International Journal of Hydrogen Energy 64 (2024) 633–642

Contents lists available at ScienceDirect

International Journal of Hydrogen Energy

journal homepage: www.elsevier.com/locate/he

Hydrogen in aviation: A simulation of demand, price dynamics, and CO_2 emission reduction potentials

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A R T I C L E I N F O

Handling editor: S Nanda

Keywords:
Aviation
Hydrogen demand
Sustainable aviation fuels
CO_2 emissions
Emission reduction

A B S T R A C T

Aviation contributes to anthropogenic climate change by emitting both carbon dioxide (CO_2) and non-CO_2 emissions through the combustion of fossil fuels. One approach to reduce the climate impact of aviation is the use of hydrogen as an alternative fuel. Two distinct technological options are presently under consideration for the implementation of hydrogen in aviation: hydrogen fuel cell architectures and the direct combustion of hydrogen. In this study, a hydrogen demand model is developed that considers anticipated advancements in liquid hydrogen aircraft technologies, forecasted aviation demand, and aircraft startup and retirement cycles. The analysis indicates that global demand for liquid hydrogen in aviation could potentially reach 17 million tons by 2050, leading to a 9% reduction in CO_2 emissions from global aviation. Thus, the total potential of hydrogen in aviation extends beyond this, considering that the total market share of hydrogen aircraft on suitable routes in the model is projected to be only 27% in 2050 due to aircraft retirement cycles. Additionally, it is shown, that achieving the potential demand for hydrogen in aviation depends on specific market prices. With anticipated declines in current production costs, hydrogen fuel costs would need to reach about 70 EUR/MWh by 2050 to fulfill full demand in aviation, assuming biofuels provide the cheapest option for decarbonization alongside hydrogen. If e-fuels are the sole option for decarbonization alongside hydrogen, which is the more probable scenario, the entire hydrogen demand potential in aviation would be satisfied according to this study's estimates at significantly higher hydrogen prices, approximately 180 EUR/MWh.

1. Introduction

Aviation contributes to anthropogenic climate change by emitting both carbon dioxide (CO_2) emissions and so-called non-CO_2 species (nitrogen oxides (NO_x), sulfur oxides (SO_x), water vapor (H_2O), aerosols, and the formation of contrails and contrail cirrus). According to Lee et al. [1], global aviation is responsible for 'a few percent to anthropogenic radiative forcing. So-called non-CO_2 impacts comprise about 2/3 of the net radiative forcing.' However, it has to be noted that there are still large uncertainties concerning the impact of some of these species, especially NO_x emitted at high altitudes, and cloud effects [1]. Air traffic is likely to grow in the coming years and decades, which will lead to increasing climate-relevant emissions from the sector (see for instance Gelhausen et al. [2] and Gelhausen et al. [3]). One element in a strategy to reduce the climate impact of air transport and to reach net-zero CO_2 emissions targets is the use of hydrogen (H_2). Other elements considered in science and politics and partly already implemented are the use of sustainable aviation fuels (SAF), technological efficiency improvements in aviation as well as market-based measures such as CO_2-emission trading schemes regulating air transport, among other policy measures.

The future use of hydrogen has been strategically planned and launched by a number of industrialized and other countries in recent years. Japan has been among the first industrialized countries with an own hydrogen strategy for industrial and transport sectors launched in 2017 [4]. In 2020, the European Commission published a 'hydrogen strategy for a climate-neutral Europe'. Since December 2022, a cooperation agreement on the future use of hydrogen has been in place between Japan and the European Union (EU) [5]. Australia is also a forerunner in terms of implementing a national hydrogen strategy as it is planning large-scale industrial production and export of green hydrogen [6]. The same applies to Saudi Arabia, for example [7]. Some southern European states also plan to produce green hydrogen in the future [8]. These developments indicate that, on the one hand, cost degressions in the production and use of green hydrogen can be expected in the future. On the other hand, competing uses for green hydrogen are foreseeable, so that aviation will be only one demander of many for hydrogen in the

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https://doi.org/10.1016/j.ijhydene.2024.03.241
Received 4 October 2023; Received in revised form 7 March 2024; Accepted 17 March 2024
Available online 30 March 2024

future.

The objective of this paper is to investigate the options and challenges for a successful introduction of hydrogen in aviation from an economic point of view. To the best of the authors' knowledge, this research will contribute to the so far lacking literature on this issue. First, hydrogen demand potentials in the aviation sector are estimated for the years 2040, 2045 and 2050. This simulation is based on a comprehensive model that considers recent technological advancements in liquid hydrogen-based aircraft technologies, current aviation market forecasts, and aircraft retirement cycles.

Second, this approach also provides the opportunity to calculate the potential for CO_2 emission reductions through the use of hydrogen in aviation. As the non-CO_2 impacts of a hydrogen strategy for aviation, and in particular the impact of water vapor, are still under discussion in the atmospheric science community [9,10], this research focuses on the CO_2 impacts of such a strategy. And third, after determining the hydrogen market potential in aviation, price-specific hydrogen demand curves are estimated. This enables an understanding of what hydrogen fuel prices are necessary in 2050 to achieve the full hydrogen demand potential and, consequently, to realize opportunities for reducing CO_2 emissions. The analysis of demand patterns is dependent on the cost of alternative options for decarbonization, specifically biofuels and e-fuels. Unlike sustainable aviation fuels, which can be accommodated by existing aircraft technologies and airport infrastructures, incorporating hydrogen in aviation also necessitates the introduction of new aircraft as well as new refueling and storage infrastructures at airports.

A main contribution of this paper hereby is linking the simulated hydrogen demand potential, derived from the latest simulations in future aircraft technologies by the German Aerospace Center (DLR), with economically grounded assumptions about a potential demand curve for hydrogen in aviation. This study also provides current estimates of potential CO_2 savings from the use of novel aircraft technologies powered by liquid hydrogen. By considering expected future prices of aviation fuels, necessary maximum prices for liquid hydrogen are defined, ensuring the full exploitation of the calculated demand potential. Lastly, guidelines are also provided on how to ensure the usage of hydrogen in the future and as well as necessary actions from a political perspective.

This paper is structured as follows: Section 2 provides a literature review of the expected hydrogen demand in the future, followed by a brief overview of the current technological options for the use of H_2 in aviation. Then the current and future costs of hydrogen production and use are analyzed. After methodological considerations in Section 3, the hydrogen potential for aviation and an aviation-specific H_2 demand curve are derived and discussed. The paper closes with conclusions and policy recommendations.

