SCENARIOS FOR THE INTRODUCTION OF HYDROGEN AS ENERGY CARRIER IN AVIATION

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Abstract

Reducing its climate footprint is one of the main requirements for aviation posed by society and politics nowadays. New propulsion technologies and energy carriers for propulsion play a central role in fulfilling subsequent climate targets. One of these new, often-discussed aviation fuels is hydrogen, whether it is directly burned or used for powering fuel cells. Despite the regular political expression to support the uptake of hydrogen in aviation, many uncertainties need to be overcome in doing so. Thus, the complex setting of the aviation environment and the requirements of many stakeholders need to be considered. This paper discusses three scenarios dealing with this uncertainty. By means of scenario techniques, we depict the range of possible developments in the aviation macro environment. After describing the scenario methodology used and the three resulting scenarios, we focus on the enablers necessary for hydrogen uptake in aviation. These factors are identified as playing vital roles in all scenarios. Furthermore, we shed light on our view of the scenarios' implications for the necessary ground infrastructure for hydrogen. This comprises the production and transport of hydrogen as well as its storage and distribution at the airport. These potentially extensive changes to the ground infrastructure are often not considered in the literature about hydrogen in aviation. With this work, we aim to contribute to a basic holistic system view as a basis for further research, e.g., on the estimation of the effects of introducing hydrogen-powered aircraft on aviation global emissions in the coming decades.

Keywords

Hydrogen, Scenario Analysis, Fuel Supply Infrastructure

ABBREVIATIONS

ACARE	Advisory Council for Aviation Research and Innovation in Europe
ATAG	Air Transport Action Group
DOC	Direct Operating Costs
ESA	European Space Agency
EU-ETS	EU Emission Trading Scheme
GDP	Gross Domestic Product
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
OEM	Original Equipment Manufacturer
OPEC	Organization of the Petroleum Exporting Countries
SAF	Sustainable Aviation Fuels
TUM	Technical University of Munich
TRL	Technology Readiness Level

1. MOTIVATION AND INTRODUCTION

In recent years, the general public and policy making has increasingly demanded that air travel‘s environmental footprint be substantially reduced in the coming decades, and that aviation become climate neutral by mid-century. Particularly, the European Commission launched a series of initiatives to accelerate the sustainable transition of the European air travel system. Most notably, aviation emissions are addressed by several measures of the Fit-for-55 package, including a mandatory quota for sustainable aviation fuels (SAF), increased obligations in the EU Emission Trading Scheme (EU-ETS), and a reform of the EU Energy Taxation Directive, which could result in higher taxation of fossil kerosene [1].

Consequently, there is growing consensus within the aviation industry that air travel should reach climate neutrality by mid-century, as laid out in various recently published reports. The Air Transport Action Group (ATAG) and the High Level Group on Aviation Research, in collaboration with the Advisory Council for Aviation Research and Innovation in Europe (ACARE), already defined emissions targets at the fleet and aircraft level respectively [2]. The International Air Transport Association (IATA) set ambitious targets for carbon-neutral growth from 2020 and a 100% reduction in net carbon-emissions from aviation by 2050.

There are various technological and operational possibilities of reducing aviation emissions. While more efficient aircraft and operational procedures reduce the overall fuel burn at the aircraft-level, sustainable energy carriers reduce the carbon footprint of energy use. Just a few years ago, advanced biofuels, yielding kerosene from extensively available raw materials such as straw or wood, were considered the most plausible option for energy transition in aviation. Nowadays, synthetic kerosene – which is based on green hydrogen and a sustainable CO_2 source – is gaining particular attention due to its scalability in the mid-term. While synthetic kerosene has the advantage of being compatible with existing aircraft and infrastructure, the need for a renewable CO_2 source makes its production more complex and costly. [3] Thus, the question arises if the direct use of hydrogen as an energy carrier would be a better option for the long-term defossilization of aviation.

Therefore, within the discussion about new sustainable energy carriers for aviation, hydrogen plays an important role. The use of hydrogen in aircraft, be it through direct combustion in jet engines or through fuel cells, does not create any CO_2 emissions. Also, non-CO_2 effects of hydrogen use are expected to be substantially lower than those of any hydrocarbon [4]. Further, the production of hydrogen by electrolysis is among the most cost-effective methods of obtaining a renewable energy source for aviation. This paradigm shift is essentially based on the significant cost reductions in the solar and wind energy sector [5]. However, the use of hydrogen in aviation requires a deep transformation of the aviation system, especially in terms of fuel production, infrastructure requirements, and aircraft development (see Fig. 1 [6]).

Such profound changes of the aviation system with the introduction of hydrogen create substantial uncertainties in terms of potential future transition pathways. This paper seeks to explore these possible pathways by applying scenario methods. It thereby aims to depict the enablers for hydrogen uptake at the aviation system level with a focus on infrastructure. Furthermore, different levels of political and societal involvement regarding the start of hydrogen operations as well as their overall influence on aviation climate impact are considered.

