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Estimation of potential hydrogen demand and CO_2 mitigation in global passenger air transport by the year 2050

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Abstract

Decarbonizing aviation is one of the biggest challenges for the industry in the upcoming years. The transition to sustainable aviation fuels, e.g., hydrocarbon drop-in fuels, is a strategy to achieve this goal in the short to medium term. Looking further into the future, the introduction of new aircraft solely powered by clean hydrogen could contribute to make air transport completely carbon-free, at least in the long term. In this paper, the authors estimate the potential demand for the new energy carrier for global scheduled passenger flights. The demand forecast for hydrogen is based on a traffic forecast at airport-pair level, and an aircraft fleet model that considers aircraft retirements and entry-into-service of new types. Based on the strong assumption of market entry of hydrogen aircraft starting by 2040, gradually replacing conventional aircraft and serving future passenger demand on all global routes of less than 1,500 nm, we estimate a global hydrogen demand of 19.2 million tons for passenger aviation in the year 2050. For flights departing European airports (including Switzerland, the UK, and EEA member states), the demand for hydrogen is estimated to be 3.3 million tons by 2050. To reveal the impact of the forecast assumptions, the authors present a sensitivity analysis with variations of parameters such as the maximum range of hydrogen aircraft, entry-into-service, and variations in traffic growth. The paper furthermore outlines the challenges for the aviation industry in the context of the introduction of hydrogen in future air transport.

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Keywords: Climate change; hydrogen; decarbonization; aircraft technology; air transport forecast

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1. Introduction

The decarbonization of aviation is one of the biggest challenges for the industry in the upcoming years. Aviation is considered to be a "hard-to-abate" sector (Ueckerdt et al., 2021). Public awareness with respect to alternative energy, e.g. electric and hydrogen power, has increased with the introduction of battery electric vehicles and public debates about climate change (Hardman et al., 2013). Further, expectations of local communities with respect to sustainability and corporate responsibility are higher than in previous decades, particularly in the publicly visible and safety-critical aviation industry.

The reduction of carbon emissions in air transport to "net-zero" is associated with high costs and investment efforts. Considering effectiveness, energy density and other characteristics, liquid hydrocarbon fuels will continue to be the preferred energy source in the future. In order to achieve carbon reduction targets, such as IATA's "Fly Net Zero" strategy (IATA, 2021), hydrocarbon fuels from non-fossil sources, also called "sustainable aviation fuels" (SAF), will be an important step toward the decarbonization of aviation, at least in the short and medium term.

As an alternative energy carrier in aviation, hydrogen has been studied for a long time (e.g. Energy, 1987), but has become particularly interesting in recent years for both academia and the industry. Already in the year 1988, one engine onboard a modified Tupolev TU-154 aircraft was operated on hydrogen (Cecere et al., 2014). A major research effort on theoretical considerations for using hydrogen in aviation was undertaken in the CRYOPLANE study, led by Airbus in the years 2000 to 2002 (Airbus, 2003). Most notably, the concept aircraft published by Airbus as part of its "ZEROe" strategy (Airbus, 2020) has gained considerable publicity.

The transition to hydrogen in commercial aviation is associated with substantial efforts, such as the design of new aircraft, provision of electricity from renewable sources to produce "green" hydrogen, distribution between production locations and airports, hydrogen liquefaction, and the development of new processes for re-fueling aircraft. For the planning of future investments in infrastructure such as electrolyzers, pipelines, liquefiers and storage facilities, an estimation of the potential future hydrogen demand in commercial aviation is an important decision-making baseline.

In this paper, based on a number of assumptions, we estimate the potential future hydrogen demand in aviation for different scenarios up to the year 2050. The demand forecast for hydrogen was conducted based on a global traffic forecast on airport-pair level, and in combination with an aircraft fleet model that considers aircraft retirements and entry-into-service of new aircraft types. Future concept hydrogen aircraft types used in the analysis have been developed in the DLR project EXACT (Exploration of Electric Aircraft Concepts and Technologies), which covers both fuel-cell hydrogen regional aircraft (40-100 seats), as well as short- and medium-haul aircraft (160-250 seats) with turbofan jet engines and direct combustion of hydrogen (Hartmann and Nagel, 2021).

