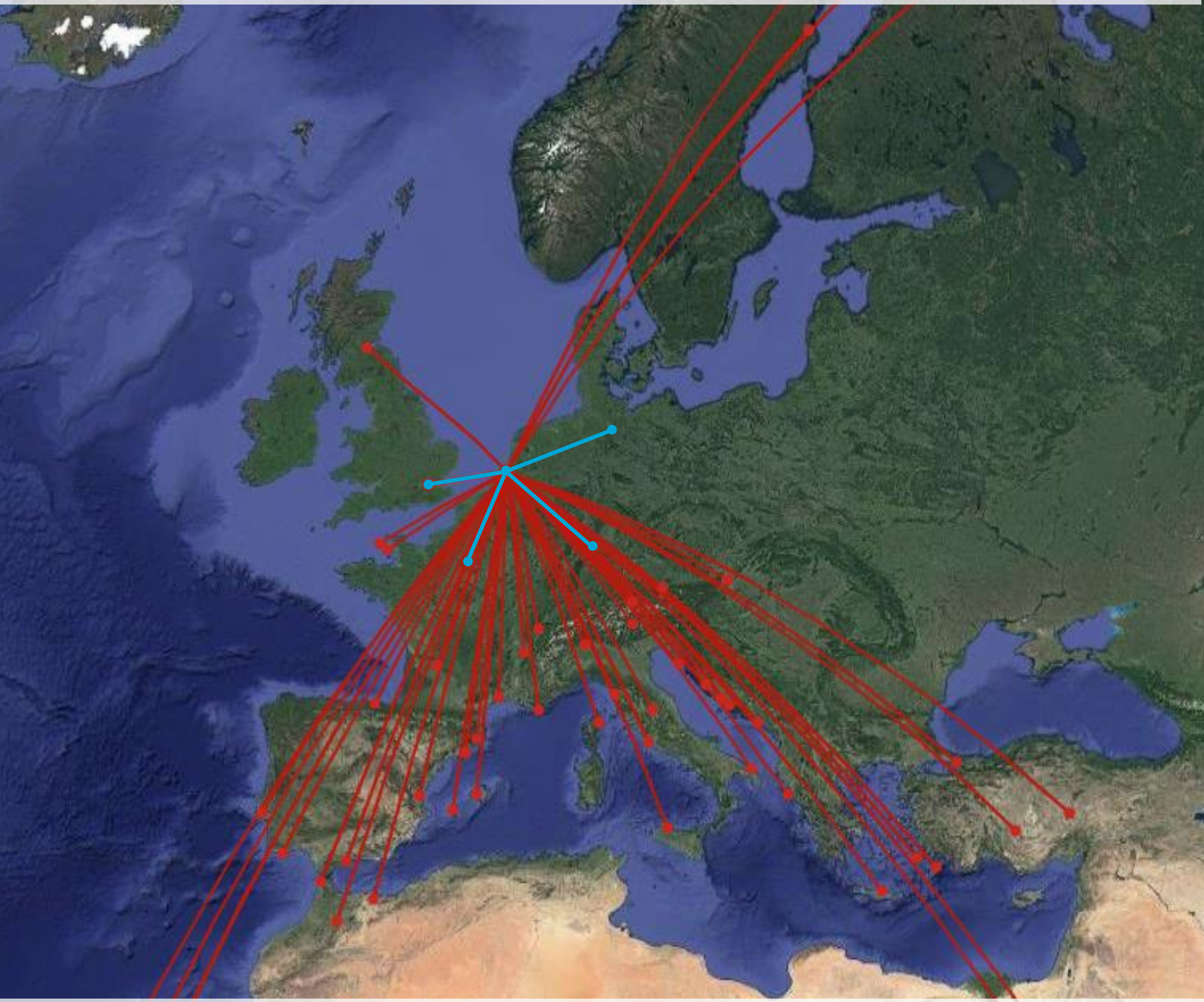
Transitioning to sustainable aviation:

A techno-economic analysis of hydrogen fuel potential at Rotterdam The Hague Airport

Filip H. Saad



Rotterdam The Hague Airport

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Executive Summary

The environmental concerns, the urgent need for an alternative to fuels currently used in aviation, the present direction of industrial policy, the interest within the aviation industry, and the readiness level of hydrogen propulsion and hydrogen supply technologies, altogether present a reality where airports need to investigate the requirements for transitioning to hydrogen and to find the conditions that constitute a commercially sustainable solution. This leads to the following research question "Under which conditions does the transition to hydrogen fuel constitute a commercially sustainable solution for an airport?".

Current research focuses on the use of liquid hydrogen as a fuel for sustainable propulsion in aviation due to the high potential of the energy density in liquid hydrogen. But before liquid hydrogen technology will be available for large-scale deployment in aviation, a decade-long time gap was found where gas hydrogen technology can be implemented to serve smaller and shorter-range aircraft. Taking that into account in this research, a two-stream approach was analyzed where gas hydrogen infrastructure would start the transition to hydrogen fuel and by doing so contribute to accelerating the development of the supply infrastructure, regulations, and expertise necessary for the large-scale transition to hydrogen.

To answer the above question, the chosen research approach was to perform a techno-economic analysis using a case study where both the gas and liquid hydrogen streams could be implemented. The airport selected as the case study for this research was Rotterdam The Hague Airport (RTHA) due to the share of small jet and regional aircraft in the air traffic departing from the airport, its location between major travel hubs in the region, the availability of free space for the necessary infrastructure, and the interest of the airport organization in this research.

A basic analysis of the technology readiness level for the hydrogen propulsion systems and the technologies necessary for the different subsystems needed for the production, storage, transport, and refueling of hydrogen concluded that such a transition to hydrogen fuel is foreseeable in the near future. The design of the two hydrogen streams for the case study was implemented based on the assumptions outlined in Table 1.

Table 1: Assumptions defining the diffusion scenarios of hydrogen aircraft technology.

Scenario	Aircraft segment	Entry into service (EIS)	Ramp-up [years]	Take-rate [%]
Best case	Small jet and regional (gas hydrogen)	2024	2	100
	Single aisle	2035	3	100
	Medium widebody	2035	4	67
Worst case	Small jet and regional (gas hydrogen)	2026	4	80
	Single aisle	2037	5	67
	Medium widebody	2037	6	50

The initial requirements and system boundaries for the infrastructure of both hydrogen supply streams were determined by forecasting future jet-fuel (kerosene) demand based on pre-COVID air traffic data. The results of which were later confirmed using actual pre-COVID fuel consumption data. The forecasted kerosene demand was then converted to the equivalent energy content in hydrogen while taking into account changes in aircraft efficiencies (presented in Table 2).

Table 2: Design requirements used in sizing the hydrogen infrastructure subsystems.

Scenario	Annual demand in 2050 [tons]	Peak Daily demand in 2050 [tons/day]	Peak hourly demand in 2050 [tons/hour]
Gas best-case	800	40	7.5
Gas worst-case	600	5	0.4
Liquid best-case	13000	75	14
Liquid worst-case	7000	7	0.6

After determining the feasibility of both delivery streams and the assumed diffusion scenarios based on the required land area and its availability at the airport. The economic results were presented in the form of a total annual cost and levelized cost of hydrogen (Table 3). This was further investigated by breaking the costs down to the level of each subsystem and comparing them between the different streams as well as the different scenarios. This was then followed by a sensitivity analysis to identify the design decisions that can have larger effects on the levelized cost of hydrogen.

Table 3: Total annual cost and levelized cost of hydrogen for different streams and scenarios.

Scenario	C_{TAC} (Mn €$_{2020}$)	LCOH (€$_{2020}$/kg)
Gas best-case	4.58	5.25
Gas worst-case	3.09	4.83
Liquid best-case	34.55	2.57
Liquid worst-case	19.43	2.66

Based on the analysis of the results it was concluded that price parity of hydrogen fuel with jet fuel (kerosene) in the case of Rotterdam The Hague Airport is achievable with a high increase in carbon tax (95 to 198 €$_{2020}$/ton$_{CO2}$) if no carbon allowances were to be traded (Table 4). Such carbon tax values are below the estimated carbon abatement values required for restricting global warming to 1.5°C degrees in 2050. To achieve the 1.5°C goal the average estimated carbon abatement is 220€$_{2020}$ in 2030 and 600€$_{2020}$ in the year 2050.

Table 4: Carbon tax for price parity with kerosene.

Scenario	LCOH (€$_{2020}$/kg)	Equivalent increase in kerosene cost (%)	Increase translated to a carbon tax (€$_{2020}$/ton$_{CO2}$)
Gas best-case	5.25	260	155
Gas worst-case	4.83	231	198
Liquid best-case	2.57	101	137
Liquid worst-case	2.66	108	95

The results apply to RTHA as well as to other airports that have enough free space for infrastructure, access to hydrogen gas via trucks or a pipeline, and a similar distribution of air traffic among the different aircraft segments. The advantage in the case of Rotterdam airport is its proximity to the industrial zone of the Port of Rotterdam where synergies with other industries demanding hydrogen would provide the benefits of economics of scale in the hydrogen supply. The addition of an electrolyzer to produce the necessary hydrogen locally at the airport instead of purchasing it from a central producer is estimated to cost an additional 0.5 to 2.75 €$_{2020}$/kg on top of the levelized costs of hydrogen for each scenario.

To place the above costs into perspective (table4), assuming no change in the current carbon tax value and an emissions trading value of €100 per ton of CO_2, a single one-way ticket for a flight from RTHA to London City airport on gas hydrogen (best-case LCOH) would cost an average of €230 as opposed to €75 for an equivalent estimate of kerosene-fueled flight. Without reduction through carbon abatement, the hydrogen-fueled flight ticket would cost an average of €330.

The above results show how dependent the viability of commercially sustainable hydrogen fuel implementations at airports is on the carbon tax and the emissions trading policies. The results also show the importance of the perceived value by the passenger and their willingness to pay for hydrogen-fueled flights.

As a result of this research, the following recommendations are proposed. To start communication channels with policy makers, industry leaders, influential groups, and the public. To use the established channels as a means to gather support for the necessary policies and regulations, increase acceptance levels of the necessary cost changes among the end-users, and estimate demand levels.

Also, to continuously monitor the developments in the hydrogen supply subsystem technologies in order to maintain up-to-date information relating to system design requirements such as the use of purge gas and leakage factors. As well as acquiring the latest efficiency parameters, cost estimates, and technology diffusion rates for an up-to-date cost model.

Additionally, it is recommended to implement a technology learning rate in the cost model used in this research and to undertake more detailed research into the design criteria that are necessary for a more optimal design. That research applies to criteria such as the necessary storage buffer factor and the transfer rates using network optimization techniques that would span multiple airports.

Finally, it is recommended to further investigate and follow the current research on the potential effects of large-scale adoption of hydrogen on the environment and how to mitigate any potential risks. As well as investigating the potential effect of the large-scale adoption on the cost of hydrogen and other resources (for example green energy and rare earth metals).

Contents

List of Acronyms

a	Annuity factor
CAPEX	Capital expenditure
C_{El}	Cost of electric power
C_{H2Loss}	Cost of hydrogen loss
CO_2	Carbon dioxide
Com	Compressor
COVID	Corona Virus Disease
$C_{PurgeGas}$	Cost of purge gas
Cryo	Cryogenic pump
C_{TAC}	Total annual cost
C_{Trans}	Cost of trucking fuel
E_{EL}	Electric energy
EHB	European Union Hydrogen Backbone project
EIS	Entry into service
FCH2	Fuel cell and Hydrogen 2 research program
GBow	Gas bowser
GHG	Greenhouse gas
GH	Gas Hydrogen
GSto	Gas storage
LBow	Liquid bowser
LCOH	Levelized cost of hydrogen
LFP	Liquefaction plant
LH	Liquid hydrogen
Liq	Liquefier
LSto	Liquid hydrogen storage
O&M	Operation and maintenance
OPEX	Operational expenditure
RTHA	Rotterdam The Hague Airport
TEA	Techno-economic analysis
TRL	Technology readiness level
UH2	Universal Hydrogen company

CHAPTER 1: Introduction

With the recent developments in hydrogen propulsion systems for aircraft as well as the increasing interest in making the aviation industry more sustainable from the side of policymakers, industry, and end-users answering questions regarding the commercial feasibility of providing hydrogen as fuel at airports becomes more pressing. Hence this research was undertaken with the aim to answer the following question “Under which conditions does the transition to hydrogen fuel constitute a commercially sustainable solution for an airport?”.

Hydrogen-ready airports will need the infrastructure and operational capacity to refuel aircraft. This includes transport, storage, control, and metering infrastructure as well as the trained staff and the operational procedures that will guarantee safety and short turnaround times. Through a literature review, a research gap was found in addressing the economics of compressed gas hydrogen supply systems at airports. Such systems have a higher technology readiness level and can be used in fueling smaller aircraft segments with a shorter range before liquid hydrogen supply and propulsion is technically feasible.

To that end, the research approach chosen for answering the above question is a techno-economic analysis of a case study where two streams of hydrogen can be implemented over different timelines. This will narrow the applicability of the result to one airport but will allow for more concrete inputs. The details of the research done as well as the results are presented in this report.

In the second chapter, an outline of the literature review is presented where the motivation for the transition was reviewed, the current position of the industrial policy and aviation industry was inspected, the supply chain was explored, and the technology readiness level of different subsystems was investigated.

In the third chapter, the research approach is developed, and the gathered information is implemented in a case study at the Rotterdam The Hague Airport (RTHA). The case study is used to develop a preliminary design of the hydrogen supply network. Then the cost model for the supply network is introduced.

The fourth chapter presents the results found from assessing the physical feasibility of the design for RTHA as well as the costs of implementing the design with different scenarios of hydrogen aircraft adoption. The results are then translated to an industry-relevant measure and further investigated through a sensitivity analysis. Then the findings are discussed from three directions, the cost model and the system design, the industrial policy, and the commercial viability.

The main conclusions and recommendations are detailed in chapter five while the data and parameters used as well as the more detailed calculations are presented in the Appendices.

CHAPTER 2: Literature review

The literature review started with a general review of the motivation for transitioning to hydrogen. Next, the literature on the current industrial policy related to the transition was reviewed with an emphasis on the application within the aviation industry. This was followed by a literature review on the technology readiness level for different subsystems required for the transition and the relevant cost estimates. The information gathered helped in further defining the research question and the research method.

a. Current state and motivation for transition

According to the Intergovernmental Panel on Climate Change, human-induced climate change is affecting weather and climate extremes all around our planet. To limit the degree of global warming and lower the level of climate damage it is necessary to limit the cumulative CO_2 emissions to at least a net-zero level as soon as possible (IPCC, 2021b).

Climate change is explained based on the greenhouse gas effect that increases the net positive radiative forcing of the atmosphere. This, in turn, leads to the accumulation of more energy in the form of heat within the atmosphere, the effects of which are evident already across the globe and within Europe. In Europe, climate change is taking the form of an increase in hot temperature extremes, heavy precipitation, as well as agricultural and ecological drought (IPCC, 2021a).

It is expected that climate change will cause an increase in low-probability high-impact events that can have high potential socio-economic costs. Hence, it is important to pursue both adaptation and mitigation policies to minimize net costs (Köberle et al., 2021).

To restrict the rise in temperature to between 1.5 and 2.0 °C from preindustrial temperature levels, net-zero $C0_2$ emission levels must be reached by 2050. For the net-zero goal to be achievable within such a period, two approaches must be followed simultaneously. One is demand-side action by reducing consumption of carbon-intensive goods and services, for example by increasing energy use efficiency, reducing waste, and consumers adopting behavioral lifestyle changes. And the second is supply-side action where emissions are reduced for example by adopting decarbonization strategies and moving energy production to sustainable sources (IPCC, 2021a).

The current aviation industry's contribution to global CO_2 emissions is estimated to be around 3%. It causes 5-6% of the global warming effects (van Manen, 2021). Reducing carbon emissions from aviation is an integral element of a net-zero emissions transition. This evident need for change in the aviation industry, inspired a literature review to find the current state and direction of change in both the industrial policy and the aviation industry towards a more sustainable future. Based on the conclusions of that preliminary literature review, hydrogen as a sustainable solution was selected and both the technological and economical aspects of adopting hydrogen were further investigated through reviewing both academic and gray literature.

b. Industrial policy and aviation industry

Within Europe, the direct emissions from aviation accounted for 3.8% of total CO_2 emissions as of 2017. The aviation sector creates 13.9% of the emissions from the transport industry, making it the second-biggest source of transport greenhouse gas (GHG) emissions after road transport (European Commission, 2021).

Figure 1 illustrates how the aviation industry growth in the past decades nullified the gains caused by the increase in aircraft operational efficiency. Such growth is projected to increase further. Hence, to reduce CO_2 emissions from the demand-side a very large behavioral lifestyle change will be needed and a tremendous scale down of the aviation industry will be necessary (Lee et al., 2021).

