS) model, which provides a comprehensive framework for optimizing fleet assignments across a global network by considering various operational, economic, and environmental constraints [24]. This model is discussed in subsection 2.5.2. Lastly, for the sake of completeness, this chapter is concluded with a section, subsection 2.5.3, explaining which non-optimization methods for fleet development have been considered and discarded.

2.5.1. Three primary optimization models for aviation networks

The three primary optimization models for aviation networks by B. Santos are discussed in this chapter [22] [23]. First, the models are explained in more detail, followed by a comparison.

The Hub & Spoke (H&S) model relies on centralizing flight operations at major hub airports. As shown in Table 2.2, the inputs for this model include hub location data, demand data, and aircraft fleet characteristics. The model itself focuses on maximizing profit through strategic hub-based operations while managing constraints like capacity, demand verification, hub transfers, continuity, and aircraft utilization. The outputs of this model are flight plans detailing schedules and frequencies, passenger flows, and profit estimations. The H&S model can optimize resource utilization by consolidating traffic through hubs.

Input	Model	Output
• **Hub location data**: Airports designated as hubs • **Demand data**: Passenger demand per route • **Aircraft fleet (homogeneous)**: Characteristics and availability • **Route data**: Possible routes and distances • **Financial outlook**: Revenue per RPK, operation costs	**Objective function examples**: • Maximise profit **Constraints**: • Demand verification • Capacity • Hub transfers • Continuity • Aircraft utilization	• **Flight plan**: Flight schedules, frequencies • **Passenger flow**: # of pax transported on legs with distinction between transfers and OD movements at hub • **Profit estimation**: Expected profit and costs

Table 2.2: Hub & Spoke Model Overview

The Point-to-Point (P2P) model operates on a decentralized network structure, providing direct flights between origin and destination airports. As shown in Table 2.3, its inputs include route network data, passenger demand data, aircraft fleet characteristics, and financial outlooks. The model aims to maximize profit, minimize costs, and maximize revenues while managing constraints such as capacity, demand verification, continuity, and aircraft productivity. The outputs include a flight plan, passenger flow statistics, and profit estimation.

Input	Model	Output
• **Route network**: Airports and routes • **Demand data**: Passenger demand per route • **Aircraft fleet (homogeneous)**: Characteristics and availability • **Financial outlook**: Revenue per RPK, operation costs	**Objective function examples**: • Maximise profit • Minimise costs • Maximize revenues **Constraints**: • Capacity • Demand verification • Continuity • Aircraft productivity	• **Flight plan**: Flight legs, frequencies • **Passenger flow**: # of pax transported on legs • **Profit estimation**: Expected profit and costs

Table 2.3: Point-to-Point Model Overview

The Fleet & Network model integrates both H&S and P2P network strategies while allowing for diverse aircraft types. As listed in Table 2.4, the inputs for this model encompass a set of airports to operate from, demand data, various aircraft types, and cost data related to aircraft purchase and operations. The model is designed to optimize fleet composition and network efficiency to maximize profit, minimize costs, and maximize revenues, subject to a range of constraints including demand verification, capacity, continuity, aircraft productivity, range, and budget constraints. The outputs are more comprehensive, including flight plans per aircraft type, fleet composition strategies, profit estimation, and budget allocation plans.

Input	Model	Output
• **Airports**: Set of airports to operate from • **Demand data**: Passenger demand per route • **Aircraft types**: Types and characteristics • **Cost data**: A/C purchase and operational costs	**Objective function examples**: • Maximise profit • Minimise costs • Maximize revenues **Constraints**: • Demand verification • Capacity • Continuity • Aircraft productivity • Range constraint • Budget constraints	• **Flight plan per aircraft type**: Flight legs, frequencies • **Fleet composition**: Optimal fleet size and types • **Profit estimation**: Expected profit and costs • **Budget allocation**: Aircraft purchasing within budget

Table 2.4: Fleet & Network Model Overview

In the context of LH2 adaptation at airports in the future, and modelling this with in a network, each model presents a set challenges.

The Fleet & Network model offers flexibility due to its ability to deploy different aircraft types. This distinction in aircraft and their according characteristics and availability is crucial when it comes to considering the transition to LH2. This can help model airlines decisions to selectively use LH2-powered aircraft on routes where they are most advantageous, such as shorter routes between airports equipped with LH2 refueling capabilities. Conventional aircraft are then to be used on longer routes or for those with airports that have a lower infrastructure readiness.

2.5.2. Fleet Assignment in the Global Air Transportation System (ATS) model

The Fleet Assignment in the Global Air Transportation System (ATS) model provides a detailed framework for assigning fleets across a global network. As shown in Table 2.5, this model's inputs include route networks with available seat capacity, details of the aircraft fleet and their availability, and performance data of different aircraft types, such as engine specifications and range. The model focuses on optimizing key performance indicators such as DOC/ASK (Direct Operating Costs per Available Seat Kilometer), schedule delays, and travel time while adhering to constraints related to route network coverage, fleet limits, payload-range relationships, runway length, airport capacity, and market concentration. The outputs from the ATS model provide fleet assignments, including which aircraft types are used on specific routes, their frequency, and the proportion of seat capacity allocated. This model is particularly adept at globally optimizing fleet usage, taking into account a wide array of operational and economic constraints.

Input	**Model**	**Output**
• **Route network**: With available seat capacity • **Aircraft fleet**: Available units per A/C type • **Aircraft Performance Data**: e.g., engine, mass, range	**Objective function**: • DOC/ASK • Schedule delay • Travel time **Constraints**: • Route network coverage • Aircraft fleet limit • Payload-range relation • Runway length • Airport capacity • Market concentration	• **Fleet assignment**: Which aircraft type is used for which proportion of the seat capacity on which route? • **Route-specific aircraft mix** • **Route network of each aircraft type** • **Flight frequency on each route**

Table 2.5: Kuhlen et al. Model Overview

2.5.3. Non-optimization models

Three commonly used non-optimization models used for fleet development prediction are the Aviation Integrated Model (AIM), the Future Aviation Scenarios Tool (FAST) and the Fleet System Dynamics Model (FSDM) [25]. These models simulate fleet development, emissions and technology adoption under various scenarios. Thereby, they focus on external factors such as fuel prices and technological advancements. However, they never specifically mention hydrogen-powered aircraft as a category on it's own. The AIM evaluates the impact of new technologies and carbon pricing on fleet emissions [26]. The FAST forecasts the future of aviation networks based on different technological and economic conditions [27]. FSDM uses a system dynamics approach to model fleet chagnes over time, providing a long-term view of fleet turnover and technological integration [28] [29].

So in summary, all of these models contribute to the future understanding states of the aviation networks but they do not actively optimize the network performance or minimize specific metrics.

As elaborated upon later, the research question focuses on identifying the aviation network model that minimizes the percentage change in LH2 flight movements under LH2 adaptation risks, therefore, optimization models are essential. Unlike the non-optimization models, optimization models are designed to find the best solution under a defined set of constraints and objective. With an objective function one can minimize the impact of LH2 integration risks or optimize the usage of certain aircraft types for example. This approach therefore allows for a targeted analysis of the trade-offs between the Hub & Spoke and Point-to-Point models.

3
Academic Research Gap

General outlooks for aviation suggest that the transition towards hydrogen-powered aircraft represents one of the most significant technological shifts in the aviation industry. While there are various projections and socio-technical imaginaries for the future of hydrogen-powered aviation, as mentioned in section 2.2 and section 2.3, there is currently no academic study providing a numerical outlook for the risks associated with the adoption of hydrogen aircraft specifically. Existing studies primarily focus on conventional aircraft and propulsion systems or general technology trends, often neglecting to include hydrogen-powered aircraft as a distinct category.

Moreover, while the benefits of hydrogen-powered flight—such as reduced carbon emissions—are frequently highlighted, the literature lacks a detailed assessment of the implications and challenges associated with this transition. These risks are multifaceted, as discussed in section 2.4. For instance, integrating hydrogen aircraft into existing airport infrastructure presents significant challenges, yet the severity of these risks is rarely quantified. Current models do not consider the specific requirements for liquid hydrogen (LH2) adaptation, such as the need for compatible refueling systems, storage facilities, and the development of a network of airports capable of supporting hydrogen-powered aircraft. This creates a critical gap in our understanding of how to integrate hydrogen aircraft into the aviation network most efficiently and effectively.

An opportunity arises with optimization models, particularly those discussed in section 2.5, where the ability to dynamically adjust constraints and scenarios can enhance our understanding of the implications of these risks.

The literature currently lacks trade-offs ranking the severity of these risks by airport and network type. This research aims to fill these gaps by developing an optimization model that explicitly incorporates hydrogen-powered aircraft and allows for the adjustment of various constraints related to key risks that need to be identified. This research will enable a more informed and strategic integration of hydrogen-powered aircraft into the future aviation network.

4
Research Question

In this chapter the main research question is presented and elaborated upon in section 4.1. This is followed by subquestions and their explanations in section 4.2.

4.1. Main Research Question

The main research question is: How do obstacles to hydrogen adaptation alter the projected distribution and frequency of hydrogen-powered flights in a European commercial aviation network by 2050?

First of all, the year 2050 is taken as a reference point for the model, as introduced before with the socio-technical imaginaries of climate-neutral aviation theory by C. Muehlberger et al [12]. The scope of 2050 aligns with global climate goals, including achieving net-zero emissions by 2050. This timeframe should allow for the necessary technological advancements and infrastructure changes to get a network with a significant number of hydrogen-powered aircraft.

The obstacles to hydrogen adaptation are discussed in section 2.4. Their effect is to be taken into account by the model.

This performance is to be measured by the change in Liquid Hydrogen flight movements and their distribution throughout a European aviation network.

To systematically address the main question, several subquestions are formulated. Each explore a different phase of the research.

4.2. Research Subquestions

The first subquestion reads as follows: Which obstacles associated with Liquid Hydrogen (LH2) adaptation are most likely to occur at airports?

In this phase, the objective is to identify the most likely risks associated with the adaptation of LH2 at airports. The obstacles found are to be sorted by importance and likelihood of occurrence at airports.

The second subquestion reads as follows: Given an optimization network model, established to project the demand for aircraft in 2050, including both a partial network of Liquid Hydrogen (LH2) and conventional aircraft, what are the projected number of flight movements?

This phase is created to establish the baseline model to project the demand for aircraft in 2050. The projected demand should make a distinction between LH2 and conventional aircraft movements.

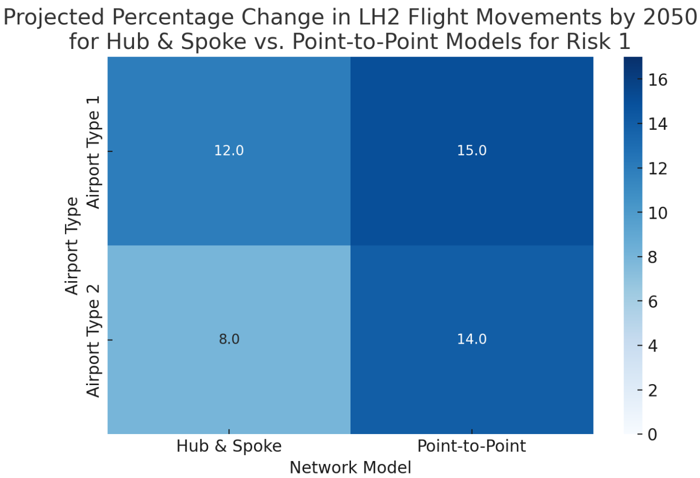
The third subquestion reads as follows: How do the identified key obstacles impose constraints for airports in the model?

This phase addresses the adaptation of the actualization of the obstacles in the model. The idea is that the key obstacles will impose constraints on the airport within the model. Thereby having an impact on the amount of movements that can be facilitated by an airport.

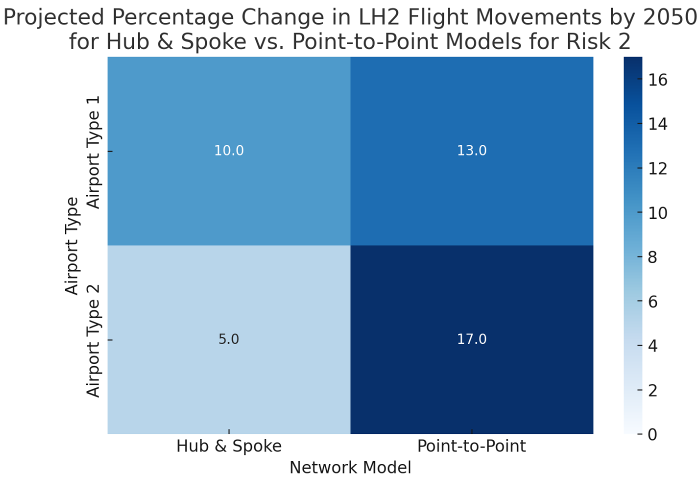
5 Expected Results

The research question cannot be answered with a black and white answer.

The conclusions made should be supported by numerical data. For now, the thought is that this could be in the form of a heat map. Where per obstacle, per airport type where the obstacle is activated, the overall percentage change in flight movements is indicated per network type. An exemplary table per risk is provided in Figure 5.1a and Figure 5.1b.



(a) Projected percentage change for risk 1



(b) Projected percentage change for risk 2

Figure 5.1: Example data for visualization purposes of projected percentage change in LH2 Flight Movements by 2050 for Hub & Spoke vs. Point-to-Point Models

Moreover, the outcome of an imposed obstacle can be visualized in a map. This can help visualize the change in movements throughout the network. In Figure 5.2, a network is shown that consists of regional airports and international hubs. One of the regional airports, the adapted regional airports, has suffered from the risks considering the LH2 adaptation at airports, and therefore is unable to accommodate full LH2 flight movements. This results in a percentage decrease of certain routes in the network (indicated by the orange percentage change).