The structure of this paper is as follows: Section 2 provides a brief overview of literature with respect to CO_2 emissions mitigation and hydrogen in the aviation sector, and respective prospects and challenges. Section 3 introduces the methodology applied for the estimation of potential future hydrogen demand. Results are presented in Section 4, including a sensitivity analysis of key parameters. The paper concludes with a discussion of the challenges and prospects of hydrogen utilization in aviation.

2. Hydrogen and CO_2 Emissions Reduction in Air Transport

With respect to the introduction of hydrogen in future air transport, a variety of studies and reports have been published in recent years.

EUROCONTROL (2022) developed scenario forecasts for CO_2 mitigation toward net-zero from the years 2019 to 2050, considering, among alternatives, the potential introduction of revolutionary aircraft powered by hydrogen and electric fuel cells. They estimate that these new types of aircraft could contribute with 2-3 % to the overall CO_2 emissions reductions in the aviation sector in Europe by 2050. With an entry-into-service after 2040, EUROCONTROL expects only a share of 8 % of all flights to be operated by electric or hydrogen aircraft in Europe in 2050. The largest part of reductions is likely to be achieved by sustainable aviation fuels, followed by market-based measures such as cap-and-trade (about 30 %). Future improvement of current fossil-fuel aircraft is expected to contribute with 17 % by 2050.

Bruce et al. (2020) published an assessment report in collaboration with Boeing, referring to IATA's target of a 50 % reduction of the 2005 CO_2 emissions levels by the year 2050. They reveal potential for hydrogen fuel cells powering aircraft with 100 passengers on flights up to 1600km. For long-distance flights, however, fuel cells are limited due to their power density limitations. Liquid (cryogenic) hydrogen can be directly combusted in jet-engines and produces no CO_2 emissions during combustion. With its higher energy density by mass compared with kerosene but lower volumetric density, new aircraft and engine designs are required. It is therefore a promising approach for introducing hydrogen planes in the long term closer to 2050. Required lead times for hydrogen infrastructure development at airports, and the rollout of new aircraft technology are obstacles that prevent a rapid large-scale introduction soon.

Considering CO_2 emissions levels in the time horizon up to 2050 (Åkerman, 2005), discussed CO_2 mitigation options include sustainable aviation fuels (SAF), aircraft technology improvements for superior drop-in fuel efficiency, and increased operations efficiency in terms of airport operations and air traffic management (ATM). Studies suggest that the largest part (i.e., about 40 %) of all mitigation options will come from sustainable aviation fuels such as biofuels or synthetic fuels (Bauen et al., 2020). However, hydrogen powered aircraft are expected to become more important by 2050 and onwards. Further analysis of liquid hydrogen supply for air transport is given, for example, by Sethi et al. (2022), Pinheiro et al. (2020), and Johnson (1995).

Regarding future air traffic growth, the number of global passengers is expected to double to 8.2 billion passengers per year by 2037, with business-as-usual projections showing a three-fold growth in CO_2 emissions by 2050 (Bruce et al., 2020). EUROCONTROL (2022) projects 16 million flights in European skies by 2050 in its 30-year forecast. This corresponds to a 44 % flight growth compared to the year 2019, or, in other words, an average growth rate of 1.2 % per year. Long-term future air traffic growth is expected to be in the range of about 4 % per year despite the recent COVID-19 pandemic and geopolitical downsides such as the war in Ukraine, see Rizzi and Rizzi (2022). Demand growth leads to a substantial risk that any measures leading to reduction of specific CO_2 emissions will be offset, so that total emissions would not decline to a level required to achieve the objectives of the Paris Agreement, which was negotiated in 2015 (United Nations, 2015).