In 2019, before the COVID-19 pandemic, 3.6 % of world GDP and 65.5 million jobs were supported by the aviation industry. This includes the aviation industry's activities and its supply chains (direct and indirect) and as an enabler of other industries (induced and as a tourism-catalytic). The share of the European Common Aviation Area (ECAA) in the numbers mentioned earlier is 10m jobs and about €800bn (Gittens et al., 2019).

Alongside the economic benefits of the aviation industry, there are also important social benefits including connectivity, essential services (health and humanitarian aid), educational opportunities, and quality of life improvement (Gittens et al., 2019).

In view of the economic and social benefits provided by the aviation industry, it appears likely that the aviation industry will continue its growth and that demand-side changes will never suffice. Change from the supply-side is necessary in the form of the aviation industry transitioning to a sustainable source of energy for aircraft propulsion (IRENA, 2020).

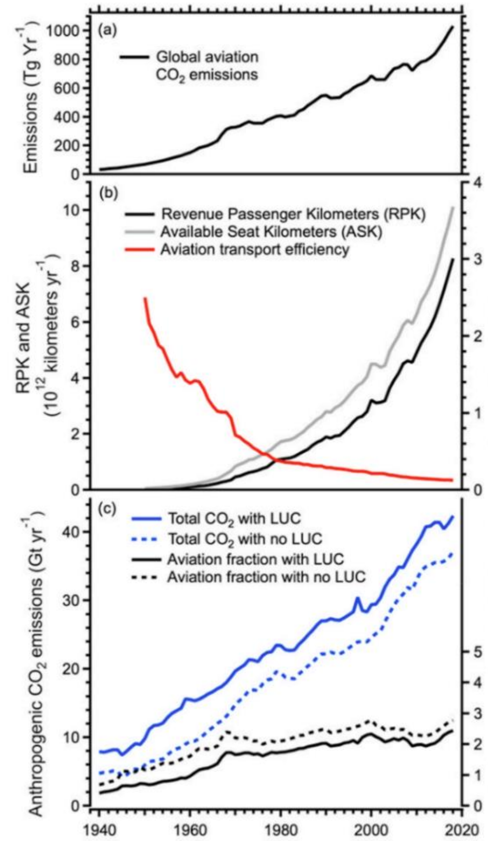

Figure 1: Data related to the growth of aviation traffic and CO2 emissions from 1940 to 2018 (Lee et al., 2020).

Such motivation for change inspires both policymakers as well as industry leaders to fund and invest in the development and adoption of new technologies. One such technology is green hydrogen as a means for transporting and storing energy. The appeal of green hydrogen is based on the fact that its production and use have zero greenhouse effect. It also allows for decoupling energy production from utilization (an important issue in sustainable energy) as it offers high energy content per kilogram when stored (Goldmann et al., 2018).

The European Union's investment into sustainable energy for green hydrogen as well as the necessary infrastructure for production, storage, and transport of green hydrogen is estimated to total €430bn by 2030. Alongside that investment support grants and subsidies are estimated to total €145bn by 2030 (H2 Europe, 2021).

Along with financing the production and delivery of hydrogen, policymakers have adopted an approach that encourages the uptake of hydrogen with a short-term focus on industries that would create the largest difference and at the same time already have mature technologies that are suitable for their relevant applications (Figure 2). Next to that, a long-term approach is adopted to further develop technologies that can enable hydrogen adoption by other industries in the future. To achieve that, strategies are developed based on long-term visions shared by the industry partners and different stakeholders (IRENA, 2020a, 2022).

A policy that adopts long-term goals for financing, can be described as a patient (transcending the political cycle) and hence it is suitable for the long-term nature of the undertaking. At the same time, it provides the necessary presence of various sources and types of finance along the research path to influence both the rate and direction of innovation. Such characteristics do agree with the academic literature on good practice in financing innovation (Mazzucato, 2013; Mazzucato & Semieniuk, 2017, 2018; O'Sullivan, 2006).

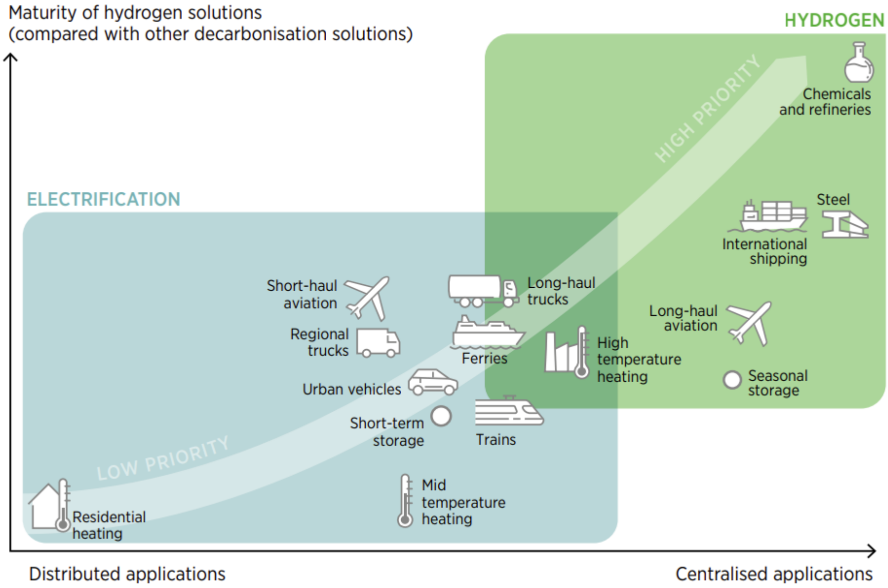

Figure 2: Policy prioritization (Source: IRENA, 2022) based on estimated hydrogen demand (x-axis) vs. technolo readiness level (y-axis) as compared to fully electric technology solutions.

For the aviation industry alone, the European Union has passed a resolution (European Parliament, 2020) that allocates over €1.7bn to the Clear Sky 2 initiative. Clear Sky 2 is now known as Clean Aviation. Clean Aviation, in turn, is investing in the Fuel-Cell and Hydrogen 2 (FCH2) research programs. These programs include research and educational organizations as well as industry partners. Clean Aviation is also in the process of preparing and implementing a "comprehensive European hydrogen-powered aviation research roadmap" (Horizon Europe, 2021).

Aviation industry leaders in the adoption of hydrogen can be divided into two types, First, startups that focus on immediate application of available hydrogen technology into existing aircraft in the small jet and regional aircraft segments. Examples of such companies are Zero Avia, and Universal Hydrogen (UH2). Such companies are already testing the porotypes of their technologies and plan to enter the commercial market in 2024 and 2025 (Universal Hydrogen Co., 2022; ZeroAvia Inc., 2022). Second, established companies that adopt longer-term road maps and plan to enter the commercial market by 2035. Examples of such companies are Airbus and MTU Aero Engines (Airbus S.A.S., 2021; MTU Aero Engines, 2022).

c. Technology readiness and the value chain

Based on a literature review covering papers published between 2005 and 2019 (Dahal et al., 2021), the choice of hydrogen as a potential replacement for the currently used aviation fuel (Kerosene also known as Jet Fuel) stems from the following:

- Per kilogram, hydrogen has three times the energy content compared to kerosene.
- Hydrogen provides higher safety due to its high buoyancy in standard atmospheric conditions, short flammability time, and higher stability range.
- If produced and transported using sustainable energy, hydrogen is a clean fuel with zero carbon and particulate matter emissions. The only pollutant produced in hydrogen combustion is NOx which is produced at a much lower amount than when kerosene is used.
- Other physical attributes such as low dynamic viscosity, high thermal conductivity, and high heat capacity can contribute to smaller, quieter, and more efficient propulsion systems with longer lifetimes.

The disadvantages associated with hydrogen use are (Cecere et al., 2014; Dahal et al., 2021):

- The low density of hydrogen, which even in liquid form requires four times the storage volume used for the equivalent energy content in kerosene.
- The higher price of green hydrogen relative to kerosene.
- The necessary investment in infrastructure for production, transport, and airport equipment and personnel to accommodate the needs for refueling hydrogen aircraft.

Given the above advantages and disadvantages, green hydrogen as an alternative fuel for aviation offers both the lowest environmental and economic impact when compared to other alternatives (Sharma & Strezov, 2017). But before concluding that it is a viable solution to adopt and invest in, it is important to analyze the level of preparedness of relevant technologies.

Hydrogen flights have been successfully tested as far back as 1955 when the Lewis Flight Propulsion Laboratory of the National Advisory Committee for Aeronautics (NACA) flight-tested their hydrogen fuel system onboard a B-57B. The test involved flying the aircraft using one of its jet engines running on liquid hydrogen (LH) for 21 minutes. This was done to demonstrate the use of liquid hydrogen as a fuel for high-altitude flight (Cecere et al., 2014; Sloop, 1977). However, for commercial aviation to adopt hydrogen on an industry scale, many technologies need to reach an acceptable level of maturity and reliability.

Figure 3: B-57 modified to use liquid hydrogen (Sloop, 1977). The heavy smoke was a normal occurance during engine startup on conventional fuel.

In 2009, the Fuel Readiness Level (FRL) standard was introduced by the Commercial Aviation Alternative Fuel Initiative. This standard was endorsed by the International Civil Aviation Organization in the same year (Altman et al., 2010; CAAFI, 2022). FRL has been adopted by different jet bio-fuel producers as a means of comparing relevant technologies and their readiness levels (Delbecq et al., 2021). So far, this standard is not used to compare jet biofuels with other propulsion methods of propulsion such as hydrogen and/or electric propulsion. Hence the Technology Readiness Level (TRL) standard is used in this thesis.

Retrofitting existing aircraft for hydrogen use is possible using current technologies but does not make full use of the positive physical attributes of hydrogen as a fuel. New designs are necessary to achieve higher efficiency and accommodate the higher volume of storage (Cecere et al., 2014).

According to McKinsey & Company (2020), commuter aircraft prototypes and the first standardization of hydrogen certification procedures are expected by 2025 while regional and short-range prototypes by 2028. But alongside developments in aircraft and aircraft propulsion technologies, other technologies are required to complete the value chain. In this thesis, the focus is on the technologies relevant for airports to operate hydrogen-fueled aircraft. Table 5 is an overview of the technology readiness level (TRL) of such necessary technologies (ATI, 2022).

Table 5: Technology readiness level for hydrogen fuel chain (ATI, 2022).

Component	Current TRL
Electrolyzers	TRL7-8
Hydrogen liquefaction system	TRL7-9
Liquid hydrogen storage tanks	TRL9
Gas Pipeline	TRL5-6
Delivery Tankers	TRL9
Liquid Hydrogen Hydrant System – Cryogenic Pipe	TRL5-6
Liquid Hydrogen Hydrant System – Transfer Tank	TRL2-3
Liquid Hydrogen Hydrant System – Mobile Refueller Vehicle	TRL1-2
Liquid Hydrogen Hydrant System – Overall System	TRL1-2
Liquid Hydrogen Bowsers – Manually Operated	TRL3-4
Liquid Hydrogen Bowsers – Automation Operated	TRL1-2

The technology's readiness level for producing green hydrogen through water electrolysis is demonstrated in many projects around the world (IRENA, 2020b). But the existing projects (~5 MW electrolysis plants) are small in comparison with the scale necessary for mass production. Larger projects (up to 100 MW) have already been announced and experience in operations on such scale needs to be acquired (ATI, 2022).

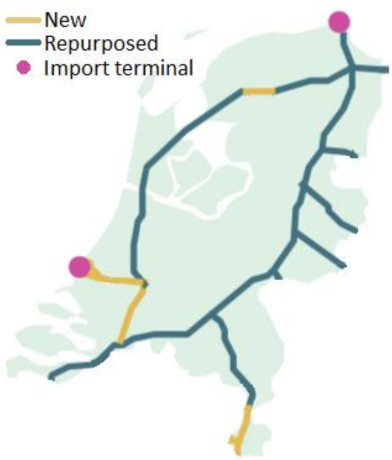

Figure 4: European Hydrogen Backbone project map 2030 (EHB, 2020).

The same applies to liquefaction systems: although they are used in many projects the large-scale liquefaction plants needed for mass production have not been implemented yet and the operational experience has not been acquired yet (ATI, 2022).

Large-scale storage of both gas and liquid hydrogen has been demonstrated in many projects (ATI, 2022) including both storage in infrastructure tanks and long-term storage in underground caverns and depleted wells. For example, long-term storage of hydrogen in a cavern near Zuidwending in the Netherlands began in August 2021 through an existing borehole (IEA, 2021).

Gas pipelines for transporting hydrogen currently exist between production and storage facilities and within industrial sites where hydrogen is used. The knowledge and experience for scaling such pipelines up for long-distance and large mass transport are being acquired and implemented in the EU hydrogen backbone project (EHB). Where both repurposed and new pipelines will be used (ATI, 2022; EHB, 2020).

An alternative means of transporting hydrogen to airports involves the use of delivery trucks. Such trucks have been widely used for some time (ATI, 2022). That said, there is a slow but continuous development in the transport sector and transport regulations that allows for larger and more efficient trailers and tractors (Bonner, 2018).

An often-suggested solution for distributing hydrogen within an airport to refuel aircraft is to use a pipe hydrant system. Similar systems are currently used in airports for kerosene. Such systems do require a higher initial investment than refueling trucks (bowsers) but they have a lower operational cost. The issue of using this solution with liquid hydrogen is the need to reliquefy the boil-off (hydrogen in the gas state) and to maintain constant pressure in the system. Also, larger pipe cross-sections will be necessary due to the lower density of liquid hydrogen compared to kerosene (ATI, 2022).

Such hydrant systems have not been implemented at a scale necessary for airport infrastructure, but smaller and simpler versions are already used in the chemical industry. According to Mangold et al. (2022), the larger-scale systems are technically feasible. But before such technology can be implemented to match the requirements of an airport further modeling, design, and testing of such systems and their subsystems is necessary (ATI, 2022). Furthermore, some authors find that such systems would be cost-technically infeasible for use with liquid hydrogen at airports until 2040 (Clean Sky 2 JU, 2020).

The alternative solution to the use of hydrant systems is to use trucks that are fitted with tanks and bowsers. Bowsers for refueling liquid hydrogen are expected to be commercially available by 2035 (ATI, 2022). While bowsers for gas hydrogen are already in use in other industries (Air Products, 2012), in aviation they are currently used in testing prototype hydrogen-fueled aircraft and the operational procedures for refueling are being developed (ZeroAvia, 2022).

From the above, it is clear that different approaches and system designs can be followed to achieve hydrogen refueling infrastructure at airports. The latest literature on hydrogen supply systems for aviation focuses on two approaches, one is to produce and process hydrogen to its liquid form on-site at the airport and the other is to deliver already liquefied hydrogen to the airport (ATI, 2022; Hoelzen, Flohr, et al., 2022; Hoelzen, Silberhorn, et al., 2022; Hong et al., 2021; Janić, 2014; Mangold et al., 2022; McKinsey & Company, 2020; Rao et al., 2020; Rondinelli et al., 2014). Both approaches are motivated by the high energy density of liquid hydrogen which enables longer-range flights and makes it more suitable for a larger customer base. But that does not mean that the lower energy density of gaseous hydrogen and the resulting lower range of aircraft fueled by it, cannot provide a commercially viable service. A service that could be a transitionary solution until the technology readiness level of liquid hydrogen reaches the necessary level for commercial application.

d. Conclusion

The urgent need for an alternative to fuels currently used in aviation, the present direction of industrial policy, the interest within the aviation industry, and the readiness level of hydrogen propulsion and supply technologies, altogether present a reality where airports need to investigate the requirements for transitioning to hydrogen and to find the conditions that constitute a commercially sustainable solution. Such a solution can be approached using different system designs in different timelines. One of which is to first transition to gas hydrogen for shorter-range aircraft and then to liquid hydrogen-fueled aircraft at a later stage. Research into the commercial viability of such a solution was not found in current literature.

CHAPTER 3: Methodology

Through the literature review, a better understanding was achieved of the technologies related to hydrogen production, transport, storage, and use. Next, the techno-economic analysis (TEA) method was selected to assess the feasibility and cost of the transition to hydrogen from the perspective of a small airport. This chapter will present the reasoning behind the choice of the study case and its boundaries, as well as the adopted cost model.

a. Research approach

The research approach adopted for evaluating the economic feasibility of transitioning to hydrogen is a techno-economic analysis of a real-world case.

The techno-economic analysis approach was selected based on its suitability for analyzing process designs when adopting new technologies (Mahmud et al., 2021). The economic assessment of the system was based on capital expenditure (CAPEX) and operational expenditure (OPEX) estimates for the different components in the system. To evaluate the effect of different input parameters on costs a sensitivity analysis was performed.

The case study approach was selected because it allows for analyzing the potential for the transition to hydrogen through a real-life context (Yin, 2009). The choice of the airport for the case study was based on the conclusion that hydrogen technology will be available for use in smaller aircraft segments before defusing into larger aircraft segments (Chapter 2). This inspired the choice of an airport with substantial traffic in the small jet aircraft segment. Another selection criterion was that the airport must be cooperative in allowing access to air traffic data and other relevant information. Finally, the choice of the airport was constrained to airports within the Netherlands.