Section 2.1 introduces the current state of affairs in hydrogen technology applications and the future potential of hydrogen as an aviation fuel. Section 2.2 then focuses on scenario techniques as a method of dealing with uncertain yet complex future issues and their use in aviation. Section 3 describes and compares the three established scenarios. Section 4 discusses implications for the aviation sector, highlights areas for future research and concludes the paper.

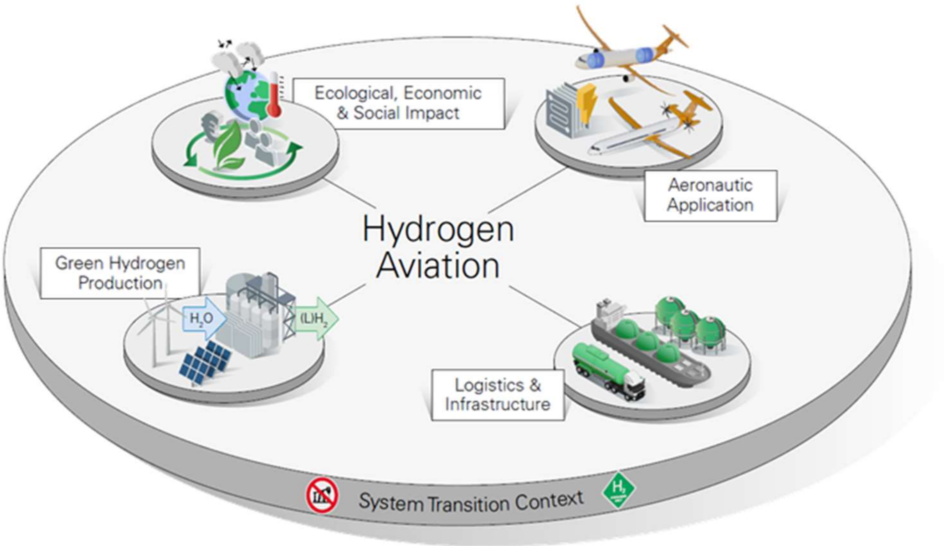

FIGURE 1. Hydrogen system transition [6]

2. STATE OF AFFAIRS

This section sets the scene by introducing the state of affairs for research on hydrogen as future aviation fuel on the one hand and for scenario methodologies on the other.

2.1. Hydrogen in Aviation

The possible transformation of the aviation system in order to foster the implementation of hydrogen has received increasing attention recently, and research as well as initial technical application / demonstration projects have been gaining momentum.

In terms of the aircraft design space, a wide range of technological applications are currently being considered and investigated. Figure 2 depicts the CO_2 emissions contribution of different air transport segments, in terms of number of passengers transported per flight and the range segment covered.

Currently, different projects and initiatives are focusing on the potential to introduce hydrogen to these different segments, either in the form of direct combustion or as fuel cells [7-9]. The integration of liquid hydrogen into aircraft requires different and potentially revolutionary aircraft designs, e.g., considering tank integration into the fuselage. When it comes to the necessary infrastructural system or transporting and storing hydrogen for aviation, two aspects are of particular importance. First, most hydrogen aircraft concepts rely on storing hydrogen in liquid form in the aircraft due to its higher volumetric energy density in comparison to compressed hydrogen. Thus, H_2 would need to be either liquefied or stored in larger quantities at the airport. Both options bring about substantial energy losses along the production chain. It is yet unclear whether it is more efficient to liquefy hydrogen at the airport or deliver it to airports already as liquid hydrogen. Second, hydrogen storage is subject to substantial energy and mass losses, which decreases the overall energy efficiency of the process. Important research progress will be necessary to increase overall production efficiency. [10]

Finally, delivery of hydrogen to the aircraft and the corresponding refuelling process require potentially significant and expensive adaptations to the airport fuel supply systems and the aircraft turnaround process [7]. Moreover, airlines would need to invest in new maintenance procedures, for example.