In addition, policy and regulation must be involved with respect to the future market entry of hydrogen aircraft. Today, there is a lack of policies regarding standard operating and safety procedures for hydrogen aircraft and their respective ground handling at airports (see Benson et al., 2019). However, these will certainly be addressed in the future in collaboration with international organizations such as IATA, ICAO, and the aviation industry (Gössling and Lyle, 2021). For example, Bows et al. (2008) and Gudmundsson (2019) reveal lessons for European policy regarding climate change and aviation.

Today, the EU has set clear targets for aviation emissions reduction outlined in the Green Deal and Fit-for-55 package. In addition, the European emissions trading scheme (EU ETS) is under constant revision (Wild et al., 2021). However, additional regulatory frameworks will be required to ensure that carbon offsetting is not the only economical way for air transport operators to achieve their emission targets.

We conclude that, while a plethora of literature on the technological and economic challenges associated with decarbonisation of air transport in general and the introduction of hydrogen in particular exists, only very few sources deal with quantitative estimations for future energy requirements for the aviation sector. We consider such estimations as a valuable addition for investment planning and sizing of required infrastructure. Hence, we introduce in the next section the methodology and hydrogen demand scenarios.

3. Methodology

The methodology applied for the estimation of potential hydrogen demand consists of the following steps:

The main input on future air transport development is a traffic forecast, which includes future passenger demand and the number of flight movements at the airport pair level up to the year 2050. The key drivers of passenger demand are income (GDP per capita), the development of air fares, and population (Gelhausen et al., 2019). The traffic forecast, in particular, captures airport capacity constraints, leading to a continued trend of increasing average aircraft size, and, uncaptured passenger demand in the long run (Gelhausen et al., 2019).

The results of the traffic forecast are used in an aircraft fleet model, in which the required number of aircraft are calculated in 5-year steps from 2020 to 2050. This step considers aircraft retirements, traffic growth, available aircraft types on the market, and seat load factors. For each aircraft type, the reduction of the operational fleet due to aircraft retirement is calculated by applying the survival probability of each individual aircraft, based on the logistic regression model used by ICAO CAEP/12 (Clean Sky 2 Joint Undertaking, 2021). The reduction factor of the operational fleet is projected on the flight frequencies of the respective aircraft type – for example, if 20 % of aircraft are retired, 20 % of scheduled flights previously operated with this type will require the introduction of new aircraft. Due to demand growth, the number of frequencies and/or the average aircraft size increases over time, so that the number of newly acquired aircraft typically exceeds the number of retired aircraft. For future replacement and growth, a set of aircraft in 12 seat classes (ranging from 19 to 550 seats) is available, based on current technological level, including e.g. the Airbus A320neo family, Boeing 787-8, Airbus A350-900 and Boeing 777-9. Starting at the year 2040, hydrogen aircraft as shown in Table 1 are assumed to enter service and will be used for aircraft replacement and growth on all flight routes, where their respective seat capacity and maximum range fits the requirements of the individual airport pair. Hence, we assume for new aircraft on mission distances up to 1500 nm and a capacity of up to 250 seats a 100 % market share of hydrogen aircraft. Furthermore, it is assumed that hydrogen can be supplied at each airport without any constraints. For all other requirements (e.g. long-haul flights), conventional aircraft of current state-of-the-art continue to be used up to the forecast horizon of the year 2050.