Rotterdam The Hague Airport (RTHA) satisfied the above criteria. In 2019, 27% of the flights departing from RTHA were small jets and regional aircraft. Aircraft from those two segments covered 20% of the kilometers flown from RTHA in 2019 (RTHA, 2022). This implies that the two segments use a considerable percentage of fuel provided at the airport (Appendix A). Furthermore, the airport management showed interest in the potential for transitioning to hydrogen and offered access to its data and personnel through an internship contract and an access permit.

Based on the technology readiness level, two hydrogen streams are chosen for the adoption of hydrogen technology in RTHA. The first stream involves adopting solutions for providing gas hydrogen for small and regional aircraft in 2024. The second stream builds on the first and involves preparing for the provision of liquid hydrogen in 2035.

b. System design and boundaries

The system boundaries were defined as the boundaries of RTHA (the main stakeholder). This means that system design is confined by the limited availability of free space inside the airport perimeter and that the required consumables (input energy and material) are assumed to be delivered by third parties at market price.

The hydrogen is delivered in the gas form initially through trucks and then at a later stage through a pipeline (assumed to be connected to the airport as part of the hydrogen backbone project and to be functional by 2035).

The demand for liquid hydrogen is assumed to begin a few years after the adoption of compressed gas hydrogen by smaller aircraft segments. Hence, the system is initially required to provide hydrogen in compressed gas form only and then to be upgraded to provide liquid hydrogen alongside the compressed gas hydrogen in 2035.

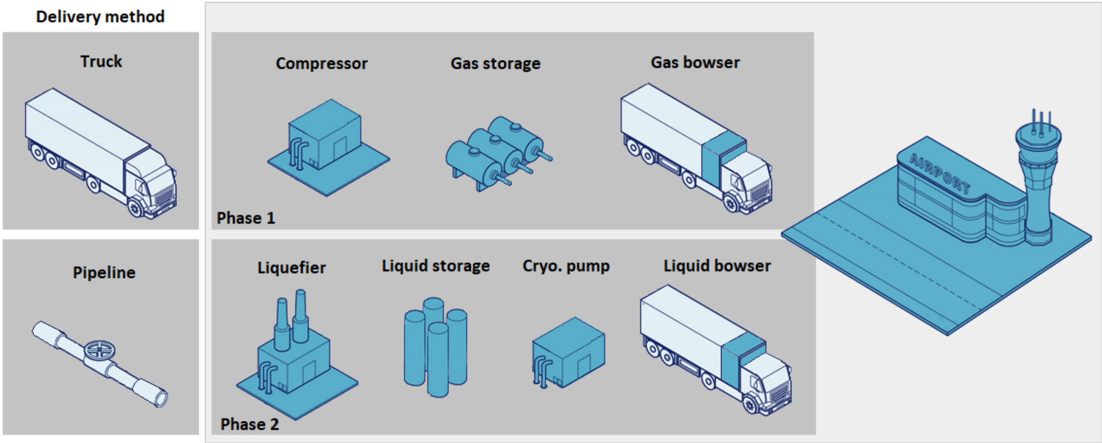

Figure 5: First and second phases of transition represented in two streams (flow direction left to right) one delivering gas and the other delivering liquid hydrogen to aircraft (elements in this image were obtained from Airbus S.A.S., 2021).

Figure 5 illustrates the hydrogen flow of the initial system's setup (Phase 1) that will provide gas hydrogen as well as the system upgrade (phase 2) that will allow for the provision of liquid hydrogen. The initial setup allows for the hydrogen gas that is received by the airport via road transport (truck) to be compressed to a higher pressure and stored in a high-pressure tank. When needed gas hydrogen trucks transport the compressed gas hydrogen from the storage tank to the aircraft for refueling. In 2035 the infrastructure for liquid hydrogen is added allowing the liquification of part of the compressed gas hydrogen and the storage of the resulting liquid hydrogen. The liquid hydrogen is then stored in a liquid hydrogen storage tank and a cryogenic pump is used to transfer the liquid hydrogen to bowsers that then transport the liquid hydrogen to aircraft for refueling. The addition of a cryogenic pump in the liquid hydrogen stream enables the transport of liquid hydrogen since the pressure of hydrogen in the storage vessel is not sufficient for the transfer of the liquid from storage to truck at the necessary rates. For simplification, the system integration of the different components is assumed to take no time.

To design the system future demand for hydrogen fuel at RTHA had to be estimated and used in estimating the size of the necessary subsystems. To do that, the following steps were followed:

- Air traffic data for 2019 (pre-COVID) is collected from RTHA and processed to find relevant information per aircraft segment (Appendix A).
- The air traffic information found is used together with worldwide air traffic growth forecasts to estimate RTHA air traffic change from 2019 to 2050 (Appendix B).
- Two scenarios are developed for the adoption of hydrogen aircraft by users at RTHA. The rate of adoption for both scenarios is relative to the estimated RTHA future air traffic (Appendix C).
- Jet-A1 (kerosene) fuel consumption by the forecasted RTHA air traffic is calculated while considering fuel efficiency improvement over time (2019-2050) (Appendix D). The estimated total use of kerosene by all aircraft segments in 2019 was later found to be within 5% of the total consumption reported (RTHA, 2022).
- Hydrogen fuel consumption projections for the portion of the fleet predicted to run on hydrogen are estimated based on energy content factor (hydrogen vs kerosene) and

segment-specific conversion factors that consider the efficiency of the aircraft in each segment (Appendix E).

Taking into account that the full scale of hydrogen-fueled aircraft manufacturing infrastructure and facilities will not be available at EIS, a manufacturing ramp-up time is assumed. Next, a take-rate is applied to consider that not all demand for new aircraft will shift to aircraft with hydrogen propulsion.

A worst-case (with more modest goals) scenario assumes that due to unforeseen technological, regulatory, and/or economic barriers EIS and the ramp-up time will be delayed by 2 years. It also considers a lower take-rate from the demand side. The manufacturing ramp-up and the take-rate values used for both scenarios are adopted from Hoelzen et al. (2022). Table 6 presents the parameters that define both base and worst-case scenarios.

Table 6: Assumptions defining the diffusion scenarios of hydrogen aircraft technology.

Scenario	Aircraft segment	Entry into service (EIS)	Ramp-up [years]	Take-rate [%]
Best case	Small jet and regional	2024	2	100
	Single aisle	2035	3	100
	Medium widebody	2035	4	67
	Large widebody	2035	n/a	n/a
Worst case	Small jet and regional	2026	4	80
	Single aisle	2037	5	67
	Medium widebody	2037	6	50
	Large widebody	2037	n/a	n/a

c. Cost model

The economic assessment of the system was based on estimated capital expenditure (CAPEX) and operational expenditure (OPEX) to find the annual cost for each subsystem (excluding consumable commodities) while using the annuity payment factor as presented in equations 1 and 2. Where r is the interest rate, dp_i the depreciation period, a_i the annuity factor, $C_{O\&M}$ the annual operations and maintenance cost as a percentage of CAPEX, N_i the number of units, C_{CAPEXi} the capital expenditure cost, and C_{Exi} the cost excluding consumable commodities.

$$a_i = \frac{(1+r)^{dp_i} \cdot r}{(1+r)^{dp_i} - 1} \qquad (1)$$

$$C_{Ex_i} = C_{CAPEX_i} \cdot N_i \cdot (a_i + C_{O\&M_i}) \qquad (2)$$

The interest rate is assumed to be fixed over time at 6% and equal for all components (Hoelzen, Flohr, et al., 2022). The subsystems represented in each *"i"* are the compressor (Com), gas storage (GSto), gas bowser-truck (GBow), liquefier (Liq), liquid storage (LSto), cryogenic pump (Cryo), and liquid bowser-truck (LBow) units. The values and process of estimating the values needed for applying the above equations to each subsystem can be found in appendixes F and G.

Next, the cost of consumables is calculated for each subsystem (in equation 3). Depending on the subsystem in question that can include electric power (C_{El}), purge gas ($C_{PurgeGas}$), trucking fuel (C_{Trans}), and/or hydrogen loss costs (C_{H2Loss}). Each consumable is calculated by multiplying the quantity of the consumable used per year by the price per unit. The cost of consumables is estimated using forecasts presented in the relevant literature.

$$C_{Cons_i} = \sum_i (C_{H2Loss_i} + C_{EL_i} + C_{PurgeGas_i} + C_{Trans_i}) \qquad (3)$$

Finally, summing the cost of consumables (C_{Cons}) with the cost excluding energy (C_{Ex}) for all subsystems and adding the cost of hydrogen input (input is demand plus the estimated leaked hydrogen) results in the total annual cost (C_{TAC}) (equation 4).

$$C_{TAC} = C_{H2} + \sum_i (C_{EX_i} + C_{Cons_i}) \qquad (4)$$

All costs need to be calculated in constant prices (in Euros) for the year 2020 (€$_{2020}$). The average European Central Bank reference exchange rate for 2020 is used as the conversion rate for converting from US Dollars to Euros (European Central Bank, 2022).

Once the total annual cost is calculated, it is possible to calculate the cost per kg of hydrogen by dividing the cost by hydrogen demand. Next, the cost composition is analyzed and sensitivity analysis is used to better understand the relations between the input and output variables.

To put the results in perspective, the calculated results are compared to the costs of kerosene and using cost ratios an estimate of a resulting flight ticket price is calculated.

d. Conclusion

In this chapter, the chosen research approach was outlined. The selection of the Rotterdam The Hague airport as the airport to use in the case study was justified. A method for defining the necessary system requirements and system boundaries was outlined. The cost model used in the techno-economic analysis was outlined. And the approach to analyzing the results was defined. Next, the described methods are applied and the results are analyzed and discussed.

CHAPTER 4: A case study of RTHA

This chapter will cover the application of the cost model to the case study of the Rotterdam The Hague Airport. The presented results are based on a fixed cost of hydrogen (average of the forecasted price). The first part presents the required land area and consumable quantities. The second part presents a decomposition of the estimated cost. Then a sensitivity analysis of the estimated cost is presented followed by a discussion of the results and their consequences.

a. Sizing demand and system requirements (land area and consumables)

The research approach outlined in chapter 3 results in finding the key parameters necessary for sizing the hydrogen system components for the assumed scenarios. For both scenarios, the subsystem components are sized according to annual demand, the peak daily demand, and the peak hourly demand as estimated for 2050. The peak values are used to estimate the required capacity and volumetric requirements that in turn are used to check for space availability at the airport.

Table 7: Design requirements used in sizing the hydrogen infrastructure subsystems.

	Annual demand in 2050 [tons]	Peak Daily demand in 2050 [tons/day]	Peak hourly demand in 2050 [tons/hour]
GH worst case	600	5	0.4
LH worst case	7000	7	0.6
GH best case	800	40	7.5
LH best case	13000	75	14

In Table 7, the design requirements are presented. A distinction is made between a 'best-case' scenario and a 'worst-case'' scenario. The best-case scenario (an ambitious goal) for the adoption of hydrogen propulsion technologies is based on the estimated entry-into-service (EIS) as estimated by manufacturers. ZeroAvia estimates EIS in 2024 and that is used as a reference for small jet and regional aircraft segments (RTHA, 2022). Airbus on the other hand estimates EIS in 2035 and that is used for the larger aircraft segments (Airbus S.A.S., 2021; RTHA, 2022).

The system designed based on the calculated hydrogen demand projections introduces different requirements that are important to account for in further stages of the system development. Table 8 presents the land area needed for installing the system components as well as the annual electric energy and hydrogen supply needs (including losses).

Table 8: calculated system requirements.

Scenario	Facility area [m^2]	Electric Energy [MWh]	Hydrogen gas [tons/year]
GH best	332	2623	873
GH worst	237	1922	640
LH best	1785	116751	13462
LH worst	1143	66314	7297

Such information is important for future negotiations with different stakeholders when allocating resources. For example, when designing energy or pipeline connections to the airport and when planning space utilization.

Figure 6: Scale of land area necessary for both gas and liquid hydrogen facilities calculated for the best-case scenarios (source: Google Earth, accessed June 26th, 2022). Note: this does not suggest the location of the area.

The facility area was determined based on the most space-demanding subsystem, the gas hydrogen storage system. For that, an assumption of a 5-meter high ceiling limit was used to find the required area (RTHA, 2022). Then a 1.5 factor was used to calculate the space between circular cross-sections (1.27 is the ratio between the area of a square and circle). The result was then multiplied by 2 to accommodate for the remaining subsystems with the resulting area illustrated in Figure 6.

The electric energy requirement was calculated based on specific energy consumption models for each subsystem. The most energy-intense process in the case of gas hydrogen system is the compressor subsystem and in the case of liquid hydrogen that is the liquification and cryogenic pump subsystems.

The hydrogen gas requirement is based on the forecasted amount of hydrogen needed by aircraft plus the estimated losses of each subsystem due to leakage. The different types of hydrogen have different cost forecasts as shown in figure 7. The production method used in the supply of hydrogen to the airport is assumed to provide Green-hydrogen. That means that the hydrogen was produced through electrolysis that was powered using renewable green energy. Other types of hydrogen include, Pink-hydrogen produced through electrolysis powered by energy from nuclear power, Grey-hydrogen produced from methane through steam reforming, and Blue-hydrogen is the same as Grey-hydrogen but with the addition of carbon capture technology to collect the resulting CO_2 (Port of Rotterdam, 2022).

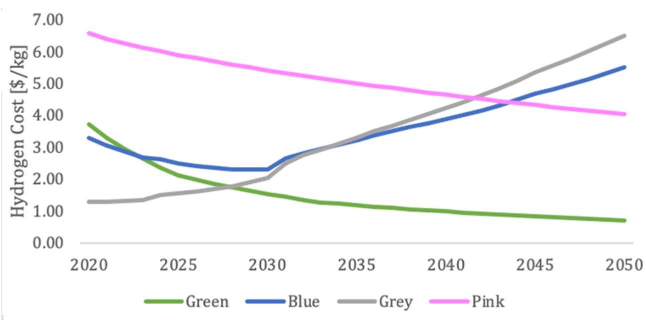

Figure 7: Global average hydrogen price based on the production method (Source: Morgan, 2021).

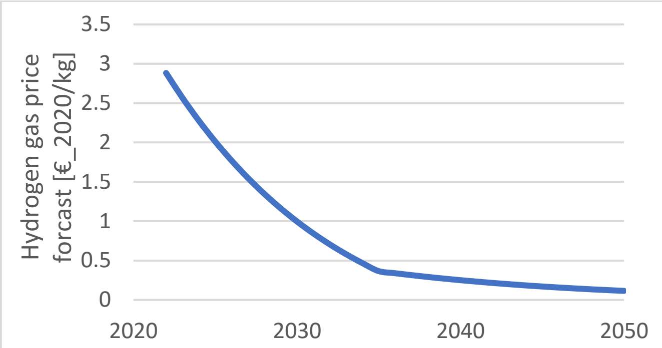

Figure 8: Forecasted present value of green hydrogen gas.

Due to the expected reduction in the price of green hydrogen production, transport, and storage costs caused by the technology learning rate, the price of green hydrogen is forecasted to reduce over the next 30 years as shown in Figure 8 (BloombergNEF, 2020; Morgan, 2021). From the current average price of \$3.70/kg the green hydrogen price is forecasted to fall to \$1.00/kg in 2035 and further to 0.75/kg in 2050 (Rethink Energy, 2022). The above values are linearly extrapolated to find the intermediate prices and the results are then calculated in $€_{2020}$ using the present value calculation and an annual 6% discount rate. The results of this are presented in figure 8 and are used in calculating the average cost of hydrogen incurred by the airport. This results in a fixed price of hydrogen of €1.58/kg.

Helium is selected for use as purging gas. That is used to clear the system from contamination every time a pipe or a refueling nozzle is disconnected. The choice of helium is based on it being an inert gas with a low boiling point (4.2°K) that allows for it to be used in cryogenic systems with temperatures of 20°K without causing a blockage. A price of 22 $€_{2020}$/kg of helium is used in calculating the commodity cost of purge loss (National Minerals Information Center, 2020).

Renewable electricity cost varies based on supply and demand level, geographic location, and source technology (Hoelzen, Flohr, et al., 2022). For simplicity, a fixed cost of 55 $€_{2020}$/MWh is used in calculating the commodity cost incurred by the airport (Afman et al., 2017).

b. Cost decomposition

The calculated total annual cost (C_{TAC}) for each stream in both scenarios is presented in Table 9. The values for liquid hydrogen are within the range expected based on a comparison with other literature.

Table 9: Cost for different streams and scenarios.