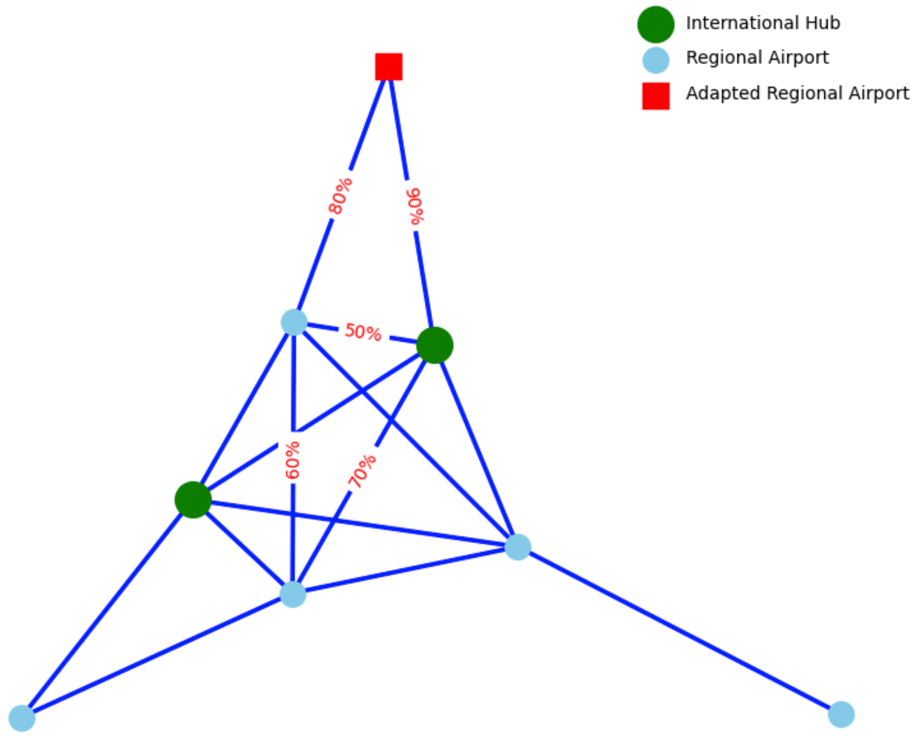


Figure 5.2: Visualization of the effect of the projected percentage change in the network

6 Methodology

The methodology is set up by means of the different phases linked to the research subquestions listed in section 4.2. A flow diagram is shown in Figure 6.1. In the following sections, the phases are elaborated upon one by one.

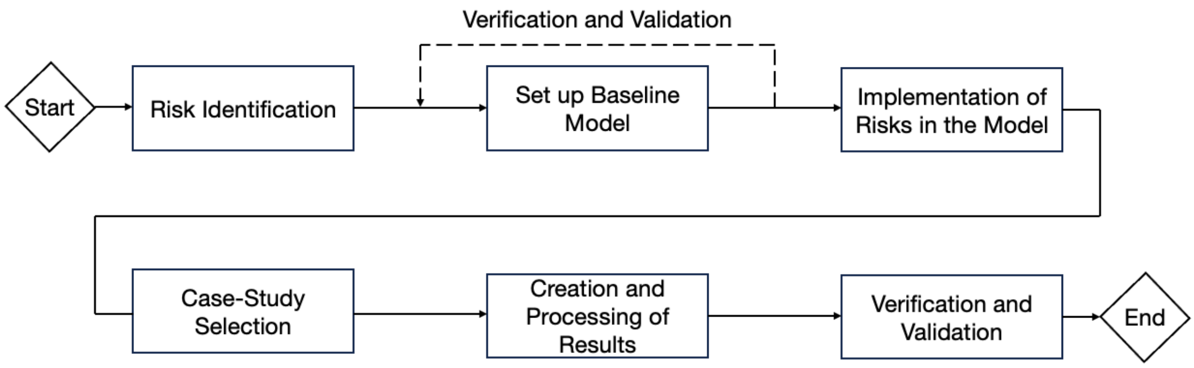


Figure 6.1: Methodology Flow Diagram

6.1. Risk Identification

For the risk identification phase, the first step involves developing an initial list of potential risks associated with LH2 adaptation at airports that create obstacles. This will be achieved through an extensive review of academic literature, industry reports, and regulatory documents. Earlier research mentioned in this report will form a basis.

This process will also involve consultations with subject matter experts, including for example airport operators (from Rotterdam The Hague Airport) and aerospace design engineers, to gather qualitative data and validate the risks identified in the literature. The outcome of this step will be a comprehensive list of potential obstacles considering LH2 adaptation at airports.

The next step is to systematically evaluate and rank these risks for each airport type. Following are a few methods that could be considered.

First of all, a qualitative risk analysis could be done. This method involves scenario-based assessments where risks are ranked based on their potential impact and likelihood. It often uses descriptive scales to evaluate risks (e.g. low, medium, high). Additionally, or else, a quantitative risk analysis can be applied. This method assigns numerical values to risks, allowing for a more objective comparison [30].

Moreover, a risk matrix could be considered, this a tool used to assess and prioritize risk by evaluating both the probability of an incident occurring and the potential loss it could cause [31]. Here the risks are plotted on a matrix that displays the likelihood of occurence on one axis and the severity of impact on the other, thereby visually representing the relative level of risk each event poses. In this way, the matrix helps identifying which obstacles require the most attention and allows for ranking for this research.

6.2. Set up Baseline Model

To create a comprehensive baseline model, the first step is to determine which optimization framework will be employed. This involves deciding whether a generalized model will be used for both the Hub

& Spoke and Point-to-Point networks, or if separate models will be developed for each network type. The choice of modeling approach should align with the overall objective of this research, which is to assess the performance of different network models under LH2 adaptation scenarios. Options for the optimization models are discussed in section 2.5.

In setting up the optimization model, it is crucial to define several core components: input data, output variables, an objective function, decision variables, parameters, and constraints. Input data, such as flight demand forecasts and airport infrastructure capabilities, must be selected to accurately reflect the aviation landscape in 2050. The output variables will represent key performance indicators, such as the number of LH2 flight movements. The objective function will be designed to minimize or maximize these indicators according to the goals of the study, such as minimizing emissions or maximizing network efficiency.

Decision variables in the model will include choices such as the allocation of flights to different network models or the proportion of LH2 versus conventional aircraft in operation. Parameters may be fixed aspects of the system, such as fuel availability or technological capabilities. Constraints will reflect real-world limitations, like airport capacity and aircraft availability. The model should be structured to ensure that the desired outputs, as described in chapter 5 are achieved.

Additionally, the model should be calibrated for the year 2050, which necessitates acquiring relevant data and forecasting future scenarios. This can be guided by documents such as IATA's Vision 2050 or Eurocontrol's vision for 2050 [7] [8]. These sources provide insights into anticipated developments in aviation, which should be incorporated into the model to ensure it's accuracy.

Assumptions regarding LH2 demand must be formulated and integrated into the model, potentially based on climate neutrality goals, as previously discussed in chapter 1. Alternatively, assumptions could be drawn from outlooks such as the World Economic Forum's 2050 outlook, which predicts that 21-38% of flights will be hydrogen-powered [11].

Verification and validation are next steps to test the model's reliability and robustness [22] [23]. Verification focuses on checking that the model is implemented correctly and operates as intended, free from errors. Techniques such as structural verification, extreme condition tests, and parameter calibration can be used to confirm that the model's internal logic and structure align with theoretical expectations and empirical data. Validation ensures that the model accurately represents real-world phenomena for its intended purpose. This involves comparing model outputs against historical data (so flight outlook data for 2050 for example). Moreover, sensitivity analyses should be conducted to examine how changes in input parameters affect outputs, (e.g. checking if the assumption about the fraction of LH2 is heavily deciding network behaviour). Moreover, statistical tests can be used to determine the significance of model results. Both local and global sensitivity analyses are crucial, as they help identify which parameters most influence the model's behavior, allowing for more focused calibration and refinement [32].

6.3. Implementation of obstacles in the Model

A selection should be made from the risks that will have been identified following the methods outlined in section 6.1, to determine the key obstacles. These risks are those that have the highest likelihood of occurrence and/or the most significant impact on the performance of the aviation network.

These obstacles are to be implemented in the model. This will be in the form of constraints in the optimization model. The constraints should model the potential operational limitations or potential disruptions for example that the obstacles could cause.

The implementation process looks as follows. First of all, the key risk must be analyzed and it is to be determined how it can be quantitatively represented within the model. For example, risks related to Hydrogen fuel availability at the airport may be modeled as constraints on the maximum allowable number of LH2 flights. Risks associated with infrastructure could for example pose risks on airport capacity or turnaround times.

Next, the model needs to be adjusted to incorporate these constraints in a way that they affect the decision variables and indirectly or directly the objective function.

A small sensitivity analysis should be included as well to test the sanity of the obstacles. The parameters of the obstacle can be varied to see how sensitive the outcomes of the model are to the risk levels.

6.4. Case-Study Selection

For the case-study selection, decisions need to be made such that a variety of real-world scenarios are modelled in this research.

The first step is to determine on a set of criteria that ensure the chosen studies are relevant and representative of the challenges identified with the risks. These criteria could include factors such as geographic diversity, variations in airport size and type, differences in regulatory environments (goals for reducing climate emissions) and the extent of the existing infrastructure for LH2 at airports for example.

Once these criterias are set, several case studies will be defined with the help of industry experts and scenarios used in current literature. It could also be in the form of a commercial network, for example KLM's European Hub & Spoke network.

The determined on case-studies will be the basis for the results.

6.5. Creation and Processing of Results

The results may be in the form of the results discussed in chapter 5. It should include an analysis of the output data and evaluate the different case-studies with the different network models, Hub & Spoke and Point-to-Point. Thereby seeing how the various risks and assumptions defined earlier in this research have taken effect.

How many results are expected will be hand in hand with the previously determined on case-studies. Moreover, it should be clear that all identified risks obtain equal attention in the results, making it an objective study.

6.6. Verification and Validation

A key component of the last verification and validation steps is to set up a sensitivity analysis. Here a comparative analysis can be performed that focusses on comparing the outcomes of the different models and case-studies based on criteria, such as operational efficiency, environmental impact or resillience of the identified risks. To what extent this is done can be determined with the creation of the model.

Kuhlen et al. for example, the last model discussed in section 2.5, used the following techniques [24].

The model used data sets for calibration and validation. This was historic data, to finetune the model's parameters based on the historic period, and thereby test its predictive capability on subsequent periods. Moreover, the optimization problem's objective was tested to ensure that it accurately represented real-world conditions, such as route seat capacities or fleet availability. And lastly, several evaluation metrics were used to validate the model's performance. Kuhlent et al. for example used the Normalized Wasserstein Distance (NWSD) to compare the model output to the historical data for fleet assignment.

7
Time Schedule

The timeline for the research is shown in Table 7.1. The Mid-term review is planned for the week of 25-11-2024. The Greenlight Review is planned for 17-02-2025.

1. Research Phase 1	**Start Date**	**End Date**	**Duration (workdays)**
Review research proposal	19-09-24	20-09-24	2
Risk identification	21-09-24	2-10-24	8
Set up baseline model	3-10-24	29-10-24	18
Implementation of risks in model	30-10-24	22-11-24	18
2. Research Phase 2	**Start Date**	**End Date**	**Duration (workdays)**
Case-Study selection and implementation	25-11-24	9-12-24	10
Creation and processing of results	10-12-24	6-01-25	15
Verification and validation	7-01-25	31-01-25	19
Work on draft thesis	1-02-25	21-02-25	15
3. Thesis Finalization	**Start Date**	**End Date**	**Duration (workdays)**
Work on final thesis	22-02-25	14-03-25	10
Prepare for thesis defense	15-03-25	4-04-25	10

Table 7.1: Research Phases and Timeline

8
Conclusion

In conclusion, the transition towards hydrogen-powered aircraft represents a pivotal technological shift in the aviation industry, yet the academic literature currently lacks a comprehensive numerical outlook for the risk of the accommodation of specifically these aircraft at airports, creating obstacles. Existing studies primarily focus on conventional aircraft and general technology trends, often failing to address hydrogen-powered aircraft as a distinct category.

Additionally, while the benefits of hydrogen-powered flight—such as reduced carbon emissions are frequently highlighted, there is a lack of detailed assessment of the implications and challenges associated with this transition, particularly regarding the integration of hydrogen aircraft into existing airport infrastructure.

This research aims to fill these gaps by developing an optimization model that explicitly incorporates hydrogen-powered aircraft, allowing for the dynamic adjustment of various constraints and obstacles. By doing so, it will enable a more informed and strategic integration of hydrogen-powered aircraft into the future aviation network, ultimately providing a clearer understanding of how to navigate the complexities of hydrogen adaptation by 2050.

References

[1] V. Masson-Delmotte et al. *Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. Summary for Policymakers. Cambridge, UK and New York, NY, USA: Cambridge University Press, 2018, pp. 3–24. DOI: 10.1017/9781009157940.001.

[2] Alexander Mitchell. *Airbus Partners With Scandinavian Carriers To Grow Hydrogen Hub Initiative*. Accessed: [Insert the date you accessed the website here]. Jan. 2024. URL: https://simpleflying.com/airbus-partners-with-scandinavian-carriers-to-grow-hydrogen-hub-initiative/.

[3] D.S. Lee et al. "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018". In: *Atmospheric Environment* 244 (2021), p. 117834. ISSN: 1352-2310. DOI: https://doi.org/10.1016/j.atmosenv.2020.117834. URL: https://www.sciencedirect.com/science/article/pii/S1352231020305689.

[4] K. Dahlmann et al. "Quantifying the contributions of individual NOx sources to the trend in ozone radiative forcing". In: *Atmospheric Environment* 45.17 (2011), pp. 2860–2868. ISSN: 1352-2310. DOI: https://doi.org/10.1016/j.atmosenv.2011.02.071. URL: https://www.sciencedirect.com/science/article/pii/S1352231011002366.

[5] H. Nojoumi, I. Dincer, and G.F. Naterer. "Greenhouse gas emissions assessment of hydrogen and kerosene-fueled aircraft propulsion". In: *International Journal of Hydrogen Energy* 34.3 (2009), pp. 1363–1369. ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2008.11.017. URL: https://www.sciencedirect.com/science/article/pii/S0360319908015048.

