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Roadmap for Implementing Hydrogen Technology at Medium-Sized European Airports

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Abstract

Like other transport sectors, the aviation industry is required to reduce its climate-relevant emissions and achieve climate protection targets. One much-discussed option offering the potential to sustainably reduce carbon dioxide (CO_2) emissions is using green hydrogen as a propellant in new aircraft technologies. This paper aims to develop a roadmap for the introduction and use of hydrogen as an alternative aviation fuel at medium-sized airports in Europe, taking Hamburg Airport (HAM) as an example. Especially the development of hydrogen demand and required infrastructures until 2050 at airport level are evaluated. This research has partly been conducted in close co-operation with experts from Hamburg Airport. Our results indicate that the introduction of hydrogen in aviation is a complex task, requiring both large industry investments and decisive political support. If these conditions are met, hydrogen can make an important contribution to the decarbonization of aviation. According to our modeling results, 60% of Hamburg Airport's departures could be operated with hydrogen aircraft in 2050, which corresponds to a CO_2 reduction of 0.5 million tons of CO_2 (-38%).

Keywords: hydrogen; air transport; airport; roadmap; aviation; decarbonization

1. Introduction and background

As other sectors, air transport is required to decarbonize and meet climate protection targets. One promising option offering the potential to sustainably reduce carbon dioxide (CO_2) emissions is the use of green hydrogen (H_2) as a propellant in new aircraft technologies. Other options include the use of Sustainable Aviation Fuels (SAF), the use of

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electricity from renewable sources for electrically powered aircraft, fuel efficiency and operational improvements, as well as market-based measures like emission trading.

An important prerequisite for the use of hydrogen in aviation is that hydrogen-powered aircraft have been developed and are operational. According to Airbus (2022) this could be the case around the year 2035. If this does come to pass, interested airlines will be able to purchase hydrogen-powered aircraft for the use in regular passenger traffic. Another important prerequisite for a successful introduction of hydrogen in aviation is that airports are able to offer this alternative fuel in sufficient quantities for regular refueling. Obviously, as many airports as possible should be able to provide hydrogen for refueling in a timely manner so that airlines can deploy their aircraft flexibly throughout the network. Due to physical and technical limitations, hydrogen-powered aircraft are currently only being designed for short- and medium-haul flights (Airbus, 2022). And some other important aircraft manufacturers, such as Boeing, seem to favor the use of SAF over H_2 – at least for the short and medium term (Boeing, 2024), as certified SAF can be used as a drop-in fuel to replace or supplement conventional kerosene, requiring no technological adjustments. It should also be noted that a complete switch to new fuels in aviation will be a long-term process which could take approximately 20 – 30 years. Against this background, it is very likely that a large number of airports will have to offer several types of fuel, namely conventional kerosene, hydrogen, SAF and possibly (green) electricity for electrically powered aircraft at least for some years in parallel.

Airports therefore have a very important role to play in the decarbonization of air transport through the use of alternative fuels such as hydrogen. What concrete steps do airports need to take to ensure that hydrogen can be offered to airlines on a regular basis and in sufficient quantities? What quantities of hydrogen are expected to be required by airlines in Germany and Europe by the year 2050? How will the hydrogen supply develop in the medium and long term? What prices are expected for hydrogen in this timeframe? What kind of investments in hydrogen infrastructure are required by airports? And finally, which political support is needed for this process?

Our research paper investigates these questions, partly based on discussions with practitioners from Hamburg Airport, and developed them further. In close cooperation with the experts from Hamburg Airport, a so-called 'Roadmap for the introduction of hydrogen at medium-sized airports in Europe' has been developed. Hamburg Airport is a medium-sized German airport and the fifth largest airport in Germany with approximately 13.6 million passengers in 2023. The flight route network of Hamburg Airport is particularly well suited for the introduction of H_2. This is because the vast majority of flights departing from Hamburg are serving short-haul or medium-haul destinations. In addition, the airport operator is very interested in the introduction of hydrogen. The results for Hamburg Airport are, in principle, transferable to other medium-sized airports in Europe.

This paper develops a "down-to-earth" pathway for a successful introduction of hydrogen at European medium-sized airports. To the best of our knowledge, this work will contribute to the so far lacking literature on this issue. Future demand and prices for green hydrogen are modeled, as well as the costs for airport infrastructure such as H_2 pipelines and storage tanks. Additionally, the policy measures for a successful introduction of H_2 are identified.

This paper is organized as follows: In section 1, the relevant literature is analyzed. Section 2 explains the modelling approach of aviation's hydrogen demand, the hydrogen supply in Europe as well as the price development until 2050. In section 3, the infrastructure requirements for the ramp-up of hydrogen at medium-sized airports are investigated. On this basis a roadmap is developed on how to introduce hydrogen at European medium-sized airports successfully in section 4. The paper closes with recommendations for both aviation industry and politics.