Scenario	C_{TAC} (Mn $€_{2020}$)	LCOH ($€_{2020}$/kg)
GH best	4.58	5.25
GH worst	3.09	4.83
LH Best	34.55	2.57
LH worst	19.43	2.66

Due to the high forecasted demand for liquid hydrogen and the need for a higher capacity system the annual cost of the larger system is higher. A more informative indicator is the levelized cost of hydrogen (LCOH) which includes the annualized CAPEX, OPEX, and the cost of consumables in a parameter that indicates the cost of delivering 1 kg of hydrogen. Due to the economics of scale, the found LCOH is lower for liquid hydrogen than gas hydrogen.

To illustrate the distribution of the cost among the different subsystems the LCOH is presented for each stream and scenario in a waterfall chart in Figure 9.

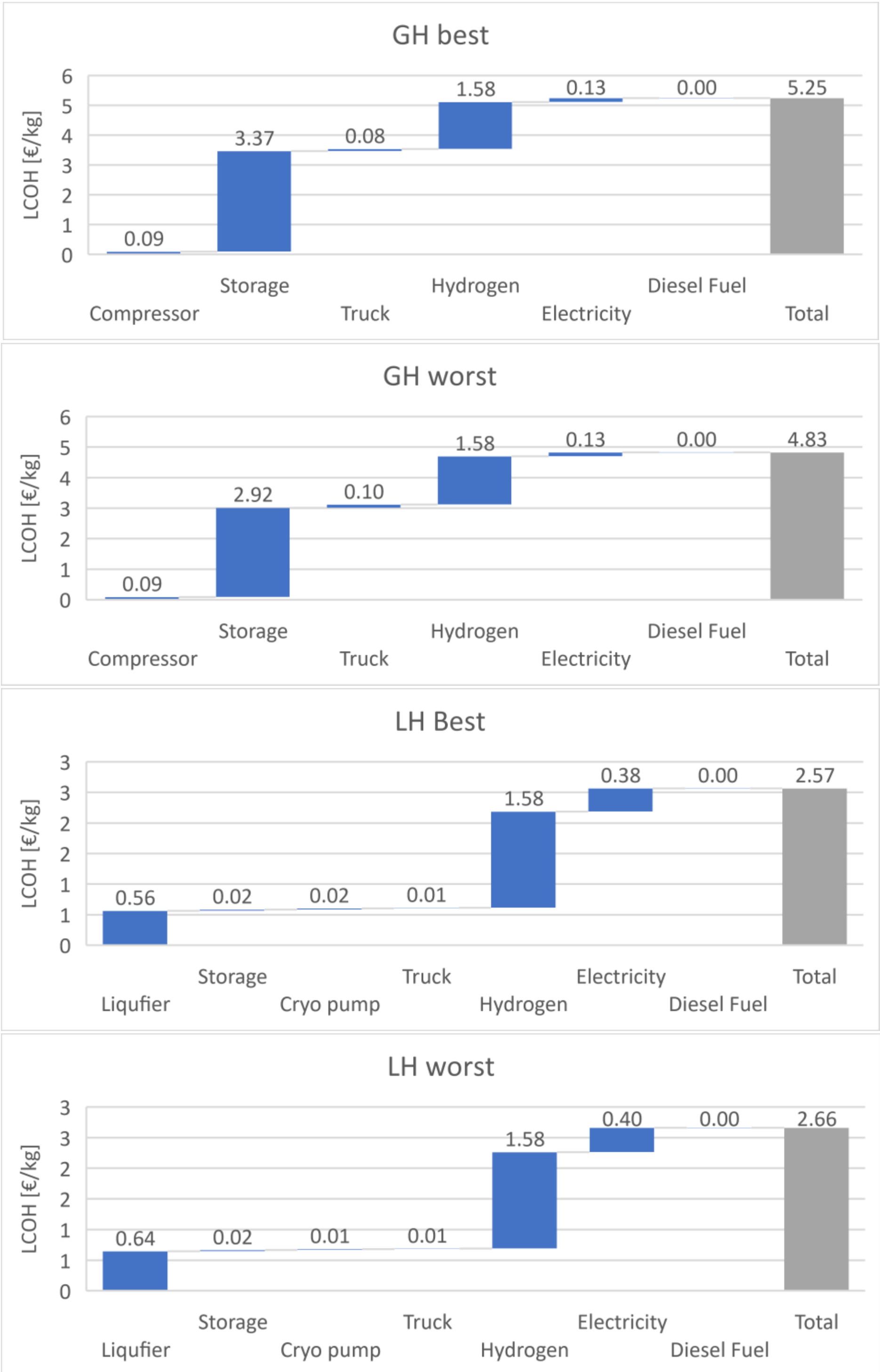

Figure 9: Decomposed LCOH for each hydrogen stream and scenario.

In the case of the gas hydrogen stream, the higher volume of storage necessary is found to overwhelm the benefit of the economics of scale (within the given variation) and results in a higher LCOH. In the case of liquid hydrogen, the economics of scale prevail due to the difference in the cost model of the liquefaction subsystem which leads to a lower LCOH in the best scenario.

On the other hand, the difference between the composition of LCOH when comparing the different streams reflects the different costs of the individual components as well as the magnitude of the cost of the consumables in each stream. The following examples illustrate that coherence,

- The higher complexity of liquification systems versus that of compressors is represented in the higher cost per kilogram of hydrogen processed.
- The cost of the storage as part of the LCOH reflects the complexity of storing compressed hydrogen gas at 950 bar versus liquid hydrogen at 1.1 bar.
- The truck component of the LCOH includes the truck, trailer, and bowser costs. The higher cost of the truck component in the case of gas hydrogen is again due to economics of scale and the fact that the capacity of the gas hydrogen truck (1.2 tons) is 3 times the hourly demand in the worst case and 2 times the hourly demand in the best case for the gas hydrogen stream (Table 7). This results in underuse of the truck's full capacity and a search for a smaller capacity truck that would require a smaller investment is recommended.
- The cost of hydrogen is equal in all the charts in figure 9 because of the assumption of a fixed hydrogen supply cost for all scenarios. Implementing a variable cost of hydrogen could provide the possibility of analyzing more future scenarios.
- The specific energy demand of the compressor in the gas hydrogen stream of 3.05 kWh_{el}/kg_{GH2} versus the specific energy demand of the liquefier in the liquid hydrogen stream of 6-10 kWh_{el}/kg_{GH2} is visible when comparing the cost of electricity as part of the LCOH for each stream.
- In all cases, the cost component of diesel fuel used in the transport of hydrogen from storage to aircraft is negligible when compared to the other costs. But that does not consider the environmental cost of its use. The same applies to the helium purge gas which is not included in the figures.

The above analysis provides a general overview of how the different subsystems in each hydrogen stream contribute to the total cost through the required capital investment and their use of consumable resources.

c. Sensitivity analysis

The above results inspire further investigation of the cost sensitivity to different parameters. For this purpose, a sensitivity analysis of the best case for each stream is conducted. The choice of parameters for the sensitivity analysis is based on the perceived magnitude of their contribution to the cost as well as the potential for improvement.

The parameters for the gas hydrogen stream are the CAPEX for all components, the storage backup factor, the operations and maintenance costs, and the prices for the major consumable's hydrogen and electricity (Figure 10). The same approach is followed when analyzing the liquid hydrogen stream (Figure 11) but without including the storage backup factor due to its small cost contribution in this stream and instead, adding the CAPEX for the liquification subsystem. Other parameters were analyzed for both streams but were found to not make a significant difference within ±20% of their original value for example the interest rate and the price of helium.

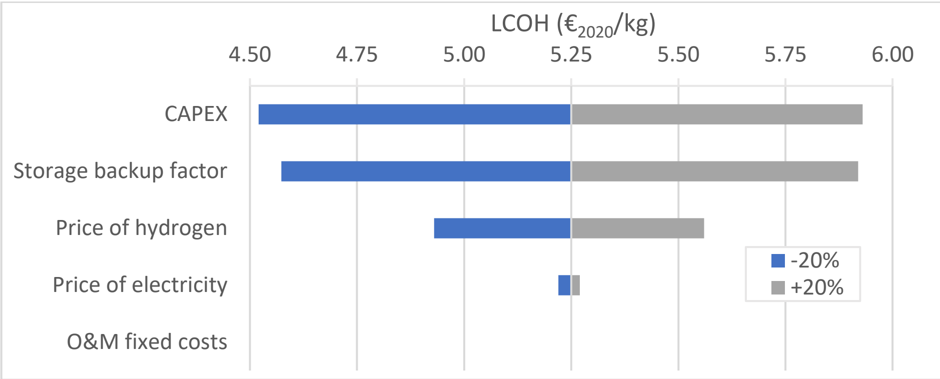

Figure 10: Sensitivity of the levelized cost of hydrogen towards changes in various inputs in the gas hydrogen stream.

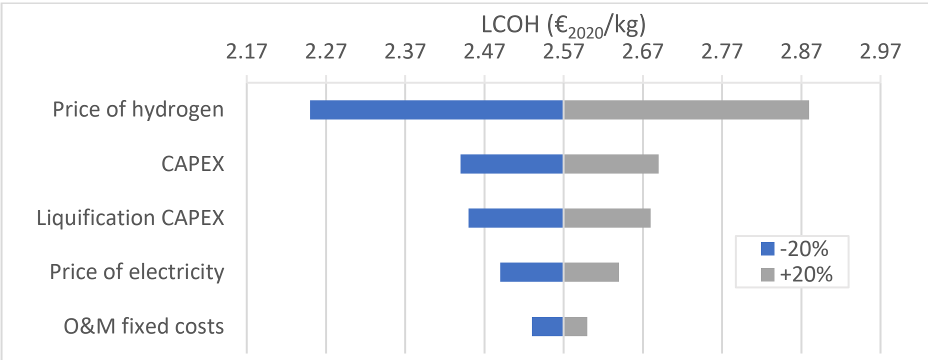

Figure 11: Sensitivity of the levelized cost of hydrogen towards changes in various inputs in the liquid hydrogen stream.

Figure 10 and Figure 11, present further insights into the cost model. One such insight is how the economics of scale reduce the effect of CAPEX increase on the levelized cost of hydrogen. This is visible when comparing the two hydrogen streams where the liquid stream is processing 15 times more hydrogen than the gas stream.

Another insight is the large effect of the storage factor on the LCOH value. This necessitates further research into the choice of the optimum value for the storage factor. The value currently used is 3 times the daily peak supply which is based on an energy industry standard that could be further optimized for this specific case.

Also, the fact that liquification is a more energy-intense process than compression translates to a higher sensitivity to variation in electricity price in the LCOH for the liquid stream. Which in turn encourages further investigation into the efficiency of the liquification systems.

d. Discussion

Cost model and system design

The values presented in the results have a high degree of uncertainty since a large portion of the subsystems evaluated have not been implemented before at the required output levels. At the same time, the effect of a future increase in demand for hydrogen infrastructure has not been considered either in the form of a learning curve that could reduce the capital and operational costs or in the form of an increase in demand for the subsystems and the materials necessary for manufacturing them that could increase the capital cost.

Nevertheless, the uncertainty of the values does not affect the reliability of the relations between the different variables. Hence, it is possible to identify the variables that have the highest effect on cost and to pursue further research into confirming or obtaining more accurate estimates.

The main academic literature source used in this analysis (Hoelzen, Flohr, et al., 2022) does not include a gas hydrogen stream but does apply the cost model for the liquid stream to three airports of different sizes. The authors of that paper agree with the assumption that a hydrant and pipeline solution would not be economically feasible on the scale of air traffic experienced at RTHA. With the switching point from truck refueling to pipeline and hydrant refueling being at 125,000 tons of liquid hydrogen demand (nearly 10 times more than the best-case scenario in this study case).

According to the system design and the model used in this work, the storage (for the GH stream) and the liquification (for the LH stream) subsystems are the costliest components. The fact that no scale factor is included in the cost model for the storage of pressurized hydrogen does not allow for the economics of scale to be accounted for. This is a shortfall for this work and further research into the cost model for this subsystem is necessary. On the other hand, the liquefaction subsystem model takes into account the economics of scale, but it still contributes to a large portion of the cost in the form of capital cost and energy demand. Hence, updating the cost model with input from the latest real-world projects would help increase the accuracy of the output. The high contribution of liquification as well as that of the hydrogen supply to the LCOH does agree with the literature (Hoelzen, Flohr, et al., 2022; Reuß et al., 2019).

A popular notion in the aviation industry is that hydrogen electrolysis technology provides a convenient localized production of hydrogen on-site at the airport (RTHA, 2022). This can be true for remote airports where hydrogen transport costs form a barrier in the transition to hydrogen, but it is not a beneficial alternative to locations where the economics of scale caused by synergies between different industries can lead to cost benefits for all stakeholders. Using literature to find an estimate for the cost of hydrogen produced using an on-site electrolyzer suggests an additional €0.5 to €2.75 ($EUR_{2020}/kg_{hydrogen}$) to the estimated costs after deducting the cost of the purchase of hydrogen (McKinsey & Company, 2020).

Other than synergies with industries around the airport, potential synergies can be identified within the airport too, such as airside mobility providers and the automotive refueling station, which could increase the demand for hydrogen compressed and/or liquified at the airport. That in turn can increase the benefits of economies of scale for the airport's hydrogen streams.

Further analysis of refueling procedures and transfer times to better define the constraints and the utilization rates of refueling trucks' usage are necessary (Hoelzen, Flohr, et al., 2022; Mangold et al., 2022).

In this research, the CAPEX and O&M for the electrical system are assumed to be part of the infrastructure connected to the airport and that must be checked for limits or bottlenecks for the electrical demand necessary. Also, the electronic components, software, and computer hardware necessary for operating both streams are not modeled independently but are assumed to be part of the cost associated with each subsystem.

Because helium is an expensive and non-renewable resource that will increase in price as demand for purging gas increases (Siegel, 2019), it is recommended to follow the developments of self-sealing quick disconnect systems that can eliminate the need for helium or/and the development in systems that allow for helium recycling (Mangold et al., 2022).

Depending on the chosen stream and scenario the estimated annual leakage of hydrogen in this model varies between 40 and 400 tones (3 to 6 % of the demand). This is considered a high percentage when compared to the estimates of leakage during the production and transport of hydrogen. Additionally, the effects of the increase in hydrogen in the atmosphere on climate and the environment are to a large extent unknown. One effect described in the literature is that after a life span of 2 to 7 years the leaked hydrogen will chemically react with other elements in the atmosphere (resulting in methane or water vapor) and by doing so indirectly cause an increase in greenhouse gases and in turn an increase in global warming (Cooper et al., 2022). This demands a further investigation into the effects of leaks and research into how to reduce such leakage, especially if hydrogen is to become a standard fuel in the aviation sector.

Industrial policy

To analyze the feasibility of such a transition the LCOH can be compared to the cost of jet fuel (kerosene) using the conversion efficiency factors defined in table 19. Assuming a constant of 0.53 $€_{2020}\backslash kg_{kerosene}$ and 3.16 $kg_{CO2}/kg_{Kerosene}$ (Hoelzen, Flohr, et al., 2022; Overton, 2022), table 10 shows the conversion factors used along with the equivalent rise in kerosene cost to equal the LCOH calculated for each scenario and based on that, the carbon tax rate is calculated that would result in price parity.

Table 10: Carbon tax for price parity with kerosene.

Scenario	Conversion fact. [$kg_{H2}/kg_{kerosene}$]	LCOH ($€_{2020}$/kg)	Equivalent increase in kerosene cost (%)	Increase translated to a carbon tax ($€_{2020}/ton_{CO2}$)
GH best	0.36	5.25	260	155
GH worst	0.36	4.83	231	198
LH Best	0.41	2.57	101	137
LH worst	0.41	2.66	108	95

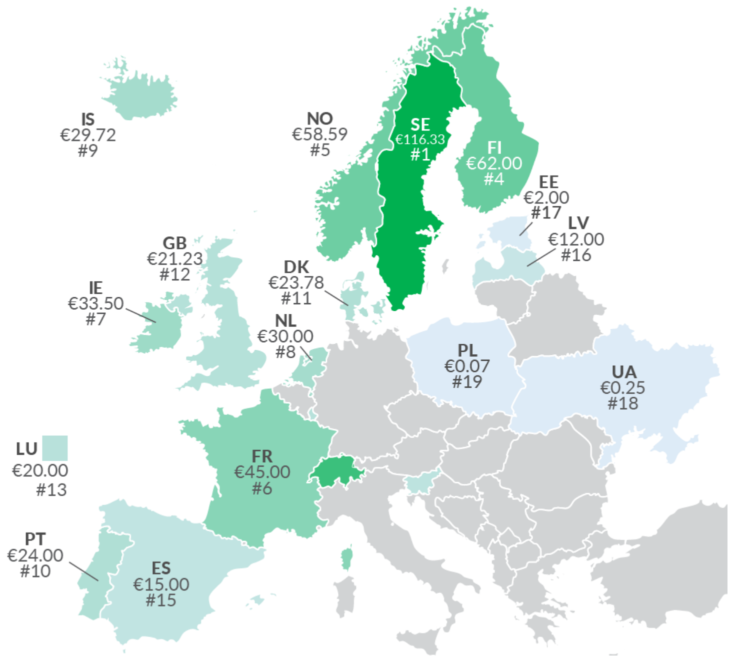

Figure 12: Carbon taxes in Europe per ton of CO_2 as of 1st of April 2021 (Source: World Bank, Carbon Pricing Dashboard converted to euros using EUR-USD currency conversion rate of April 1, 2021).