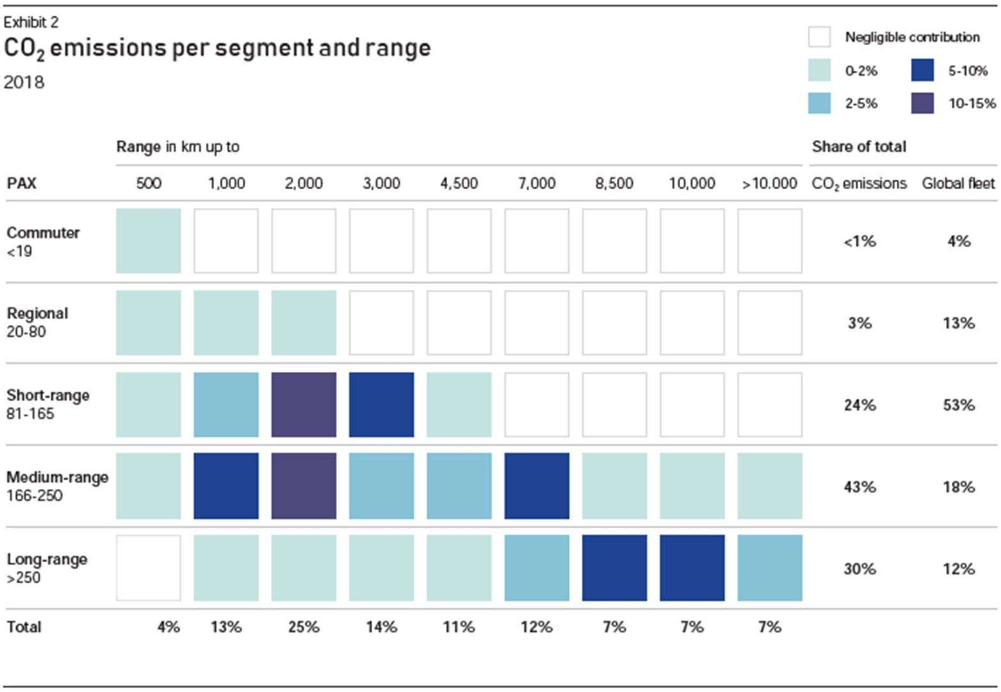

FIGURE 2. CO_2 emissions by air transport segment and range [7]

2.2. Scenario Processes in Aviation Research

This section presents scenario methods as used in aviation and elaborates on the methodological approach utilized within this paper.

The subject at hand is complex and influenced by a multitude of different factors whose development is uncertain. Thus, it is impossible to determine a single projection of the future uptake of hydrogen technologies in aviation with an acceptably high probability of occurrence (see to examples in, e.g., [11] and [12]). In this paper, we rather aim to capture the range of plausible future developments. To this end, scenario techniques allow for a proven methodological approach toward structuring intuitive assessments of different factor developments as frameworks for consistent pictures of the future. Due to the scope defined in Section 1 and the beginning-state-driven nature of the problem at hand, we derive explorative global scenarios [11].

A wide range of scenario approaches of different forms are common in aviation. Global (macro-level) or air transport-specific (meso-level) scenarios, thereby, usually extend over time periods of a few decades. Examples are investigations on novel airline business models [13] and, similar to this paper, the introduction of novel technologies into the air transport system (see, e.g., [14]) and their subsequent fleet-wide uptake [15]. Very specific topics (micro-level), on the other hand, might be investigated over short time periods, see, e.g., work on the influence of volcanic ash clouds on air traffic [16].

Within this study, we follow the scenario process as presented by Will et al. [17]. It is mainly based on the methods described by Gausemeier et al. [11]. This process setup is proven by past scenario projects at the Technical University of Munich (TUM) in cooperation with Airbus, see e.g., [17-19]. The process follows the steps shown in Fig. 3. The problem definition is represented in the introduction. A thorough environment analysis derives all important factors of influence. This process step requires a multidisciplinary team of participants as different views on the subject ensure a complete collection of all relevant aspects and factors. To this end the composition of the scenario team in this project is seen as favourable: It includes seven senior experts from aviation research, an aircraft original equipment manufacturer (OEM) and an airport. Furthermore, twelve students from different fields of engineering introduce views from outside the aviation bubble and from younger generations. The resulting set of environment factors was reduced to a set of key scenario factors by performing an uncertainty-impact analysis in order to limit the workload of the scenario team, see Section 3.1. Those factors identified as most uncertain, while having a high impact on the subject's future development, usually build the crucial points for distinguishing between different scenarios and are thus the most significant for the study.

The following step of the scenario process begins with the definition of about three projections (usually baseline, as well as best and worst case) based on available literature for the future development of each key factor. Afterwards, the consistency of any pair of projections of two different factors is evaluated intuitively. To this end, a consistency matrix is used. Other methods, such as a cross-impact balance matrix [20], are usually more time-consuming with few additional insights and were thus omitted. The intuitive nature of this process step further motivates a heterogeneous composition of the scenario team to cover all relevant viewpoints on the subject at hand. The consistency assessment is finally used to derive core scenario frameworks as those combinations of factor projections which achieve the highest overall consistency values. To this end, every factor needs to be included with exactly one projection. As this step yields a multitude of different combinations, the software tool "Foresight Strategy Cockpit" of 4strat [21] is used for clustering and ordering the scenarios accordingly. The final choice of three core scenarios was made intuitively with the goal of depicting the range of possible developments.

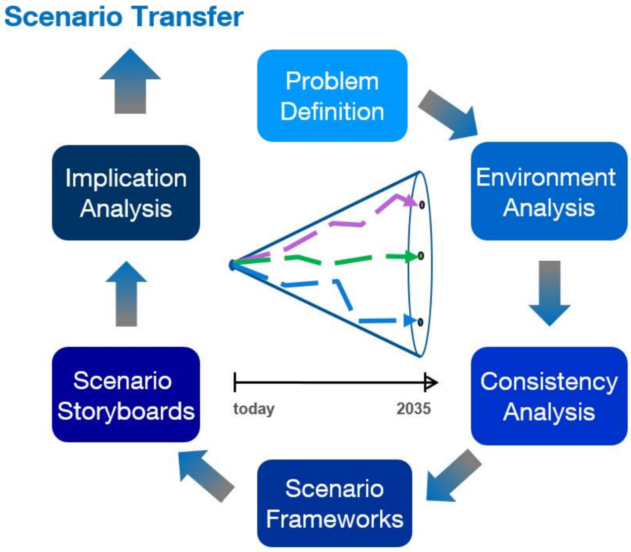

FIGURE 3. Scenario process, from Will et al. [17]

The last project steps include the extension of scenario frameworks into consistent and comprehensive scenario storyboards. Afterwards, implications are derived as key findings of the process, e.g., enablers for hydrogen uptake in the aerospace industry.
The key scenario factors, the scenarios themselves and the implications are presented in the following section.