2. Literature review

As literature on hydrogen in aviation is manifold, the following review only provides an excerpt of recent studies relevant for the research question of this paper.

Grimme and Braun (2022) estimate the potential hydrogen demand and CO_2 mitigation levels in global passenger air transport by the year 2050. Their modeling results are based on three main assumptions: 1) Market entry of hydrogen aircraft in the year 2040; 2) A gradual replacement of conventional aircraft by these novel aircraft according to regular replacement and retirement cycles of airlines; 3) Future passenger demand on all global routes of less than 1,500 nm will be served by hydrogen aircraft. As a result, global hydrogen demand in 2050 would add up to 19.2 million tons (for passenger air transport only). On the level of the EEA member states plus the UK and Switzerland, the hydrogen demand for passenger departures is estimated to be 3.3 million tons in the year 2050.

Hoelzen et al. (2022a) analyze liquid hydrogen (LH_2) refueling facilities, comparing the costs of utilizing refueling trucks versus pipeline systems. Their findings indicate that by 2050, refueling trucks will be cost-effective for airports with lower hydrogen demand, while pipelines will be more suitable for airports with higher demand. Hoelzen et al. (2022b) assess how H_2 infrastructure adjustments affect direct operating costs. Their study shows that the economic viability of hydrogen in aviation is highly dependent on the availability of affordable green liquid hydrogen, with potential increases in operating costs ranging from 10-70% for short-haul aircraft and 15-102% for medium-haul aircraft. However, in a best-case LH_2 cost scenario, operating costs could actually decrease slightly. Braun and Classen (2023) analyse the operational and infrastructure improvements and regulatory changes needed to support the ground handling of hydrogen-powered aircraft. The authors present various risk registers, e.g. for airport infrastructure and ground handling operations, and for certification, maintenance, and repair.

Degirmenci et al. (2023), after providing an historical overview of hydrogen-powered aviation from the 18th century until 2020, elaborate on the potential benefits and challenges of hydrogen in aviation. Main challenges are identified on the level of the airport hydrogen supply network. Here, several options for both delivering hydrogen to the airport as well as storing it on site are pointed out. However, all of them require large hydrogen-related investments in airport infrastructure. Gronau et al. (2023) investigate the macroeconomic impacts of using hydrogen in German air transport. Therefore, the authors develop a methodology for integrating aviation's hydrogen supply into the German Social Accounting Matrix (SAM) which is a macroeconomic dataset of the German economy. Furthermore, the hydrogen induced effects on gross domestic product (GDP) and employment on a macroeconomic level are investigated. One of the main results is that the net effect of using hydrogen in German air transport would be positive on both GDP and employment.

Raab and Dietrich (2023) compare the costs of different sustainable aviation fuels that have the potential to reduce CO_2 emissions from aviation. They find that liquid hydrogen (LH_2) has the lowest net production cost, while sustainable aviation fuels are up to 90% more expensive. Adler and Martins (2023) analyze the design, cost, and environmental impact implications of hydrogen-powered aircraft, highlighting the need for low-cost green hydrogen and significant investments in energy infrastructure. Raab et al. (2024) examine the techno-economic implications of replacing fossil kerosene in aviation with liquid hydrogen, liquid methane, and renewable kerosene, comparing their costs per passenger and 100 km for ten exemplary routes. The study finds that liquid hydrogen is the most economical option, followed by liquid methane and renewable kerosene, with aircraft acquisition costs and airport investments for cryofuels playing a minor role compared to high SAF costs.

Oesingmann et al. (2024) analyze aviation's potential hydrogen demand, the H_2 price development as well as the CO_2 emission reduction potential of this alternative fuel in the medium and long term. In particular, the authors develop a hydrogen demand model which assumes advancements in liquid hydrogen (LH_2) aircraft technologies, consider the development of aviation demand in the future as well as aircraft startup and retirement cycles. The results of the study indicate that global LH_2 demand in air transport could amount up to 17 million tons by 2050, allowing for a 9% reduction in CO_2 emissions from global air transport. However, the total potential of using hydrogen in air transport is expected to be much larger as hydrogen aircraft could also be introduced beyond the usual retirement cycles.

Finally, Rau et al. (2024) examine the operational and infrastructural changes associated with the introduction of hydrogen-powered aircraft from a flight network perspective. Their study shows that the introduction of hydrogen-powered aircraft will have a significant impact on the network structure, including flight frequency, capacity, and stopover routes, depending on the seating capacity and range of the aircraft design. The study also indicates that airports with a favorable green hydrogen supply will benefit most from the transition to hydrogen aviation.

Our evaluation of the available literature shows that, to date, mainly selected aspects of the use of hydrogen at airports have been investigated from a scientific point of view. In particular, the supply of hydrogen to airports has been examined in detail. In our view, however, an analysis of the entire process of introducing hydrogen at (medium-sized) airports, taking into account the necessary steps from all key stakeholders, is missing. This paper can contribute to closing this research gap.