2. The use of hydrogen in aviation

2.1. Hydrogen demand

Hydrogen consumption in the transportation sector is currently negligible, with only a small number of hydrogen-powered cars, buses, or trucks in operation. Total global hydrogen demand mainly comes from the chemical sector, the petrochemical industry and steel production. However, in 2020, hydrogen and hydrogen-based fuels accounted for less than 0.1% of the total final energy consumption [11–13]. By 2030, demand for hydrogen in a net-zero CO_2 emissions scenario (NZE) is likely to rise to 210 million tons (Mt) and to 530 Mt by 2050 according to the International Energy Agency's (IEA) estimates (see Fig. 1). It is projected that the transport sector's demand for hydrogen will cover approximately 23% [14] to 38% [12] of the total demand. The direct demand for hydrogen will come from road transportation, especially for fuel cell cars, buses and trucks. Hydrogen demand in air and marine transport is anticipated to arise in form of synthetic fuels and ammonia.[1]

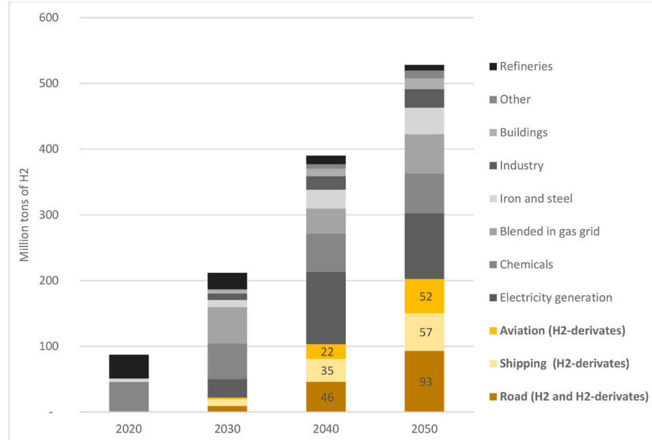

Fig. 1. Demand for hydrogen and its derivates by sector, NZE scenario 2020–2050 (in MtH_2). Data adapted from Ref. [15]. Notes: In the IEA's net zero CO_2 emissions (NZE) scenario, hydrogen demand in aviation and shipping is entirely met by hydrogen-based derivatives such as synthetic fuels. Numbers are given in million tons (MtH_2).

However, there is growing interest in using hydrogen in aviation directly for combustion and in fuel cells. According to the IEA, approximately 95% of global flights have the potential to be fueled by hydrogen. This estimation encompasses regional, short-haul, and medium-haul flights, which would contribute up to 58% of the overall fuel consumption in commercial aviation [11]. NLR and SEO [16] as well as NLR [17] forecast a CO_2 reduction potential of 16%–20% by 2050 through the direct use of hydrogen in aviation. The number of flights that could be operated with hydrogen-powered aircrafts by then varies in their estimates between 35% and 38% depending on the scenario. For Europe, this could imply a reduction in CO_2 emissions of up to 60 $MtCO_2$ by 2050. The International Air Transport Association (IATA) assumes that new energy carriers such as hydrogen could contribute to climate neutrality with a share of 13% [18].

Only a few studies have so far estimated the potential for the direct use of hydrogen in aviation in more detail. McKinsey & Company et al. [19] indicate that hydrogen could cover 7%–38% of the energy demand of the aviation sector by 2050, depending on the scenario assumed. In their reference scenario, the estimated global potential for hydrogen demand is 9 MtH_2 by 2040 and 42 MtH_2 by 2050. According to the industry association Air Transport Action Group (ATAG), the aviation sector will require 43 MtH_2 by 2050 and 79 MtH_2 by 2060 for direct usage [20]. The European Hydrogen Backbone (EHB) initiative, a joint undertaking of European energy infrastructure operators, however forecasts direct hydrogen demand in Europe of 0.27 MtH_2 in 2040 and 2.04 MtH_2 in 2050 [21]. NLR [17] conducts a calculation to assess the potential direct and indirect hydrogen demand relating to all flights originating from the European Union (EU) and the United Kingdom (UK) from 2025 to 2050. By 2050, direct demand for hydrogen could add up to 4.9 MtH_2 per year. Grimme and Braun [22] estimate the global direct hydrogen demand as well as the demand specifically attributed to European air traffic for the years 2040, 2045, and 2050. The authors

[1] Direct hydrogen demand in aviation involves the utilization of hydrogen in either gaseous or liquid form, typically in fuel cells or aircraft turbines. Indirect hydrogen demand in aviation refers to the use of hydrogen derivatives, such as synthetic fuels or e-fuels.

estimate a demand of 3.3 MtH_2 in 2050 for flights departing from Europe. According to Steer and DLR [23], there is an anticipated potential hydrogen demand of 2.6 MtH_2 for Europe, which is projected to increase up to 6.1 MtH_2 by 2050. Lastly, Steer [24] examines the hydrogen potential for intra-European commercial flights. In the reference scenario, the authors assume a potential annual demand of 6.7 MtH_2 in 2050. Figs. 2 and 3 provide an overview of the studies that have estimated the direct hydrogen demand from aviation in the years 2040, 2045, and 2050. Table A1 in the Appendix presents a summary in more detail. The cumulative demand for hydrogen from aviation, including indirect demand, could then be comparable to or even exceed the expected demand for hydrogen from other sectors like the chemical industry.

2.2. Hydrogen technologies and environmental impact

For the technological implementation of hydrogen in aviation, several options exist. The first technological option concerns the type of propulsion system. Two different options are currently being considered: hydrogen fuel cell architectures, where hydrogen is converted into electricity, subsequently driving propellers via electric motors or the direct combustion of hydrogen in gas turbines with turboprop or turbofan propulsion.

The fuel cell option requires a complex systems design involving the compression of ingested air, the fuel cell, heat exchangers and power electronics [25]. Various options for hybridization can be implemented with a fuel cell-equipped aircraft [26], for instance using a battery for peak power requirements, allowing to downsize the fuel cell components to a power level required for cruise flight. Different fuel cell technologies can be applied in the aviation sector (low or high temperature proton exchange membrane, solid oxide fuel cells), with various advantages and disadvantages, such as different reactions to load variations, efficiency, weight and optimum operating temperatures. Particularly the thermal management of fuel cells remains a challenge in the design [25,27], adding further weight, drag and complexity to the aircraft system through the integration of heat exchangers. Fuel cell powered aircraft will also cause condensation of water vapor in the exhaust plume and in ice-supersaturated environments also contrails, which are, however, less persistent and optically thinner, hence considered having a much smaller climate impact than the contrails formed by jet aircraft [28,29].

Due to sizing effects of the different components of an aircraft fuel cell power system, such a system is considered to be viable for regional aircraft, but less likely to be feasible for short- and medium-range aircraft comparable to today's Boeing 737 or Airbus A320 [25]. For such an application, the direct combustion of hydrogen in gas turbines is an option. This allows for turboprop or turbofan propulsion systems to drive also larger aircraft. While the power output can be scaled up to

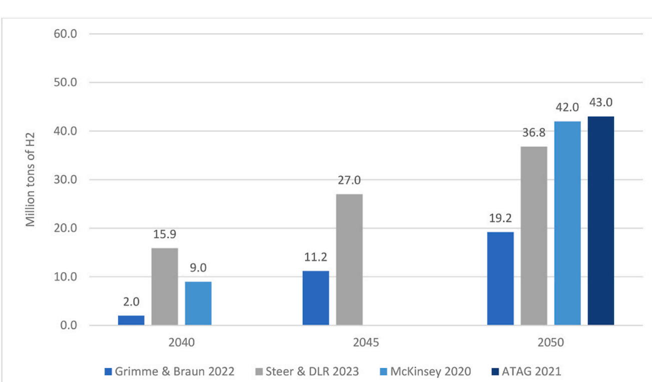

Fig. 2. Estimates of direct hydrogen demand in aviation 2040–2050 (in MtH_2), World. Compiled from Refs. [17,19–24].