[6] W.F. Lammen et al. *Hydrogen-powered propulsion aircraft: conceptual sizing and fleet level impact analysis*. Tech. rep. NLR-TP-2022-233. Presented at the 9th European Conference for Aerospace Sciences (EUCASS), Lille, 30/06/2022. Royal NLR - Netherlands Aerospace Centre, Sept. 2022. URL: https://www.nlr.nl.

[7] International Air Transport Association. *Vision 2050*. Singapore, 12 February 2011. Montreal — Geneva: International Air Transport Association, Feb. 2011. URL: https://www.iata.org/vision-2050-report.pdf.

[8] EUROCONTROL. *EUROCONTROL Aviation Outlook 2050*. STATFOR Doc 683 08/04/2022. EUROCONTROL, Apr. 2022. URL: https://www.eurocontrol.int/publication/eurocontrol-aviation-outlook-2050-report.pdf.

[9] Airbus. *Towards the world's first hydrogen-powered commercial aircraft*. https://www.airbus.com/en/innovation/zeroe. Accessed: 2024-09-02. 2024. URL: https://www.airbus.com/en/innovation/zeroe.

[10] ZeroAvia. *Scaling Hydrogen-Electric Propulsion for Large Aircraft Whitepaper*. https://www.zeroavia.com/scaling-hydrogen-electric-propulsion. Accessed: 2024-09-02. 2024. URL: https://www.zeroavia.com/scaling-hydrogen-electric-propulsion.

[11] World Economic Forum. *Innovative Liquid Hydrogen Storage to Support Space Launch System*. https://www.weforum.org/. Accessed: 2024-08-29. 2023.

[12] Clara-Marie Muehlberger et al. "Socio-technical imaginaries of climate-neutral aviation". In: *Energy Research & Social Science* 114 (2024), p. 103595. ISSN: 2214-6296. DOI: https://doi.org/10.1016/j.erss.2024.103595. URL: https://www.sciencedirect.com/science/article/pii/S2214629624001865.

[13] Airport Council International and Air Transport Action Group. *Integration of Hydrogen Aircraft into the Air Transport System*. Report. https://store.aci.aero/product/sustainable-energy-sources-for-aviation-an-airport-perspective/. 2020.

[14] Editor G. D. Brewer. *LH2 Airport Requirements Study*. Tech. rep. NASA CR-2700. Contractor Report, prepared by Lockheed-California Company, Burbank, California. Hampton, Virginia: National Aeronautics and Space Administration (NASA), Oct. 1976. URL: https://ntrs.nasa.gov/citations/19770003090.

[15] Dolf Gielen, Emanuele Taibi, and Raul Miranda. *Hydrogen: A Renewable Energy Perspective*. Report prepared for the 2nd Hydrogen Energy Ministerial Meeting in Tokyo, Japan. Abu Dhabi: International Renewable Energy Agency (IRENA), Sept. 2019. URL: https://www.irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective.

[16] International Energy Agency. *The Future of Hydrogen*. 2019, p. 203. DOI: https://doi.org/https://doi.org/10.1787/1e0514c4-en. URL: https://www.oecd-ilibrary.org/content/publication/1e0514c4-en.

[17] Fredrik Haglind and Riti Singh. “Potential of reducing the environmental impact of aviation by using hydrogen - Part III: Optimum cruising altitude and airport implications”. In: *Aeronautical Journal -New Series-* 110 (Aug. 2006), pp. 553–565.

[18] Hans J. Pasman. “Challenges to improve confidence level of risk assessment of hydrogen technologies”. In: *International Journal of Hydrogen Energy* 36.3 (2011). The Third Annual International Conference on Hydrogen Safety, pp. 2407–2413. ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2010.05.019. URL: https://www.sciencedirect.com/science/article/pii/S0360319910009547.

[19] Ramin Moradi and Katrina M. Groth. “Hydrogen storage and delivery: Review of the state of the art technologies and risk and reliability analysis”. In: *International Journal of Hydrogen Energy* 44.23 (2019), pp. 12254–12269. ISSN: 0360-3199. DOI: https://doi.org/10.1016/j.ijhydene.2019.03.041. URL: https://www.sciencedirect.com/science/article/pii/S0360319919309656.

[20] *Aerodrome Design Manual: Doc 9157*. 4th. Particular edition and year of publication may vary; please verify the latest version. International Civil Aviation Organization (ICAO). Montreal, Canada, 2024.

[21] *Airport Planning Manual: Doc 9187*. 3rd. Particular edition and year of publication may vary; please verify the latest version. International Civil Aviation Organization (ICAO). Montreal, Canada, 2024.

[22] Bruno F. Santos. *Lecture III (Part IV) – Network and Fleet Development*. Nov. 2023.

[23] Bruno F. Santos. *Lecture III (Part III) – Network and Fleet Development*. Nov. 2023.

[24] Markus Kühlen et al. “An explanatory approach to modeling the fleet assignment in the global air transportation system”. In: *CEAS Aeronautical Journal* 14.1 (2023), pp. 255–269.

[25] O. Oguntona. “Longer-term aircraft fleet modelling: narrative review of tools and measures for mitigating carbon emissions from aircraft fleet”. In: *CEAS Aeronautical Journal* 11 (2020), pp. 13–31. DOI: 10.1007/s13272-019-00424-y. URL: https://doi.org/10.1007/s13272-019-00424-y.

[26] European Commission, Joint Research Centre (JRC). *Aviation Integrated Model (AIM)*. https://www.atslab.org/. Last updated 15 May 2024. Accessed on [date you accessed the website]. 2024.

[27] Bethan Owen, David S. Lee, and Ling Lim. “Flying into the Future: Aviation Emissions Scenarios to 2050”. In: *Environmental Science & Technology* 44.7 (2010). PMID: 20225840, pp. 2255–2260. DOI: 10.1021/es902530z. URL: https://doi.org/10.1021/es02530z.

[28] Niclas Randt. “Foundations of a Technology Assessment Technique Using a Scenario-Based Fleet System Dynamics Model”. In: Aug. 2013. ISBN: 978-1-62410-225-7. DOI: 10.2514/6.2013-4383.

[29] Niclas Randt, Christoph Jessberger, and Kay Plötner. “Estimating the Fuel Saving Potential of Commercial Aircraft in Future Fleet-Development Scenarios”. In: June 2015. DOI: 10.2514/6.2015-2435.

[30] Karel Haegeman et al. “Quantitative and qualitative approaches in Future-oriented Technology Analysis (FTA): From combination to integration?” In: *Technological Forecasting and Social Change* 80.3 (2013). Future-Oriented Technology Analysis, pp. 386–397. ISSN: 0040-1625. DOI: https://doi.org/10.1016/j.techfore.2012.10.002. URL: https://www.sciencedirect.com/science/article/pii/S0040162512002466.

[31] Huihui Ni, An Chen, and Ning Chen. “Some extensions on risk matrix approach”. In: *Safety Science* 48.10 (2010), pp. 1269–1278. ISSN: 0925-7535. DOI: https://doi.org/10.1016/j.ssci.2010.04.005. URL: https://www.sciencedirect.com/science/article/pii/S0925753510001049.

[32] A. Sharpanskykh. *Lecture 5: Analysis of simulation results*. Dec. 2022.

II

Scientific Paper

Modeling the Impact of Hydrogen Adaptation Obstacles on Hydrogen-Powered Flights by 2050

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Abstract

This research investigates how the obstacles to hydrogen adaptation impact the projected distribution and frequency of hydrogen-powered flights in Europe by 2050. The prioritized obstacles in this research are economic constraints and airport capacity limitations. For the economic constraints two different cost scenarios are analysed, one where hydrogen-aircraft just become competitive with respect to conventional aircraft, and one where hydrogen-aircraft are favoured with respect to conventional aircraft. When considering airport capacity limitations, for example due to availability of green hydrogen and infrastructure modifications, a constraint is put on the maximum amount of hydrogen-powered aircraft allowed in the network. In this research, a European Hub & Spoke network for an airline is analysed. In the scenario where hydrogen-powered aircraft are favoured, the variable cost of conventional aircraft is significantly increased in the future. Then, more hydrogen-powered aircraft are deployed and these are particularly medium-range hydrogen-powered aircraft. Moreover, under different traffic growth scenarios, the higher the traffic growth, the more routes are flown by hydrogen-powered aircraft. When comparing these two results, the varying of the variable costs of future aircraft is more sensitive to the deployment of hydrogen-powered aircraft than the sensitivity of the traffic growth. When considering the implementation of a fleet constraint for hydrogen-powered aircraft, only in a scenario with high traffic growth from 2025-2050 and a favorable cost for hydrogen-powered aircraft, the capacity constraint is met. Across all scenarios, despite varying conditions, the airline's profit remains reasonably consistent and almost all demand is captured. This study emphasizes that hydrogen-powered aircraft adaptation is highly sensitive to cost dynamics. At policy level regulatory entities should implement mechanisms that create financial incentives for hydrogen adoption and Original Equipment Manufacturers should prioritize cost-efficient design.

1 Introduction

The aviation industry is undergoing a pivotal transformation as it seeks to reconcile growth with urgent sustainability goals. As one of the fastest growing contributors to global greenhouse gas emissions, aviation accounts for approximately 2% of human-made global carbon dioxide emissions and is projected to see a 115% increase in flight numbers by 2050 (IATA (2021), IATA (2024)). The International Air Transport Association (IATA (2024)) researched that aviation's contribution to global carbon dioxide emissions will double by 2050 if no measures are taken. This is unacceptable considering the established sustainability goals, such as the Paris Agreement and Intergovernmental Panel on Climate Change (2022) goal to decrease global carbon pollution by 48% from the levels of 2019 by 2030 and to reach zero carbon emissions by 2050. Addressing this challenge requires innovation, particularly in propulsion systems and fuel technologies. Air Transport Action Group (2021) states that these changes will also require updates to operations and policies.

Among the pathways toward decarbonizing aviation, sustainable aviation fuel is expected to drive 65% of the effort toward Net Zero Carbon by 2050, with new technologies contributing an additional 13% through advancements in efficiency and innovation (IATA (2024)). Hydrogen-powered aircraft represent such promising zero-carbon dioxide emission technology, given that the provided hydrogen is 'green', meaning it is produced using renewable energy sources. Baroutaji, A. (2019) states that it would eliminate almost all carbon-based emissions, soot, and sulfur oxides. The byproducts

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of hydrogen in a combustion process are water vapor and nitrogen oxides (NOx), with fuel cells solely water vapor. NOx emissions contribute to smog, acid rain, particulate matter, and ozone (O_3), with ozone acting as a climate-warming gas. These emissions also negatively impact tropospheric and stratospheric ozone levels through methane changes. However, hydrogen combustion releases significantly lower amounts of NOx compared to kerosene (Habib (2024)). This reduction is primarily attributed to the water vapor produced during hydrogen combustion, which absorbs much of the energy released, lowering peak combustion temperatures and suppressing NOx formation. The increased water vapor from hydrogen combustion and fuel cell technology contribute to contrail formation. Verstraete, D. (2009) and Bicer, Y., and Dincer, I. (2017) states that considering greenhouse gas emissions from hydrogen as a jet fuel, the impact is still substantially lower than that of kerosene.

Initiatives like the Airbus (2024b) ZEROe project and Fokker Next Gen (2024) project aim to bring hydrogen-powered aircraft to market by 2035. Designs include aircraft with a seating capacity of 100 and above, and fuel cell and direct combustion are considered. Fuel cell technology in hydrogen aviation converts hydrogen into electricity through an electrochemical reaction, which powers electric motors to drive propellers or fans, ensuring zero carbon dioxide emissions. In contrast, direct combustion technology burns hydrogen in new turbofans to generate thrust. Clean Sky 2 (2022) presents that the hydrogen-powered aircraft will increase in performance in the decades following 2035. In 2035, regional flights can be made with 80 passengers, in 2040 short-range flights with 165 passengers and only by 2045, medium-range flights with up to 250 passengers.

Whereas Sustainable Aviation Fuel (SAF) can be used as a drop-in fuel in conventional kerosene-powered engines, ensuring a close to regular operations continuity, accommodation of hydrogen-powered aircraft comes with several obstacles for airports. The Airports Council International (2024) presents that whether delivered in gaseous or liquid form, integrating hydrogen into airport operations represents a substantial shift in infrastructure requirements. This transition would require considerable capital investment, operational practice modifications and safety protocol updates. An example is the need for extended turnaround times. The specific implications depend on various factors, including the method of hydrogen utilization, the fuel volume needed and the design of the hydrogen supply chain established to support the airport's needs.

World Economic Forum (2023) states that predictions that by 2050, 24-36% of flights at major hubs such as Schiphol could be powered by hydrogen. This number is constrained with an upper bound due to limitations in hydrogen supply for airports and the interdependency of hydrogen-powered flight considering other airports, diversions and refuel options need to be available at different airports (European Commission and Directorate-General for Research and Innovation (2023b)).

The transition to hydrogen is complex in an aviation network, where the adoption of hydrogen-powered aircraft is reliant on widespread and coordinated changes to infrastructure across a diverse range of airport types to reach its full potential. Hydrogen-powered flight has been extensively explored for its environmental benefits, and the operational and infrastructural risks associated with its adoption have been identified.

It is these risks, though, that have not often been quantified and will form obstacles in network planning. Current studies lack a numerical analysis of how these risks might disrupt network operations or alter the outlook for hydrogen-powered flights. Another gap in the literature concerns the integration of hydrogen-specific constraints into network optimization models. Established models, such as Mixed Integer Linear Programs (MILPs), can model Hub & Spoke and Point-to-Point network behavior for conventional networks. Still, its advantages have not been adapted to account for the unique requirements of hydrogen-powered aircraft.

The lack of these insights hinders the ability of stakeholders to make informed decisions about the future structure and resilience of future aviation networks. To address these gaps, this research investigates how the obstacles of hydrogen adaptation at airports impact the projected distribution and frequency of hydrogen-powered flights in Europe by 2050. The research question is: How do obstacles to hydrogen adaptation alter the projected distribution and frequency of hydrogen-powered flights in a European commercial aviation network by 2050? By developing a multiperiod, scenario-based optimization model, this study incorporates hydrogen-specific obstacles and constraints to evaluate their effects on network performance. This provides insights for the strategic integration of hydrogen-powered aviation, supporting the broader goal of achieving net-zero emissions by 2050.