Table 1. Types of hydrogen aircraft derived from DLR's EXACT project

Aircraft	Number of seats	Maximum Range (nm)	Entry-into-service	Propulsion Technology
Regional Fuel Cell - FC40	40	1000	2040	Hydrogen fuel cell with electric motors
Regional Fuel Cell - FC70	70	1000	2040	Hydrogen fuel cell with electric motors
Regional Fuel Cell - FC100	100	1000	2040	Hydrogen fuel cell with electric motors
Short-/Medium Haul - TF160	160	1500	2040	Turbofan / direct hydrogen combustion
Short-/Medium Haul - TF200	200	1500	2040	Turbofan / direct hydrogen combustion
Short-/Medium Haul - TF250	250	1500	2040	Turbofan / direct hydrogen combustion

The result of the fleet model is a list of flights at airport-pair level, including aircraft type and number of flights per year for each five-year period up to the year 2050. This information is then used for calculating energy consumption for all flights, and the respective CO_2 emissions. Fuel consumption for each aircraft is calculated depending on the flight mission distance, based on data supplied by commercial flight performance calculation software Piano-X (Lissys Ltd., 2008) for conventional aircraft and by results of the DLR project EXACT for hydrogen aircraft. In our analysis, we do not consider any airport-related hydrogen demand for ground-based applications, such as for ground service equipment.

The scenarios and parameter variations for this analysis are listed in Table 2. Only scheduled passenger flights are considered, i.e., the business and general aviation sectors as well as the cargo market are excluded. For comparison of the impact hydrogen aircraft will have on energy consumption and emissions, a scenario ("Conventional") has been developed, which assumes that hydrogen aircraft will not be available in the future but airlines would need to rely on conventional fossil-fuel aircraft up to 2050 without any future technology improvements, and operated as today without using sustainable aviation fuels. The Base Case scenario is a scenario that combines assumptions considered as most likely for the introduction of hydrogen aircraft, which will substitute the current short- and medium haul fleet in the future. The scenario implies the realistic assumption of market entry of hydrogen aircraft by the year 2040 with size-classes and ranges as outlined in Table 1. The scenario further assumes that airlines would renew their fleets with hydrogen aircraft where applicable while adhering to the normal fleet lifecycle. In addition, airlines are assumed to buy aircraft with comparable seat capacity as today, i.e., a preference for regional and narrow-body aircraft (such as A320 size) on short- and medium haul routes, where applicable. In the Base Case, as well as in all other scenarios with a "low" traffic growth, average annual growth of passengers and flights is 2.6 % and 1.1 %, respectively. Scenario A is a high traffic scenario (passenger growth of 3.5 % and flight growth of 1.6 %, as in scenarios C, E and G), which assumes that the traffic density on airports and flights would be extremely high in the future due to high passenger traffic growth combined with limited airport capacity. Therefore, the airline preference in this scenario is to use wide-body aircraft even on short- and medium routes, if applicable, in order to serve the passenger demand while adhering to airport capacity limitations. Scenarios B to G are parameter variations of the Base Case and Scenario A used in the sensitivity analysis.

Table 2. Scenarios for the analysis of potential hydrogen demand

Scenario	Future passenger traffic growth	Hydrogen aircraft maximum range	Market entry of hydrogen aircraft	Airline preference on short-/medium haul routes
Conventional	low	-	-	Fossil fuel aircraft (as today) without future technology improvement
Base Case	low	1500 nm	2040	Narrow body (hydrogen) aircraft
Scenario A	high	1500 nm	2040	Wide body aircraft to capture high density traffic due to airport capacity limitations
Scenario B	low	2000 nm	2040	Same as Base Case
Scenario C	high	2000 nm	2040	Same as Scenario A
Scenario D	low	1500 nm	2035	Same as Base Case
Scenario E	high	1500 nm	2035	Same as Scenario A
Scenario F	low	2000 nm	2035	Same as Base Case
Scenario G	high	2000 nm	2035	Same as Scenario A

4. Results

Following the methodology described in Section 3 and referring to the Base Case scenario, Figure 1 shows the results for estimated hydrogen demand, first on the global scale, second for all flight departures from Europe (including EU27, EEA, Switzerland and UK), and third for all flights within Europe, i.e., intra-European traffic. Globally, an increase of hydrogen consumption from 2 million tons in the year 2040 up to 19.2 million tons in the year 2050 is forecasted. For flight departures from Europe, the demand is estimated to increase from 340,000 tons in 2040 to 3.3 million tons in 2050. As only short- and medium-haul flights are assumed to be operated with hydrogen aircraft due to long-distance limitations, the difference in results between Europe and Intra-Europe is relatively modest (3.3 million tons vs. 2.9 million tons in 2050). The small difference also shows the high intensity of flight operations within the liberalized European market compared to flights to non-European regions within the range of hydrogen aircraft (such as Northern Africa or Middle East).