3. Methodology, results and discussion

3.1. Expected hydrogen demand from European airports, hydrogen supply and hydrogen prices in the medium term

Which hydrogen quantities are required by airlines in Germany and Europe by the year 2050? How will the hydrogen supply develop in the medium and long term? What hydrogen prices can be expected in the short and medium term? In this paper, the expected hydrogen demand from European airports up to 2050 has been taken from the German Aerospace Center's (DLR) research project EXACT (see Hartmann (2021) and Hartmann and Nagel (2021)), while the analysis of hydrogen supply is based on the relevant literature. The timeframe of market entry of hydrogen aircraft is based on Airbus (2022). The hydrogen price development in the medium and long term is mainly based on own modeling results.

One of the results of the EXACT research project was the modelling of the future demand for hydrogen in Europe at airport level up to the year 2050. In the 2020 – 2023 timeframe, the EXACT research project has investigated all relevant technologies for the development of a 50-plus-seat hybrid-electric commercial aircraft. Main assumptions for the hydrogen demand forecast were: New short- and medium-haul aircraft to be purchased (due to retirement or traffic growth) are only replaced by H_2 aircraft. Availability of green H_2 is not considered to be a bottleneck. Possibly higher ticket prices do not reduce demand and a typical aircraft life cycle is 25 years. It should be noted that the assumptions of the DLR EXACT model are deliberately optimistic in order to estimate a full market potential. The corresponding results for the expected hydrogen demand modeled by Hamburg Airport are lower due to different market growth assumptions, but show the same direction.

At this point, the differences between GH_2 (gaseous hydrogen) and LH_2 (liquid hydrogen) shall be mentioned. According to our modeling results, first (maiden) flights will be conducted with small aircraft, for example by ZeroAvia aircraft (20 seats or less) starting in 2030. These aircraft will be powered by fuel cells using GH_2. From the year 2035, both regional jets with turboprop engines, up to 100 seats and a maximum range of 1850 km as well as aircraft with turbofan engines, up to 250 seats and a maximum range of 3700 km could enter into service (Airbus, 2022). In the EXACT modeling scenarios, both turbojet and turbojet hydrogen-powered aircraft are powered by direct combustion of liquid hydrogen (LH_2).

Figure 1 shows the expected development of departures of hydrogen flights at Hamburg Airport between 2035 and 2050, differentiated by aircraft type.

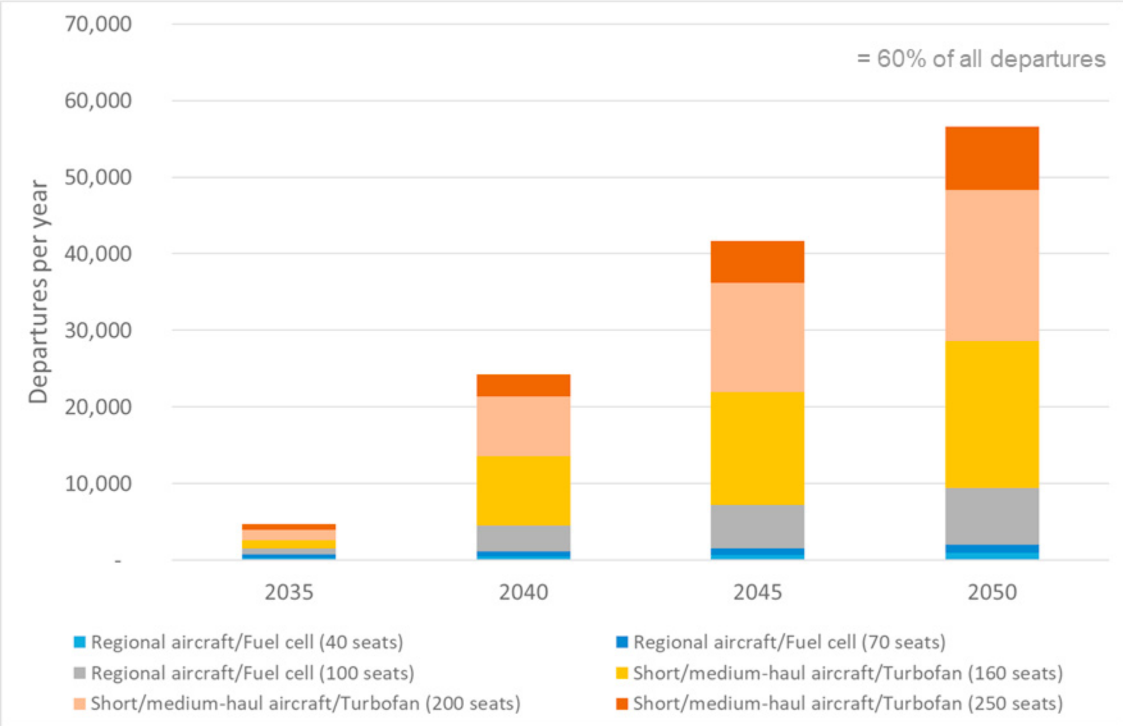

Fig. 1. Departures of hydrogen aircraft p.a., 2035-2050 (Source: EXACT modelling results)