2 Literature Review

To support the methodology presented in section 3, this section provides a literature review of relevant topics.

This literature review is structured into four sections. First of all, section 2.1 discusses passenger demand forecasts. Thereby focusing on growth patterns globally and in Europe to identify what is relevant for the scope of this research. Next, in section 2.2, the technical and commercial potential of hydrogen aircraft are explored, including advancements by manufacturers and their promised operational capabilities. The results are taken as specifications for the aircraft used in the model for this research. This is followed by section 2.3, which addresses the obstacles to hydrogen implementation at airports. Thereby also identifying which are to be acknowledged in this research and incorporated into the model. And finally, fleet optimization models are explored and categorized in section 2.4.

2.1 Aviation Passenger Traffic forecast

The aviation industry is expecting growth, and different assumptions are available on how significant this growth will be.

Gelhausen, M., et al. (2019) forecasts aviation passenger growth for 2030 and 2040 based on empirical data and model-driven approaches that analyze historical air traffic growth trends and airport capacity constraints. Key factors include methods to estimate airport capacity, such as hourly and annual capacities, and metrics like the capacity utilization index and air traffic ranking curves. Their models focus on long-term forecasts for large networks, addressing the impact of limited physical and administrative infrastructure on future air traffic growth. Table 1 shows the annual passenger volume growth rate forecast per year from 2016-2030 and 2030-2040 by Gelhausen, M., et al. (2019). Separate estimations are made for the global scale and flights within Europe, so the origin and destination are in Europe.

Table 1: Forecast annual passenger volume growth rates per year from 2016-2040

Growth Rate	2016-2030	2030-2040
Global	+4.1%	+3.1%
Europe	+3.3%	+2.6%

Additionally, IATA (2024) published a global outlook for air transport. They state that over the next 20 years, from 2023-2043, the Compound Annual Growth Rate (CAGR) expected globally is 3.8%. For Europe, the expectation is slightly lower, with a CAGR of 2.3 %. This lower CAGR is reflected in the difference between Europe's GDP per capita growth and its impact on air travel. While Europe's GDP per capita growth nearly matches global growth, the number of trips per capita in Europe is expected to increase by about 50% over 20 years, 25% less than the worldwide average of approximately 75% growth.

Airbus (2024a) presents in their global market forecast an expected traffic CAGR of 3.7 % from 2027 to 2043. Lower traffic growth is expected in mature flows such as intra-Western Europe and intra-Eastern Europe (intra means origin and destination in the corresponding region), with a CAGR of 1.7 % from 2027 to 2043.

To summarize these findings, over the next 25 years, global traffic is expected to have a CAGR between 3.1 - 4.1 % and passengers intra-Europe between 1.7 - 3.3 %.

2.2 Hydrogen Aircraft Outlook

Starting in 2035, the aviation network includes the integration of the Fokker Next Gen (2024) and the Airbus (2024b) ZEROe hydrogen-powered aircraft, among others.

Fokker Next Gen (2024) presents a dual-fuel regional airliner capable of operating on hydrogen and Sustainable Aviation Fuel (SAF), with an entry into service in 2035. It features a capacity of 120 passengers and a range of up to 4,000 km when utilizing both fuel types. This aircraft uses a combustion engine and requires advanced infrastructure for hydrogen storage and refueling, such as facilities capable of handling gaseous helium for tank cooling.

Airbus (2024b) presents multiple concepts, including two aircraft ready for service in 2035. First, a twin combustion-engine configuration that is hydrogen-powered and can carry 200 passengers with a range exceeding 3704 km. The second aircraft is a ZEROe turbofan that can take just under 100 passengers with a range of 1852 km. This aircraft is powered by hydrogen combustion with two turboprop engines.

This research focuses on a European aviation network, focusing on the following aircraft types: regional, short-range and medium-range aircraft. These are categorized based on their range and typical seat capacity. Regional flights cover distances of less than 1,500 km and typically use aircraft with fewer than 100 seats. Short-range flights extend up to 3,000 km and are serviced by aircraft seating between 100 and 200 passengers. Medium-range flights operate within a range of 3,000 to 6,000 km, accommodating between 150 and 300 passengers. These classifications are not internationally standardized.

2.3 Obstacles of Hydrogen Implementation at Airports

Several challenges impact the adoption of hydrogen at airports. The two factors included in this research are economic constraints and airport limitations. In this section, the relevant obstacles for these two factors are introduced.

Economic obstacles primarily relate to investment and funding challenges and supporting government policies. The capital investment required for hydrogen infrastructure is a significant obstacle. World Economic Forum (2023) states that achieving net-zero emissions by 2050 necessitates an investment of $700 billion to $1.7 trillion across the hydrogen value chain. Approximately 90% of this funding is allocated to off-airport infrastructure, with the highest costs associated with power generation, hydrogen electrolysis and electrification. Within airports, substantial modifications are necessary to accommodate hydrogen fuel.

Airports will need significant funding to modify existing infrastructure or construct new facilities for hydrogen operations. International Energy Association (2019) analyzed that hydrogen occupies four times the volume of Jet A-1 fuel for the same energy content, necessitating larger storage tanks and extensive modifications to existing facilities. Airports Council International (2024) calculated that medium-sized airports may require up to 30,000 m^2 for hydrogen storage and refueling, while more significant hubs could require 80,000 m^2. World Economic Forum (2023) also highlights the financial impact, estimating an investment of approximately $3.9 billion for an intercontinental hub and $1.3 billion for a major regional airport.

Another key concern is the cost of renewable hydrogen production. The viability of hydrogen as an aviation fuel depends on access to affordable and clean hydrogen. Oesingmann, K., et al. (2024) discusses that renewable hydrogen fuel costs must be lowered to around 70 EUR/MWh by 2050 to meet aviation demand. However, European Commission and Directorate-General for Research and Innovation (2023a) and Scot, M. (2023) predict that renewable hydrogen costs will still be between 104 and 120 EUR/MWh by 2050.

Thus, aviation stakeholders must consider these financial uncertainties when developing long-term hydrogen adoption strategies.

Airport capacity factors further constrain hydrogen adaptation. As previously discussed, one of the obstacles is the availability of clean hydrogen, and accordingly the integration of hydrogen infrastructure into existing airport operations. Airports Council International (2024) shows that several logistical and technical challenges emerge. Complex supply chain logistics for hydrogen delivery are a key issue, requiring dedicated transportation and storage solutions. Onsite hydrogen production remains limited due to the large area required, creating risks for supply reliability.

Airports Council International (2024) also identifies infrastructure modifications as a challenge. Hydrogen storage and refueling require specialized facilities. Integrating hydrogen supply pipelines into existing airport layouts is complex and resource-intensive and could lead to operational disruptions. Additionally, physical constraints could present themselves when considering the design of a hydrogen aircraft concerning conventional aircraft. Airports Council International (2024) shows that a taxiway is not broad enough for a new wing profile. This could restrict the number of hydrogen-powered aircraft an airport can accommodate.

Comparing the identified obstacles with previous research, Terpstra, X.D. (2024) conducted a STEEP analysis at Delft University of Technology, identifying critical uncertainties in hydrogen supply chain pathways at airports. His study highlighted five major factors: investment and funding, technological innovation, availability of green hydrogen, hydrogen infrastructure integration and support for government policies and investments.

It is evident that economic constraints and airport capacity limitations will significantly impact the feasibility of accommodating hydrogen-powered aircraft in the aviation network. Insufficient investment and funding could restrict infrastructure development, while varying levels of government support may result in inconsistencies in hydrogen adoption across airports. Hydrogen supply availability and logistical challenges could further hinder operational efficiency, limiting the number of flights airports can accommodate. These constraints will be incorporated into the model and case studies to assess their impact.

2.4 Fleet Assignment Models

Various modeling approaches can be utilized to assess the implications of hydrogen adaptation at airports on the European aviation network.

Fleet assignment models are ideal for this research as they explicitly account for aircraft type-specific constraints such as extended turnaround times, infrastructure limitations, or higher variable costs. They can integrate demand forecasts with operational constraints, ensuring efficient allocation of aircraft types across a network. Their flexibility allows for scenario-based analysis, evaluating how uncertainties in propellant availability, infrastructure, or policy impact network performance.

These models are well-established in aviation research and are being used to assess aircraft's economic and operational implications in networks. Kühlen, M., et al. (2022) identifies three categories for fleet assignment models: individual airlines, multiple airlines that are competing and the global fleet.

When looking at a single airline, mathematical optimization can be done for a maximal operating profit. Typically, linear programming or mixed-integer programming techniques are applied. This dates back to the work done by Abara, J. (1989) and Hane, C.A., et al. (1995). More recently, more extensive problems have been tackled where for example, integrated flight scheduling is possible, or passenger behavior and preferences are modeled via supply-demand interactions (Wei, K., et al. (2019),Birolini, S. (2021)). A fleet assignment model for multiple competing airlines can model the open market's competitive nature. One airline's fleet assignment and flight frequencies can change considering the moves of another, to achieve this game theory approaches are applied. Early work was done by Hansen, M. (1990), more recently extensive problems including different aircraft sizes were tackled by Doyme, K. (2019) and Wei, W. (2007). For a global fleet assignment problem, the Aviation Integrated Model (AIM) is an example. It uses a multinational logit model to model the aircraft size for which routes. It is calibrated with historic flight schedule data. Route specifics such as route distances and demand data are required. Dray, L.M., et al. (2019) and Reynolds, T., et al. (2007) apply versions of the AIM. Kühlen, M., et al. (2022) presents a global fleet assignment problem solved as an optimization problem. Just like in a single airline's optimization problem, an objective function is set up. Still, this time, it takes into account the airline's and passengers' perspectives. For example via direct operating cost and travel time.

3 Methodology

This section presents the approach used to model the impact of obstacles on hydrogen-powered flights in Europe by 2050. First of all, in section section 3.1, the chosen baseline model is introduced. Next, in section 3.2, the modifications to this model to address this study's specific focus are described according to key assumptions derived from the literature review. Finally, the mathematical model is provided in section 3.3 and explained accordingly.

3.1 Model Selection

The choice of which model to use is made by reflecting on the different types of models discussed in section 2.4. To effectively explore the impacts of hydrogen adaptation risks at airports, a single airline fleet assignment model is chosen for its simplicity and focus on localized decision-making for this research. While global and multi-airline models offer insights into market dynamics and inter-airline competition, these complexities are unnecessary for this research. The primary aim is to assess how specific hydrogen-related constraints, such as limited infrastructure and required investment costs, can affect the allocation of aircraft and route frequency within a controlled network environment.

When it comes to fleet planning, revisiting decisions at multiple points in time to reflect how uncertain factors, such as demand, should be considered. Instead of making a single and static decision for the entire planning horizon, this is a dynamic approach. This research can accordingly show the impact of obstacles to hydrogen adaptation in different growth scenarios.

Repko, M.G.J., and Santos, B.F. (2017) set up a model to approach this dynamic problem, presented is a scenario tree model, which organizes possible demand developments and decision points over time. The fleet assignment model from this research, a Mixed Integer Linear Program (MILP), is taken as the baseline model for this research. The mathematical formulation of the model, including its key variables, constraints and objective function, are presented in section 3.3. section 3.1.1 introduces scenario tree modeling, which is a key concept of the selected model.

3.1.1 Scenario Tree Modeling

Repko, M.G.J., and Santos, B.F. (2017)'s model uses a complex scenario tree with 81 possible outcomes. While this structure remains used in this model, the final analysis is simplified by considering only the three scenarios: low, medium and high. This simplification allows for a clear interpretation of results while maintaining relevance to different growth scenarios.

In this scenario tree, the root node is the first period. From this root, branches extend to different demand developments, so in this case: low (L), medium (M), or high (H) demand changes. The same demand development is chosen with each future time period. With the previously mentioned forecasts in section 2.1, for this model, the Compound Annual Growth Rates (CAGRs) for a low, medium and high demand change are provided in Table 2.

Table 2: Compound Annual Growth Rates (CAGRs) and probability per low, medium, or high scenario

Scenario	Low	Medium	High
CAGR	+1.7%	+3.0%	+4.1%

3.2 Model specifications and assumptions

Multiple assumptions are required to adjust Repko, M.G.J., and Santos, B.F. (2017)'s model to represent a future European network incorporating hydrogen-powered flights. This section lists the assumptions made for different aspects of the model, including additions concerning the original model.

Aircraft categories and specifications
In this research, three categories of aircraft types are chosen to represent both the current generation of conventional aircraft and the emerging hydrogen-powered alternatives: regional, short-range and medium-range. The hydrogen-powered regional range is powered with fuel-cell technology, and the short- and medium-range with hydrogen combustion. Their specifications can be found in Table 3. These numbers are based on Clean Sky 2 (2022) estimations for regional, short-range and medium-range outlooks for hydrogen-powered aircraft. Moreover, these numbers align with the estimations discussed in section 2.2.

Table 3: Aircraft Types Representative for a Future Hydrogen-Powered European Network

Aircraft type	Range [km]	Seats [-]
Current Generation Regional	1500	100
Current Generation Short-range	3000	150
Current Generation Medium-range	6000	200
Hydrogen-Powered Regional	1000	80
Hydrogen-Powered Short-range	1852*	100
Hydrogen-Powered Medium-range	3704*	200

* Values 1852 and 3704 are converted from nautical miles to kilometers (1 nautical mile = 1.852 km).

Another critical aspect of this analysis is the operational cost differences. Clean Sky 2 (2022) states that hydrogen-powered aircraft exhibit higher variable CASK compared to their conventional counterparts, and an estimate of these numbers is shown in Table 4. Moreover, the Entry Into Service (EIS) is expected to differ, also presented in Table 4. Clean Sky 2 (2022) also presents that Turn Around Times (TATs) for hydrogen-powered aircraft vary significantly based on the propulsion technology and fuel type. Hydrogen fuel cell aircraft, which are most feasible for the regional and short-range segments, can face 1–2x longer refueling durations than conventional aircraft. Hydrogen turbine-powered aircraft require 2–3x longer refueling times for medium-range operations. For the fuel cell-powered regional aircraft, a minor turnaround increase is taken with respect to the hydrogen combustion-powered aircraft.