Comparing the calculated carbon tax for price parity with recent values used in different European countries (Figure 12 and Figure 13), does imply that such an increase in the carbon tax is possible albeit far from the current values for most countries. Hence, further investigation into both EU and national Dutch policy is needed to understand the feasibility of the transition on a regional scale. Also, an investigation of the carbon allowance policy for the aviation industry on both Dutch and regional scales is required.

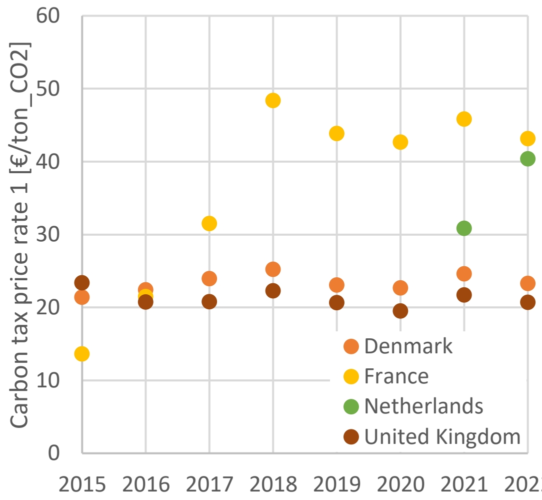

Figure 13: Changes in national carbon taxes (Source: World Bank, Carbon Pricing Dashboard converted to euros using EUR-USD currency conversion rate of April 1, 2022).

International Air Transport Association (IATA) is working with the European Union on pushing the aviation industry towards a more sustainable future (de Juniac, 2019). At the same time, the European Commission has integrated decarbonization goals into the green deal initiative through an emphasis on tax reform (Holger, 2019). But the industry leaders and cross-industry groups who realize the importance of decarbonization and are taking action towards it, are still hindered by the disunity of legislation and regulations within different countries (Harper & Kaminski-Morrow, 2020). This problem is acknowledged and addressed by different stakeholders who emphasize the potential of the European Emissions Trading Scheme (EU ETS) and the ICAO Carbon Offsetting and Reduction Scheme for International Aviation (CORISA) in curbing emissions by providing a market-based incentive to accelerate the transition and provide an equal playing field for aviation industry players across the EU including international flights outside the EU (Royal Netherlands Aerospace Centre and SEO Amsterdam, 2021). The aviation industry is not considered as one of the industry sectors that are susceptible to carbon leakage hence it will not receive a higher carbon allowance to protect the industry from leaking to other economies where carbon cost is lower (European Commission, 2021).

Figure 14: Historical EU carbon permit prices (source: Trading Economics. Date accessed: June 22nd, 2022).

The market-based nature of this approach motivates carbon emitters to invest in cost-effective measures for life cycle carbon emission reduction. Green hydrogen with zero carbon emissions would provide airlines with the financial incentive gained by trading 100% of their carbon permits to compensate for the higher cost of hydrogen used. This assumes the actual availability of green hydrogen which is already in high demand and insufficient supply. To the extent that the European Commission amended the Renewable Energy Directive to include a target to only satisfy 50% of demand for hydrogen with green hydrogen by 2030 (Leguijt et al., 2022).

If the European Commission is successful in transferring the true cost of the environmental impact through carbon allowance and taxation policy to the aviation industry, resulting in the consumers facing the true cost of choosing to fly, then the growth in the demand for air travel can be slowed down (McManners, 2012). This can help in easing the shortage in supply of green hydrogen but that will not be sufficient with the forecasted increase in demand rate from other industries. This emphasizes the importance of increasing the capacity of renewable energy production to reduce the effect of the high demand on renewable energy prices and at the same time the recommendation to increase the capacity for green hydrogen production and import to satisfy future demand.

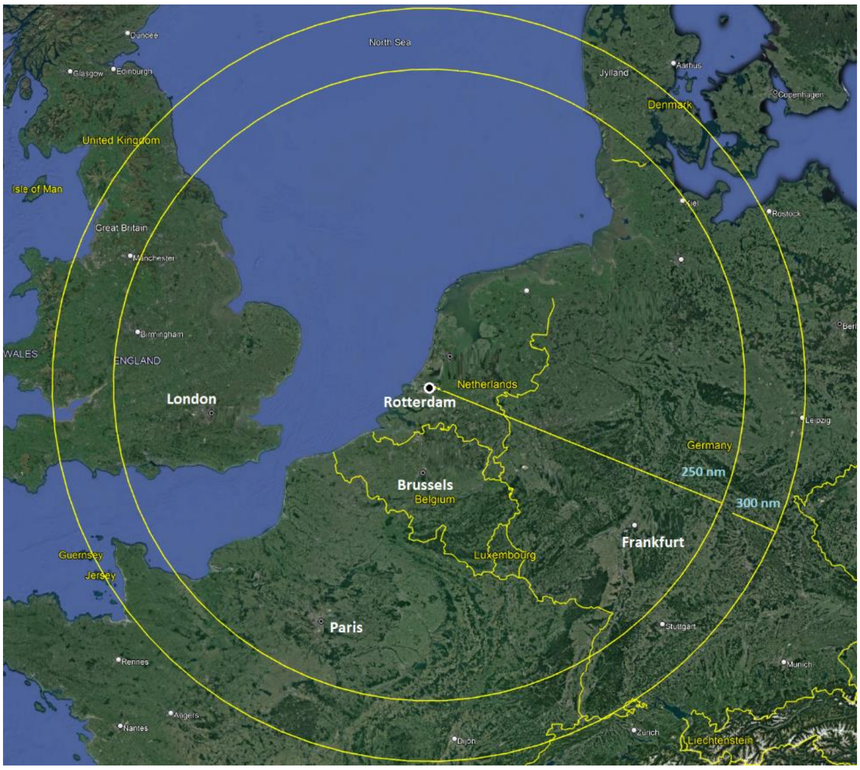

Figure 15: Area within a range of 250 to 300 nautical miles from RTHA (source: Google Earth).

Commercial viability

Having four out of the five busiest airports in Europe (GetToCenter, 2019) within the estimated range of the first hydrogen-fueled aircraft in the small-jet and regional segments (ZeroAvia, 2022), RTHA is in a position to serve as a sustainable connecting hub between the province of North and South Holland and some of the major cities in western Europe. Examples of such cities are London, Paris, Frankfort, Hamburg, and Brussels as illustrated in Figure 15.

As an example, the already established route connecting RTHA (ICAO code: EHRD) and London City Airport (EGLC) has served 92 thousand paying passengers through 1600 flights departing from RTHA in 2019. These flights transport an average of 57 passengers per flight mostly in the Embraer ERJ190 single-aisle aircraft. The amount of $C0_2$ saved and the cost of fuel used per flight and per passenger can be calculated as shown in Table 11: Comparing costs and emissions of kerosene vs. Gas-hydrogen fueled route between Rotterdam and London.Table 11, using the same assumptions used earlier in calculating jet fuel consumption, pricing, conversion rate to hydrogen, efficiency in aircraft segments, and the calculated LCOH for gas hydrogen in the best-case scenario. This calculation also assumes that 20-seat regional hydrogen gas fueled aircraft will serve this route while maintaining a much higher occupancy rate of 95%, the use of 100% green hydrogen and that an 80% cost to revenue ratio is used by the airport when providing the hydrogen fuel to the operator.

The results in Table 11 show that 3400 tons of $C0_2$ can be saved annually by using gas hydrogen while flying that single route in both directions. Without considering the cost of replacing the aircraft or upgrading them with hydrogen gas aircraft propulsion technology, the added fuel cost per passenger will be around €25 per flight per passenger after trading the allocated carbon emissions at an assumed price of €100 per ton.

Table 11: Comparing costs and emissions of kerosene vs. Gas-hydrogen fueled route between Rotterdam and London.

	Kerosene	Gas hydrogen
Total number of paid passengers in 2019 (EHRHD-EGLC)	92000	92000
Total number of flights in 2019 (EHRHD-EGLC)	1600	4800
Number of seats per flight (ERJ190)	100	20
Occupancy rate [%]	0.58	0.96
Amount of fuel used per flight [kg/flight]	1072	165
Cost of fuel [€/kg]	0.66	6.56
Fuel cost per flight [€/flight]	710	1085
Co2 emissions per flight [kg/flight]	3388	-
Fuel cost per passenger [€/P.PAX]	12.25	56.53
Co2 emissions per passenger [kg/P.PAX]	58.41	0.00
Value for trading carbon permits [€]	-	339
Fuel cost per passenger (inc. traded permits) [€/P.PAX]	-	37.33

To put the above example into perspective, the cost of fuel as a percentage of airline expenditure has varied between 32% and 16% over the last 10 years (Burgueño Salas, 2022; IATA, 2022). Applying the same share of costs to hydrogen and the 80% cost to revenue ratio translates to a total cost of €150 to €290 per passenger per flight (an average of €230) as opposed to €50 to €100 per passenger in the case of kerosene (an average of €75).

The above example is based on many assumptions and simplifications, but it serves the purpose of presenting a basic ballpark figure of the effect of an increase in the cost of fuel on the end-user. It also indirectly emphasizes the need for the policy incentives applied on an international level to accelerate the transition. For this specific route without a regional carbon allowance policy and tradable permits, the same flight would translate to a total cost of €220 to €440 per passenger per flight (an average of €330).

Reflections

Technically, hydrogen fuel can be the answer to eliminating CO_2 emissions in aviation and in doing so contributing to saving the world from global warming. It might also be an intermediate step in the evolution of energy storage and transport technology towards a more sustainable solution. But as James M. Utterback explained "The emergence of a dominant design is not necessarily predetermined but is the result of the interplay between technical and market choices at any particular time." (1996), following that line of thought and based on the above example there is a lot to be done both in the policy and social spheres to create the favorable environment that would foster the development and diffusion of hydrogen fuel technology.

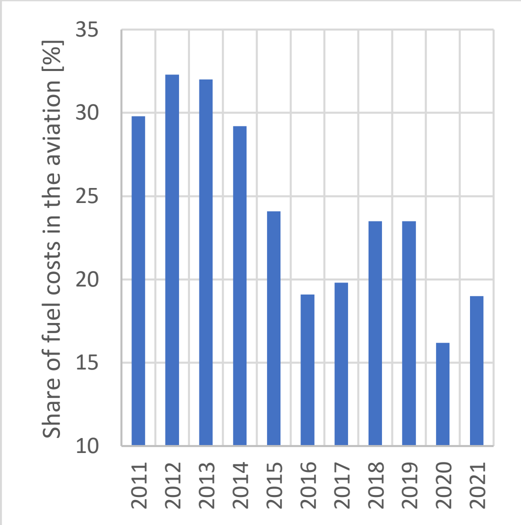

Figure 16: Share of fuel costs in the aviation industry expenses (sources: Ststistia and IATA).

Following a simple policy cycle model approach (Cairney, 2011; Hogwood & Gunn, 1984; Sabatier, 1986) to analyze the current situation from a broad perspective, it appears that agendas were set, policies were formulated, legitimized, and are being implemented in the form of industrial policy incentives for research and development as well as in the form of market incentive (carbon tax and allowances). In the implementation stage of those policies, the apparent objectives are clear, and it appears that the policies are working (are based on valid theories that are effective in driving the technology, market, and industry forward). Furthermore, required resources are allocated and committed, and we assume the implementation is undertaken by skillful personnel.

The remaining conditions for the success of policy implementations are minimal dependency relations, support from influential groups, and the absence of conditions beyond the control of policymakers.

Those remaining conditions do require attention. Since the success of hydrogen fuel in aviation is subject to a dependency-relation on the policy followed by other countries including countries outside the European Union. That makes the push for an international policy both critical and urgent to ensure the availability of hydrogen at destination airports and for the establishment of an international standard.

Also, the support from influential groups is currently lacking in the form of lack of public awareness and lack of willingness to accept the higher costs or even the inconvenience of selecting other means of transport. Since the public is an influential group that is critical in supporting the long-term goals of the policies it is necessary to better communicate the policies and educate the public.

Finally, the conditions beyond the control of the policy maker such as international conflicts and economic crises do affect priorities and distract resources (this is beyond the scope of this research)

In general, the three conditions stated above require continuous evaluation and policy maintenance from the policy maker and regulator to cope with the changes and ensure the development and diffusion of hydrogen fuel technology. As a stakeholder that is strongly affected by the success of the concerned policy, the airport must contribute to its success.

This can be done through collaborating with the policymakers and regulators as part of the feedback loop that serves in policy evaluation. At the same time, part of increasing public awareness and engaging with the various stakeholders can be viewed as process management. To aid in managing such a network of stakeholders an Actor Analysis can help in understanding the collective decision-making power layout and aligning the airport goals with opportunity windows (de Bruijn & ten Heuvelhof, 2018).

From the perspective of an airport that is planning to provide a product in a market characterized by derived demand, it is important to monitor and forecast the behavior and buying patterns among the end-users (Kotler & Keller, 2016) by monitoring the current public awareness and measuring the willingness to pay for and the perceived value of hydrogen-fueled travel. It is also important to study the viable routes within defined gas hydrogen-fueled aircraft ranges and capacities with the goal to estimate the possible future demand on those routes. Then to use the estimated demand, the developed cost model, the slot availability, and the local policies at the concerned airports to find the optimum hydrogen gas infrastructure output for each airport on a network level. The output of such an analysis could be of great value in the development of airport business models and revenue structures on a regional scale.

e. Conclusion

After determining the feasibility of both streams and scenarios based on the required land area and its availability at the airport. The economic results were further investigated by breaking them down to the level of each subsystem and comparing them between the different streams as well as scenarios. This was followed by a sensitivity analysis to identify the design decisions that can have larger effects on the LCOH. In the discussion section, different elements from the model assumptions and results were further elaborated and a comparison with the current jet fuel (kerosene) was presented.

CHAPTER 5: Conclusion and recommendations

The goal of this research was to identify the condition under which a transition to hydrogen fuel would constitute a commercially sustainable solution for an airport. To answer that a broad literature review was undertaken to first understand the motivation behind the transition, then to acquire an up-to-date understanding of the technical and economic states of the technologies necessary as well as, the currently pursued developments and the main contributors in the field.

The outcome of the literature review was a preliminary design of the system necessary to deliver process, store and use hydrogen as fuel. The sizing of the system was based on air traffic data obtained for the case study at the Rotterdam The Hague Airport and the forecasted increase in air traffic until 2050. The adopted design was based on the choice to acquire hydrogen from a centralized production facility to benefit from the economics of scale. The acquired hydrogen is to be received through truck deliveries and later through a pipeline and processed at the airport through two processing streams.

The two processing streams approach was adopted due to the large gap in technology readiness level that was found when comparing gas hydrogen and liquid hydrogen processing and propulsion technologies. This led to the design decision to implement a gas hydrogen stream first to serve smaller aircraft segments that are closer to commercial application. Then implement the liquid hydrogen stream when the necessary technology is ready for commercialization. For both streams two diffusion scenarios were implemented; a best-case scenario based on the timeline set by industry leaders and a worst-case scenario where hydrogen fuel adoption is delayed by 2 years.

The cost model was adopted from existing literature and adjusted for the specifics of the two hydrogen streams with each subsystem sized according to the demanded flow and the necessary buffering for each given stream. The cost model is a function of the capital investment costs, the operational and maintenance costs, and the costs for consumables (electricity, leaked hydrogen, purging gas, and transportation fuel). The estimates for the variables were found in different literature based on the calculated demand and the results were found to agree with the literature.

Based on the analysis of the results it was concluded that price parity of hydrogen fuel with jet fuel (kerosene) in the case of the Rotterdam The Hague Airport is achievable with a high increase in carbon tax (95 to 198 $€_{2020}/ton_{CO2}$) and without carbon allowance for the aviation industry.

To place the above costs into perspective, assuming no change in the current carbon tax value and an emissions trading value of €100 per ton of CO_2, a single one-way ticket for a flight from RTHA to London City airport on gas hydrogen (best-case LCOH) would cost an average of €230 as opposed to €75 for an equivalent estimate of a kerosene-fueled flight.

The results agree with the literature and again show how dependent the viability of commercially sustainable hydrogen fuel implementations at airports is on the carbon tax and the emissions trading policies. It also shows the importance of the perceived value by the passenger and their willingness to pay for hydrogen-fueled flights.

The results apply to RTHA as well as to other airports that have enough free space for infrastructure, access to hydrogen gas via trucks or a pipeline, and a similar distribution of air traffic among the different aircraft segments. In general, the advantage in the case of RTHA is its proximity to the industrial zone of the Port of Rotterdam where synergies with other industries demanding hydrogen would provide the benefits of economics of scale in the supply chain for hydrogen. A more specific advantage for this case study is the air traffic distribution at RTHA among the aircraft segments which allows for the provision of gas hydrogen.