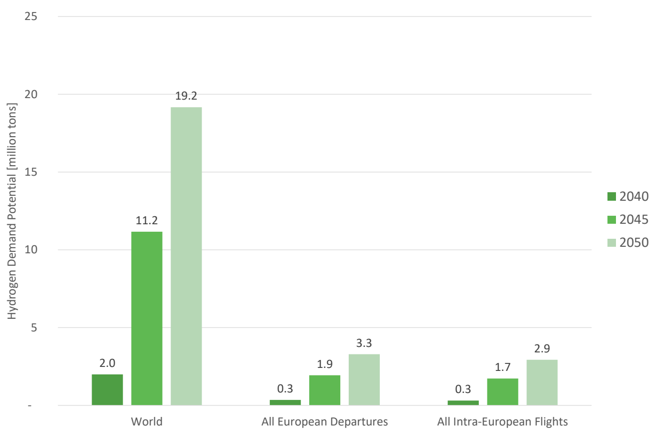

Fig. 1. Aviation hydrogen demand potential in Europe/Worldwide for 2040-2050, Base Case scenario.

The share of energy consumption (Figure 2) that could be replaced by hydrogen in aviation is relatively small as well, as most of the fuel energy is consumed on long-distance flights, which in all scenarios will continue to be operated with conventional aircraft.