The model requires cost specifications to determine a fleet assignment based on profitability. For now, a Cost per Available Seat Kilometer (CASK) and Fixed Cost (FC) per week are determined per aircraft type. The CASK determines the Variable Costs (VC) per aircraft type per route; this is shown later in section 3.3. The CASK and FC are listed per aircraft type in Table 5. For the different categories of current generation aircraft, the CASK is taken as a combination of industry numbers (Lufthansa Group, 2023) and scientific research, (Hoelzen, J., et al., 2022), using interpolation with weights. Next, with the cost increase per category, as shown in Table 4. The increase is only used for the CASK, as the principal increases in cost are expected in the Variable Cost (VC) Clean Sky 2 (2022). The FC is determined by examining the costs for future aircraft types set up by Jansen, P., et al. (2016). Again, interpolation was used to obtain the numbers in Table 5 based on seat capacity and ranges.

To ensure hydrogen aircraft competitiveness concerning current generation aircraft, another category of aircraft is introduced in this model: future generation aircraft. This category has the exact specifications as current generation aircraft, the one difference is concerning costs. The future generation aircraft become available from 2035 onwards, when hydrogen aircraft first become available, as specified in Table 4. From this time point onward, current generation aircraft cannot be bought anymore, just hydrogen and future aircraft. The Fixed Costs (FC) will remain the same, it is the Variable Costs (VC) that will increase with a factor. A cost ratio is to be determined, which will apply to the regional, short-range and medium-range categories. It is defined as shown in Equation 1. This ratio will increase the CASK of future aircraft, making the cost of hydrogen aircraft competitive. The cost ratio is evaluated and determined in section 5.1.

$$\text{cost ratio} = \frac{\text{future } CASK}{\text{current generation } CASK} \tag{1}$$

Table 4: Specifications Change for Hydrogen-Powered Aircraft concerning Conventional Aircraft

Aircraft type	**Cost increase**	**EIS**	**TAT**
Hydrogen-Powered Regional	10%	2035	50%
Hydrogen-Powered Short-range	25%	2040	100%
Hydrogen-Powered Medium-range	35%	2045	100%

Table 5: Variable and Fixed Costs per Aircraft Type

Aircraft type	**CASK [€ per ASK]**	**FC [€] per week]**
Current Generation Regional	0.056	62,000
Current Generation Short-range	0.054	93,500
Current Generation Medium-range	0.049	155,800
Hydrogen-Powered Regional	0.056 * 1.1	62,000
Hydrogen-Powered Short-range	0.054 * 1.25	93,500
Hydrogen-Powered Medium-range	0.049 * 1.35	155,800

Range Constraints for Hydrogen Aircraft
A route is a flight from origin to destination and back from the same destination to its origin. All routes in this model originate and return to a hub, creating Hub-Spoke-Hub (HSH) movements. It is assumed that no refueling possibilities are possible at the spokes. Hence, a hydrogen-powered aircraft's range must be larger than the route distance to fly. Current generation and future aircraft can refuel at the spokes. The mathematical notation of this assumption is shown in Equation 10.

Limitations on Hydrogen Aircraft Adoption in the Network
It is assumed that an airport can only facilitate hydrogen-powered flights to a certain extent in some scenarios. Considering airport limitations, this is coupled with the obstacles mentioned in section 2. The obstacle is translated into a constraint in the model, which states the amount of hydrogen-powered aircraft that can be adopted in the whole network at a particular time. World Economic Forum (2023) states that 24-36% of Amsterdam Schiphol Airport's flights by 2050 will be hydrogen-powered. Considering Lufthansa's fleet size (Lufthansa Group, 2025), it is estimated that in 2050, 60 medium-range hydrogen-powered aircraft can be accommodated. A mix of two short-range or regional hydrogen-powered aircraft may be adopted

instead of one medium-range hydrogen-powered aircraft. Moreover, this constraint is phased in from 2035 onwards, when hydrogen-powered aircraft first become available. Hence, from 2035-2040, 20 hydrogen-powered medium-range aircraft may be owned, from 2040-2045 40, and 2045-2050 60. Still, there is the note that two short-range or regional hydrogen-powered aircraft may be adopted instead of one medium-range hydrogen-powered aircraft.

Behavior network up until 2035

It is assumed that before the introduction of hydrogen aircraft in 2035, the conventional aircraft are bought and sold as if conventional aircraft were to be the norm for the upcoming decades. This is done such that with the increase in costs for hydrogen and future aircraft, no compensation for these costs can be made. This behaviour translates into the buying more conventional aircraft in the time period 2025 till 2035, ensuring less future or hydrogen aircraft need to be bought, the more expensive option.

3.3 Mathematical model

In this section, the mixed-integer linear programming model is presented and used to find the ideal fleet composition over multiple periods. The model is programmed with Python (version 3.9) and utilizes the Gurobi Optimizer. The sets, decision variables and parameters are listed in Table 6, Table 7 and Table 9.

Table 6: Sets and subsets used in the model

Set	Description
T	Set of time periods
A	Set of aircraft types, where $A_C \cup A_H \cup A_F = A$
A_C	Subset of A, representing current conventional aircraft
A_H	Subset of A, representing hydrogen-powered aircraft
A_F	Subset of A, representing future conventional aircraft
R	Set of routes

Table 7: Decision variables used in the model

Variable	Description
x_{ta}	Number of aircraft type a in time period t
y_{tar}	Amount of times aircraft type a flies route r in time t in a week
q_{tr}	Quantity of passengers on route r in time t in a week
z_{ta}	Number of aircraft added of type a in time t
u_{ta}	Number of aircraft removed of type a in time t

Table 8: Parameters used in the model

Parameter	Description [Unit clarification]
d_t	Discount factor in time period t
n_t	Number of flights in time period t
$fare_r$	Fare on route r [€/passenger]
vc_{ar}	Variable cost of aircraft type a on route r [€]
fc_{ta}	Fixed cost of aircraft type a in time period t [€]
pen_{ta}	Penalty cost for removing aircraft type a in time period t [€]
BT_a	Block time of aircraft type a [hours]
OTr	Operating time required for route r [hours]
TAT_a	Turnaround time for aircraft type a [hours]
dem_{tr}	Demand on route r in time t [passengers]
cap_a	Capacity of aircraft type a [seats]
LF_r	Load factor on route r
IF_a	Initial fleet size of aircraft type a
R_a	Range of aircraft type a [km]
D_r	Distance of route r [km]
t_e	Entry into service period hydrogen-powered aircraft
$x_{max,t}$	Maximum amount of aircraft type a allowed in time t

* The demand increases per time period with low, medium or high traffic growth (Table 2)

The MILP formulation is:

$$\text{maximize} \sum_{t\in T} d_t \cdot n_t \cdot \Big(\sum_{r\in R} [2 \cdot fare_r \cdot q^{tr}] - \sum_{a\in A}\sum_{r\in R} [vc_{ar} \cdot y_{tar}] - \sum_{a\in A} [fc_{ta} \cdot x_{ta}] - \sum_{a\in A} [pen_{ta} \cdot u_{ta}]\Big) \tag{2}$$

$$BT_a \cdot x_{ta} \geq 2 \sum_{r\in R} (OT_r + TAT_a) \cdot y_{tar}, \quad \forall t \in T, a \in A \tag{3}$$

$$q_{tr} \leq dem_{tr}, \quad \forall t \in T, r \in R \tag{4}$$

$$q_{tr} \leq \sum_{a\in A} cap_a \cdot LF_r \cdot y_{tar}, \quad \forall t \in T, r \in R \tag{5}$$

$$x_{1a} \geq IF_a, \quad \forall a \in A \tag{6}$$

$$x_{ta} = x_{(t-1)a} + z_{(t-1)a} - u_{(t-1)a}, \quad \forall t \geq 2, a \in A \tag{7}$$

$$x_{ta} = 0, \quad \forall t < t_e, a \in A_H, A_F \tag{8}$$

$$z_{ta} = 0, \quad \forall t \geq t_e, a \in A_C \tag{9}$$

$$y_{tar} \cdot (\mathrm{R}_a - D_r) \geq 0, \quad \forall t \in T, r \in R, a \in A_H \tag{10}$$

$$x_{ta} \leq x_{max,t}, \quad \forall t \geq t_e, a \in A_H \tag{11}$$

$$x_{ta}, y_{tar}, z_{ta}, u_{ta} \in \mathbb{Z}^+, \quad q_{tr} \in \mathbb{R}^+ \tag{12}$$

The objective function, given in Equation 2, aims to maximize the expected operational profit across all periods. $d_t \cdot n_t$ adjusts for the temporal discount factor and the number of weeks in each period t. The profit per period is calculated as the difference between revenue and costs. Revenue is calculated using $\sum_{r \in R} [2 \cdot fare_r \cdot q_{tr}]$, which is the income generated by transporting passengers on route r in time t. The operational costs are calculated by $\sum_{a \in A} \sum_{r \in R} [vc_{ar} \cdot y_{tar}]$, summing the variable costs of operating aircraft a on route r at frequency y_{tar}. Ownership costs are represented by $fc_{ta} \cdot x_{ta}$, accounting for the fixed costs of owning aircraft type a in time t, while $pen_{ta} \cdot u_{ta}$ introduces a penalty for disposing of aircraft a in time t.

The constraints in the model ensure feasibility and compliance with operational requirements. Constraint Equation 3 guarantees that the total block time required for operating routes does not exceed the available block time for each aircraft type a. Constraint Equation 4 ensures that the number of passengers transported on route r does not exceed the demand for time t per week. Constraint Equation 5 sets a capacity limit based on the aircraft type and its load factor. The total number of passengers transported on a route must be less than or equal to the available capacity, which is derived from the aircraft type a, its seating capacity cap_a and the maximum load factor LF_r of a route r.

Initial fleet size considerations are addressed in constraint Equation 6, ensuring that the number of aircraft in the first period exceeds the initial fleet size IF_a. The continuity of fleet sizes across periods is maintained by Equation 7. This constraint ensures that the fleet size in any period t is determined by the fleet size in the previous period, adjusted for acquisitions z_{ta} and disposals u_{ta}.

Constraint Equation 8 ensures that no aircraft from the hydrogen-powered subset A_H or the future aircraft subset A_F can be operated ($x_{ta} = 0$) before they enter into service. Specifically, this applies to all periods $t < t_e$, where t_e denotes the entry-into-service time for these aircraft types.

Constraint Equation 9 restricts the addition of conventional aircraft from the subset A_C into the fleet during periods $t \leq t_e$. Setting $z_{ta} = 0$ ensures that no new conventional aircraft can be introduced after the entry of hydrogen-powered aircraft into the fleet, aligning with the transition toward sustainable aviation.

Constraint Equation 10 ensures that the operational range R_a of hydrogen-powered aircraft in A_H is sufficient to cover the distance D_r of a given route $r \in R$. This is achieved by enforcing that $y_{tar} \cdot (R_a - D_r) \geq 0$.

Constraint Equation 11 caps the fleet's total number of hydrogen-powered aircraft. The number of aircraft $x_{max,t}$ for each $a \in A_H$ is restricted to a maximum value $x_{max,t}$ in periods $t \geq t_e$.

Finally, the non-negativity and integrality of decision variables are enforced by Equation 12. The variables x_{ta}, y_{tar}, z_{ta}, u_{ta} are restricted to non-negative integers, ensuring discrete aircraft and flight numbers. q_{tr} is a non-negative continuous variable representing the number of passengers transported.

4 Case Studies

This section outlines the case studies analyzed in this research, focusing on the scenarios used to evaluate the impact of hydrogen-powered aircraft on the European commercial aviation network by 2050. First, the network choice is presented in section 4.1. A scenario selection follows this in section 4.2. For each scenario, the results are evaluated in section 5.

4.1 Network selection

First, in this research, the data chosen to represent a European commercial aviation network is Lufthansa's network, which only includes routes with origin and destination in the European continent. This network is viewed as a Hub & Spoke network, with Munich Airport (ICAO code EDDM) and Frankfurt Airport (ICAO code EDDF) as the hubs. Hence, every route is originating from either Munich or Frankfurt. If a full route is flown (HSH), a movement takes place. There are also movements present between the two hubs.

From flightradar24 (2024), the routes were selected. In total there are 160 routes. Minima (min), maxima (max) and averages (ave) are provided for relevant route parameters in Table 9.

For every route, the frequency per week was noted, and an average seat capacity was based on the aircraft types that frequented the route. Moreover, with an average cruising speed assumption of 840 km/h, the operating time for each route was assumed. With a yield of €0.096 (obtained from Lufthansa Group (2023)) the average ticket fare for a route was determined on. A load factor (LF_r) of 0.829 is for every route (also obtained from Lufthansa Group (2023)). Moreover, a turn around times of 30, 45 and 60 minutes were adopted for regional, short-range and medium-range aircraft, respectively. The increased turn around times for hydrogen aircraft can be calculated with the information in Table 4. The block time was set at 90 hours for every aircraft.

Table 9: Route specifications

Parameter	Min	Max	Ave
Route Distance [km]	157	2637	969
Seat Capacity [-]	90	208	155
Movements per week [-]	1	97	20
Demand per week [passengers]	75	13590	2644

4.2 Scenario selection

The case studies explore a scenario tree structure of three levels: cost ratios, hydrogen fleet constraints and traffic growth rates. This structure ensures it can be analyzed how these factors influence the deployment and utilization of hydrogen-powered aircraft.

A scenario tree shows the branching towards 12 sets of results, C_1 till C_{12}, as shown in Figure 1.