As a result of this research, the following recommendations are proposed. To start communication channels with influential groups and the public to gather support for the necessary policies, increase acceptance levels of the necessary cost changes among the end-users, and estimate demand levels. At the same time start cooperating with other airports within the estimated aircraft range to ensure that the facilities for providing the hydrogen are available when needed at the destination as well as diversion airports.

To continuously monitor the developments in subsystem technologies to maintain up-to-date information relating to system design requirements such as the use of purge gas and leakage factors. As well as up-to-date efficiency and cost parameters to maintain an up-to-date cost model. The same applies to the forecasts of air traffic, costs of consumables, and technology diffusion rates.

Additionally, it is recommended to implement a technology learning rate in the cost model used in this research and to undertake more detailed research into the design criteria that are necessary for a more optimal design. That research applies to criteria such as the necessary storage buffer factor and the transfer rates using network optimization techniques.

Finally, it is recommended to further investigate and follow the current research on the potential effects of large-scale adoption of hydrogen on the environment and how to mitigate any potential risks. As well as the potential effect of the large-scale adoption on the cost of hydrogen and other resources (for example green energy and rare earth metals).

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Appendix A. Air traffic data from RTHA

Data from Rotterdam The Hague Airport RTHA,

- Flight codes
- Aircraft type
- Aircraft registration
- Historical data

Public data:

- Global airport database (Partow-> Downloads -> The Global Airport Database version 0.0.2).
- Individual airport websites and national civil aviation authorities.
- Aircraft data (P. Jackson et al., 1995; P. A. Jackson, 2012)

Aircraft segmentation algorithm:

- Helicopter if propulsion type in Aircraft Registration table is “H”.
- Small if the maximum number of seats < 20.
  - If the aircraft type is “small” and if the engine is jet or turboprop, then it’s a “Small Jet” else it is a “Small Prop”.
- Regional if the maximum number of seats <= 100.
- Single aisle if the maximum number of seats <=250 and maximum take of weight <= 150000 (kg).
- Widebody medium if maximum number of seats <=300 and maximum take of weight <= 250000 (kg).
- Widebody Large if the maximum number of seats > 300 and maximum take of weight > 250000 (kg).

The flight distance is estimated by calculating (eq. 5) the great-circle distance between two points on a sphere given their latitudes (λ), longitudes (φ), and the earth's mean radius (r). This results in the shortest distance and ignores the actual flight path governed by air traffic routes as well as the time spent loitering before landing. But it will still be useful in comparing fuel demand for different categories.

$$2 \cdot r \cdot \operatorname{asin}\left(\sqrt{sin^2\left(\frac{\varphi_2 - \varphi_1}{2}\right) + \cos(\varphi_1) \cdot \cos(\varphi_2) \cdot sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)}\right) \tag{5}$$

Resulting data per aircraft segment:

Table 12: Total values of relevant parameters per aircraft type segment

Segment	Tot. Flights	Tot. seats	Tot. Pay Pax	Tot. Kilometers
Helicopter	133	1164	36	9121
Small Prop	3215	12738	31	462947
Small Jet	3015	32555	5178	2755130
Regional	289	17118	10397	171341
Single aisle	8379	1302164	1028863	11866059
Widebody medium	8	2098	795	20203
Widebody large	1	269	169	1552

Table 13: Airline metrics per aircraft segment

Segment	Revenue passenger kilometer (RPK)	Occupancy [%]
Helicopter	328356	3.09
Small Prop	14351357	0.24
Small Jet	14266063140	15.91
Regional	1781432377	60.74
Single aisle	12208549060917	79.01
Widebody medium	16061385	37.89
Widebody large	262288	62.83

Table 14: Average values of relevant parameters per aircraft segment

Segment	Avg. seats	Avg. Pay Pax	Avg. Kilometers	Avg. RPK
Helicopter	8.75	0.27	68.58	18.52
Small Prop	3.96	0.01	144	1.44
Small Jet	10.8	1.72	913.81	1571.75
Regional	59.23	35.98	592.88	21331.82
Single aisle	155.41	122.79	1416.17	173891.51
Widebody medium	262.25	99.38	2525.38	250972.26
Widebody large	269	169	1552	262288

Table 15: Aircraft types in different segments based on the segmentation algorithm

Segment	Aircrafts (VBA macro F9)
Helicopter	EC-135, AW-139, R-44, EC-120, AS-355, AW-109SP, EC-130, AS-365, A-109S, B-505, SA-365, CH-47D, G2-CA, NH90, AH-64, AS-350, MC-130J, AS-532, EC- 145, EC-155
Small Prop.	SR-20, AT-01, R-2160, DV-40, DR-400, PA-28, TB-20, TB-10, C-172N, P2010, C-182Q, SR-22, PA-28T, PA-30, PA-32R, DA-62, C-172, TB-9, BE-36, P-92S, C-210L, BE-33F, DA-42, BE-35, PN-68B, PA-23, C-421B, PA-12, PA-46, A-210, S-2B, PA-28R, MO-20R, PA-46P, EUROPA, C-172R, C-172P, C-177R, C-177, P2006T, GA-8, MO-20K, C-402B, MO-20J, AC-114, SR-22T, C-150, A-2A, C-172S, C-404, PS-28, RV-10, MO-20E, BO-208, C-172M, PA-18, AA-5, DV-20, C-152, BE-58, PA-31, PA-34T, LONGEZ, AA-5B, R-44, BN-2A, J5-B, C-182, C-182R, CTSW, C-303, C-340, C-206, MO-20T, LC-40, S200, C-210R, C-210N, C-337, MO-20V, BE-36G, TL3000, DR-500, BL17-31, FALCO, C-206T, CP-323, EA-400, PN-68C, RV-7A
Small Jet	C-525B, C-560L, BD-100, PC-12, TBM850, DA2000, RH-400, BE-300, LR-45, DA-7X, C-560X, CL-350, C-425, BE-350, TBM700, P-180, BE-200, C-680, C-680A, EMB505, C-525, HS25-8, PC-7, C-650, G-V, C-510, G-450, G-550, SA-227, HB25-7, C-550, EMB500, G-650, BD5000, RH-390, LR-55, G-650ER, BD6000, C-525A, WW1125, G-VI, C-525C, LR-75, ERJ650, CL-850, C-501, HS25-9, DA-10, G-IV, PA-46M, SA-226, CL-600, 400XT, EMB450, CL-604, C-560, BD-700, C-550B, G-200, LR-35A, BE-400, C-750, CL-605, DA-100, DA-900, C-551, DA-8X, BE-90, BE-90C, LR-31, C-208, BE1900, CL-650, G-500, PA-42, LR-40, C-441, ERJ600, HS25-7, TBM900, BE-90B, HDJT, EMB550, AS-365, NH90, LR-60, RH4000, G-400, AW-139, BH-407, G-280, RH-750, AS-355, E-500, AS-350, G-150, G-100, BH-206, PA-31T, A-109S, EC-135H, A-109E, CC-144, C-26, R-66, DO-228, B-105C, CL-601, DA-50, BH-230, PC-24, SF-50, AH-64, LR-36A, C-37A, BD7000
Regional	ERJ170, ATR-72, B737BJ, ERJ135, BAE146, DHC8-2, SF-340, DHC8-4, CRJ200, DO-328, DO328J, B735BBJ, C-32A, ERJ145, UH-60A, DC-3, A319CJ, E175LW, CH-47F, CRJ900, AS-532, ERJ175
Single-aisle	B737W8, B737W7, ERJ190, A320N, A320-2, FK-100, A319-1, B737M8, B737S8, A321-2, B737W9, C-40, A321N, RJ-85, A318-1, B737-8, E195-E2, ERJ195, RJ-100, A400M
Widebody med.	B767-3, A310-3, A330-2
Widebody large	A340-3

Conclusions:

- Omitting the Helicopter segment because of its small size. Also, the national nature of the responsible organizations as well as the services provided by the helicopters will require a different transition process.
- Skip Small Propeller aircraft's segment because of the higher feasibility and efficiency of electric and battery propulsion in that segment.
- Small jets and regional segments together represent 28.26% of the flights, 3.67% of the seats, 1.49% of the passengers, and 19.75% of the kilometers of the total (after excluding helicopters and small propeller aircraft).

To find the required fuel storage capacity when designing the fuel system infrastructure, the seasonal and daily variations need to be taken into account when calculating the peak value of demand which is one of the important parameters used in designing the system. Figures 17, 18, and 19 present the necessary information extracted from the data.

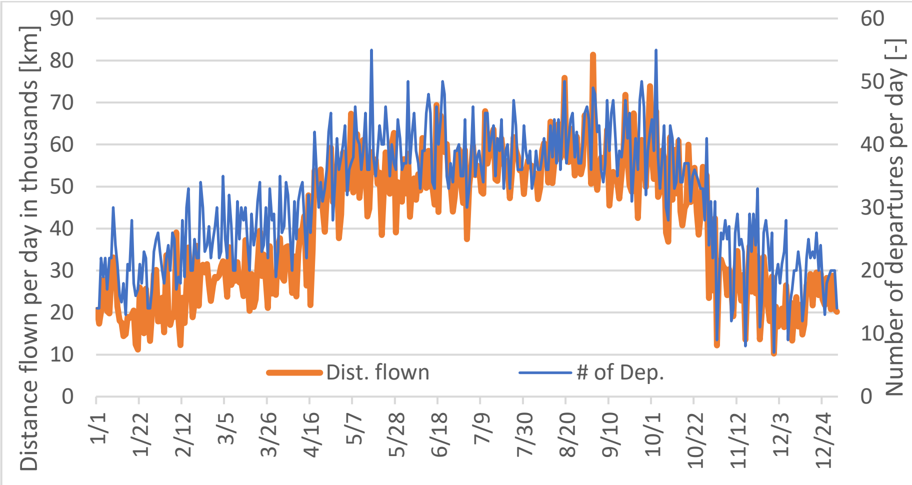

Figure 17:Seasonal variation in departures and distance flown (2019)

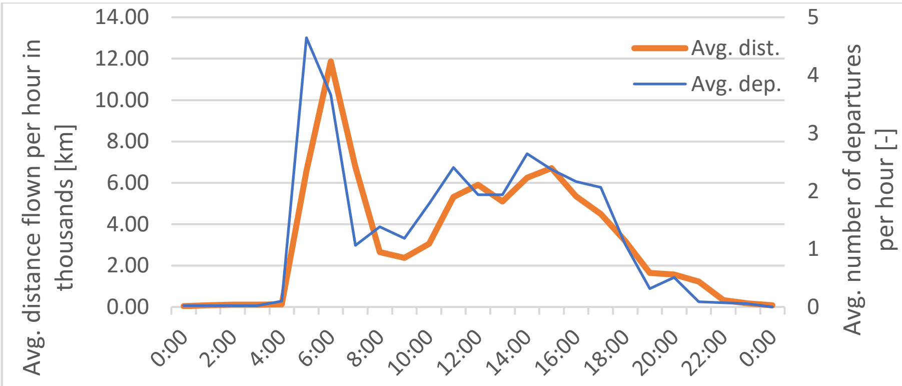

Figure 18: Daily variations in average departures and distances (2019)

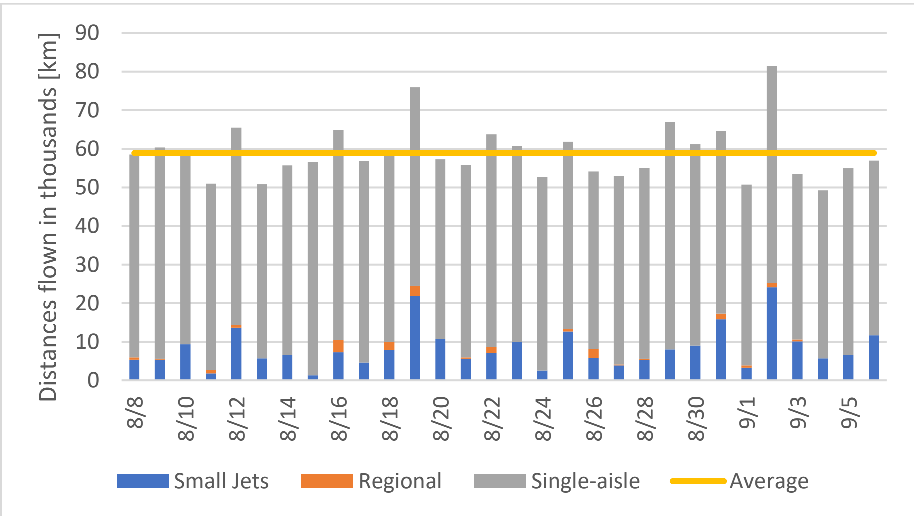

Figure 19: Distances that were flown by different segments per day and the average total per day over the busiest month.

Appendix B. Forecasting fleet size change from 2019 to 2050

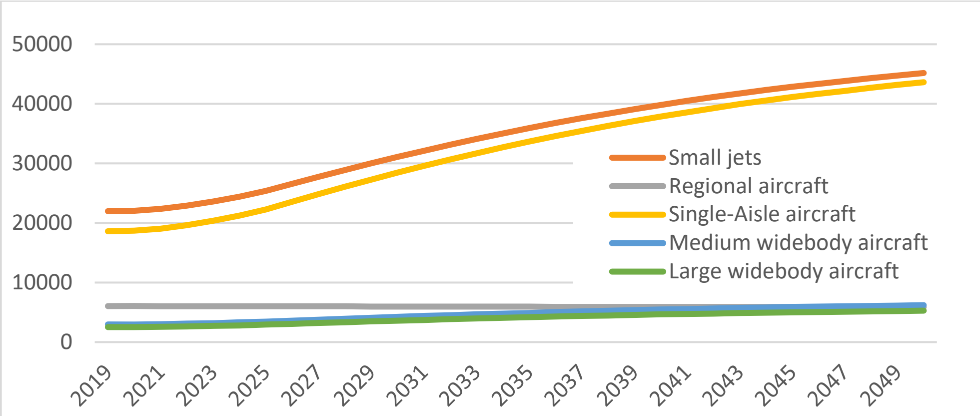

Figure 20: Forecast of the worldwide aircraft fleet per segment

1) Forecasting number of delivered aircraft:
- Existing fleet numbers in 2019 as well as estimated fleet numbers in 2029 for the small jet aircraft segment were obtained (Kress, 2021).
- Existing fleet numbers in 2019, as well as estimated fleet numbers in 2039 for Boeing aircraft (representing the Regional, Single-Aisle, and widebody aircraft segments), were obtained from the open-source database Airfleets.net, and the Boeing Commercial Market Outlook (Hoelzen et al., 2022). Embraer data is added to the regional segment to include turboprop aircraft that are not included in Boeings estimates.
- The above data is used to find the Compound Annual Growth Rate (CAGR) for each segment. Equation ((Fleet_year_i/Fleet_year_0)^(1/i))-1. The CAGR is used to calculate the annual total fleet change.
- The average total fleet change per year, Average fleet size, and the average share of deliveries related to fleet size are found. Referring to the average share of deliveries related to fleet size "The growth rates were extrapolated to 2050 since no contradictory indicators or forecasts are available for that time" (Hoelzen et al., 2022). And by extrapolated he means kept constant from 2026 to 2050. The values from 2020 to 2025 increase linearly from half to full value to take into account the effect of COVID.

2) "To account for less deliveries and more retirements of aircraft due to COVID effects the fleet projection from 2019 to 2024 is adjusted to fit reported market data from AWIN for 2020 and 2021" (Hoelzen et al., 2022).

3) Forecasting air traffic growth effect on total fleet size:
- Growth of RPK forecast (Grewe et al., 2021) in the percentage of growth is used to calculate the effect on fleet size.
- The growth percentage is divided by the average of the forecasted RPK values to find the assumed effect on total fleet size.
- Covid effect is takin into account for years 2020-2025 (using the values 0.1, 0.35, 0.6, 0.75, 0.9, and 1.05).

4) Fleet total numbers: Calculated by using the previous year's total fleet number and adding the average total fleet change after multiplying it with the assumed effect on total fleet size.

5) The number of aircraft retired: Calculated by subtracting the number of delivered aircraft per year from the change in the total aircraft fleet.

Appendix C. Scenarios for hydrogen aircraft adoption

Assumptions for every aircraft segment include the year of entry-into-service (EIS), years for achieving full manufacturing scale (ramp-up years), and take-rate. The values are based on estimates from NLR and clean sky 2 reports (Clean Sky 2 JU, FCH 2 JU, 2020; Royal Netherlands Aerospace Centre and SEO Amsterdam Economic, 2021). Both assume that all technological barriers can be overcome.

In both cases, the Large Widebody aircraft segment is assumed to continue using jet fuel until 2050, but in the form of sustainable aviation fuel (SAF) instead of kerosene.

Table 16: Assumptions defining the diffusion scenarios of hydrogen aircraft technology.