3. SCENARIOS FOR HYDROGEN POWERED AVIATION 2035+

This section starts with the depiction of chosen environment factors as well as the selection of key scenario factors. It proceeds by introducing the three scenarios as well as a comparison of key scenario elements.

3.1. Environment Factors

Table 1 depicts the environment factors considered for establishing the hydrogen scenarios. These factors, in the areas of 'sustainability, politics and regulation', 'technology and environment' and 'airline and airports', as well as 'society and passengers', have been selected within the scenario team based on expert judgement (see Section 2.2) and a literature review in terms of the elements that are considered important in the implementation of hydrogen aviation (see Section 2.1). These aspects address the technological ramp-up potential of hydrogen aircraft and the alignment of required infrastructure, the political and regulatory implementation frameworks, and airline strategies to adopt hydrogen.
From these, the set of key scenario factors for this project was chosen using an uncertainty-impact analysis. Figure 4 shows the results of this analysis with the key factors for usage in the consistency analysis marked in green. A comparison with Table 1 shows that the key factors cover all defined fields. This indicates a high level of uncertainty in the scenario team regarding the development of hydrogen aviation. From this analysis, we observe that the market penetration of hydrogen aircraft is significantly influenced by the readiness of hydrogen technologies and technical progress in general, the necessary investment for the provision and adaptation of infrastructure, and the integration into airline operations. It, thereby, ranges from global implementation to niche applications in specific regions. Furthermore, general cost considerations are important, and political support is expected to have the highest impact on introducing hydrogen. Based on these factors, the resulting three scenarios for the period 2035+ differ in particular with regard to technological developments, political incentives and subsidies, synergy effects with other industries, and the availability of green hydrogen. These scenarios are described in detail in the following section.

TABLE 1. Overview of selected environment factors

SUSTAINABILITY, POLITICS & REGULATION
▪ Implementation of IATA aviation climate targets ▪ Popularity of hydrogen as energy source globally (demand / investment) ▪ Political support for hydrogen (taxation and incentives) ▪ Availability of renewable energy for H_2 production ▪ Jet A1 fuel price development ▪ Global economic development / GDP ▪ Global regulation and certification for hydrogen-powered aviation (by ICAO or other bodies)
TECHNOLOGY & ENVIRONMENT
▪ Future energy source mix in air travel ▪ Development of H_2-technologies for aviation (Technology Readiness Level TRL) ▪ Climate impact of H_2-powered aircraft ▪ Synergies in industry for hydrogen development
AIRLINES & AIRPORTS
▪ Air traffic development incl. COVID-19 recovery ▪ Ability to integrate hydrogen-powered aircraft into flight operations ▪ H_2-infrastructure costs ▪ Application potential for H_2-powered aircraft ▪ Green H_2-availability at airports ▪ Compatibility of airport infrastructure for hydrogen and conventional fuels ▪ Investment costs for H_2-powered aircraft for airlines ▪ Operational costs of hydrogen-powered aircraft
SOCIETY & PASSENGERS
▪ Public perception of H_2-powered aircraft ▪ Media presence of hydrogen in aviation ▪ Passenger ticket price (business – leisure) on H_2-powered aircraft ▪ Development of aviation share in future modal split on short- / mid-range ▪ Passenger environmental awareness and action (willingness to pay)

3.2. Three Scenarios at a Glance

For each scenario, a storyboard is developed, which describes and evaluates the possible development of hydrogen introduction to the aviation sector.

3.2.1. Scenario A – Optimistic Case for Hydrogen Uptake

The first is the most optimistic scenario for future hydrogen use in aviation. Both global developments as well as changes in the aviation sector support a sustained transition to renewable energies. Assuming that climate change mitigation will become a high priority of global politics, governments all around the globe will push for the reduction of anthropogenic greenhouse gas emissions. Regarding energy production, investments in renewable energy sources are accelerating globally. This creates the possibility for cheap and environmentally-friendly hydrogen production, combined with planning certainty for investments in H_2-technology.