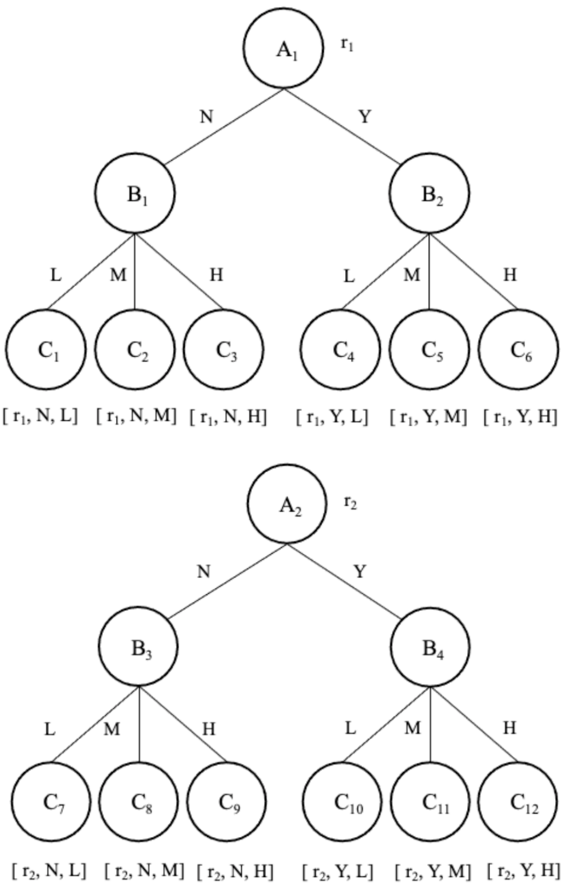

Figure 1: Scenario tree based on cost ratio (r_1 or r_2), hydrogen fleet constraints (Yes or No) and traffic growth rates (Low, Medium or High).

The first level of the scenario tree examines two cost ratio options, r_1 and r_2. The scenarios are A_1 and A_2 accordingly. As elaborated upon in section 3.2, these ratios represent the relative cost competitiveness of hydrogen-powered aircraft compared to future aircraft. The lower cost ratio assumes a more conservative scenario where the economic viability of hydrogen-powered aircraft is limited. The higher cost ratio reflects a scenario where hydrogen-powered aircraft are more competitive and deployed near full potential. The result for this process is shown in section 5.1.

The second level of the scenario tree introduces the hydrogen fleet constraint, either it being present, noted by Y, or not, indicated by N. Four different scenarios are generated, B_1 till B_4. Hence, in scenarios without fleet constraints, the deployment of hydrogen-powered aircraft is determined solely by operational (including extended TAT) and economic considerations. The scenarios with fleet constraints limit the number of hydrogen-powered aircraft deployed within the network. This concept represents limitations such as infrastructure readiness and hydrogen availability.

The final level of the scenario tree incorporates traffic growth rates, distinguishing between low, medium and high demand growth scenarios. Thus, the scenarios are selected where low, medium, or high growth was chosen every time. These generate the final 12 scenarios, C_1, till C_{12}, for which the results are generated. Based on the discussed traffic growth outlooks, in section 2.1, the low-growth scenario assumes an annual demand growth rate of 1.7%, reflecting a conservative estimate of future air traffic demand. The medium-growth scenario assumes a 3.0% annual growth rate, representing a baseline projection for the European aviation market by academic sources. The high-growth scenario, with a 4.1% annual growth rate, is an optimistic outlook where demand for air travel grows significantly, reflective of global growth estimates.

The scenarios can be identified by choosing a cost ratio, with or without hydrogen fleet constraint, and with specific traffic growth. For example, with cost ratio choice 1, no hydrogen fleet constraint, and low expected traffic growth, the notation is $[r_1, N, L]$.

5 Results

This chapter presents the results for the different scenarios as discussed in section 4.2, with Lufthansa's European network as elaborated upon in section 4.1. First, section 5.1 elaborates on the selection of the cost ratio. Next, in section 5.2.1, the results for the two different cost ratios are discussed and compared. Finally, in section 5.2.2, the resulting influence of the fleet constraint is elaborated upon.

5.1 Cost ratio selection

The first cost ratio to be determined is a more conservative scenario for the deployment of hydrogen aircraft. The second scenario is where the hydrogen aircraft are favored over future aircraft. Results have been created for the model with different cost ratios, ranging from 1.00 to 2.63. Figure 2, shows what percentage of flight movements are powered by hydrogen based on cost ratios in this range. These results are displayed per time period where hydrogen aircraft have become available, and no tick is shown if the percentage of flight movements powered by hydrogen is equal to zero.

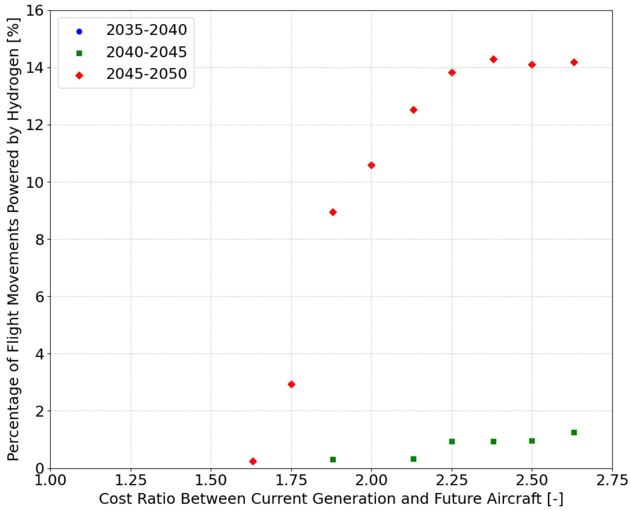

Figure 2: Hydrogen-Powered Flight Movements Fraction by Time Period

The lowest cost ratio where hydrogen aircraft become cost competitive concerning future aircraft, is at 1.63, here some flight movements are flown with hydrogen aircraft. With 1.63 only from 2045 onwards hydrogen-powered aircraft are flown. The first point where there is also movements from 2040 onwards, is 1.83. From this cost ratio onwards, not only medium-range hydrogen aircraft are flown, but also other hydrogen types. This cost ratio of 1.83 is hence taken as the first cost ratio r_1, a conservative estimate. From a certain cost ratio onwards, the percentage of flight movements powered by hydrogen stabilizes at approximately 14 %. This is because with the growing demand, only a limited number of new aircraft are to be bought in the last periods to account for this increasing demand. From a cost ratio of 2.25 onwards, one can see the first sign of this stabilization. Just before this point is the value of 2.13, showing a percentage of flight movements powered by hydrogen of approximately 12.5%. This is where hydrogen aircraft are used to great potential but not exhausted in demand. This point of 2.13 serves as the second cost ratio r_2.

5.2 Results per scenario

This results section is split up into two sections. First of all, in section 5.2.1, the results for the two different cost ratios are analysed, without fleet constraint. Next, the effect of the fleet constraint is analysed in section 5.2.2. The model finds and optimal solution within 10 minutes on a Macbook Pro (manufactured in 2019).

5.2.1 Cost Ratio Influence

Tables showing the amount of aircraft per time period per scenario C_1 till C_3, with the lower cost ratio and no fleet constraint, and per scenario C_7 till C_9, with the higher cost ratio and no fleet constraint, can be found in Table 10 till Table 15. They include a notation reminder per scenario, referencing the choice for cost ratio (r_1 or r_2), with or without fleet constraint (Yes or No), and choice for traffic growth (Low, Medium, or High). First the amount of Current Generation (CG) aircraft are listed, then the Hydrogen-powered (HY) aircraft, followed by the Future Generation (FG) aircraft. All categories consist of Regional (R), Short-range (S) and Medium-range (M) aircraft.

The amount of conventional aircraft from 2025 till 2035 was determined by running the model for L, M and H growth scenarios, with only conventional aircraft available. This resulted in a set amount of conventional aircraft up until 2035, shown in Table 10 till Table 15. As expected with higher traffic growth, more conventional aircraft are bought. The results show the medium-range aircraft are most cost favorable, with more than one hundred medium-range aircraft being acquired with respect to a single regional aircraft and about ten short-range aircraft. In none of the scenarios, short-range hydrogen-powered or future generation aircraft are deployed. With the lower cost ratio and low traffic growth, Table 10, shows that only one hydrogen-powered medium-range aircraft is deployed. Medium-range aircraft only become available from 2045 onwards. The number of hydrogen-powered medium-range aircraft increase with higher traffic growth. With medium traffic growth, shown in Table 11, 3 hydrogen-powered medium-range aircraft are deployed, and with high traffic growth, shown in Table 12, 5 hydrogen-powered medium-range aircraft are deployed. In both scenarios, more future generation medium-range aircraft are bought to capture the increase in demand. Note that future generation medium-range aircraft show to be more cost efficient than regional or short-range future generation aircraft in all scenarios.

With the introduction of the higher cost ratio, hydrogen-powered aircraft become more favorable concerning future generation aircraft. In the low growth scenario C_7, whereas previously 1 hydrogen-powered medium-range aircraft was deployed from 2045 onwards, now there are 7 being deployed. Also one hydrogen-powered regional aircraft is bought. Not the full increase in demand from 2045 onwards is captured by buying hydrogen aircraft, there is still 7 future generation aircraft being bought, this could be due to the larger range of this aircraft. The seat capacity of future generation and hydrogen-powered medium-range aircraft are the same: 200 seats.
With an increased traffic growth to medium, Table 14 shows that, again, more hydrogen-powered medium-range aircraft are deployed, equalling a number of 42. This time however, the purchase of future generation medium-range aircraft is limited to 1 aircraft, with respect to the 42 hydrogen-powered. Table 15, with high traffic growth, shows the same behaviour, with 93

medium-range hydrogen-powered aircraft being bought for deployment after 2045. Whereas the total number of future-generation medium-range aircraft, equals 59 in 2040 till 2045, 13 of these aircraft are sold (despite the penalty cost), ensuring more hydrogen-powered aircraft are bought. The total equals 93 hydrogen-powered medium-range aircraft from 2045 onwards.

Figure 4 till Figure 9 show the difference in the amount of movements for the hydrogen-powered aircraft per scenario with different cost ratios. With the lower cost ratio, movements by the hydrogen-powered aircraft are limited to under 100. With the higher cost ratio, with low demand as shown in Table 13, there are tens of movements made with the regional hydrogen-powered aircraft from 2040 onwards. Moreover, with the increased traffic growth, the amount of movements by hydrogen aircraft increase drastically, with the difference between medium and high growth, ensuring a doubling of the amount of hydrogen-powered movements.

As shown in the previous tables and graphs, in every scenario, only from 2045 till 2050 (except for C_8), hydrogen-powered aircraft are deployed. Figure 10 till Figure 15 show the amount of aircraft movements per aircraft type per week in time period 2045-2050, for the scenarios with no fleet constraint.

In general, conventional aircraft are centered around the longer routes since they have lower variable costs. The same goes for hydrogen aircraft, they also fly the longer routes that are within their range constraint. It is the future generation aircraft that are mostly flying the shorter routes. On the shorter routes, also current generation regional and short-range aircraft remain active.

In scenario C_7, a single hydrogen-powered regional aircraft is deployed. Figure 3 shows the movements per week on a map of Europe. The routes flown by hydrogen-powered regional aircraft range from 0 to 1000 km, which is within its range constraint of 1000 km (as stated in Table 3.

In all scenario's the load factor of 0.829 is almost completely reached, entailing the full demand is captured. Moreover, when looking at the objective function and the profit captured, it shows that with higher traffic growth, a higher profit is obtained. With medium traffic growth, with respect to low traffic growth, a 12 % increase is shown. With high traffic growth, with respect to low traffic growth, a 24 % increase is shown.

When increasing the cost ratio, so from r_1 to r_2, whether it is low, medium or high traffic growth, a slight decrease in profit is shown. This in the order of magnitude of a few percentiles.

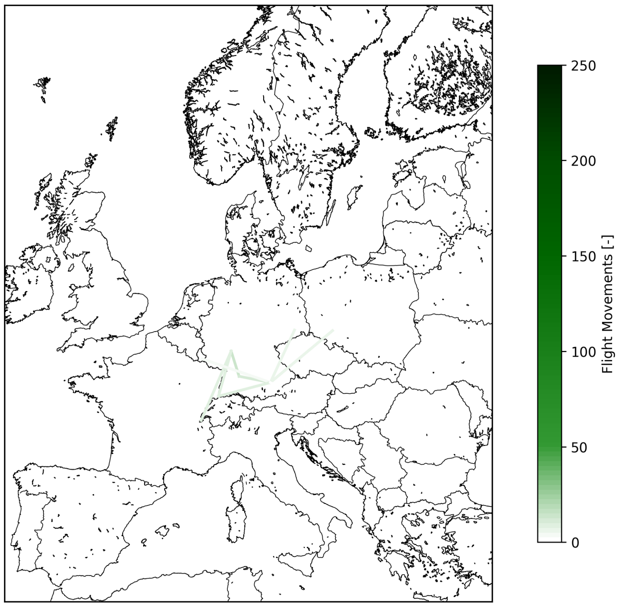

Figure 3: Regional hydrogen-powered aircraft movements per week in 2045-2050, for scenario C_7 ($[r_2, N, L]$)

Table 10: Amount of aircraft per aircraft type from 2025 - 2050 in scenario C_1 ([r_1,N,L])

From till:	2025 2030	2030 2035	2035 2040	2040 2045	2045 2050
Type					
CG-R	1	0	0	0	0
CG-S	10	9	9	9	9
CG-M	104	115	115	115	115
HY-R	-	-	0	0	0
HY-S	-	-	-	0	0
HY-M	-	-	-	-	1
FG-R	-	-	0	0	0
FG-S	-	-	0	0	0
FG-M	-	-	9	19	31

Table 11: Amount of aircraft per aircraft type from 2025 - 2050 in scenario C_2 ([r_1,N,M])

From till:	2025 2030	2030 2035	2035 2040	2040 2045	2045 2050
Type					
CG-R	1	0	0	0	0
CG-S	9	8	8	8	8
CG-M	105	124	124	124	124
HY-R	-	-	0	0	0
HY-S	-	-	-	0	0
HY-M	-	-	-	-	3
FG-R	-	-	0	0	0
FG-S	-	-	0	0	0
FG-M	-	-	17	40	65

Table 12: Amount of aircraft per aircraft type from 2025 - 2050 in scenario C_3 ([r_1,N,H])