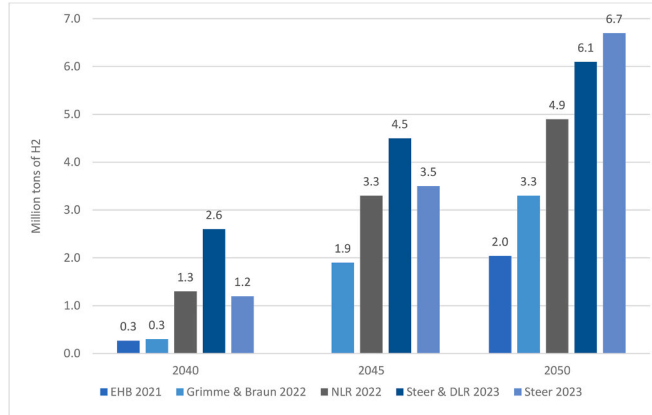

Fig. 3. Estimates of direct hydrogen demand in aviation 2040–2050 (in MtH_2), Europe. Compiled from Refs. [17,19–24].[3]

Notes: The estimates include all departing flights from Europe (EU27 countries plus Switzerland, United Kingdom, Iceland and Norway); for [17] only from EU27 + United Kingdom [24] provides the reference scenario and includes only intra-European flights.

engines powering long-haul, widebody aircraft, this propulsion technology continues to emit nitrogen oxides (NO_x) and water vapor, potentially condensing to ice particles and forming contrails [30,31]. Silberhorn et al. [32] expect that new combustion techniques will become available over the next decades which will be able to reduce NO_x emissions of hydrogen-powered jet engines by up to 99.8%. The overall climate impact measured by the metric average temperature response over a 100-year timeframe (ATR_{100}) of a middle-of-the-market hydrogen aircraft with 261 seats is expected to be reduced by 75–85% compared to the Boeing 767 as baseline aircraft [32]. This is a considerable improvement over current technologies, but the traffic growth expected over the next decades is likely to absorb a substantial share of reductions in climate impact of individual flight missions. Hence, stakeholders are still far from reaching a zero emissions or climate neutral aviation system through the introduction of hydrogen aircraft.

The second technological option refers to the type of on-board hydrogen storage. Hydrogen has a low volumetric, but high gravimetric energy density. For aviation applications, compressed gaseous or cryogenic storage are in discussion, while other hydrogen storage technologies (metal hydrides, liquid organic hydrogen carriers or methanol) are currently dismissed due to weight and/or efficiency issues. The sizing of the hydrogen storage system will determine aircraft range and is also likely to be a factor in the operating economics. Unlike with jet fuel powered aircraft, where the majority of fuel is stored in the wings, hydrogen will require cylindrical or spherical tanks, which are likely to be placed inside the fuselage. This will either reduce the commercially useable floor space or will require to design longer or wider aircraft, which in turn can have impacts on airport compatibility and/or aerodynamic efficiency. Cryogenic hydrogen tanks will provide particular challenges, as the materials involved have to withstand temperatures of −253 °C, while at the same time to remain lightweight, durable and affordable.

Various concept studies for hydrogen aircraft and concrete projects are currently under development. Most advanced seem the projects where existing airframes with conventional propulsion systems are planned to be converted with hydrogen fuel cell propulsion systems. Zero Avia envisages a 19-seat commuter aircraft based on the Dornier Do228 with 450+ kilometers range to enter service in 2025, followed by a 40–80 seat regional aircraft with 900+ kilometers range in 2027. With a similar strategy, Universal Hydrogen intends to offer conversion kits for the larger regional aircraft ATR (Avions de Transport Régional) 72 and de Havilland Dash 8. These projects have in common that compressed hydrogen is used, as it reduces complexity over cryogenic liquid hydrogen (LH_2) and that they are less time-consuming than a clean-sheet design with regards to certification and production. Three clean-sheet designs have been proposed by Airbus for aircraft capable of decarbonizing the short-/medium-haul aviation segment with up to 200 passengers and ranges of 3750+ kilometers. However, these concepts are likely to enter the market only after 2035.

2.3. Hydrogen supply and cost expectations

Hydrogen is currently produced by methane steam reforming (SMR) and using fossil energy such as natural gas (grey hydrogen) or by coal gasification (brown hydrogen). Both processes are CO_2-intensive and the associated emissions in the European Union (EU) amount to about 100 $MtCO_2$ each year. At present, low-carbon hydrogen accounts for less than 1% of the total hydrogen production. To achieve the goal of carbon neutrality by 2050, 70% of the hydrogen used must be produced as low-carbon in 2030 and 100% in 2050. Low-carbon hydrogen can either be produced by capturing and storing the emitted CO_2 (blue hydrogen) or by using renewable energy sources (green hydrogen).[2] The most mature process for producing green hydrogen is by water electrolysis. This electrochemical process splits water (H_2O) into gaseous hydrogen (H_2) and oxygen (O_2) using electrical energy from renewable sources such as solar energy, wind energy or hydropower. The necessary quantities of water can only be obtained from seawater, which must be desalinated before electrolysis [11,33,34].

So far, there is no global hydrogen market and hydrogen prices are not publicly available. Hydrogen is currently produced either by industrial gas suppliers or directly on site by specific industrial plants that require hydrogen. In the future, the production of green hydrogen will have to be increased on a large scale to meet global demand. In its net-zero CO_2 emissions (NZE) scenario, the IEA assumes that 40% of low-carbon hydrogen in 2050 will be supplied as blue hydrogen and 60% as green hydrogen [11,12]. However, the potential for producing green hydrogen from solar power and wind energy is unevenly distributed around the world. On the African continent there are favorable conditions for generating energy from solar power, with regions in North and South Africa as well as on the Arabian Peninsula being particularly suitable for photovoltaic or solar thermal plants. Constant and efficient use of wind energy is particularly favorable near the coast or off-shore, for example in the North Sea region (e.g. Norway), but also in parts of South America (Chile, Argentina) and in Canada [35–37]. Germany, like other countries in Central Europe, has a rather medium potential for producing green hydrogen from renewable energy sources. In the IRENA [14] report on global hydrogen trade, the world is divided into net hydrogen exporting countries and net hydrogen importing countries. In net exporting countries (e.g. countries in North Africa, Chile, Australia, Italy, Spain), the hydrogen supply index is higher than the demand index, while in net importing countries (e.g. Germany, Turkey, Japan, Korea) the opposite is the case (see Fig. 4).

As a result of the variations in production potentials, countries across the globe also exhibit differences in estimated hydrogen production costs. Production facilities in North Africa could realize production costs of 0.7 USD/kgH_2 in an optimistic scenario and 1.3 USD/kgH_2 in a pessimistic scenario in 2050 [14]. Steer [24] estimates production costs in North Africa of around 1.5–2.0 EUR/kgH_2 (1.6–2.1 USD/kgH_2)[3] by 2050. Though a comparison of hydrogen costs should consider all components of the hydrogen production process and supply chain.

Fig. 4. Low-carbon hydrogen supply and demand potentials in 2050, IRENA index. Based on data derived from Ref. [14]. Note: The supply index gives the common logarithm ($\log_{10}$) of hydrogen production per year, the demand index gives the logarithm of hydrogen plus ammonia demand per year.

Hydrogen unit costs therefore include production, distribution and liquefaction costs and refer to the costs that would be charged to airlines as fuel costs.