Based on these assumptions, up to 60% of departures in Hamburg could be carried out by hydrogen aircraft in 2050. This translates into an annual hydrogen demand of 60,000 tons and a CO_2 reduction of just over 0.5 million tons of CO_2 in 2050 (~38% CO_2 savings). On average, a single LH_2-powered flight requires just over one ton of liquid hydrogen (LH_2). In a Germany-wide scenario, the demand for hydrogen in aviation would correspond to 0.73 million tons in 2050, which would save 6.5 million tons of CO_2 (~20% CO_2 savings). In total, up to 80% of departures in Hamburg offer the potential for hydrogen aircraft. However, this potential could only be fully exploited after 2050.

In the future, demand for green hydrogen is expected to grow not only in the aviation sector but also in other industries, particularly in the chemical, iron and steel industries. Based on data from the International Energy Agency (IEA, 2023), the industrial sector is expected to account for more than 30% of the global demand for low-emission hydrogen of 410 million tons in 2050, while the share of aviation is expected to be 13%. These estimates assume that the demand for hydrogen for aviation will be mainly indirect in the form of synthetic fuels (10%), with only a small part of the hydrogen demand (3%) coming from the direct use of hydrogen as an alternative fuel.

Green hydrogen is generated by splitting water into oxygen and gaseous hydrogen using electricity from renewable energy sources. The growing demand for green H_2 can be explained by the fact that the combustion of this kind of fuel is very climate-friendly, as it is CO_2-free and more and more sectors (and countries) are committed to achieve climate protecting targets. However, the production potential for renewable energies is unevenly distributed in the world. Figure 2 shows the regions of the world with the highest potential for producing photovoltaic power and which are most suitable for the production of renewable energy (World Bank, 2019). Due to the limited potential for domestic green hydrogen production and the associated higher costs, Germany—similar to other Central European countries—is expected to become a net importer of green hydrogen (Oesingmann et al., 2024). National projections as well suggest that Germany's domestic hydrogen production capacity will likely fall short of meeting the total demand and that between 50% and 70% of this demand will need to be fulfilled through imports (Federal Ministry for Economic Affairs and Climate Action [BMWK], 2024).

The willingness to pay for green hydrogen will most likely differ by sector according to the specific decarbonization costs. According to Oesingmann et al. (2024), high sector competition on the hydrogen market in Europe is foreseeable in the medium and long term. Therefore, it will be important for aviation to become aware of its own hydrogen demand and secure purchase volumes at an early stage.