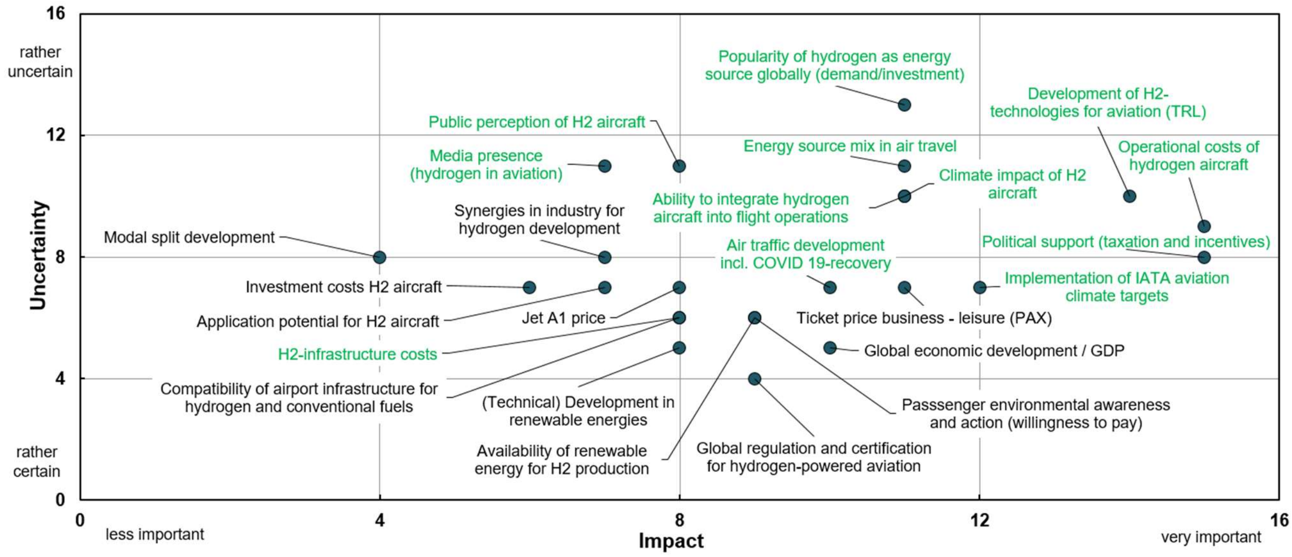

FIGURE 4. Uncertainty-impact analysis, key scenario factors marked in green

Within holistic decarbonization strategies, sustainable transportation is identified as a key action point. This paradigm shift includes an international tax on Jet A1 fuel and strict emission reduction pathways to support the timely achievement of climate targets. As the profit margins of airlines are reduced for conventionally fuelled flights, airlines and industry are heavily incentivized to search for new cost-effective, CO_2-neutral alternatives. Different energy carriers such as hydrogen, renewable electricity, and sustainable aviation fuels, show the technical and economic potential of becoming major buildings blocks of sustainable aviation. In parallel, media and public attention turn toward H_2-powered aviation as a promising solution for sustainable air traffic.

A smooth introduction of hydrogen aircraft is facilitated as the International Civil Aviation Organization (ICAO) forms a certification and regulation body for H_2-powered aircraft at an early stage. Common and focused standards guide aircraft manufacturers, airlines, and airport operators along a streamlined path toward certification and safe operation. While battery-electric solutions are considered for commuter distances, hydrogen-electric propulsion is investigated for the important short-haul market. Due to the high energy consumption of SAF production and rising demand for the long-haul sector, hydrogen can economically outperform SAF in the short-haul markets. The long-range application of hydrogen is still not technically viable, as larger tank sizes lead to wider fuselages, which increase energy consumption and the cost by 30 to 40% per passenger.

Economic and technical agreements between aviation industry stakeholders (e.g., aircraft manufacturers, airlines, and airport operators) lead to lower investment uncertainty, shared risks and a continuous exchange of knowledge. High investments into the research and development of H_2-powered aircraft, supported by industry coalitions, will accelerate technological development and the achievement of technology readiness level (TRL) 9 some years before 2035. OEMs are able to design versatile H_2 propulsion systems with comparable mission performance to conventional reference aircraft (especially regarding turnaround times and flight operations).

Start-ups and small companies with a clear focus on H_2-powered aviation complement and improve the hydrogen aircraft value chain. For involved airlines, the purchase price of hydrogen-powered aircraft is comparable with the price of fossil-powered aircraft. High maturity thanks to improved maintenance procedures and minimal additional training requirements for existing ground staff leads to low direct operating costs (DOC). Synergies between different hydrogen industries and the roll-out of cheap renewable energy lead to relatively low prices for H_2, so that it is competitive with highly taxed fossil energy carriers.

Long-term planning, inter-industry agreements, and public support reduce the investment costs for new H_2 transport and refuelling systems (pipelines, tanks and storage facilities) for airports. All main European, North American, and Asian airports are integrating hydrogen infrastructure into their facilities in time for the market entry of H_2-powered aircraft via cooperation and common standards.

As a result of high synergies, low DOC and penalties on conventional fuel, the ticket prices in the ramp-up phase are just slightly higher than for fossil fuel-powered airplanes. This increases the willingness of travellers to use sustainable transportation.

Public perception and media presence of hydrogen aviation are favourable due to low ticket prices, good safety ratings (as a result of strict certification and intensive research and development) and a trend toward hydrogen technology in multiple key areas of the global economy.

From 2035 onward, parallel deployment of SAF for long range, H_2 for short and medium range, and electric propulsion options for regional market segments in the aviation sector supports the achievement of IATA climate goals within the given timeframe.