Table 1 displays the production and unit costs of low-carbon hydrogen as reported in a selection of studies and papers. In 2050, the average production costs worldwide range from 1.0 to 3.2 USD per kgH_2. Considering additional costs for distribution, liquefaction, storage, and refueling, the estimates provided by ATAG [20] suggest that the costs of low-carbon hydrogen would amount from 2.2 to 3.7 USD per kgH_2. Steer and DLR [23] assume, under conservative assumptions, liquid hydrogen unit costs of 4.00 EUR/kgH_2 in 2050. Steer [24] forecasts hydrogen unit costs of 3.45 EUR/kgH_2 in 2050 for the European market, which accounts for 83% of total hydrogen-related costs. Unlike sustainable aviation fuels (SAF), which can be used with existing aircraft technologies and airport infrastructure, the use of hydrogen in aviation requires new aircrafts and new refueling and storage infrastructure at airports. The remaining 17% therefore encompass expenses linked to airport infrastructure adjustments and aircraft development. If these costs were passed on to airlines, the hydrogen unit costs in 2050 would amount to 3.97 EUR/kgH_2 considering infrastructure costs, and to 4.16 EUR/kgH_2 considering both infrastructure and aircraft development costs. Gronau et al. [38] expect liquid hydrogen costs for the German aviation market at a much lower level. Production costs vary by pathway (liquid hydrogen imports vs. inland production) and total hydrogen costs including infrastructure measures range between 2.35 EUR/kgH_2 and 3.30 EUR/kgH_2 in 2050.

3. Materials and methods

3.1. Modeling aviation-specific hydrogen demand potentials

Several factors need consideration when estimating the future demand for hydrogen in aviation. A model framework comprising three modules is employed for this purpose. For the assessment of four different scenarios, assumptions concerning aircraft technologies are varied. With this approach, differences in energy consumption/CO_2 emissions can be assessed, with other factors (such as traffic growth or air fares) held constant. In the first module, future traffic demand on each airport pair will be modelled. The two main parameters relevant for future aircraft demand will be passengers and flight movements, which are both modelled in 5-year steps up to the year 2050. For this model, a traffic forecast is used, whose methodology is described in detail by Gelhausen et al. [2]. This traffic forecast was originally developed by the German Aerospace Center (DLR) for use in the EU funded research project 'Clean Sky 2 Technology Evaluator', which also evaluates global, fleet-wide impacts of new aviation technologies [3].

[2] In addition to green hydrogen, the EU regards the production and use of blue hydrogen as an important option on the way to decarbonization. However, this production route is also questioned, since sufficient free areas (underground) must be available for permanent carbon storage [5,33].

[3] Exchange rate as of 1 January 2023: 1 EUR = 1.0703 USD. See https://www.exchangerates.org.uk/EUR-USD-spot-exchange-rates-history-2023.html, accessed 14.06.2023.

Table 1
Projected production and unit costs of hydrogen in USD/EUR, 2020–2050.

Study	Type of costs	Today (2019/2020)	Short and medium-term (2030/2035/2040)	Long-term (2050)
IEA [39]	Production costs low-carbon hydrogen	SMR with CCS: 1.2–2.0 USD/kgH_2 Electrolysis: 3.2–7.7 USD/kgH_2		SMR with CCS: 1.2–2.0 USD/kgH_2 Electrolysis: 1.2–3.2 USD/kgH_2
McKinsey & Company et al. [19]	Unit costs green hydrogen		Europe: 2.6–3.5 USD/kgH_2 Imports: 2.4 USD/kgH_2	
IEA [12]	Production costs green hydrogen	3.5–7.5 USD/kgH_2	1.5–3.5 USD/kgH_2	1.0–2.5 USD/kgH_2
NLR and SEO [16]	Production costs green hydrogen			Europe: 2.2 EUR/kgH_2
NLR [17]	Production costs green hydrogen	Europe: 8.0 EUR/kgH_2	Europe: 3.0 EUR/kgH_2	Europe: 2.2 EUR/kgH_2
ATAG [20]	Production costs green hydrogen (=IEA's estimates)	3.5–7.5 USD/kgH_2		1–2.5 USD/kgH_2
	Distribution, liquefaction, storage, refueling	1.2 USD/kgH_2		+1.2 USD/kgH_2
		= 4.7–8.7 USD/kgH_2		= 2.2–3.7 USD/kgH_2
Steer and DLR [23]	Unit costs green hydrogen	Europe: 6.33 EUR/kgH_2	Europe: 5.00 EUR/kgH_2	Europe: 4.00 EUR/kgH_2
Steer [24]	Unit costs green hydrogen		Europe: 3.90 EUR/kgH_2	Europe: 3.45 EUR/kgH_2
	Unit costs + infrastructure			+0.52 EUR/kgH_2 = 3.97 EUR/kgH_2
	Unit costs + infrastructure + aircraft development			+0.71 EUR/kgH_2 = 4.16 EUR/kgH_2
Gronau et al. [38]	Unit costs green hydrogen + infrastructure			Europe: 2.35 EUR/kgH_2; 2.71 EUR/kgH_2; 3.30 EUR/kgH_2

Notes: SMR = Steam methane reforming, CCS = Carbon capture and storage, green hydrogen = hydrogen obtained by electrolysis using renewable energies.

Among others, the main parameters used for estimating the future aviation demand are GDP and population forecasts from external sources, as well as air fares, which have been extrapolated based on long-term times series and associated price elasticities of demand.

The second module required to predict the number of new aircraft entering service is a model estimating the retirement of individual aircraft being in service in each 5-year forecast period. For this, the logistic regressions from the models used in the Committee on Aviation Environmental Protection (CAEP) of the International Civil Aviation Organization (ICAO) are used, with updated coefficients of the model as described by Kar et al. [40]. The coefficients, which include aircraft age and aircraft category (turboprop, regional jets, narrowbody jets and widebody jets) determine the survival probability of individual aircraft, depending on their age. The aircraft-specific conditional 5-year survival probability is applied to each aircraft in the fleet to determine whether that aircraft will be available in the next period. The percentage of surviving aircraft in each sub-fleet, as determined by IATA specific aircraft codes in the forecast year, is applied to the frequencies of the respective aircraft sub-fleet on all airport pairs in order to determine the number of frequencies on each airport pair for which new aircraft will be required.

The third module is a model of aircraft entering service in the future, which contains a list of available aircraft including their top-level characteristics, such as maximum range with a commercially viable payload and an algorithm for the assignment on specific routes. This algorithm assigns the best-fitting available aircraft to each route based on distance, passenger demand and the remaining fleet after the calculation of retirements of aircraft. The number of aircraft to be delivered to meet traffic growth and the traffic previously served by retired aircraft is calculated using an aircraft utilization regression model, which determines the total annual distance an aircraft can fly based on the average length of individual flights. The model is calibrated with empirical aircraft utilization data from Flightradar24.com, an internet data provider that collects transponder data from each aircraft.

The characteristics of liquid hydrogen-powered aircraft were derived from the work of the German Aerospace Center (DLR) funded research project EXACT (Exploration of Electric Aircraft Concepts and Technologies, 2020–2023). In this project, several new aircraft types were developed, which are combined to assess four scenarios here. The aircraft families include regional aircraft powered by fuel cells and electric motors, as well as short- and medium-haul aircraft with hydrogen direct combustion with turboprop and turbofan engines.