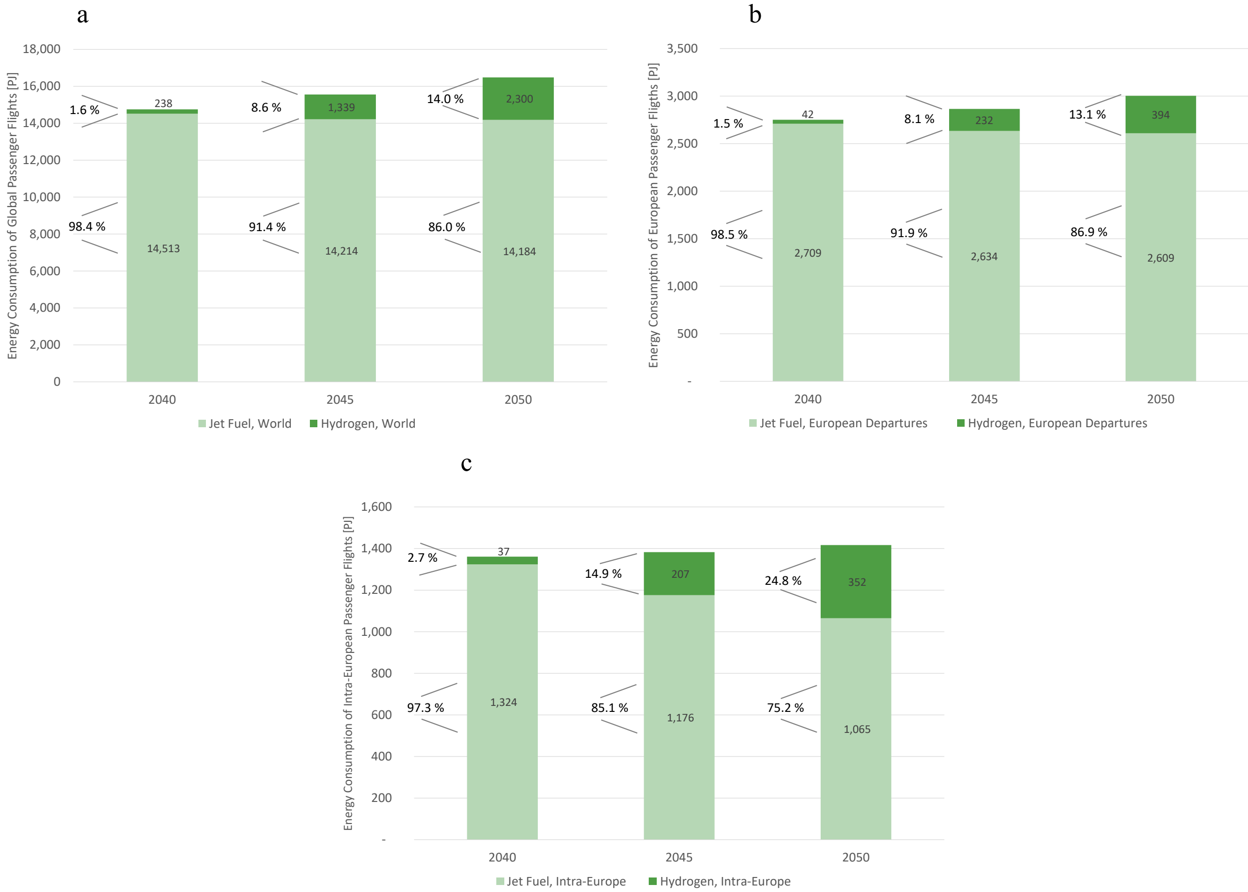

Fig. 2. Share of hydrogen energy consumption; (a) Global flights; (b) All European departures; (c) Intra-European flights.

Hence, the global share of hydrogen in aviation energy consumption is in the order of about 14 % in the year 2050. For intra-European flights, energy consumption increases to about 25 % as most of the flights in the intra-European markets are short- and medium-haul. The 25 % result shows the potential for hydrogen utilization within the European region (Figure 2c).

The global share of hydrogen energy consumption outlined in Figure 2 is also reflected in the reduction of CO_2 emissions, which can be considered as the prime objective for the transition to hydrogen air transport. For this purpose, we have compared the Base Case scenario with the scenario operating conventional fossil-fuel aircraft (see Conventional scenario in Table 1). The Conventional scenario uses fossil-fuel aircraft as the only option for capturing future air traffic demand, and is the only option for future aircraft replacement.

The results of this comparison are shown in Figure 3. The chart reveals that in 2050, global aircraft fleets would emit 196 million tons less of CO_2 compared to the worst-case scenario, resulting in a total of 1,047 million tons. This is equivalent to global savings in CO_2 of 15.8 % through the market-entry of hydrogen aircraft such as outlined in the Base Case scenario. However, this is an optimistic comparison, as we assumed a “technology freeze” of today’s conventional aircraft for the worst-case scenario. If improved conventional aircraft with higher fuel efficiency as today will enter the market in the future, the CO_2 emissions gap between both scenarios shrinks.