3.2.2. Scenario B – Baseline Case

Strongly driven by mitigation efforts regarding the effects of climate change, in this scenario, the G20 states are increasing political support for renewable energy, including support for the aviation sector. Due to increased tensions between, and protectionism of, different states, the GDP (gross domestic product) growth rate has settled at around 2.5% per year. Air traffic growth within the considered timeframe also amounts to 2.5% p.a., driven by higher taxation and a reduction of oil production by OPEC

(Organization of the Petroleum Exporting Countries), which causes a Jet A1 fuel price increase of around 7% p.a. The historical relationship between GDP and air traffic growth is therefore decoupled in this scenario.
For several reasons, hydrogen is the only feasible alternative for short and medium range aircraft until after 2035. For one, the limited available supply of SAF is directed to the long-haul aviation market. Second, no major developments in battery technology limit the application of fully electric aircraft to regional niche markets. Thus, the introduction of hydrogen to those particular market segments is supported politically and will lead to a well-established framework for hydrogen technology development from 2026 onwards. In addition, the competition between the EU, the U.S. and China to release the first hydrogen-powered aircraft is amplifying investment and political support. The uptake of hydrogen in this sector is also facilitated by the establishment of global certification standards for hydrogen-powered aircraft in 2020, and by a good public perception of these technologies.
Since the supply and handling of hydrogen is only moderately compatible with today's airport infrastructure, specific adjustments and investments are required, a scenario which needs strong political support. Until 2036, the main hub airports in North America, the European Union and Eastern Asia will complete upgrading on the basis of global certification standards. With a main focus on the adjustments and implementation at major hubs, the application potential of hydrogen-powered aircraft is still limited. Production capacities and the lack of green electricity to produce hydrogen contribute to the still small application potential as well as high turnaround times for these types of aircraft.
These aspects contribute to slightly increased DOC for hydrogen-powered compared to conventional reference aircraft. Subsidies for the former allow for competitive ticket prices, with these facing an overall increase in the aviation market compared to current levels (year 2021).

3.2.3. Scenario C – Pessimistic Case for Hydrogen Uptake

The post-pandemic world is more unstable compared to pre-COVID-19 times. Energy crises, local conflicts and dampened economic development pose difficulties for the aviation sector. Nevertheless, in this scenario, the international air traffic volume reached pre-pandemic levels by the end of 2023. However, long-haul flights are more focused on leisure travel than on business trips. The increase in remote meetings marks a change in airline business models across the world. Also, with short-haul flights, airlines are under pressure due to a decrease in business trips and by high-speed rail connections.
Regarding the prices and provision of energy in times of conflict, the aviation industry is pushing for sustainability to achieve both the IATA goals and stable energy prices in long term. The political foresight is less ambitious for H_2 and is connected with economic risk. This lack of support leads to high uncertainty for profits in H_2 technologies, also reflecting on the late commitment of companies in taking the first steps in developing these technologies. Only a few industries are investing in H_2 technology development, which is leading to high individual development costs and risks for companies, causing an overall slowdown of the development process and fewer synergies.
Heterogeneity in future energy resources is appearing across the leading world economies. The eastern countries are aiming to maintain their dominance on fossil fuels, while the U.S. is aiming for leadership in synthetic fuels and biofuel production. The EU applies high carbon taxes on kerosene and is establishing a flight ban on regional flights for conventional aircraft on distances below 800 km if there is a high-speed train connection.
The EU is aiming for leadership in the development of H_2 technologies in order to reduce dependency on fossil fuels from the rest of the world. Furthermore, synergies with ESA (European Space Agency) and Arianespace, that are highly experienced in using cryogenic H_2 for their launch vehicles, support the choice of H_2 as the future propellant for intra-European aviation. Because of the lower risks involved with developing smaller aircraft, both battery-electric and H_2-powered planes are targeting the short-range market. Here, European OEMs are pushing toward the use of H_2, focusing on both fuel cells and H_2-burning gas turbines.
In contrast, Chinese manufacturers are focusing on their expertise in battery technology and American OEMs are investigating further into SAF technologies. In 2035, the overall SAF usage is 12%, which is still below the IATA target [22]. As there is no focus on a single technology approach, the learning curve in H_2 and renewable energy technologies is flat, resulting in a TRL of 7 for H_2-powered and battery-electric short haul aircraft in 2035.
The split in development is also hindering the development of a global certification scheme for H_2-powered aircraft, reducing potential markets that OEM can target. The strong worldwide increase in electrical mobility consumes a high share of the available renewable energy. As the production volume of renewable energy is still limited globally, there is not enough green hydrogen available to satisfy demand. Since the expected amount of H_2-powered aircraft is small, no major changes in the airport infrastructures are required. Hydrogen fuel-trucks and special interim tanks are necessary. The investment cost and risk per flight for airports are still high, considering the limited flight volumes. Low production numbers for the required technology, higher safety factors because of unfamiliarity with the new technology and challenging new operational procedures are pushing the DOC upwards. However, even though the DOC is high, ticket prices are only slightly higher than for conventional aircraft. This is because H_2-powered flights are still very seldom and are on short routes. Thus, airlines are promoting H_2-powered aircraft with competitive ticket prices. The additional DOC are covered by the incomes of other more frequent and profitable routes.