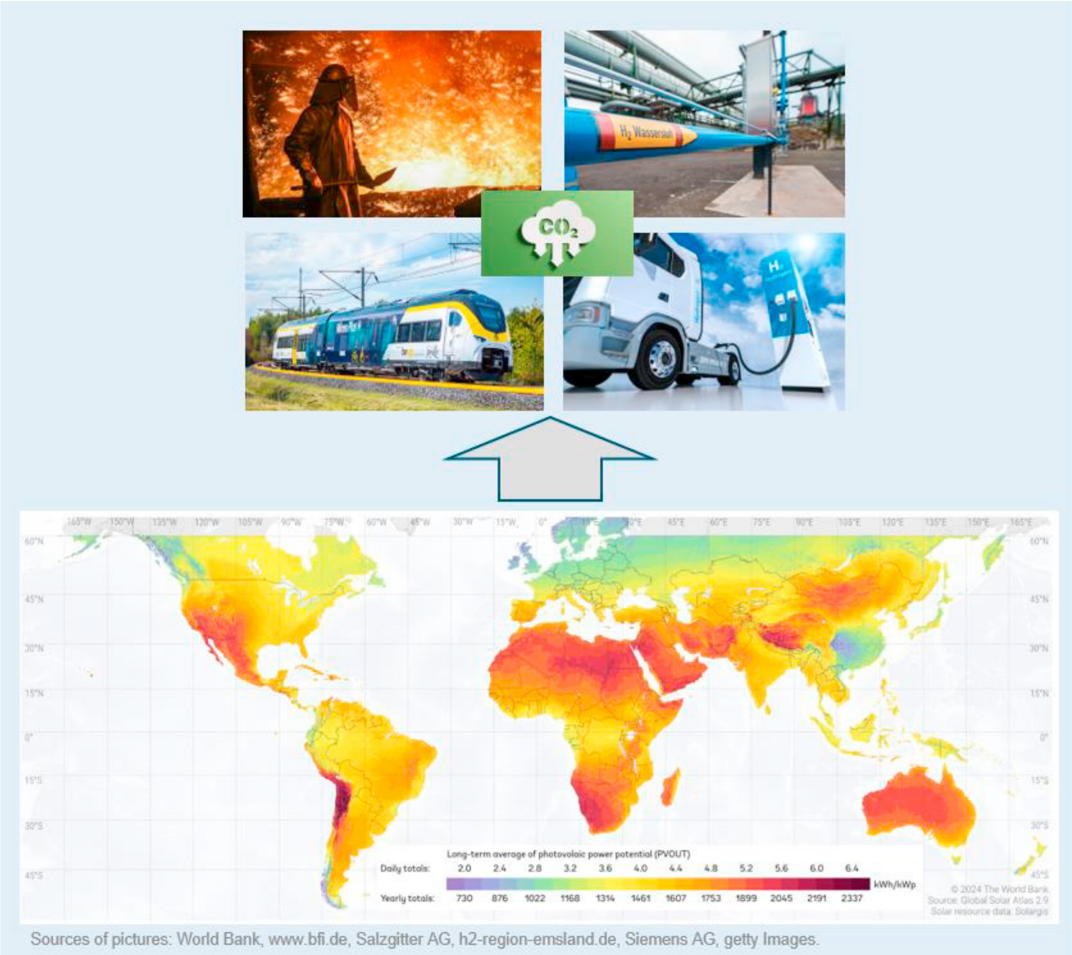

Fig. 2. Photovoltaic power potentials – most suitable world regions (Source: World Bank Group (2024))

Current and future hydrogen prices are an important factor for the hydrogen demand. Currently, no market and therefore no market prices for alternative fuels such as hydrogen exist. Therefore, we have modeled the prices for alternative fuels in air transport at present and their development until 2050 in EUR per megawatt hours (MWh) based on Steer and DLR (2023) (Figure 3). The cost of liquid hydrogen depends mainly on the cost of renewable energy sources and liquefaction costs, and is modeled at €150 per MWh in 2030 and €120 per MWh in 2050. Obviously, the prices for any type of alternative fuel are currently much higher than the price for conventional kerosene, with current prices for liquid hydrogen at about 280 EUR/MWh (Rabb and Dietrich, 2023) compared to fossil fuel prices of 62 EUR/MWh (EIA, 2024). However, over time, a cost degression is expected due to economies of scale for alternative fuels. In the year 2050, the modelling results indicate a lower market price for LH_2 (120 EUR/MWh) than for SAF (180 EUR/MWh) and a decreasing price premium over kerosene. The production of synthetic SAF (e-fuels / PtL fuels) is likely to be more costly than the production of liquid hydrogen. Hydrogen is used as an input within the e-fuels production process and is further processed with CO_2. An efficient carbon pricing could further reduce the price premium over conventional kerosene and promote the market ramp-up of alternative fuels. $_2$.

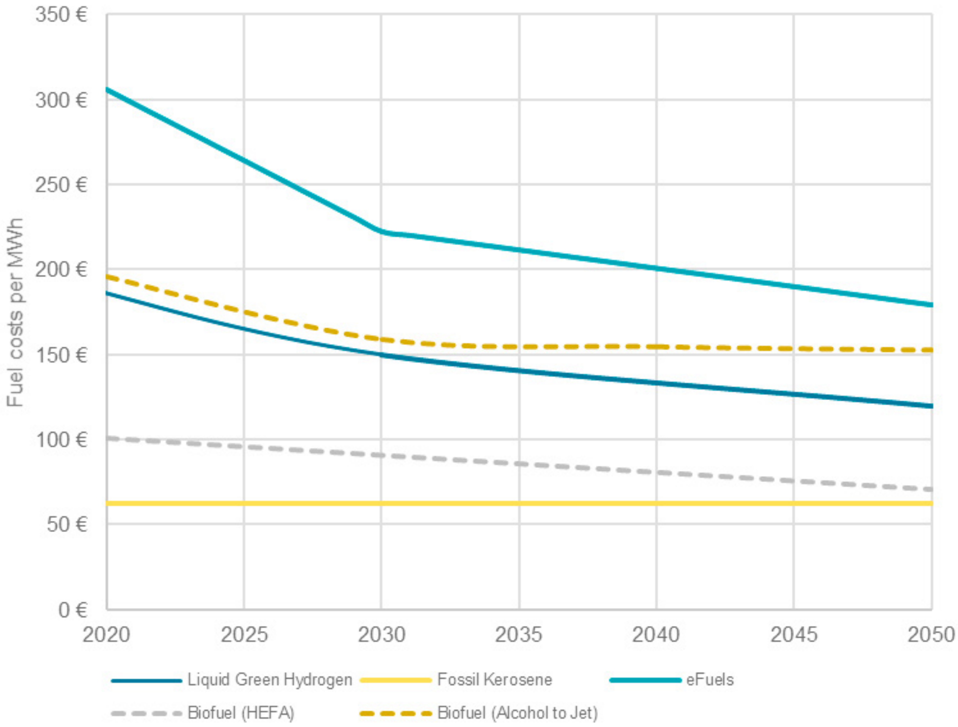

Fig. 3. Fuel cost comparison, 2020 – 2050 (Source: Authors modelling results based on Steer and DLR (2023))

