

Article

Emission Reduction Potential of Hydrogen-Powered Aviation Between Airports in Proximity of Seaports

Nico Flüthmann *, Tim Schunkert, Marc Gelhausen and Alexandra Leipold

German Aerospace Center (DLR), Institute of Air Transport, 51147 Cologne, Germany; tim.schunkert@dlr.de (T.S.); marc.gelhausen@dlr.de (M.G.); alexandra.leipold@dlr.de (A.L.)

* Correspondence: nico.fluethmann@dlr.de

Abstract

Green hydrogen will play a crucial role in the future of emission reduction in air traffic in the long-term, as it will completely eliminate CO₂ emissions and significantly reduce other pollutants such as contrails and nitrogen oxides. Hydrogen offers a promising alternative to kerosene for short- and medium-haul flights, particularly through direct combustion and hydrogen fuel cell technology in new aircraft concepts. Against the background of the immense capital-intensive infrastructure adjustments that are required at airports for this purpose and the simultaneously high future hydrogen demand for the shipping industry, this paper analyses the emission savings potential in Europe if airports near seaports would switch to hydrogen-powered flight connections.

Keywords: hydrogen aircraft; market potential analysis; seaports; hydrogen infrastructure; transport geography; GIS analysis; emission reduction



Academic Editor: Michael Schultz

Received: 12 June 2025

Revised: 11 July 2025

Accepted: 20 July 2025

Published: 25 July 2025

Citation: Flüthmann, N.; Schunkert, T.; Gelhausen, M.; Leipold, A. Emission Reduction Potential of Hydrogen-Powered Aviation Between Airports in Proximity of Seaports. *Aerospace* **2025**, *12*, 661. <https://doi.org/10.3390/aerospace12080661>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The aviation sector faces immense challenges in significantly reducing its CO₂ emissions in the future. In 2024, global aviation (domestic and international flights) emitted 915 MT CO₂ in total, which corresponds to a share of 2.5 percent of global emissions, while its overall contribution to climate change is considerably greater when accounting for non-CO₂ effects [1]. Without extensive mitigation measures, the CO₂ emissions from the aviation sector could significantly increase to around 1600 Mt CO₂ in 2050 [2]. Hydrogen can play a crucial role in reducing aviation-related emissions, as it has the potential to fundamentally transform aviation and enable emission-free air travel. However, the integration of hydrogen in aviation is associated with considerable technical, economical, and infrastructural challenges. For example, the use of hydrogen as direct combustion requires completely new aircraft concepts and adaptations of the fuselage structure, as liquid hydrogen can only be stored using new cryotanks. In addition to a new aircraft design, the development of a hydrogen infrastructure at airports is considered complex and cost intensive, as new storage capacities, liquefaction plants, refueling systems, and safety concepts must be developed. Finally, the production and supply of sufficient green hydrogen represents an immense challenge. On the one hand, the energy-intensive production of hydrogen requires significant further expansion of renewable energies in order to be able to produce sufficient quantities in the future. On the other hand, the transport of hydrogen is considered technically demanding and cost intensive. Accordingly, the economic viability of hydrogen use in aviation must be improved in the future through political framework conditions, economies of scale, and technological innovations. The recent postponement

of Airbus' planned market launch for a hydrogen aircraft from 2035 to the late 2030s [3] highlights the immense challenges for the implementation of hydrogen-powered aviation.

Since a large portion of the green hydrogen required in Europe will have to be imported from regions with better and cheaper hydrogen production conditions, seaports in particular play a significant role as hydrogen import hubs. At the same time, in addition to air transport, the shipping industry will also require enormous quantities of green hydrogen in the future. Thus, 40–54 MT of hydrogen will be required in Europe in 2050, of which 4–6 MT (approx. 10%) will be used for air transport alone and another 4–6 MT (approx. 10%) for shipping [4,5]. Another source estimates that in 2050—depending on the progress in expanding local renewable energy production—between 25 percent and 70 percent of hydrogen consumption in Europe will be imported through European seaports [6]. Seaports will therefore serve as important hubs for the import, distribution, and storage of hydrogen in Europe in the future.

Accordingly, airports located in close proximity to seaports could benefit when hydrogen-powered air transport connections in Europe become operational. The main advantage of these airports, especially as far as efficient logistics are concerned, is the short transport routes from the seaport to the airport, which minimizes transport costs and energy losses. In addition, the existing infrastructure and logistics of the seaports (storage capacity, transshipment facilities, liquefaction plants, etc.) can be shared, significantly reducing the airport's investment costs and enabling synergies and economies of scale. Increased security of supply with green hydrogen through the direct connection to a hydrogen hub at the seaport is also a major advantage.