3.3. Comparison of the Scenarios

All three scenarios are similar in that they show the same preconditions for widespread uptake of hydrogen technologies in aviation. This section focuses on these prerequisites. It takes into account macro- (global economic and political) as well as meso-level factors (technology and air transport system). Further, we compare the three scenarios toward meeting the preconditions. Implications at the micro-level, especially regarding infrastructure considerations, follow in the next section.
All premises required for the widespread introduction of hydrogen in aviation focus on the economic challenge of introducing this new kind of propellant into the current air traffic network. This economic burden can be reduced by four developments. First, steady growth in international air traffic volume and a stable macroeconomic environment would be favourable for airlines and other stakeholders in terms of investing in this kind of new technology. Second, competing fuels compatible with the current air traffic infrastructure should encounter significant price increases.

Third, governmental support is central to enhancing the competitiveness of hydrogen as an aviation fuel, as already seen in the uncertainty-impact matrix (Fig. 4). Fourth, despite higher prices, hydrogen needs to be accepted by passengers and the public alike as having very limited climate impact and as being a viable way forward toward emission reduction goals. Depending on these factors, while SAF are seen as the most promising climate friendly fuel option in the short- and mid-term in all three scenarios, the use of hydrogen ranges from a niche existence to the start of mass production. This is expressed in the scenarios in a long-term view, all starting from single-digit percentage shares of hydrogen in the global fuel mix in the year 2035.

Scenario A fulfils all aforementioned prerequisites necessary for widespread hydrogen uptake in aviation, emphasizing the need for the global cooperation of all stakeholders in achieving that goal. Furthermore, hydrogen has the potential to outperform other climate friendly propulsion options in terms of climate impact reduction potential as well as economic viability. Thus, in a long-term view up to 2050, hydrogen might account for up to one third of the global aviation fuel share. SAF, especially that used on long-range flights, makes up for the rest with a small niche for battery-electric solutions on regional routes.

Scenario B sees a less favourable environment for hydrogen uptake as compared to Scenario A. However, despite economic difficulties of airlines and lower hydrogen production capacities, regional political support and a lack of climate friendly and scalable alternatives is leading to a delay in the widespread introduction of hydrogen technologies in different world regions after 2035. This leads to about 20% of the global fuel share taken by hydrogen in 2050. SAF accounts for most of the remaining share while limited SAF production capacities lead to a small remaining share of conventional Jet A1.

These regional differences become prominent in Scenario C with different regions opting for different energy sources. This reduces synergies in sharing hydrogen production costs as well as the utilization of aircraft in various regions, which thus increases costs and risks for airlines and manufacturers alike. Consequently, the introduction of hydrogen technologies to the aviation market is delayed and their long-term viability is questionable. Thus, in 2050, only single-digit percentages of the global fuel share accounts for hydrogen, with Jet A1 still playing an important role owing to a lack of sufficient replacements.

While the aforementioned issues give a general outlook on the possible demand for hydrogen solutions in aviation, their prospects for actual implementation highly depend on the compatibility or adaptability of current air traffic infrastructure to hydrogen-powered aircraft. The next section gives a brief outlook on the implications of the scenarios, such as the required airport infrastructure.

4. CONCLUSION AND OUTLOOK

In this paper, we explored potential development paths for hydrogen in aviation. By applying a scenario method, we were able to show how different framework conditions, technological progress, and economic dynamics might influence the long-term introduction of H_2-powered aircraft.

Hydrogen as an energy carrier for aviation has a variety of potential advantages, but its introduction is characterized by significant challenges and uncertainties. Thus, if consensus on the introduction of hydrogen is present, a clear vision and roadmap, supported by all aviation stakeholders, are needed for hydrogen aviation to be scalable in the long term. While the technical feasibility of hydrogen-powered aircraft is questioned less and less, three major aspects remain to be scientifically discussed. First, it is still unclear if, and under which conditions, hydrogen aircraft can be similar to, or more energy efficient than, kerosene-powered aircraft. This, however, is a pivotal question when it comes to evaluating the overall potential of hydrogen for aviation.

Second, the question of energy efficiency also extends to hydrogen infrastructure. A variety of questions are still not sufficiently explored, so that optimal infrastructure configurations do not exist to date – adding substantial uncertainty to the prospective introduction of hydrogen. Across the three scenarios discussed in this paper, different hydrogen supply chains from production to supply at the airport are envisaged. The liquefaction of hydrogen, for example, is assumed to take place at different stages of the supply chain, as depicted in Figure 5. Scenario B even considers liquefaction and storage onsite at the airport. For the transport of (liquid) hydrogen, multiple options such as pipelines, trucks, railways and ships are considered, depending on the location of liquefaction and storage sites. At airports, the low hydrogen volumes in Scenario C imply that fuel transport by truck to the few hydrogen aircraft is sufficient, effectively limiting required infrastructure investments. Scenarios A and B, which prepare for the uptake of comparably large volumes of hydrogen, require the current airport fuel distribution systems to be extended for hydrogen use. This alone raises the question of which stakeholder(s) would bear the resulting, potentially high infrastructure investments. As, for example, airports will be neither willing nor able to account for these costs alone, this highlights the need for cooperation among industry partners. Such high infrastructure costs might well pose a show-stopper for hydrogen in aviation in general, underlining the need for further research in this area.