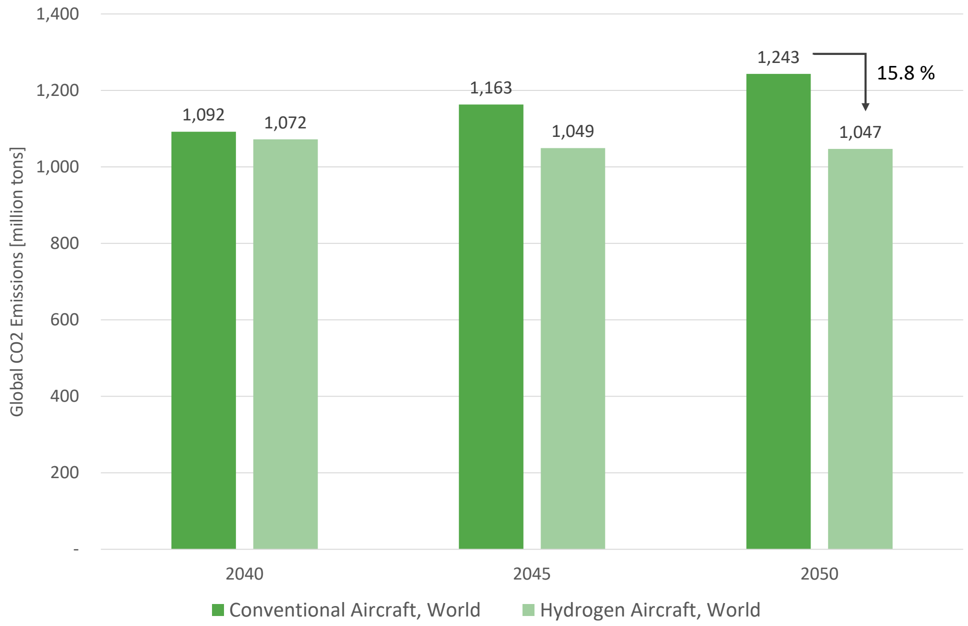

Fig. 3. Global reduction potential of CO_2 emissions with hydrogen aircraft, assuming market-entry in 2040.

The introduction of hydrogen aircraft will depend on various factors. In our Base Case scenario, we have combined conservative assumptions, such as a maximum range of 1,500 nm for hydrogen jet aircraft and a market entry by the year 2040. Figure 4 shows the results of the sensitivity analysis and respective impacts of variations in assumptions as outlined in Table 2 on estimated global hydrogen demand in the year 2050.

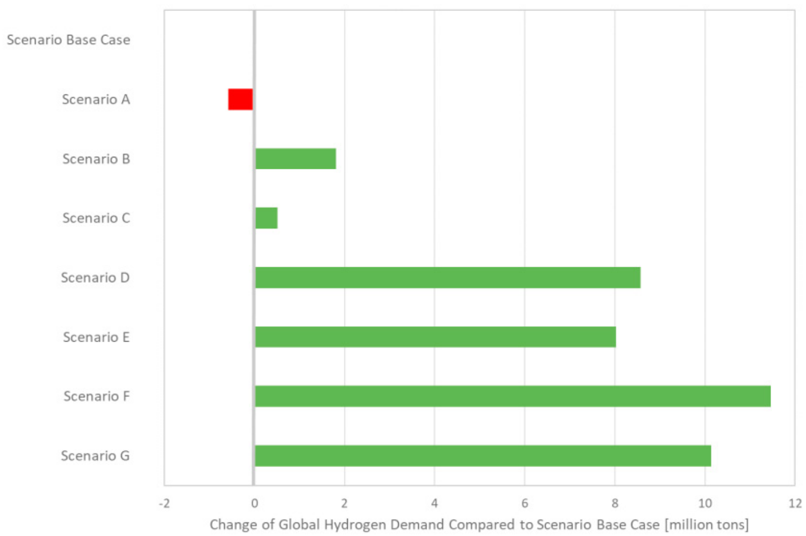

Fig. 4. Sensitivity of hydrogen demand by 2050 in relation to assumptions of range, market-entry, and traffic forecast.

The market entry (varied between 2035 and 2040) shows the highest sensitivity in terms of impacting hydrogen demand – hydrogen aircraft entering five years earlier into the market would potentially result in an 8 million tons increase in global hydrogen demand according to the forecast, all else being equal (Scenario E). The maximum range, however, has a smaller impact compared to market entry. An increase in aircraft range for short- and medium-haul aircraft from 1,500 nm to 2,000 nm, would result in an increase in hydrogen demand by 1.8 million tons (Scenario B).