3.2. Hydrogen infrastructure at medium-sized airports and necessary process changes

Which investments in hydrogen-specific infrastructure are required by airports? Specific infrastructure on airport-level will be necessary for the delivery of hydrogen to the airport as well as for the storage of H_2 on site. In addition, investments in cryo-pumping systems and LH_2 apron refueling vehicles will be needed. Assuming that LH_2 bowsers are initially used for deliveries, we have calculated that a medium-sized airport such as Hamburg Airport will require at least 3 trucks per day in 2035, 17 trucks in 2040 and 40 trucks per day in 2050. These tankers will require large parking spaces on site. If GH_2 is delivered via a GH_2 pipeline, which could be possible from the early 2030s, the number of tankers can be reduced. This in turn would require a liquefaction plant at the airport to convert gaseous hydrogen into liquid hydrogen.

In addition, hydrogen has to be stored as a fuel reserve at the respective airport. In principle, both GH_2 and LH_2 can be stored in tanks. Depending on the amount stored as fuel reserve, the size and the investment in the tank will differ. According to our calculations, there is a potential for about 180 LH_2 departures per day at Hamburg Airport by 2050, with an average refueling of 1.06 tons of LH_2 per flight on peak days. This translates to the necessity of 1-2 large LH_2 cryo-tanks each with a capacity of 400 tons as a hydrogen buffer in case of supply shortages. Currently, to the best of our knowledge, the only tank of such capacity in the world is used at Kennedy Space Center by the NASA. Figure 4 shows the NASA tank. Such a tank has a diameter of 25m and a total height of 28m. The footprint on the ground would be approximately 1,000m². This does not include access roads and safety clearances. An appropriate foundation must also be provided to support the loads of the tank.

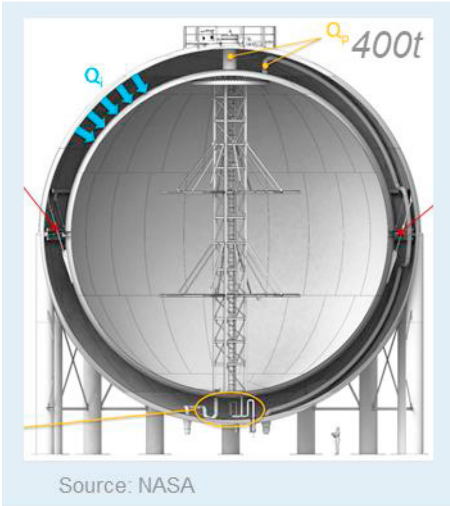

Fig. 4. Example of a high capacity LH_2-tank (Source: NASA (2021))

The costs for these investments at airport level are difficult to estimate, mainly because the costs for pipeline connections, liquefaction plants and storage tanks are currently at the level of the costs for custom-made products. With more widespread entry into the hydrogen economy, economies of scale and reduced costs for these investments are very likely. A very rough estimation by the authors indicates total investment costs for two LH_2 tanks with a capacity of 400 tons each, one GH_2 tank and fueling facilities of around 50 million Euro. This estimation is based on literature research as practical knowledge is still missing at this point in time.

Apart from investments in hydrogen-specific infrastructure, process changes at the airport are required. In terms of safety, additional safety distances for hydrogen aircraft may have to be planned and introduced at the respective airport. Also, standards and rules have to be provided by the respective air safety authority whether refueling could be conducted with (or without) passengers on board. Moreover, the inertization of hydrogen tanks has to be implemented. Finally, the airport staff will have to be trained and the fire-fighting equipment will have to be upgraded in a targeted manner.

In terms of refueling, longer refueling times are likely due to the higher tank volumes of hydrogen. Compared to kerosene, liquid hydrogen has a volume density that is four times higher for the same energy density. This leads to the risk of longer turnarounds at the airport. A possible solution could be the introduction of parallel refueling processes. Further necessary process changes refer to the cooling and draining of hydrogen as well as to a leakage management. To maintain its physical state, liquid hydrogen must be constantly cooled to minus 253°C. Figure 5 provides an impression of the required adaptation of airport infrastructure and processes.