Scenario	Aircraft segment	Entry into service (EIS)	Ramp-up [years]	Take-rate [%]
Best case	Small jet and regional	2024	2	100
	Single aisle	2035	3	100
	Medium widebody	2035	4	67
	Large widebody	n/a	n/a	n/a
Worst case	Small jet and regional	2026	4	80
	Single aisle	2037	5	67
	Medium widebody	2037	6	50
	Large widebody	n/a	n/a	n/a

1) Best case scenario

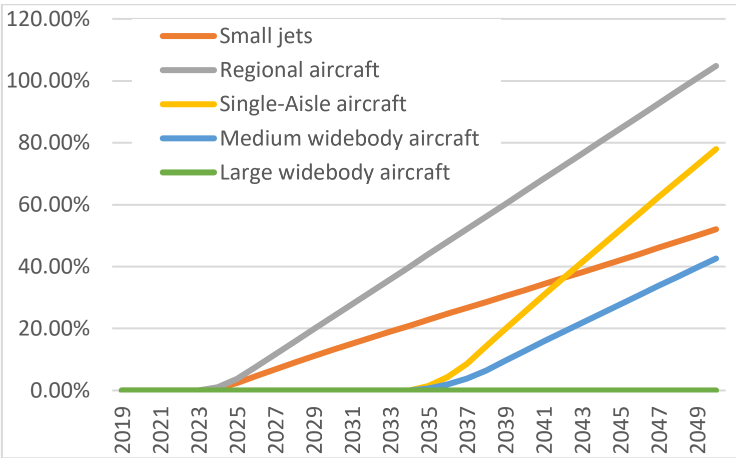

Figure 21: Share of H2 fueled aircraft in each fleet segment (best case).

The best-case scenario assumes a change in regulations limiting emissions, the introduction of a very high emissions tax, that the regulatory bodies for aircraft certification will outperform their previous certification processes, and that the estimated technology readiness is achieved by manufacturers on time. In this scenario, gas hydrogen infrastructure and refueling must be implemented at all regional airports between 2024 and 2026.

2) Worst case scenario

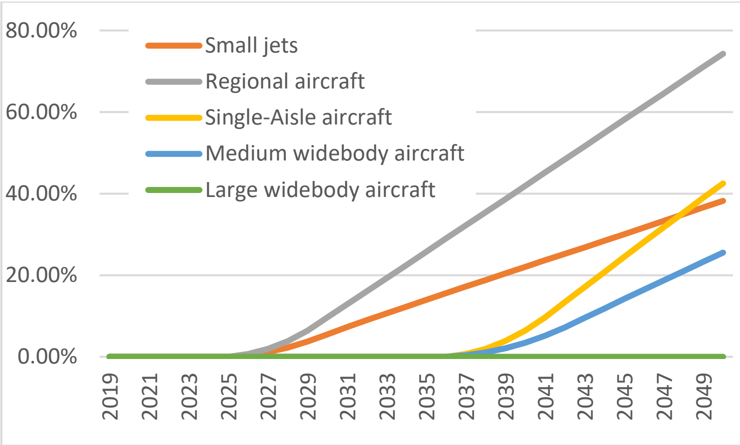

Figure 22:Share of H2 fueled aircraft in each fleet segment (worst case).

In the worst-case scenario, a two-year delay is added to entry-into-service and the manufacturing ramp-up time. This represents delays in technology readiness, production, and/or certification processes. Also, a reduction in the take-rate is applied to account for the potential lack of demand for aircraft due to a lack of policy incentives and/or hydrogen infrastructure at airports.

Further insight into route planning would help in implementing a step function instead of a gradual increase when applying the diffusion rate of hydrogen propelled aircraft to hydrogen fuel consumption. This is based on the idea that newly adopted hydrogen aircraft would most probably serve planned routes and hence increase hydrogen consumption in larger steps.

Appendix D. Jet fuel consumption projections

The distances flown out of RTHA by aircraft in each segment are found by multiplying the Average distance per flight [km] by the number of departing flights. Next, the average fuel consumption [kg/km] is multiplied by the distance flown to find the consumed fuel per segment. The

Table 17: Average fuel consumption for different aircraft segments in 2019.

Aircraft segment	Fuel consumption [kg/km]	Exemplary aircraft
Small jets	1.5	PC-12, DA-7X, C-525, C-510, P-180, DA2000, EMB505
Regional aircraft	1.3	BE18,DHC6,E-175,ERJ135
Single-aisle aircraft	3.5	E190,A318,A319,A320,A321,B737,B739
Medium widebody aircraft	6.3	A330,B787,B767
Large widebody aircraft	11.3	B777,A350,A380,B747

The fuel consumption value for the small jet segment is obtained by averaging the fuel consumption of the most used aircraft of this segment at RTHA. The values for the remaining segments are obtained using an emissions calculator (European Environment Agency, 2019).

As shown in Table 18, the estimated total fuel consumption for the considered aircraft segments in 2019 at RTHA is 46 KTons of Jet-A1 fuel. The data provided by RTHA does not include quantities of fuel used per segment but includes the total amount of Jet-A1 fuel used in 2019 by all aircraft. When comparing the estimated total value to the actual value (49 KTons) the error is found to be acceptable (within ±10%). Hence, the estimated fuel consumption per segment is used in projecting future consumption.

Table 18: Estimated fuel consumption per segment in 2019.

Aircraft segment	Average distance per flight [km]	Distance flown [km]	Fuel consumption [Tons]
Small jets	961.12	2745919.84	4118.87976
Regional	600.35	171099.75	222.429675
Single-aisle narrowbody	1416.17	11866088.43	41531.30951
Medium widebody	2525.38	20203.04	127.279152
Large widebody	1552	1552	17.5376
Total	6093.9	12058943.22	46017.43569

To estimate future annual fuel consumption two effects are taken into account,

- An annual increase in RPK.
- Change in aircraft efficiency over time.

A consensus in multiple sources was found regarding the magnitude of the above effects, Furthermore, the estimates of the above effects (Grewe et al., 2021; Hoelzen et al., 2022; Pearce, 2021) consider the effects of COVID-19 on RPK and the industry.

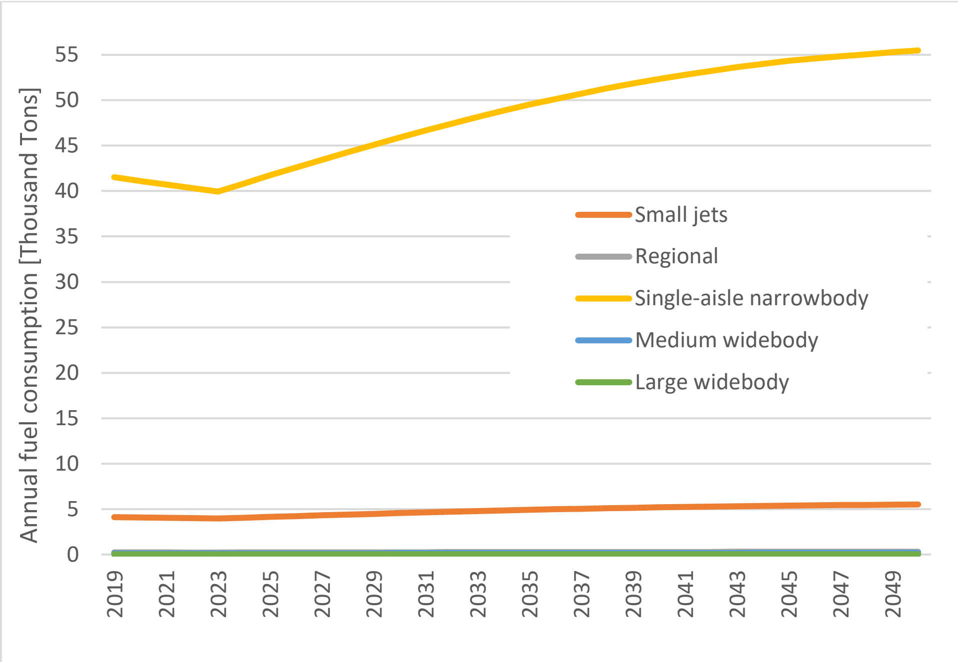

Figure 23: Projections of annual fuel consumption for each aircraft segment.

The projections in Fig. 23, demonstrate the annual fuel consumption for each aircraft segment. Over the timeline of the projection. The figure shows an increase of 34% in small, regional, and Single-Aisle aircraft segments and an increase of 49% for the widebody segments over 30 years.

The difference in the percentage of increase is due to the projections of change in RPK that are used in the calculations. The RPK projections used (Grewe et al., 2021; Hoelzen, Flohr, et al., 2022; IATA, 2021) are different for domestic and international flights. This dependency is applied to this projection by categorizing small jet, regional and single-aisle segments as domestic (within the EU) and the medium and widebody segments as international (beyond the EU).

Appendix E. Hydrogen fuel projections

As explained in chapter 2, due to the more complex nature of the supply chain for liquid hydrogen and the high cost of liquification (30% of the energy content stored is used in the liquification process), the initial use of hydrogen in aviation will be in the form of compressed gas.

Table 19: Properties of hydrogen in different states (assuming a gravimetric energy density of 33.35 [kWh/kg])

State	Pressure [bar]	Temperature [C]	Density [kg/m3]	Volumetric Energy Density [kWh/m3]
GH	350	27	23	767
GH	700	27	38	1267.3
LH	1.1	-252.87	71	2367.85
Kero	1.0	27	830	10651.67

Highly pressurized hydrogen (700 bar) properties are used in fuel conversion for small and regional aircraft. While liquid hydrogen properties are used in fuel conversion for single-aisle and widebody aircraft.

A 0.36 conversion factor is used to convert jet fuel (kerosene with a gravimetric energy density of 11.89 [kWh/kg]) to the hydrogen equivalent. But a change factor in specific energy consumption is estimated and applied to the conversion factor as shown in Table 20. This is to make up for the loss in efficiency caused by the use of hydrogen fuel systems in the aircraft (consisting of heavier components and hence higher losses in longer flights and larger airplanes) (Hoelzen, Silberhorn, et al., 2022; McKinsey & Company, 2020).

Table 20: conversion factors based on energy density and loss of efficiency.

Segments	Change of spec. energy cons.	Conversion fact. [$kg_{LH2}/kg_{kerosene}$]
Small jets	1.00	0.36
Regional	1.00	0.36
Single-Aisle	1.12	0.40
Medium widebody	1.18	0.42
Large widebody	1.42	0.51

Using the calculated hydrogen fleet adoption projections, it is possible to determine the percentage of fuel consumption that will turn to hydrogen as shown in Fig. 24.

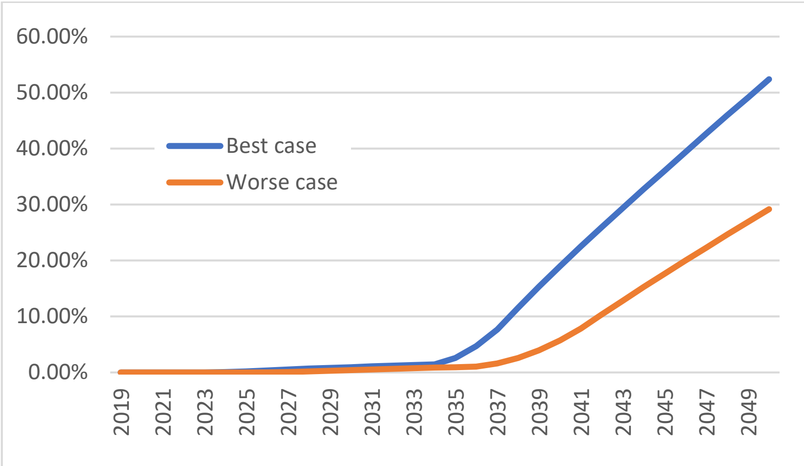

Figure 24: Percentage of jet fuel replaced by hydrogen fuel

Using the kerosene to hydrogen conversion factors it is possible to calculate the amount of hydrogen required as shown in Fig. 25. It is assumed, that the small jet and regional segments will only use compressed gas hydrogen while the single-aisle and widebody medium segments will only use liquid hydrogen.

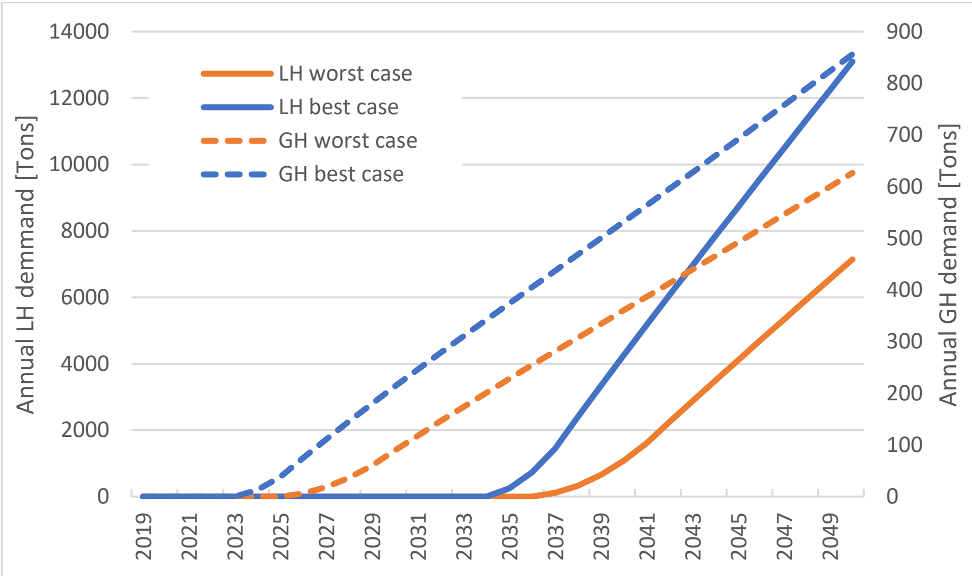

Figure 25: Annual forecasted demand for hydrogen at RTHA.

With the technological advances in the next 25 years, at some point, liquid hydrogen will be a feasible solution for small jets and regional aircraft. But due to the long-life cycle of aircraft and the earlier start of gas hydrogen aircraft technology, it is assumed that separation between the segments and the two fuel options will be stable until 2050.

The hydrogen infrastructure design requirements used in the cost analysis will be based on the hydrogen demand in 2050 as shown in table 21. The peak daily and hourly demands are calculated by applying the seasonal and daily variations in air traffic (described in Appendix A) to the projected annual demands in 2050. The resulting requirements are rounded off and presented in table 20.

Table 21: Design requirements used in sizing the hydrogen infrastructure subsystems.

	EIS [year]	Annual demand in 2050 [tons]	Peak Daily demand in 2050 [tons/day]	Peak hourly demand in 2050 [tons/hour]
GH best case	2024	860 (rounded to 10)	7 (rounded to 1)	0.6 (rounded to 0.1)
GH worst case	2026	630 (rounded to 10)	5 (rounded to 1)	0.4 (rounded to 0.1)
LH best case	2035	13100 (rounded to 100)	70 (rounded to 10)	13 (rounded to 1)
LH worst case	2037	7100 (rounded to 100)	40 (rounded to 10)	7 (rounded to 1)

The organized nature of scheduled airline air traffic versus that of private jets (that dominate the small jet and regional air traffic (operating on GH) is visible when comparing figures 26 and 27. For better estimates of peak values, a larger sample is recommended in the case of gas hydrogen.