In the first scenario, the short-/medium-haul aircraft market segment is covered from the year 2040 by turboprop aircraft with a family concept of 160, 200 and 250 seats and a range of up to 2800 km. In the second scenario, the same market segment is assumed to be covered by turbofan aircraft with the same range. Turboprop aircraft are considered very energy efficient, as these aircraft developed in EXACT offer block energy savings in the order of 20% compared to the turbofan version, albeit at a lower speed, resulting in an average 10% longer flight duration. In both scenarios, the regional aircraft market segment is covered by a family of aircraft powered by hydrogen fuel cells with propellers driven by electric motors with 40, 70 and 100 seats. Scenarios 1 and 2 can be considered as the 'innovative hydrogen aircraft scenarios'. A third and fourth scenario assuming the use of conventional turboprop/turbofan aircraft powered by hydrocarbon fuels as successors of the ATR42/72/Dash 8 and Airbus A320neo family with an estimated

Table 2
Hydrogen aircraft from DLR funded research project EXACT.

Scenario	Aircraft Type	Typical Seats	Maximum Range	Entry into Service
Scenario 1 -LH_2-Turboprop	Fuel Cell LH_2 Regional Aircraft	40/70/100	1915 km	2040
	Mild Hybrid LH_2 Turboprop	160/200/250	2800 km	2040
Scenario 2 -LH_2-Turbofan	Fuel Cell LH_2 Regional Aircraft	40/70/100	1915 km	2040
	Mild Hybrid LH_2 Turboprop	160/200/250	2800 km	2040
Scenario 3 -Conventional Aircraft (Turboprop)	Turboprop Regional Aircraft	40/70/100	2149 km	2040
	Turboprop Short-/Medium Range Aircraft	160/200/250	3446 km	2040
Scenario 4 -Conventional Aircraft (Turbofan)	Turboprop Regional Aircraft	40/70/100	2149 km	2040
	Turbofan Short-/Medium Range Aircraft	160/200/250	3362 km	2040

Note: LH_2 = Liquid hydrogen.

entry into service 2040 is evaluated to allow for a comparison of CO_2 emissions reduction potential. Table 2 provides an overview of the four scenarios under consideration and the respective aircraft characteristics.

In the LH_2-Turboprop and LH_2-Turbofan scenarios, hydrogen-powered aircraft are assumed to reach a market share of 100% after 2040, for all aircraft that need to be replaced due to retirement or enter the market to accommodate traffic growth. This applies to all routes falling within the maximum range of hydrogen aircraft. This approach estimates the maximum hydrogen demand potential in aviation considering traffic growth and conventional aircraft retirement patterns.

3.2. Modeling an aviation-specific hydrogen demand curve

As discussed in Section 2.1, the global demand for hydrogen is expected to increase in the coming years, leading to competition among countries and sectors for low-carbon hydrogen. In a market economy, the allocation of hydrogen to various sectors is determined by hydrogen market prices and each sector's willingness to pay. The willingness to pay for low-carbon energy carriers is influenced by the availability of substitutes to achieve carbon neutrality in different sectors. The cost of decarbonization varies across sectors, with some sectors considered hard-to-abate. In this study, it is assumed that by 2050, the decarbonization targets, in the form of a scenario with net-zero CO_2 emissions, will also apply to air transport in Europe. This implies that airlines will be required to operate in a carbon-neutral manner. In the aviation sector, besides the use of hydrogen, there are alternative approaches to decarbonization, such as the use of sustainable aviation fuels derived from biological or residual resources (biofuels) and hydrogen-based fuels (power-to-liquid fuels, synthetic fuels or e-fuels).[4] Also, efficiency improvements due to technological progress can contribute to this goal. The prices for liquid hydrogen will compete with the prices of these alternative aviation fuels and options.

To estimate a price-specific demand curve for hydrogen in aviation, the most cost-effective option for decarbonization in this sector must be considered. The full potential of hydrogen demand can only be realized if the price of hydrogen is competitive with the least expensive alternative. To analyze the demand response at various price levels above the level that achieves full hydrogen demand potential, price elasticities of air travel demand of -1.11, as calculated by Gelhausen et al. [2], are applied in this study This value also corresponds to a compilation of elasticities by the European Commission [41] for air travel originating in Europe. Given that fuel costs in aviation currently account for about 30% of total airline costs [42], the effect of a price change in hydrogen on demand needs to be adjusted to an elasticity of $-0.33 = 0.3 \times (-1.11)$. The generated minimum and maximum demand data points are used to predict a non-linear demand curve in the form of a typical power function: $y = a\,x^b$. A power function provides the best fit for data points that increase or decrease at a specific rate [43]. Here, y is the dependent variable presenting the amount of hydrogen demand, and x is the independent variable representing the hydrogen price levels. Parameter a determines the overall scale or magnitude of the relationship between y and x and represents the value of y when x is 1. The parameter b determines the rate at which y changes with changes in x and gives the elasticity. If b is positive, it indicates an increasing relationship (as x increases, y increases). If b is negative, it indicates a decreasing relationship (as x increases, y decreases). The magnitude of b indicates the steepness of the curve. In this case, parameter b is expected to be smaller than zero, indicating a concave-up, decreasing curve. A negative value for the parameter b can be assumed, signifying that the demand for hydrogen decreases if prices increase, as indicated by the aviation specific price elasticities. In terms of levels of the price elasticity, it is assumed that demand is more price elastic at lower price levels and less elastic at higher price levels, as is the case, for example, for business travelers [41].

Fig. 5 shows the expected development of fuel costs for alternative aviation fuels from 2030 to 2050 based on Steer [24] and Steer and DLR [23]. The assumptions regarding cost reductions for alternative fuels are conservative, as relatively low reduction rates have been applied. Fuel costs relate to the costs that would be charged to airlines (= unit cost, see Table 1). For a comparison of different energy carriers with different energy densities, the costs are provided in EUR per megawatt hour (MWh).[5] Fig. 5 shows that the fuel costs of biofuels based on the HEFA (Hydrotreated Esters and Fatty Acids) production pathway have the lowest price level and would therefore represent the cheapest option for decarbonizing aviation (76 EUR/MWh in 2045 and 71 EUR/MWh in 2050). The fuel costs of hydrogen-based fuels (e-fuels) are higher than the costs of liquid green hydrogen. This is because hydrogen must undergo additional processing, such as Fischer-Tropsch synthesis, in order to be converted into liquid fuels. In the short run, the cost of e-fuels imported from North Africa to Western Europe, including logistics to the destination, is expected to be around 300 EUR/MWh [44]. Later, due to economies of scale, cost levels for e-fuels are expected to decrease, until 190 EUR/MWh in 2045 and 179 EUR/MWh in 2050.