From till:	2025 2030	2030 2035	2035 2040	2040 2045	2045 2050
Type					
CG-R	1	1	1	1	1
CG-S	9	4	4	4	4
CG-M	105	133	133	133	133
HY-R	-	-	0	0	0
HY-S	-	-	-	0	0
HY-M	-	-	-	-	5
FG-R	-	-	0	0	0
FG-S	-	-	0	0	0
FG-M	-	-	27	63	104

Table 13: Amount of aircraft per aircraft type from 2025 - 2050 in scenario C_7 ([r_2,N,L])

From till:	2025 2030	2030 2035	2035 2040	2040 2045	2045 2050
Type					
CG-R	1	0	0	0	0
CG-S	10	9	9	9	9
CG-M	104	115	115	115	115
HY-R	-	-	0	1	1
HY-S	-	-	-	0	0
HY-M	-	-	-	-	7
FG-R	-	-	0	0	0
FG-S	-	-	0	0	0
FG-M	-	-	8	18	25

Table 14: Amount of aircraft per aircraft type from 2025 - 2050 in scenario C_8 ([r_2,N,M])

From till:	2025 2030	2030 2035	2035 2040	2040 2045	2045 2050
Type					
CG-R	1	0	0	0	0
CG-S	9	8	8	8	8
CG-M	105	124	124	124	124
HY-R	-	-	0	0	0
HY-S	-	-	-	0	0
HY-M	-	-	-	-	42
FG-R	-	-	0	0	0
FG-S	-	-	0	0	0
FG-M	-	-	17	37	38

Table 15: Amount of aircraft per aircraft type from 2025 - 2050 in scenario C_9 ([r_2,N,H])

From till:	2025 2030	2030 2035	2035 2040	2040 2045	2045 2050
Type					
CG-R	1	1	1	1	1
CG-S	9	4	4	4	4
CG-M	105	133	133	133	133
HY-R	-	-	0	0	0
HY-S	-	-	-	0	0
HY-M	-	-	-	-	93
FG-R	-	-	0	0	0
FG-S	-	-	0	0	0
FG-M	-	-	26	59	46

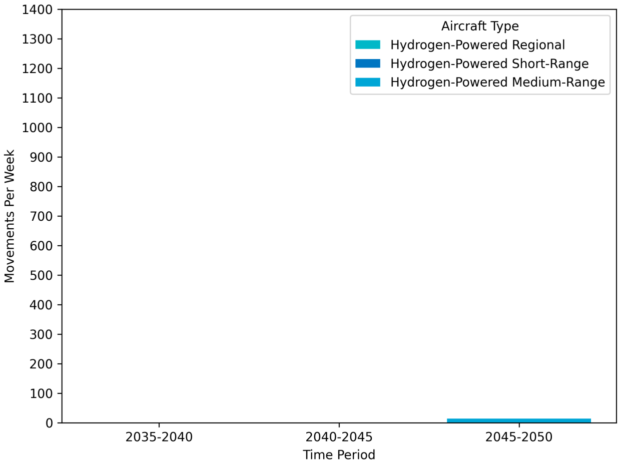

Figure 4: Amount of hydrogen aircraft movements for scenario C_1 ($[r_1, N, L]$)

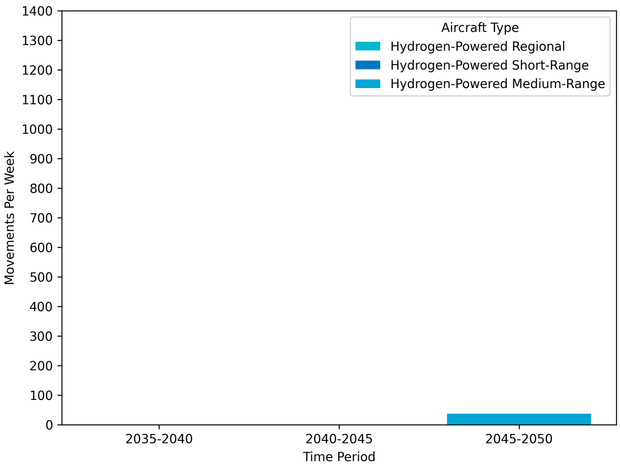

Figure 5: Amount of hydrogen aircraft movements for scenario C_2 ($[r_1, N, M]$)

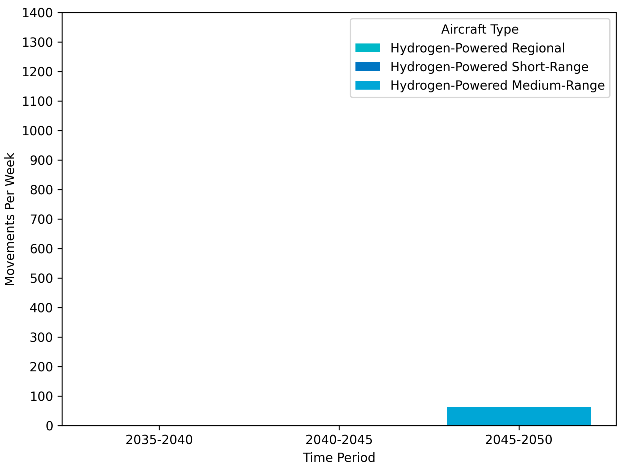

Figure 6: Amount of hydrogen aircraft movements for scenario C_3 ($[r_1, N, H]$)

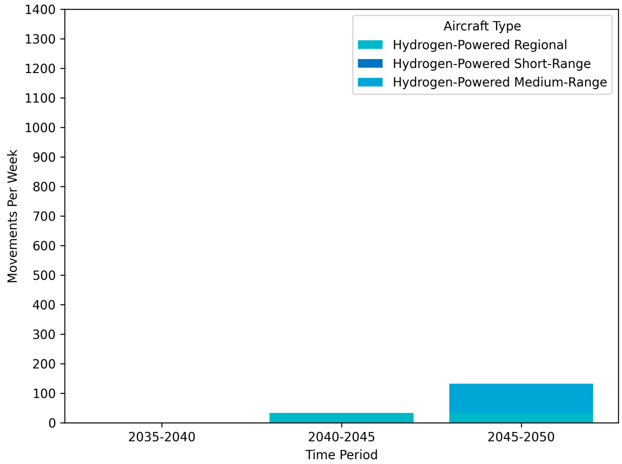

Figure 7: Amount of hydrogen aircraft movements for scenario C_7 ($[r_2, Y, L]$)

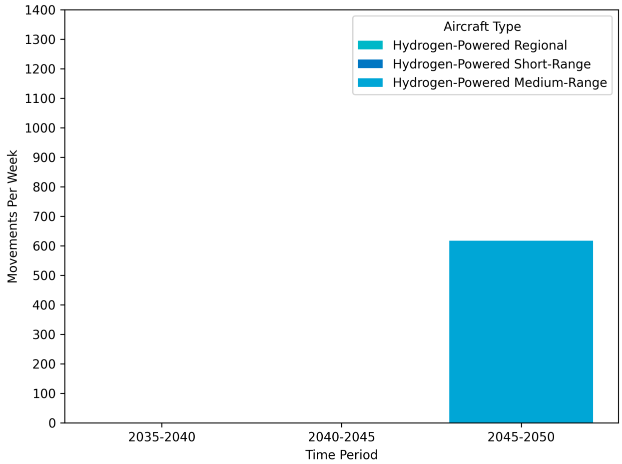

Figure 8: Amount of hydrogen aircraft movements for scenario C_8 ($[r_2, N, M]$)

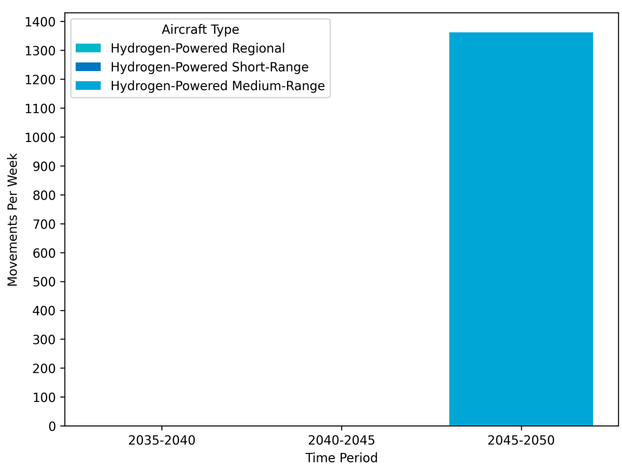

Figure 9: Amount of hydrogen aircraft movements for scenario C_9 ($[r_2, N, H]$)

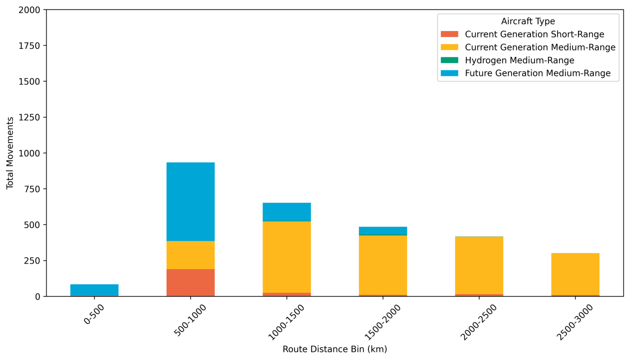

Figure 10: Amount of aircraft movements per aircraft type per week for time period 2045-2050, for scenario C_1 ($[r_1, N, L]$)

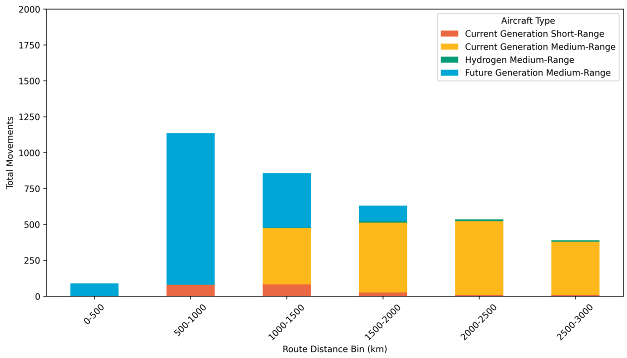

Figure 11: Amount of aircraft movements per aircraft type per week for time period 2045-2050, for scenario C_2 ($[r_1, N, M]$)

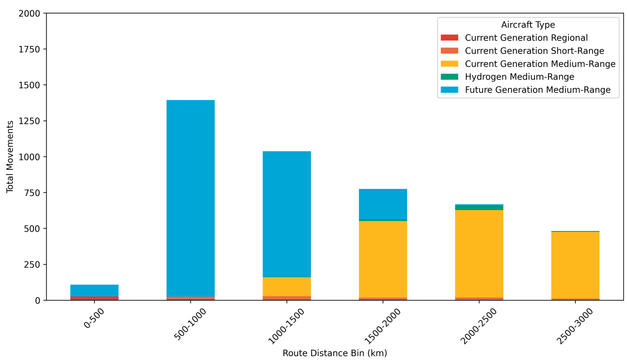

Figure 12: Amount of aircraft movements per aircraft type per week for time period 2045-2050, for scenario C_3 ($[r_1, N, H]$)

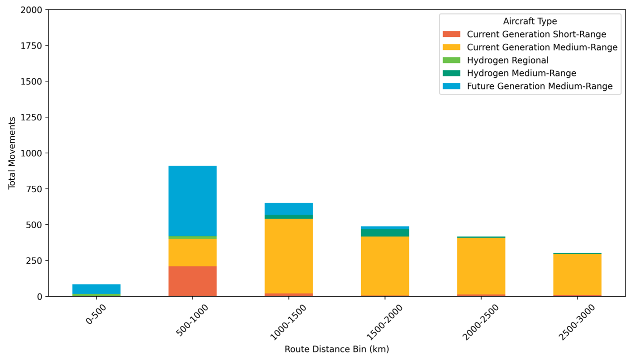

Figure 13: Amount of aircraft movements per aircraft type per week for time period 2045-2050, for scenario C_7 ($[r_2, N, L]$)

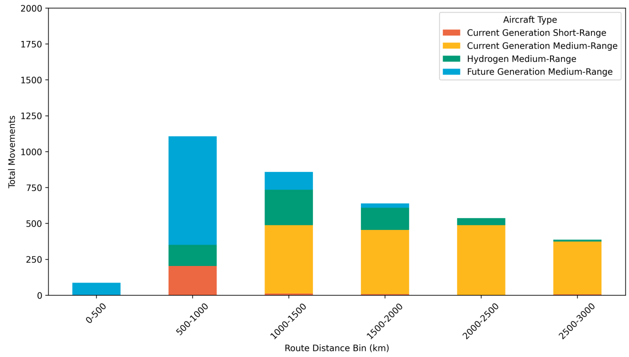

Figure 14: Amount of aircraft movements per aircraft type per week for time period 2045-2050, for scenario C_8 ($[r_2, N, L]$)

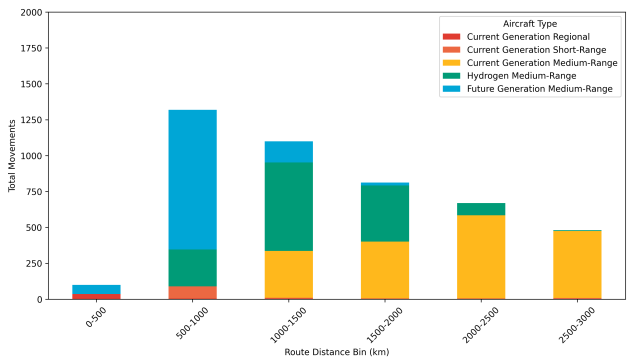

Figure 15: Amount of aircraft movements per aircraft type per week for time period 2045-2050, for scenario C_9 ($[r_2, N, H]$)

5.2.2 Fleet constraint influence

When the fleet constraint is introduced, only the scenario with the higher cost ratio, and high traffic growth, is affected. Since at this point, the constraint ceiling of 60 medium-range aircraft in 2045 till 2050 is reached. Hence, only the results of scenario C_{12} are relevant to discuss. Table 16 shows the amount of aircraft per type from 2025-2050 in scenario C_{12}. The maximum amount of 60 hydrogen aircraft is reached, and more future generation medium-range aircraft are bought from 2045 till 2050. The amount of hydrogen aircraft movements per week stagnates at about 900 movements in 2045-2050.