Finally, the scenarios (A, C, E and G in Table 1) show a decrease in hydrogen demand compared to the scenarios with low traffic growth (Base Case and scenarios B, D and F). This is explained by the fact that, on average, larger aircraft is used by airlines in the extreme "high traffic" scenarios due to a trend of utilizing wide-body aircraft (with much higher seat capacity) on short- and medium-haul routes due to airport capacity limitations. These cannot be substituted by hydrogen aircraft types with a maximum seat capacity of 250 seats per aircraft. In other words, hydrogen aircraft operated in the Base Case scenario, which exhibits a higher share of passenger traffic that can be served by aircraft with 250 seats or less, will be displaced by conventional wide-body aircraft in the scenarios (A, C, E and G), leading to lower global demand for hydrogen. In these scenarios, future passenger demand grows proportionally faster than the possible number of aircraft movements due to limited airport capacity.

5. Conclusion and Outlook

The introduction of hydrogen as energy carrier in aviation will be challenging, if not controversial, for various reasons. Long lead times for aircraft design, rollout and infrastructure development limit the contribution of this option to the decarbonization of air transport in the near future. The rollout of mature hydrogen technology and certified aircraft, including related infrastructure and processes is not expected to happen before the year 2035, even under optimistic circumstances. Hence, hydrogen aircraft will not immediately contribute to mitigate aviation's climate impact.

Even if hydrogen aircraft (such as used in this analysis) are available on the market, their potential to reduce carbon emissions is limited. This is due to the long time required for substituting global airline fleets with new hydrogen aircraft, considering that, typically, 50 % of aircraft are used for at least 22 years. Fleet replacement and total market penetration of new aircraft types are a longer process (taking about two to three decades) in order to replace a significant proportion of the global fleet. It is also because hydrogen aircraft can only be used on short-/medium-haul routes with the current concepts due to limitations of maximum range. It is therefore unlikely to replace a major part of global jet fuel consumption. In today's air transport environment, more than 50 % of fuel is consumed on routes longer than 3000 km (Clean Sky 2 Joint Undertaking, 2021), and airlines aim at increasing economies of scale in operating harmonized fleets. It remains to be seen if hydrogen aircraft can be developed for long-distance flight operations, and, with competitive operating costs compared to alternatives, such as sustainable drop-in fuels.

A major challenge will be the delivery of electricity from renewable sources to produce clean liquid hydrogen. To give an example, based on the assumption that conventional electrolyzers with an energy consumption of 54.5 kWh per kg hydrogen would be used (Zhang et al., 2010), and energy consumption of the liquefaction process would improve to 6 kWh per kg hydrogen (Stolzenburg and Mubbala, 2013), the pure electricity demand for global hydrogen production for passenger air transport would aggregate to 1,160 TWh in the year 2050 for our Base Case scenario. This compares to a global electricity production from renewable sources of 8,300 TWh in 2021 (IEA, 2022). The results have shown that about 14 % of the total energy required for global flight operations could be substituted by hydrogen, and even 25 % for the European region. For the remaining energy demand, other options will probably be preferred, e.g., power-to-liquid hydrocarbon fuels. On a global scale, hydrogen aircraft used for this analysis could potentially mitigate air transport CO_2 emissions levels by about 16 % in 2050 - by exploiting the full potential, i.e. hydrogen aircraft entering the markets in 2040 are used for the full traffic growth and to replace all retired short-/medium haul aircraft over time.

A key issue for airports, however, will be building an effective hydrogen supply chain. This includes transport to the airport, on-site liquefaction, storage, and distribution to individual aircraft stands or gates. Since hydrocarbons (based on today's infrastructure) will probably coexist with hydrogen solutions in the long term, the buildup and operation of an additional hydrogen refueling infrastructure is required. This is not only a challenge from an investment perspective, but in practice also leads to additional space and operational requirements at airports.

Equally important are policies, regulatory frameworks, and incentives with respect to future investments in hydrogen infrastructure, the supply chain, and the deployment of hydrogen aircraft on a global scale. Significant investment efforts will be required for a large-scale market entry and the transition to a hydrogen economy. Therefore, government support in terms of subsidies, tax regulation or other incentives will be crucial to make this vision come alive. For a proper assessment of policy measures, future research must include comparisons with other industry sectors.

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