The costs for liquid hydrogen are projected to be 120 and 104 EUR/MWh in 2050, based on two estimates [23,24]. Gronau et al. [38], on the other hand, assume a much lower cost level of between 71 and 99 EUR/MWh in 2050, even including infrastructure measures.[6]

To the best of the authors' knowledge, Wietschel et al. [45] and Gnann et al. [46] are the only publications that have modelled price-dependent demand for liquid hydrogen that includes the transportation sector as well as aviation. The authors simulate liquid hydrogen demand for different sectors in Germany for 2030 and 2045 using agent-based and techno-economic simulations. They consider different levels of willingness to pay for hydrogen by different sectors. The prices for hydrogen are exogenous and prices are compared with the prices for other alternative energy sources, which also contribute to achieving carbon neutrality. According to Wietschel et al. [45], direct hydrogen demand in aviation (and shipping) starts at a price of about 106 EUR/MWh in 2045, which corresponds to 3.53 EUR/kgH_2. At a

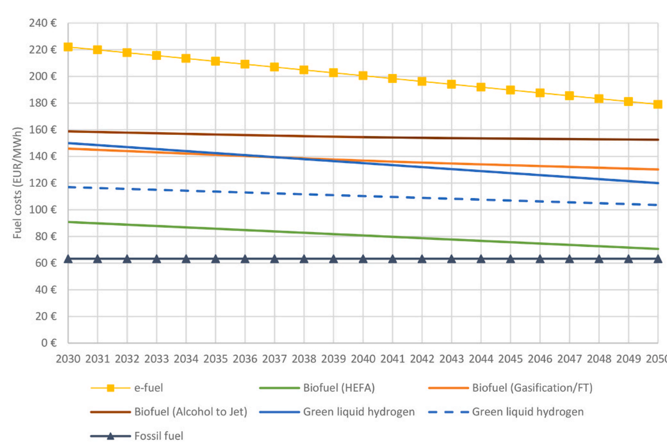

Fig. 5. Expected costs of aviation fuels, in EUR_{2020}/MWh. Adapted from Steer [24] and Steer and DLR [23]. Notes: The value for fossil fuel refers to the spot price for Jet A-1 fuel as of April 2022. HEFA, Alcohol to Jet and Gasification/FT refer to different production pathways of biofuels.

[4] In addition, electrically powered aircrafts could be used in aviation for very short distances and for commuter flights.

[5] One kilogram (kg) of hydrogen contains 33.33 kW-hour (kWh) of energy.

[6] 4.00 EUR/kgH_2 = 120.1 EUR/MWh, 3.45 EUR/kgH_2 = 103.6 EUR/MWh, 2.35 EUR/kgH_2 = 70.6 EUR/MWh, 3.30 EUR/kgH_2 = 99.1 EUR/MWh. Compare with Table 1.

price level of about 74 EUR/MWh (2.46 EUR/kgH_2) in 2045, hydrogen demand in the transport sector (excluding cars and trucks) rises to the maximum demand potential in the German market.[7]

For a graphical visualization, Fig. 6 summarizes the materials and methods as outlined in Section 3.1 and Section 3.2.

4. Results and discussion

4.1. Hydrogen demand and CO_2 reduction potentials

Fig. 7 shows the global and European[8] liquid hydrogen demand potential for aviation as modelled based on the assumptions described in Section 3.1. Demand for liquid hydrogen in Europe increases from 205,000 tons in 2040 to 2 Mt in 2050 in the turboprop scenario and from 264,000 tons in 2040 to 2.5 Mt in 2050 in the turbofan scenario, respectively. Global hydrogen demand is expected to rise in the turbofan scenario from 1.8 Mt in 2040 to 16.8 Mt in 2050. In the turboprop scenario, however, overall demand is significantly smaller, with 1.4 Mt in 2040 and 13.2 Mt in 2050. It must be acknowledged that these figures represent a demand potential that is independent of hydrogen market prices.

Taken on its own, Fig. 7 shows a comparatively large amount of liquid hydrogen demanded by aviation. In relation to the total energy consumption of air transport, however, this only corresponds to a share of 9.2% in the LH_2-turbofan scenario and 7.4% in the LH_2-turboprop scenario. The main reason for these findings is that, according to this study's assumptions, only short- and medium-haul traffic with aircraft up to 250 seats and ranges up to a maximum of 2800 km is served by hydrogen aircraft. Previous analyses have shown that the majority of energy consumption in aviation occurs on routes longer than 3000 km [47]. Furthermore, with only 10 years between entry into to service and the forecasting horizon, only a relatively small proportion of the short- and medium-haul aircraft fleet can be replaced by hydrogen aircraft. Finally, the projected traffic structure in the future also plays a role in the diffusion of hydrogen aircraft. In the traffic forecast by Gelhausen et al. [3], it is expected that due to capacity constraints at airports combined with demand growth, a growing share of widebody aircraft will also be used on short- and medium-haul routes. And the segment of aircraft larger than 250 seats is not assumed to be covered with hydrogen aircraft. Correspondingly, the total market share of hydrogen aircraft in global aviation on routes of less than 3000 km is in the order of 27% in 2050 (measured by revenue passenger kilometers), so that even on routes suitable for the operation with hydrogen aircraft, a large part of traffic is served by conventional aircraft.

At the same time, the contribution of hydrogen aircraft to reducing CO_2 emissions from aviation is limited by the suitable routes and the market diffusion of the new technology. Fig. 8 shows the global and European CO_2 emissions of aviation in the four scenarios considered for the year 2050. The key assumption here is that conventional aircraft are powered exclusively with fossil jet fuel (emissions factor of 3.16 kg CO_2 per kg fuel), while hydrogen is considered to be carbon neutral ("green" hydrogen, excluding life-cycle emissions of electrolysis, liquefaction and distribution/storage). On a global scale, in the conventional aircraft scenarios (Scenarios 1 and 2), the transition from turbofan to turboprop aircraft can reduce CO_2 emissions by 36 Mt, which is only 2.2% of aviation's global CO_2 contribution. The transition to hydrogen can reduce CO_2 emissions by 145 Mt compared to the conventional aircraft (turbofan) scenario, which is equivalent to 9% of CO_2 emissions from global aviation. In Europe alone, the transition from conventional turbofan aircraft to conventional turboprop aircraft is estimated to result in a CO_2 saving of 6 Mt, while the transition to hydrogen may reduce CO_2 emissions by 23 Mt.

The CO_2 reduction is the same in both Scenario 1 and Scenario 2, as the same number of conventionally fueled aircraft are replaced by hydrogen-powered aircraft. Subsequently, the only difference between the hydrogen-powered turboprop (Scenario 1) and turbofan (Scenario 2) aircraft is the amount of hydrogen, which is assumed to be carbon-neutral.

The modeling results shown here should be placed in the context of other studies: In addition to the figures presented in Section 2.1, the following comparisons can be drawn: A study conducted on behalf of the European Commission [23] indicates a global demand for hydrogen of 36.8 Mt in 2050, substantially more than the 16.8 Mt shown here. The difference can be explained by diverging assumptions, mainly on entry into service years of hydrogen aircraft and the retirement of conventional aircraft. While the present study assumes an entry into service in 2040, the study conducted on behalf of the European Commission assumed 2035. Moreover, the present study assumes an unchanged aircraft retirement pattern with 50 % of aircraft being operated for 21 years or more compared to 18 years in the study for the European Commission. Grimme and Braun [22] show a demand of 19.2 Mt of hydrogen for global aviation in 2050 with similar assumptions as shown in this study, increasing to more than 30 Mt when an early retirement and slightly longer ranges of aircraft are assumed. Furthermore, Grimme and Braun [22] have shown the sensitivities in relation to the assumptions, identifying market entry as the most relevant factor for hydrogen demand, in case there are no constraints in the production of hydrogen aircraft. The industry consortium Mission Possible Partnership [48] provides even higher hydrogen demand figures for 2050, depending on the scenario between 95 and 160 Mt. This includes, however, both hydrogen demand for direct use and hydrogen as feedstock for power-to-liquid (PtL) fuels.