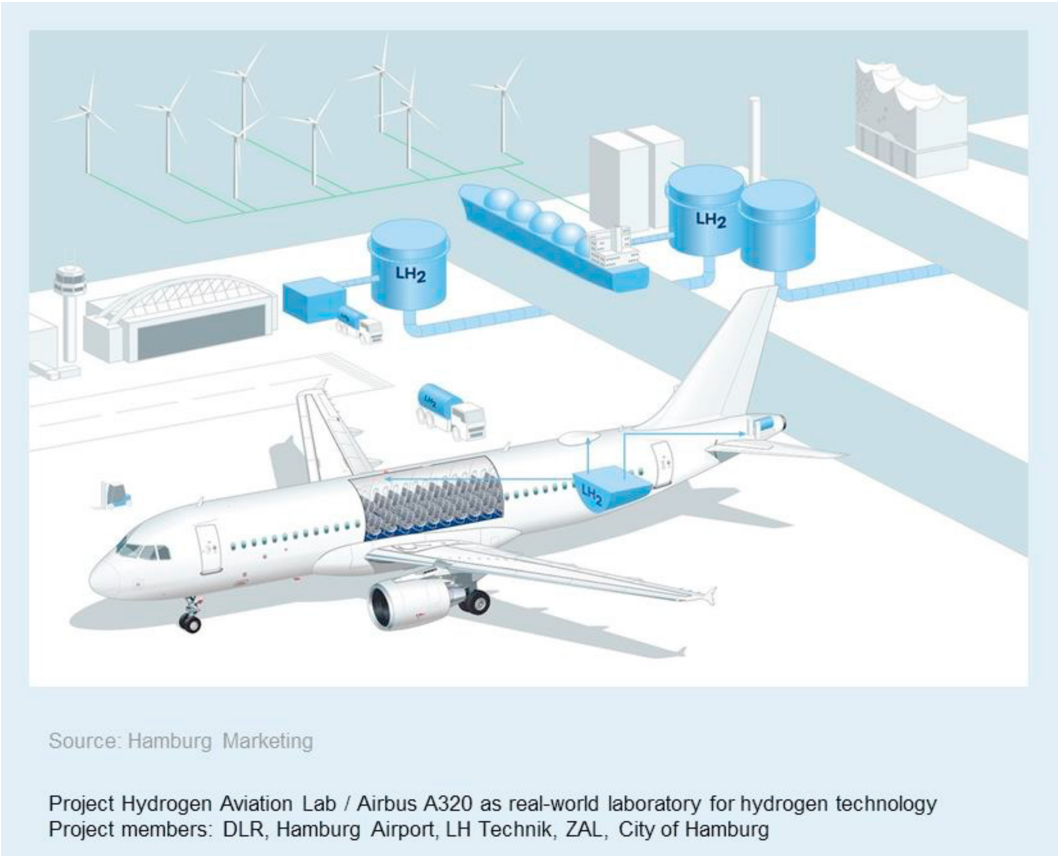

Fig. 5. Adaptation of airport infrastructure and processes (Source: Hamburg Aviation (2021))

3.3. Roadmap for the introduction of hydrogen at medium-sized airports in Europe

Figure 6 illustrates the 'Roadmap for the introduction of hydrogen at medium-sized airports in Europe', which we developed together with experts from Hamburg Airport as mentioned above. For this roadmap, we have assumed that the airport will be delivered with gaseous and liquid hydrogen by tankers in the time period 2030 – 2050 and will gradually be additionally delivered with gaseous H_2 by pipeline from 2035 onwards. As the demand for liquid hydrogen is expected to increase from 2035, it may be necessary to install a liquefaction plant to convert the gaseous hydrogen delivered by pipeline into liquid hydrogen. This in turn would reduce the number of LH_2 tankers required daily. As shown in Fig. 6, the introduction of hydrogen at airports in Europe is a complex task, requiring aircraft manufacturers, airlines, airports, aviation safety institutions and politicians to work hand in hand to promote the market ramp-up of hydrogen in aviation. Joint pilot projects can pave the way.

Policy will have to support the introduction of hydrogen in aviation as the economic viability of hydrogen is unlikely to be achieved within the next few decades. In principle, a number of policy measures is possible. For example, the introduction of direct subsidies to airlines and/or airports for hydrogen-specific investments could provide incentives to build the necessary technology and infrastructure. Measures to reduce the price premium of hydrogen over conventional kerosene, such as higher EU ETS allowance prices or other fuel taxes, could also encourage the use of hydrogen. Also, mandatory quotas for the use of sustainable aviation fuels, which can be met by the use of hydrogen in aviation, as the EU has introduced for European Aviation by the ReFuelEU Aviation Regulation (The European Parliament and the Council of the European Union, 2023) will support the ramp-up of hydrogen. Furthermore, the funding of pilot projects will support the introduction of hydrogen. Above all, however, there must be long-term predictability and reliability in the policy rules and incentives for the aviation industry, these companies will have to make major investments and adapt its processes. Therefore, financial incentives and planning certainty will be crucial. If there is a political will to promote hydrogen in aviation, the introduction of such policies must begin as soon as possible, as a successful process will take decades.