Third, hydrogen is most likely to be available at reasonable cost to aviation if synergies with other economic sectors can be achieved. In turn, more interdisciplinary insights are needed to better understand if and how inter-industry synergies can be expected.

Considering these existing uncertainties, policymaking can play a substantial role in supporting the uptake of hydrogen in air transport. Most notably, it can create a level playing field with fossil fuels by increasing taxation for CO_2-emitting energy carriers. Further, support of infrastructure investments and pilot projects can help reduce the initial uncertainty related to large scale infrastructure shifts. It can also help to create cross-industry coalitions for the fast and wide-scale uptake of hydrogen to maximise synergies between sectors. Here, a shared vision with, for instance, the chemical industry, shipping, or road transportation could prove particularly beneficial. Finally, the production of large quantities of hydrogen will require large amounts of renewable electricity. Here, early market signals can be helpful in increasing the pace of additional renewable electricity capacity. Otherwise, a shortage of renewable electricity in the mid-term could lead to rising prices and delays in green hydrogen production.

Despite all these challenges ahead, we see interesting potential for hydrogen in aviation which motivates both further academic research, industry interest, and policy action. The scenarios presented can be used as a starting point for further research, e.g., for fleet-level investigations on hydrogen uptake and subsequent estimations of climate impact reduction potential through the introduction of corresponding aircraft concepts and production capacity assumptions into an evolutionary fleet development model.

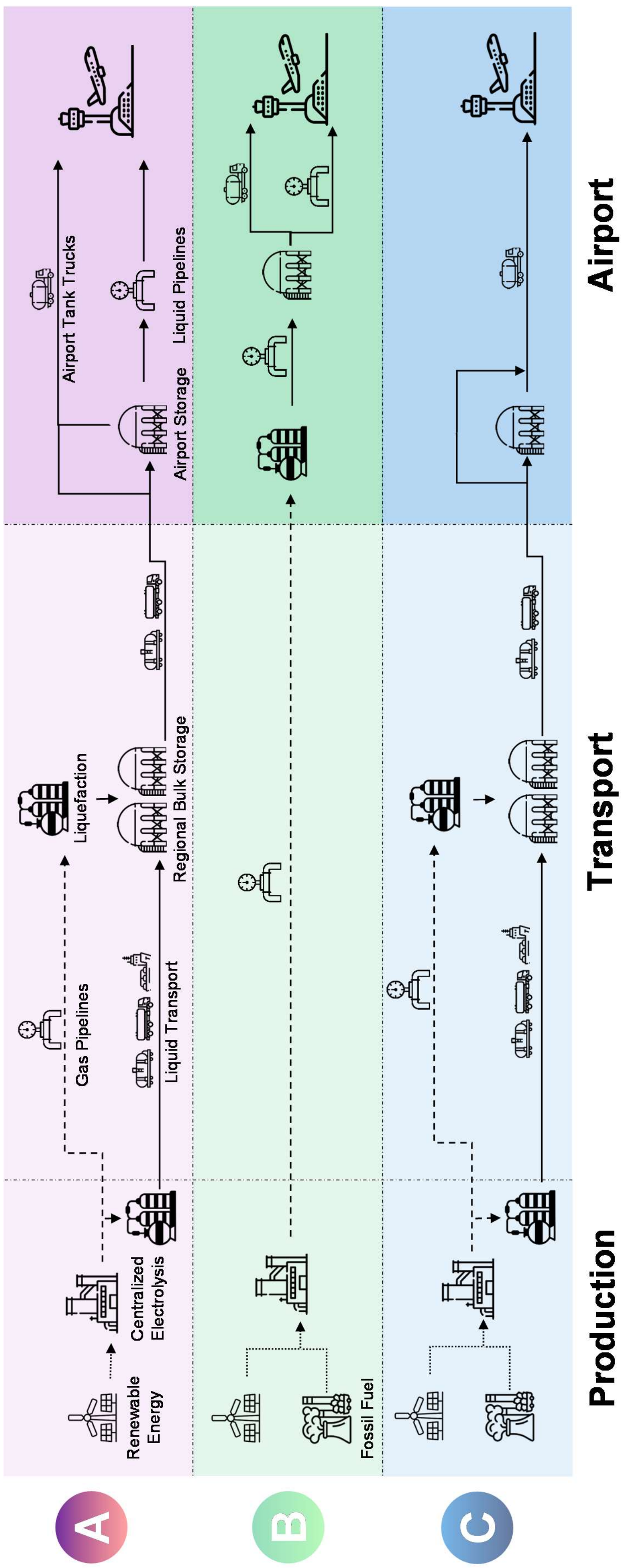

FIGURE 5. Hydrogen supply chains from production to aircraft for all three scenarios

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