4.2. Price-specific hydrogen demand curves

As outlined in the introduction, an objective of this study is to estimate a price-specific hydrogen demand curve for aviation based on the demand potentials presented in Section 4.2. The demand potentials from Scenario 2 - LH2-Turbofan will be used as the reference scenario for the demand curve modelling. An underlying assumption is that the full potential of hydrogen demand will not be realized until the cost of green liquid hydrogen equals that of the cheapest alternative for decarbonization. Until then, less expensive carbon-neutral aviation fuels, such as biofuels, will be preferred. This assumption is based on basic economic theory, which suggests that companies aim to minimize costs to maximize revenues. Moreover, due to technological constraints, hydrogen demand cannot surpass maximum potentials. Lastly, it is assumed that, due to net-zero CO_2 emissions goals, the aviation industry must operate carbon-neutral by 2050. Given the expectation that European countries will establish uniform decarbonization objectives, the demand curve will solely be constructed for Europe.

According to Fig. 5, the use of biofuels produced via the HEFA production pathway would be the least expensive option to decarbonize aviation. For the year 2045, the projected biofuel cost level is 75 EUR/MWh and 71 EUR/MWh for the year 2050. When estimating the demand curve, the price-point of 71 EUR/MWh is taken as the point that yields the full hydrogen demand potential in aviation in 2050. From this point, the price elasticity of demand for air travel of -1.11 is used to simulate demand at higher price levels. As fuel costs in aviation currently relate to about 30% of total cost [42], the effect of a price change in hydrogen on demand is adjusted to an elasticity of $-0.33 = 0.3 \times (-1.11)$. Based on minimum and maximum demand-price-level combinations obtained, a power function is estimated that best fits the data in the following form: $y = a\,x^b$. In terms of price elasticities, this implies that demand is more price elastic at lower price levels and less elastic at higher price levels.

Fig. 9 illustrates four price-specific demand curves for hydrogen in

[7] The price-level data is taken from Fig. 5 in Wietschel et al. [45].

[8] Europe defined as EU27, the European Economic Area (Norway, Iceland), the United Kingdom and Switzerland.

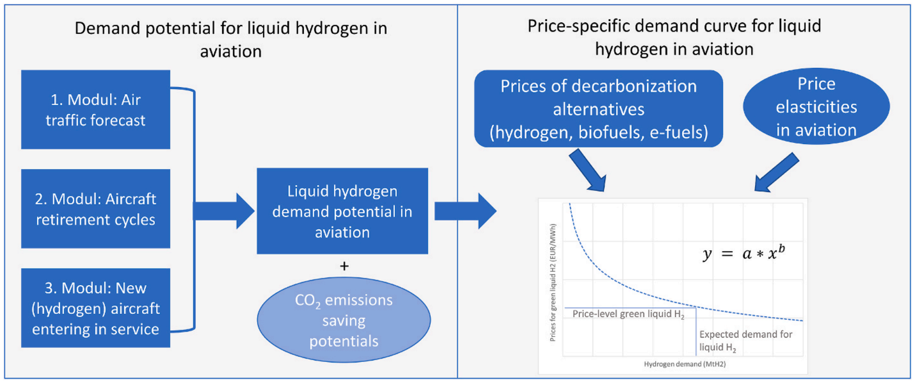

Fig. 6. Visualization of the materials and methods: Modeling liquid hydrogen demand in aviation for 2040, 2045 and 2050.

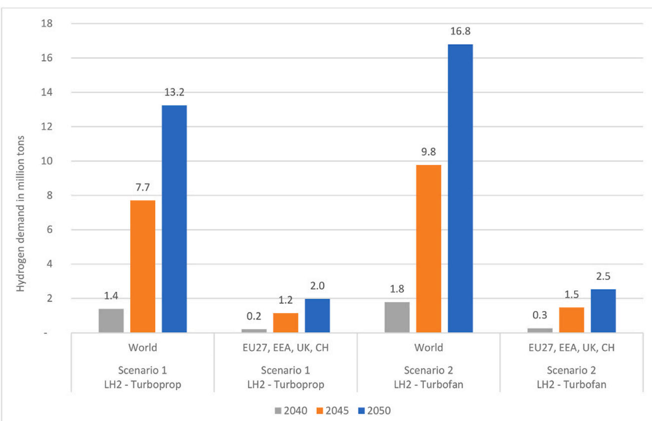

Fig. 7. Global and European liquid hydrogen demand by aviation in the LH_2-Turbofan and LH_2-Turboprop scenarios (in MtH2), 2040–2050.

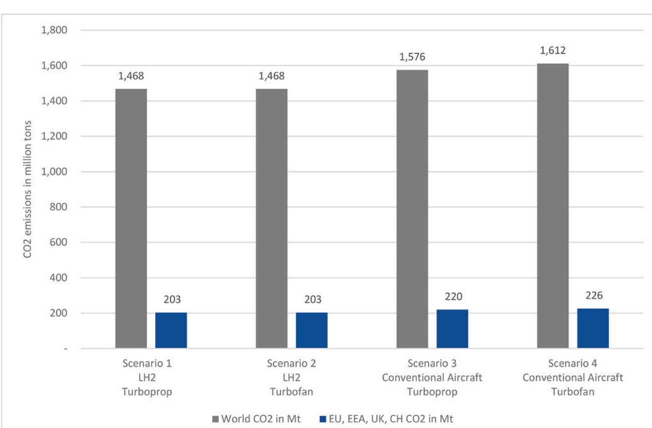

Fig. 8. Estimation of global and European aviation CO_2 Emissions (in Mt), 2050.

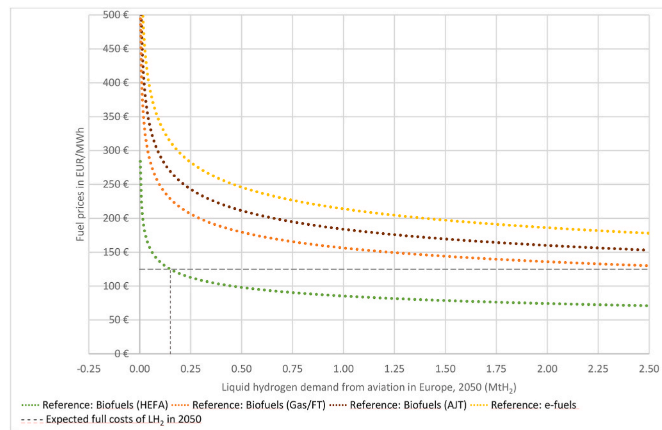

Fig. 9. Price-dependent hydrogen demand curves for aviation and expected LH_2 price, Europe 2050. Decarbonization reference prices of 71, 130, 153 EUR/MWh for different biofuels and 179 EUR/MWh for e-fuels. LH_2 = Liquid hydrogen.

the aviation sector in 2050, which depend on the prices of the decarbonization alternatives besides hydrogen. The fuel cost level is given on the y-axis and the demand level on the x-axis, presenting the inverse demand function as typically used when plotting the relation between prices and demand in economics. The fuel costs for green liquid hydrogen need to reach levels comparable to alternative aviation fuels to unlock its full potential. When HEFA-biofuels provide the cheapest alternative for decarbonization (lowest demand curve in Fig. 9), full liquid hydrogen demand potential of 2.5 MtH_2 in Europe can only be realized at a quite low price level of 71 EUR/MWh.[9] However, as indicated in Section 2.2 and depicted in Fig. 5, the production costs of liquid hydrogen are unlikely to reach these price levels. Only under optimistic assumptions, hydrogen prices may become competitive with these biofuels (see price levels by Ref. [20]; Gronau et al. [38]). Instead, the expected full hydrogen costs, including infrastructure and aircraft development, are projected to be around 125 EUR/MWh (=4.16 EUR/kgH2) in 2050 [24]. If liquid hydrogen competes with biofuels (HEFA), projected hydrogen demand would only be around 0.15 Mt applying the estimated demand function (compare Fig. 9). In terms of price elasticities, the shape of the demand curve implies, that demand is more price elastic at lower price levels and less elastic at higher price levels.