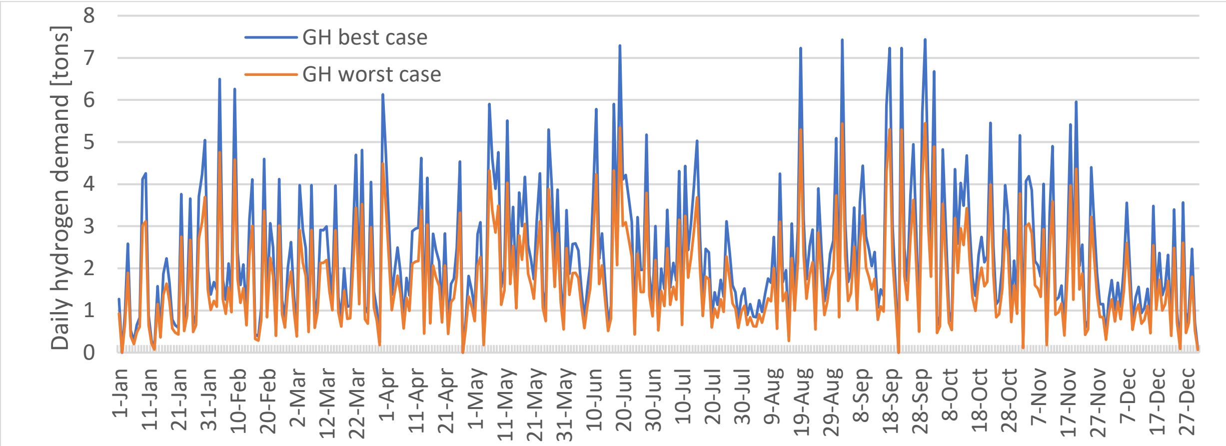

Figure 26: Seasonal variations in daily gas hydrogen demand

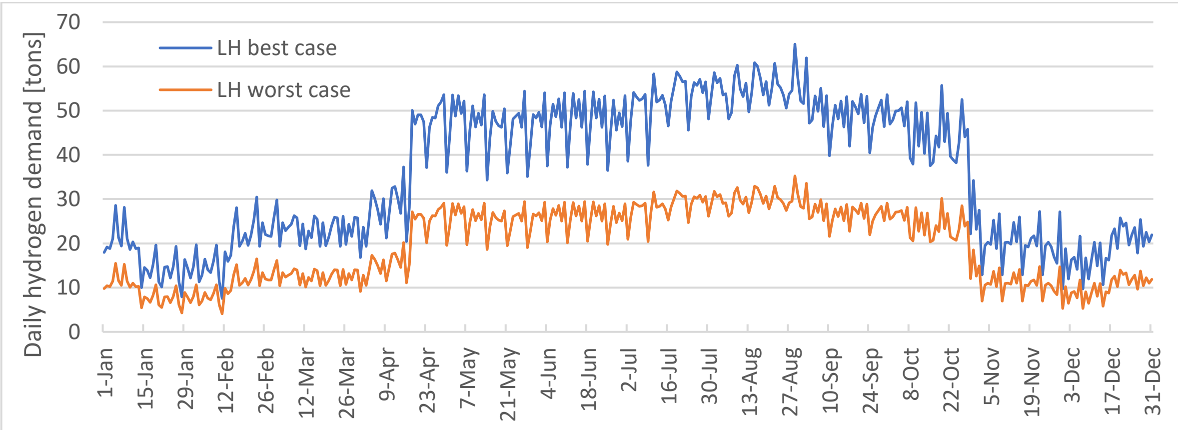

Figure 27: Seasonal variations in daily liquid hydrogen demand

Appendix F. Techno-economic parameters LH infrastructure

Liquefaction plant (LFP)

The necessary capital investment and specific energy consumption for a liquification station vary with the maximum capacity of the station (maximum amount of hydrogen it can produce per day). Capital and energy cost estimates for different output level requirements are found (Hoelzen et al., 2022) and trendline equations are estimated. These results in Eq. 6 and 7 are illustrated as the Power and polynomial curves in figures 28 and 29.

$$CAPEX_{LFP} = 10.5\ X^{0.643} \quad (6)$$

$$E_{El} = -2\ (E - 17)\ X^3 + 3\ (E - 11)X^2 - 2\ (E - 5)X + 9.84 \quad (7)$$

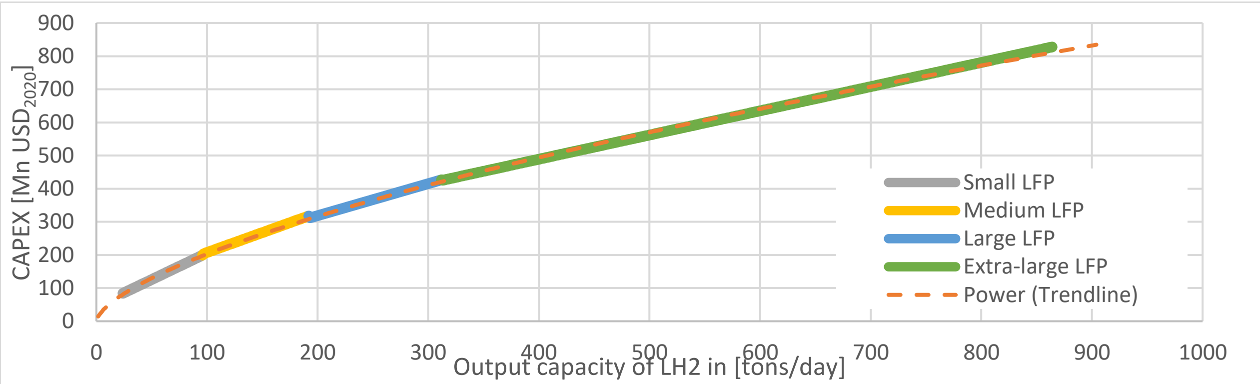

Figure 28: A power curve regression model fitting the liquification plant CAPEX data.

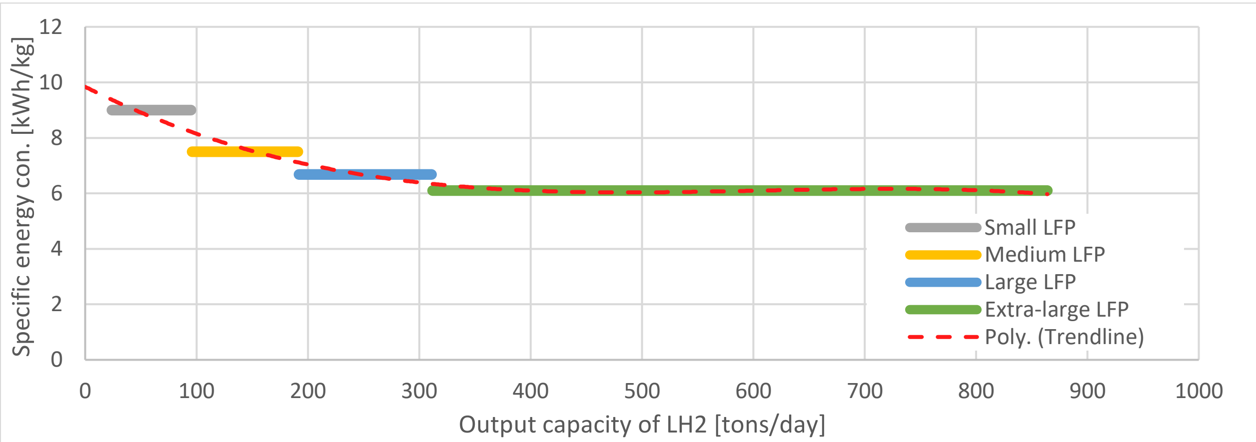

Figure 29: A polynomial curve regression model fitting the liquefaction plant spec. energy consumption.

Other relevant parameters are summarized in Table 22.

Table 22: Techno-economic parameters for LFPS (Hoelzen, Flohr, et al., 2022).

Depreciation Period [years]	20
Annual O&M costs [% of CAPEX]	4
Specific losses per kg [% of feed]	1.65

Buffer storage

Storage facility for liquified hydrogen including a recycling system for extracting and reliquefying any hydrogen vapor through the liquification plant (LFP). Figure 30 illustrates the CAPEX necessary for different scales of the storage facility, and a power curve regression model fitting the data is presented in Eq. 4.

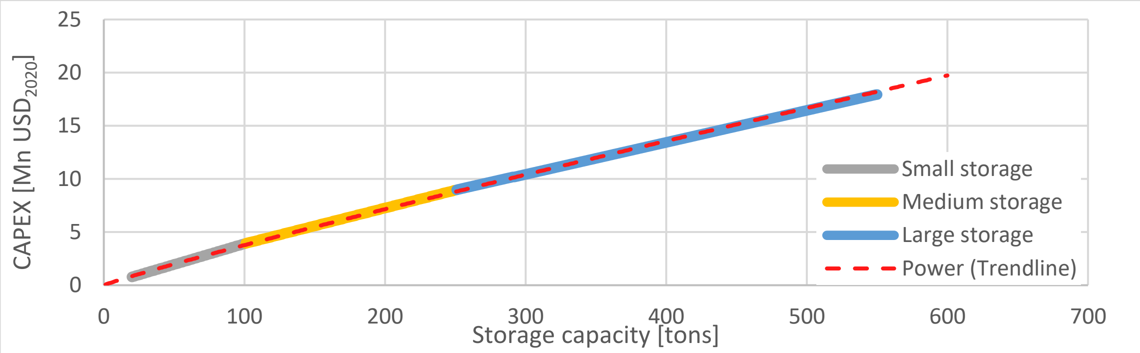

Figure 30: A power curve regression model fitting the CAPEX for LH storage as a function of maxim storage capacity

$$CAPEX_{sto} = 53493.2\ X_{sto}^{0.923957} \quad (8)$$

Table 23, shows the remaining necessary techno-economic parameter estimates relevant for the storage facility (Hoelzen et al., 2022).

Table 23: Techno-economic parameters for LH storage (Hoelzen, Flohr, et al., 2022).

Depreciation Period [years]	20
Annual O&M costs [% of CAPEX]	2
Specific losses per kg stored [%]	-0.0325 X + 0.1333

Liquid Hydrogen Pump System

Also referred to as a cryogenic-hydrogen pump or a cryogenic pump is a necessary component that enables the transfer of liquid hydrogen.

Table 24: Techno-economic parameters for LH cryogenic pump system (Hoelzen, Flohr, et al., 2022).

Capacity [t_{LH2}/h]	1.2 m_{LH2_max}
CAPEX [USD_{2020}/t_{LH2}/h]	256300
Depreciation period [years]	10
Specific energy demand [kWh_{el}/kg_{LH2}]	0.1
Annual O&M costs [% of CAPEX]	3
Specific losses per kg LH2 feed [%]	0%

Refueling Trucks & Dispenser

The truck and a trailer consisting of a tank, pump, and dispenser (bowser) are also referred to as a bowser truck or a truck and dispenser. The truck and dispenser solution was chosen over pipeline & hydrant infrastructure because the latter will not be cost-effective even at the best-case scenario rate of hydrogen use in RTHA in 2050.

Table 25: Techno-economic parameters for LH cryogenic pump system (Hoelzen, Flohr, et al., 2022).

LH2 truck	
CAPEX in [USD_{2020}/truck]	90000
Depreciation period [years]	12
Specific energy cost [USD_{2020}/km]	0.35
Annual O&M costs [% of total CAPEX]	3
LH2 trailer	
Capacity [t_{LH2}]	4
CAPEX [USD_{2020}/truck]	550000
Depreciation period [years]	12
Annual O&M costs [% of total CAPEX]	2
Specific losses [kg/kgH2 feed]	1%

Appendix G. Techno-economic parameters for GH infrastructure

The compressed hydrogen gas infrastructure will use hydrogen gas that will be delivered using tube trailers at a pressure that varies between 200 and 500 bar. Direct pipeline infrastructure will not be connected to the airport until 2030 and hence it is not considered in the early stages of hydrogen use in aviation. But when the pipeline is connected, the remainder of the system can function with minor alterations.

Compressor System

The delivered hydrogen needs to be compressed to a pressure of 700-900 bars before it can be placed in buffer storage. This is to avoid the need for compression before refueling.

Table 26: Techno-economic parameters for the compressor (Reuß et al., 2019) *specific energy from* (Gardiner, 2009).

Capacity [kg_{GH2}/h]	1.2 $m_{GH\_H\_peak}$
CAPEX [USD_{2020}/kgG_{H2}/h]	15000*x^0.6089
Depreciation period [years]	15
Specific energy demand [kWh_{el}/kg_{GH2}]	3.05
Annual O&M costs [% of CAPEX]	4
Specific losses per kg feed [%]	0.5

Buffer Storage

Table 27:Techno-economic parameters for gas hydrogen storage (Caponi et al., 2021; NREL, 2014; Reuß et al., 2019) .

Capacity [kg_{GH2}]	3* $m_{GH\_D\_peak}$
Specific CAPEX [USD_{2020}/kg_{GH2}]	1450
Depreciation period [years]	12
Annual O&M costs [% of CAPEX]	2%

Refueling Trucks & Dispenser

Table 28: Techno-economic parameters for gas hydrogen tractor (Hoelzen, Flohr, et al., 2022)*and trailer (Reuß et al., 2019).*

GH2 truck	
CAPEX [USD_{2020}/truck]	90000
Depreciation period [years]	12
Specific energy cost [USD_{2020}/km]	0.35
Annual O&M Costs [% of total CAPEX]	3
GH2 trailer (500bar)	
Capacity [t_{GH2}]	1.2
CAPEX [USD_{2020}/truck]	550000
Depreciation period [years]	12
Annual O&M costs [% of CAPEX]	2
Specific losses [% of kgH2 feed]	1%

Appendix H. Costs for the Transition Scenarios

Best case scenario

A) GH infrastructure

Compressor		
CAPEX	571420	[€_2020]
Electric energy	3.05	[KWh/kg]
Depreciation Period	15	[years]
Cost of O&M	0.04	[%]
Cost of O&M	22857	[€_2020]
Specific losses	4.343	[ton/year]
Annuity factor	0.1029	[-]
Storage		
CAPEX	21116488	[€_2020]
Electric energy	-	[KWh/kg]
Depreciation Period	12	[years]
Cost of O&M	0.02	[%]
Cost of O&M	422330	[€/year]
Specific losses	0	[ton/year]
Annuity factor	0.1193	[-]
Bowser		
Number	1	[truck]
Truck transport capacity	1.2	[tons_LH2/truck]
CAPEX	443828	[€_2020]
Depreciation period	12	[years]
Distance	1.5	[km]
Energy cost (diesel)	659	[€/year]
Cost O&M	0.0314	[-]
Cost O&M	13921	[€/year]
Specific losses	8.6	[tons/year]
Annuity factor	0.1193	[-]

B) LH infrastructure

Liquification plant		
CAPEX	59454446	[€_2020]
Electric energy	8.57	[KWh/kg]
Depreciation Period	20	[years]
Cost of O&M	0.04	[%]
Cost of O&M	2378178	[€/year]
Specific losses	216.15	[ton/year]
Annuity factor	0.0872	[-]
Storage		
CAPEX	2747141	[€_2020]
Electric energy	-	[KWh/kg]
Depreciation Period	20	[years]
Cost of O&M	0.02	[%]
Cost of O&M	54943	[€/year]
Specific losses	14.7	[ton/year]
Annuity factor	0.0872	[-]
Cryogenic pump		
CAPEX	1460640	[€_2020]
Electric energy	0.1	[KWh/kg]
Depreciation Period	10	[years]
Cost of O&M	0.02	[%]
Cost of O&M	29213	[€/year]
Specific losses	0	[ton/year]
Annuity factor	0.1359	[-]
Bowser		
Number	4	[truck]
Truck transport capacity	4	[tons_LH2/truck]
CAPEX	935211	[€_2020]
Depreciation period	12	[years]
Distance	1.5	[km]
Energy cost (diesel)	3439	[€/year]
Cost O&M	0.03	[%]
Cost O&M	28056	[€/year]
Specific losses	131	[tons/year]
Annuity factor	0.1193	[-]

Worst case scenario

A) GH infrastructure

Compressor		
CAPEX	397303	[€_2020]
Electric energy	3.05	[KWh/kg]
Depreciation Period	15	[years]
Cost of O&M	0.04	[%]
Cost of O&M	15892	Mn [€/year]
Specific losses	3.1815	[ton/year]
Annuity factor	0.1029	[-]
Storage		
CAPEX	13423999	[€_2020]
Electric energy	0	[KWh/kg]
Depreciation Period	12	[years]
Cost of O&M	0.02	[%]
Cost of O&M	268480	[€/year]
Specific losses	0	[ton/year]
Annuity factor	0.1193	[-]
Bowser		
Number	1	[truck]
Truck transport capacity	1.2	[tons_GH2/truck]
CAPEX	443828	[€_2020]
Depreciation period	12	[years]
Distance	1.5	[km]
Energy cost (diesel)	482.62	[€/year]
Cost O&M	0.0314	[-]
Cost O&M	13920	[€/year]
Specific losses	6.3	[tons/year]
Annuity factor	0.1193	[-]

B) LH infrastructure

Liquification plant		
CAPEX	36906792.37	[€_2020]
Electric energy	9.0765	[KWh/kg]
Depreciation Period	20	[years]
Cost of O&M	0.04	[%]
Cost of O&M	1476272	[€/year]
Specific losses	117.15	[ton/year]
Annuity factor	0.0872	[-]
Storage		
CAPEX	1457495	[€_2020]
Electric energy	-	[KWh/kg]
Depreciation Period	20	[years]
Cost of O&M	0.02	[%]
Cost of O&M	29150	[€/year]
Specific losses	8.4	[ton/year]
Annuity factor	0.0872	[-]
Cryogenic pump		
CAPEX	699981	[€_2020]
Electric energy	0.1	[KWh/kg]
Depreciation Period	10	[years]
Cost of O&M	0.02	[%]
Cost of O&M	14000	[€/year]
Specific losses	0	[ton/year]
Annuity factor	0.1359	[-]
Bowser		
Number	2	[truck]
Truck transport capacity	4	[tons_LH2/truck]
CAPEX	416167	[€_2020]
Depreciation period	12	[years]
Distance	1.5	[km]
Energy cost (diesel)	1864	[€/year]
Cost O&M	0.03	[%]
Cost O&M	12485	[€/year]
Specific losses	71	[tons/year]
Annuity factor	0.1193	[-]