Table 16: Amount of aircraft per aircraft type from 2025 - 2050 in scenario C_{12}

From	**2025**	**2030**	**2035**	**2040**	**2045**
till:	**2030**	**2035**	**2040**	**2045**	**2050**
Type					
CG-R	1	1	1	1	1
CG-S	9	4	4	4	4
CG-M	105	133	133	133	133
HY-R	-	-	0	0	0
HY-S	-	-	-	0	0
HY-M	-	-	-	-	60
FG-R	-	-	0	0	0
FG-S	-	-	0	0	0
FG-M	-	-	26	59	65

Scenario C_{12}'s results can be compared to scenario C_9's results, since they have the same characteristics apart from the fleet constraint: r_2 and H. Figure 16 shows the amount of aircraft movements per aircraft type per week for time period 2045-2050 for scenario C_{12}. The same behavior as for the previously analysed scenarios can be seen, that the hydrogen aircraft are deployed on the longer routes, within their range constraint. Whereas with scenario C_9, the medium-range hydrogen-powered aircraft were deployed on routes from 500-1000 km, with scenario C_{12} this is not the case. This can also be seen with the maps of Europe showing the movements of hydrogen-powered medium-range aircraft for scenario C_9 and C_{12} in Figure 17 and Figure 18, respectively. Figure 17 shows shorter routes flown with medium-range hydrogen-powered aircraft, with a magnitude of movements per week over 100. The longer routes are maintained with a similar frequency of movements as shown in Figure 18.

The profit obtained in the optimal solution for scenario C_{12} is only slightly lower than the profit obtained in scenario C_9. Moreover, the majority of the demand is still captured, with a load factor close to 0.829.

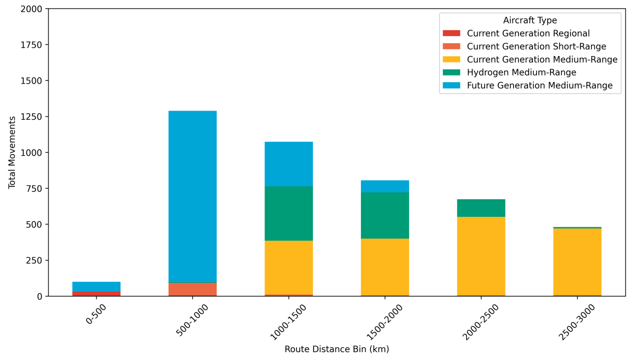

Figure 16: Amount of aircraft movements per aircraft type per week for time period 2045-2050, for scenario C_{12} ($[r_2, Y, H]$)

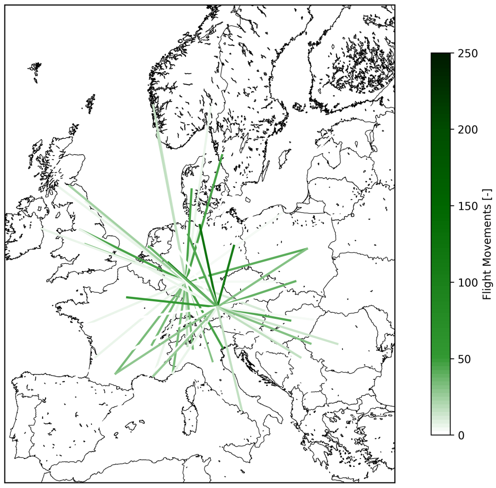

Figure 17: Hydrogen-powered medium-range aircraft movements on geographic map for scenario C_9 ($[r_2, N, H]$)

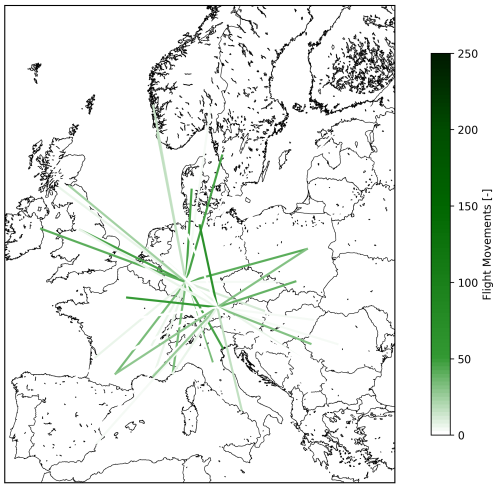

Figure 18: Hydrogen-powered medium-range aircraft movements on geographic map for scenario C_{12} ($[r_2, Y, H]$)

6 Conclusions

This research's objective was to evaluate how the obstacles concerning hydrogen adoption influence the projected distribution and frequency of hydrogen-powered flights in a European commercial aviation network by 2050. A multiperiod, scenario-based optimization model has identified key trends regarding fleet deployment under a hydrogen fleet constraint and cost assumptions.

As the cost ratio becomes more favorable (that is, scenarios incorporating r_2), the adoption of hydrogen aircraft increases with the introduction of regional and particularly medium-range hydrogen aircraft. In all scenarios, medium-range hydrogen-powered aircraft are most attractive, ensuring that only from 2045 onwards (the entry into service time of this aircraft), the larger share of hydrogen-powered aircraft is deployed. These medium-range hydrogen-powered aircraft tend to be deployed on the longer routes. This is because in this paper, it is assumed that they will have a lower variable cost than the variable cost for future aircraft (with the same performance specifications as conventional aircraft).

The increase in cost ratio for future aircraft with respect to conventional aircraft in this research was 13 % (from $r_1 = 1.88$ to $r_1 = 2.13$). With this increase in cost ratio, there was a significant increase in the hydrogen-powered aircraft fleet, increasing in size by 6 to 17 times with the higher cost ratio. This shows that there is a high sensitivity in the relation between the cost ratio and the size of the hydrogen-powered aircraft fleet.

Moreover, with the lower cost ratio r_1 and high traffic growth, the number hydrogen-powered medium-range aircraft is 5. With the higher cost ratio r_2 and low traffic growth, the number of hydrogen-powered medium-range aircraft is equal to 7. This shows that the cost ratio has a more significant impact on the deployment of hydrogen-powered aircraft than traffic growth.

When implementing the fleet constraint, it only showed effect in scenario C_{12}, with the higher cost ratio and high traffic growth. The number of medium-range hydrogen-powered aircraft was constrained to 60, this number was fully met and the remaining demand is covered by deploying more future generation aircraft. The overall profit from 2025-2050 was not significantly affected due to this constraint.

Another finding is that short-range hydrogen aircraft are never deployed across any scenario. Furthermore, a regional aircraft was deployed only once. Even in the most optimistic projections with high traffic growth and favorable cost ratios, the model does not select them as the prominent viable option. This suggests that hydrogen propulsion does not offer a competitive alternative for short-haul operations within the given network structure under current technological (e.g. range) and economic assumptions (for variable and fixed costs).

Several aspects remain open for further exploration.

The results of this study emphasize that hydrogen aircraft adoption is highly sensitive to cost dynamics. There is a range of cost ratios that were not explored in this research, which would show different fleet compositions. From the literature review and the results, it is evident that favorable cost initiatives or other measurements need to be present for hydrogen aircraft to make them competitive with conventional aircraft. Under the current state-of-the-art performance outlook, initiatives like Airbus ZEROe and the Fokker Next Gen project will struggle to gain traction before 2045.

Also, the differences in price between the regional, short-range and medium-range aircraft variable costs can impact the results. In these results, the short-range aircraft were never chosen and the regional aircraft only in one scenario, by varying these costs, they could be selected.

To facilitate competitive deployment, Original Equipment Manufacturers (OEMs) must prioritize cost-efficient design for hydrogen-powered aircraft. Both fixed investment costs and variable costs should be limited. For example, this could be achieved by using lightweight materials for the new technology and by ensuring efficient manufacturing. At the policy level, regulatory bodies should implement mechanisms that create financial incentives for hydrogen adoption. Hydrogen-powered aircraft will require targeted subsidies, tax incentives or market-based measures such as carbon pricing adjustments. Airlines will only scale up hydrogen adoption when the cost gap is sufficiently narrowed.

Additionally, this study assumes a relatively static demand profile across the year. Introducing a seasonal component, such as incorporating summer peaks, could alter the network distribution and provide a more comprehensive overview of hydrogen aircraft's potential. Investigating which seasonal demand patterns better align with hydrogen aircraft operational characteristics could help determine which routes to deploy the aircraft. This can ensure the barrier to commence the deployment of hydrogen-aircraft in general is easier to overcome.

Moreover, this study focused on a hydrogen fleet constraint in a network, but future research could incorporate more detailed infrastructure readiness assessments. While this research provides insights into how a network structure responds to hydrogen related obstacles, further integration of airport-specific limitations and refueling logistics should be considered. This could be done by investigating a range of turn around times, for example.

Another insight could be what happens to the network if one of the spokes also becomes available for hydrogen refueling. Thereby looking at potential frequency increases on that route or even making this spoke a potential 'refueling stop' for another route that would require it due to limited range. This can give insight to coordinating investments in airport hydrogen infrastructure.

By addressing these challenges considering cost efficiency, regulatory support and infrastructure readiness, hydrogen-powered aircraft can become a viable option in the European aviation network. Addressing these factors is essential to achieve sustainability goals, such as reaching zero carbon emissions by 2050.

References

Abara, J. (1989). Applying integer linear programming to the fleet assignment problem. *Interfaces*, 19(4):20–28.

Air Transport Action Group (2021). Waypoint2050, an air transport action group project. balancing growth in connectivity with a comprehensive global air transport response to the climate emergency: a vision of net-zero aviation by mid-century. report.

Airbus (2024a). Global market forecast 2024. report.

Airbus (2024b). Zeroe. www.airbus.com.

Airports Council International (2024). Integration of hydrogen aircraft into the air transporation system: An airport operations and infrastructure review. report, Aerospace Technology Institue.

Baroutaji, A. (2019). Comprehensive investigation on hydrogen and fuel cell technology in the aviation and aerospace sectors. *Renewable and Sustainable Energy Reviews*, 106:31–40.

Bicer, Y., and Dincer, I. (2017). Life cycle evaluation of hydrogen and other potential fuels for aircrafts. *International Journal of Hydrogen Energy*, 42(16):10722–10738.

Birolini, S. (2021). Integrated flight scheduling and fleet assignment with improved supply-demand interactions. *Transportation Research Part B: Methodological*, 149:162–180.

Clean Sky 2 (2022). Hydrogen-powered aviation a fact-based study of hydrogen technology, economics, and climate impact by 2050. report.

Doyme, K. (2019). Simulating airline behavior: Application for the australian domestic market. *Transportation Research Record*, 2673(2):104–112.

Dray, L.M., et al. (2019). Aim2015: Validation and initial results from an open-source aviation systems model. *Transport Policy*, 79:93–102.

European Commission and Directorate-General for Research and Innovation (2023a). *Market uptake and impact of key green aviation technologies : final report*. Publications Office of the European Union.

European Commission and Directorate-General for Research and Innovation (2023b). *Market uptake and impact of key green aviation technologies – Final report*. Publications Office of the European Union.

flightradar24 (2024). Lufthansa routes and destinations. https://www.flightradar24.com/data/airlines/lh-dlh/routes.

Fokker Next Gen (2024). The aircraft. www.fokkernextgen.com.

Gelhausen, M., et al. (2019). *Airport Capacity Constraints And Strategies For Mitigation - A Global Perspective*.

Habib, M.A., e. a. (2024). Hydrogen combustion, production, and applications: A review. *Alexandria Engineering Journal*, 100:182–207.

Hane, C.A., et al. (1995). The fleet assignment problem: Solving a large-scale integer program. 70:211–232.

Hansen, M. (1990). Airline competition in a hub-dominated environment: An application of noncooperative game theory. *Transportation Research Part B: Methodological*, 24(1):27–43.

Hoelzen, J., et al. (2022). Hydrogen-powered aviation and its reliance on green hydrogen infrastructure – review and research gaps. *International Journal of Hydrogen Energy*, 47(5):3108–3130. Hydrogen Energy and Fuel Cells.

IATA (2021). Non-co2 aviation emissions. report, IATA.

IATA (2024). Net zero carbon 2050 resolution. report, IATA.

Intergovernmental Panel on Climate Change (2022). *Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. Cambridge University Press.

International Energy Association (2019). The future of hydrogen. report.

Jansen, P., et al. (2016). Coupled optimization of aircraft families and fleet allocation for multiple markets. *Journal of Aircraft*, 53(5):1485–1504.

Kühlen, M., et al. (2022). An explanatory approach to modeling the fleet assignment in the global air transportation system. *CEAS Aeronautical Journal*, 14.

Lufthansa Group (2023). Annual report 2023. investor-relations.lufthansagroup.com.

Lufthansa Group (2025). Fleet. www.investor-relations.lufthansagroup.com.

Oesingmann, K., et al. (2024). Hydrogen in aviation: A simulation of demand, price dynamics, and co2 emission reduction potentials. *International Journal of Hydrogen Energy*, 64:633–642.

Repko, M.G.J., and Santos, B.F. (2017). Scenario tree airline fleet planning for demand uncertainty. *Journal of Air Transport Management*, 65:198–208.

Reynolds, T., et al. (2007). Modelling environmental economic impacts of aviation: Introducing the aviation integrated modelling project. volume 1.

Scot, M. (2023). Analysing the costs of hydrogen aircraft. report.

Terpstra, X.D. (2024). Sustainable h2 supply chain pahthways for local fossil-fuel airports. Master's thesis, Delft University of Technology.

Verstraete, D. (2009). The potential of liquid hydrogen for long range aircraft propulsion.

Wei, K., et al. (2019). Airline timetable development and fleet assignment incorporating passenger choice. *Transportation Science*, 54.

Wei, W. (2007). Airlines' competition in aircraft size and service frequency in duopoly markets. *Transportation Research Part E: Logistics and Transportation Review*, 43(4):409–424.

World Economic Forum (2023). Target true zero: Delivering the infrastructure for battery and hydrogen-powered flight. report.