In contrast, if hydrogen competes with biofuels generated by other pathways or with e-fuels, hydrogen is more likely to reach its full demand potential, as those prices are expected to be higher than those of liquid green hydrogen. If biofuels obtained by the Alcohol-to-Jet (ATJ) or Gasification/FT pathway are considered, full hydrogen demand would already be met at a price level of 130 EUR/MWh respectively 153 EUR/MWh. When e-fuels are the only option for decarbonization alternatives, full hydrogen demand potential of 2.5 MtH_2 in Europe then

[9] The inverse demand function, assuming HEFA fuels offer the most cost-effective decarbonization option, is calculated as $y = 85.334x^{-0.201}$, for example, where y represents the price level and x represents the demand level. Please refer to Fig. 9.

exploits already at hydrogen prices at around 179 EUR/MWh (highest demand curve).

Given the uncertainties regarding the capacity of feedstocks, whether organic or from residues, to meet the demand for biofuels, e-fuels may become the sole option for decarbonizing aviation, especially on long-haul routes. This will be the case if the production capacities for biofuels remain minimal and are not sufficient to meet the demand for biofuels in the future. This is the most likely scenario at present. Even when factoring in infrastructure and aircraft development costs, e-fuels are likely still to be the more expensive option for decarbonizing short- and medium-haul flights. In this context, e-fuels should be considered for long-haul flights, while hydrogen could be the more economically viable choice for short- and medium-haul routes.

5. Conclusion and policy recommendations

Climate neutrality for all sectors including transport by 2045 or 2050 is one of the main goals of the European Union and of individual states such as Germany. Hydrogen is often hailed by politicians and society as the energy carrier of the future, as it promises climate-neutral production of many goods and services, especially in but not limited to the aviation sector, if renewable electricity is used for its production ('green hydrogen'). This research indicates that the use of hydrogen in aviation is technically feasible in principle, as has been shown in Section 2. However, there are a number of technical restrictions that must be considered. It is reasonable to conclude that the actual contribution of hydrogen to CO_2 emissions reduction in aviation in the future will depend on a number of factors: the entry into service year of hydrogen aircraft, the cost of hydrogen aircraft, the cost of hydrogen refueling and storage infrastructure at airports, the global acceptance of hydrogen aircraft, the market share of such aircraft and the retirement rates of conventional aircraft, among others. However, as shown in this paper, for a meaningful climate-protecting contribution, larger hydrogen aircraft with higher ranges would be necessary which is technically challenging.

From an economic point of view, no global or national hydrogen market is currently existing as hydrogen is not publicly traded. Accordingly, there are no hydrogen market prices today. However, in the upcoming years, hydrogen demand will increase considerably as a large number of industrial countries have declared a strategic interest in this energy carrier in their national hydrogen plans as discussed in Section 1. As a consequence, a competition between states especially for green hydrogen can be expected in the future with impacts on the market price for this energy carrier.

Against this background, difficult, very capital-intensive and long-term investment decisions will have to be made by companies in the aviation industry in the upcoming years, especially by airports, airlines and manufacturers of aircraft and their propulsion systems: Which sustainable energy source should and will be used in what quantities in aviation in the future? In principle, sustainable aviation fuels (SAF), electric propulsion systems and hydrogen come into question, each with different technical and economic restrictions. Since the development of completely dual systems, e.g., SAF and hydrogen, is very capital-intensive, there is definitely a risk of stranded investments for the companies involved. If hydrogen shall be introduced in air transport, large investments will be essential for both airlines and airports, as hydrogen aircraft will have to be purchased by the airlines and hydrogen infrastructure at airports will have to be built up. The latter refers to the necessary hydrogen tanks, a hydrogen transport system to the airports (hydrogen trucks and/or hydrogen pipeline systems) and eventually a liquefaction plant at the respective airport [49,50].

At this point, policymakers are called upon to provide a clear, long-term framework. If the declared political goal is to support the use of hydrogen in aviation, appropriate legislation and incentivizing (funding) measures must be introduced. This also applies, for example, to the question of which sectors of the economy should use hydrogen in the future. Considerable competition for use is to be expected, especially from heavy industry sectors such as iron and steel production, whose willingness to pay is likely to be higher than for air transport. Furthermore, hydrogen could play an important role in the decarbonization of other transport modes, and will be needed for the production of synthetic fuels. In 2050, about 50% of hydrogen demand will be derived from the transport sector alone, if no appropriate policy framework is introduced. Should a supply shortage actually occur, the willingness to pay of the individual sectors and thus the market price will regulate the distribution of hydrogen among the sectors.

A possible starting point for solving this foreseeable competition for use problem could lie in temporarily introducing a subsidy for the use of hydrogen for air transport so that the different demand curves of the sectors can be balanced. This could include, for example, contracts for difference (CfD), where the energy costs for fossil kerosene plus CO_2 costs are used as a benchmark. Only if hydrogen comes at the same price (thus including infrastructure costs) as the price for fossil kerosene plus CO_2 price, there would be an incentive to use it. With the CfDs, the airlines would have a hedge against the economic risks.

In addition, a demonstrator program could also be introduced for an early phase - for example, the EU could finance a limited number of hydrogen aircraft (e.g. 20) and lease them to interested airlines. This would allow airlines to gain operational experience and send a signal to other airlines that hydrogen works in aviation. This would bridge the actual gap between pure European research (Clean Aviation + Horizon Europe) and practical use. Another option would be to build up direct trade relations in the form of supply contracts and volume commitments with hydrogen producing companies outside of Europe. This can only be initialized on political level. In addition, the direct investment in own hydrogen production plants abroad, if applicable by project developers, by companies from the air transport sector (see for instance project HyShiFT Sustainable Aviation Fuel developed in South Africa, [51,52]) or in Germany together with industrial partners is also conceivable.

Complicating matters further is the fact that aviation is an international sector. Policy frameworks and support measures in favor of H_2 use in aviation should therefore be introduced at least at the European level, or better still globally. As the International Civil Aviation Organization ICAO is rather not known for fast decisions, the European Union should act as a forerunner on promoting the use of H_2 in air transport. A set of policy recommendations to overcome technical and financial barriers in this regard has already been published by the Steer and DLR [23]. Most importantly from the point of view of the air transport companies involved will be a reliable and long-term policy framework to minimize the risk of stranded investments. This will also allow for the largest benefit in terms of climate protection through the use of hydrogen in air transport.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This paper was prepared as part of the German Aerospace Center's (DLR) self-funded projects EXACT and VMo4Orte.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2024.03.241.

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