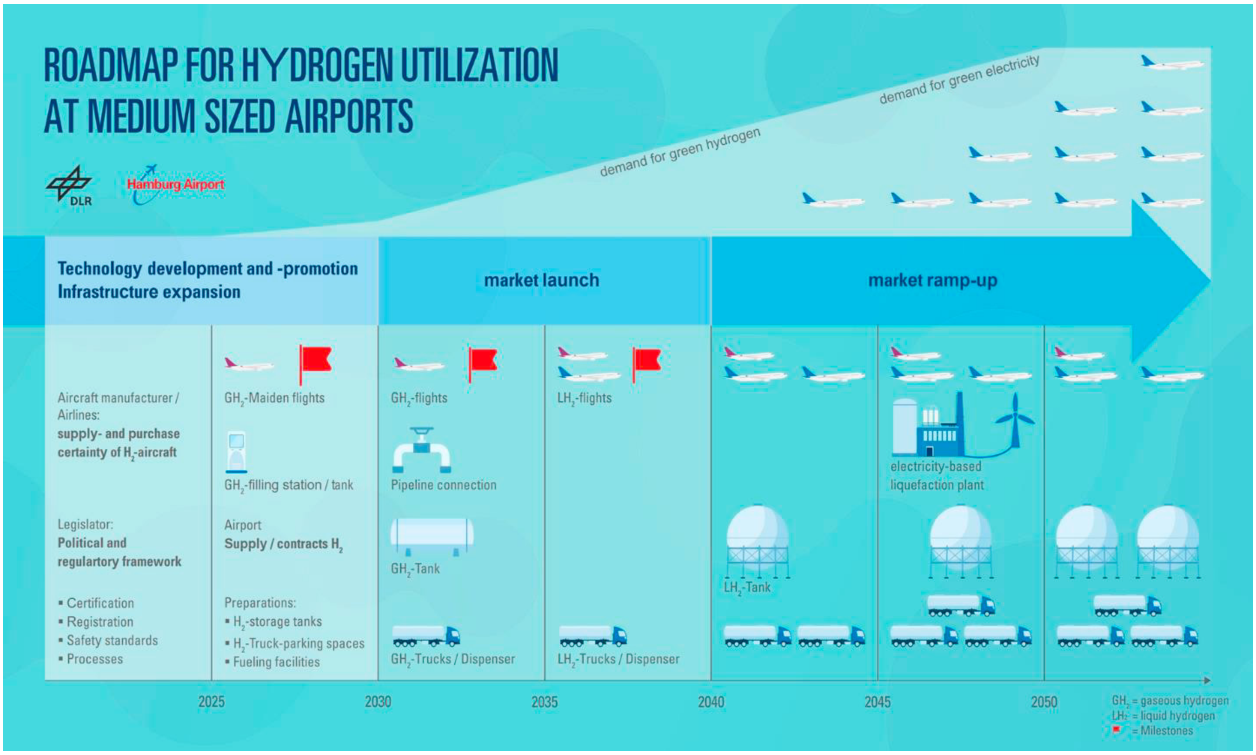

Fig. 6. Roadmap for the introduction of hydrogen at medium-sized airports in Europe (Sources: DLR and Hamburg Airport (2023)

4. Conclusions and recommendations for industry and policy makers

This paper develops a "down-to-earth" roadmap for a successful introduction of hydrogen at European medium-sized airports. Our results indicate that the introduction of hydrogen in aviation is a complex task, requiring both significant industry investment and strong political support. If these conditions are met, hydrogen can make an important contribution to the decarbonization of aviation.

In 2050, 60% of departures at Hamburg Airport could be operated with hydrogen aircraft, which corresponds to a CO_2 reduction of 0.5 million tons of CO_2 (-38%). However, high demand for green hydrogen will also be expected from other sectors. Aviation needs to secure purchasing volumes early on. This applies to both airlines and airports. To promote hydrogen in aviation, it will also be important for the air transport industry to carry out pilot projects for the use of hydrogen and to develop hydrogen infrastructure masterplans for the relevant airports. In addition, the necessary process changes should be well prepared at airport level and harmonized – at least on a Europe-wide basis. Also, the respective air transport safety institutions have to provide standards and rules for the use of hydrogen in aviation at an early stage.

Political measures can promote the switch to new technologies. In principle, a number of policy measures is possible. As presented on Figure 6, the introduction of some political measures will be important at the beginning of the hydrogen ramp-up process. This refers to the (co-)funding of pilot projects for the use of H2 in aviation. Also, national hydrogen supply contracts with suppliers from European and non-European countries could be initiated on political level. Apart from these measures, the introduction of direct subsidies to airlines and/or airports for hydrogen-specific investments or price incentives (increase in kerosene price or EU-CO_2-Allowances prices) could incentivize the use of hydrogen. Mandatory quotas for the use of sustainable fuels, including hydrogen, in aviation, as introduced by the EU for European aviation through the ReFuelEU Aviation Regulation (The European Parliament and the Council of the European Union, 2023), will also support the ramp-up of hydrogen. If policymakers want to promote hydrogen in aviation, the introduction of such policy instruments must be initiated now. In addition, supporting policy instruments should have a long-term perspective. This is especially important because investing companies require long-term planning security, as extensive and costly infrastructure investments and process adaptations will be necessary.

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