This paper therefore examines the potential of hydrogen-powered air transport connections in the year 2050 between European airports located in close proximity to seaports and analyses the impact of varying vehicle-specific (range) and infrastructure-specific (distance to the seaport) assumptions on the market potential and emission reduction potential of hydrogen aircraft in Europe.

2. Literature Review

As mentioned in the previous introductory section, the use of hydrogen as an energy carrier in aviation is considered one of the most promising options for paving the way to long-term sustainable aviation. However, the scientific discussion on this topic is characterized by a multitude of issues, ranging from technological and infrastructural challenges to questions of market integration and demand.

Against the background of the research focus of this paper, publications identified in this literature review are grouped into two central topic areas according to their thematic focus. On the one hand, "Infrastructure and Challenges", which includes publications that deal with the technical, logistical, and regulatory requirements for the development of a hydrogen infrastructure in aviation. On the other hand, "Market and demand", which summarizes publications examining the potential market penetration of hydrogen technologies in aviation, emission saving potentials, and demand potentials. This thematic structuring enables a systematic presentation of current research results and provides an overview of the most important findings in the context of the potential of hydrogen in aviation.

2.1. Infrastructure and Challenges

Gu et al. (2023) emphasize in their review of airport infrastructure requirements that there is a global lack of planning, available space, and necessary resources for hydrogen deployment at airports. They highlighted the need for a structured roadmap to support airport planners in adapting infrastructure for the aviation energy transition [7]. Braun and Classen

(2023) emphasize the need for qualitative risk management for future hydrogen-capable airports. They identified risks, particularly in the areas of ground handling, refueling, and the integration of emission-free ground services [8]. Scheelhaase et al. (2024) showed that the introduction of hydrogen technology at medium-sized European airports is a complex project that requires considerable investment by the industry and clear political support. Modeling using the example of Hamburg Airport shows that up to 60% of departures could be carried out with hydrogen aircraft in 2050, which corresponds to a CO₂ reduction of 0.5 million tons or 38%. However, implementation depends largely on long-term political framework conditions and targeted funding measures [9]. Hoelzen et al. (2022) highlighted that the economic viability of hydrogen aircraft depends heavily on the availability of cost-effective green hydrogen infrastructure. In scenarios with high costs of green hydrogen, operating costs could increase by up to 102 percent [10]. Another publication by Hoelzen et al. from 2022 analyzed the technological design and economic viability of hydrogen refueling systems at airports. It was shown that the integration of a hydrogen infrastructure is technically feasible, but significant investment and supply chain planning are necessary to realize economical and sustainable hydrogen-based aviation [11]. Van Dijk et al. (2024) used Rotterdam Airport as an example to analyze how airports can establish a liquid hydrogen infrastructure. It was shown that local factors such as proximity to hydrogen hubs and the availability of renewable energy are crucial for the design of a hydrogen value chain. Instead of investing in resource-intensive local production facilities, the airport benefits from synergies with Rotterdam's strategic hydrogen hub, which includes both the existing and planned import and liquefaction capacity [12]. The Japanese–Australian demonstration project HySTRA successfully proved the end-to-end feasibility of long-distance LH₂ transport via maritime routes. This included the establishment of a complete supply chain with import and export terminals equipped with cryogenic LH₂ storage tanks and automated loading arm systems with cryopumps (Takaoka et al., 2023) [13]. Building on this practical implementation, Zhang et al. (2023) reviewed the current state of technological development across the hydrogen supply chain and emphasizes that for transport distances exceeding 2000 km, shipping liquid hydrogen may offer cost advantages compared to alternative hydrogen transmission methods such as pipelines or synthetic carriers [14]. The paper by Degirmenci et al. (2023) provides a comprehensive historical overview of hydrogen-based aviation and analyses in particular the challenges and prospects of hydrogen use in aviation as well as the importance of an efficient hydrogen supply network at airports. It emphasized that hydrogen has great potential for the decarbonization of aviation but also highlighted that the development of a reliable infrastructure is a key challenge for successful implementation [15]. Jaffary and Wiedemann (2025) examined the safety requirements and challenges of refueling aircraft with hydrogen at airports in the context of climate-neutral aviation. The authors showed that safe hydrogen refueling requires special infrastructures, clear regulations, and comprehensive staff training. They emphasized that the development and implementation of appropriate safety standards is crucial for the successful introduction of hydrogen as an aviation fuel [16]. Gronau et al. (2025) pointed out the need to take a macroeconomic view of the entire hydrogen supply chain and examined the effects of integrating hydrogen-powered aviation in Germany. The authors showed that the expansion of a hydrogen infrastructure for aviation can set significant economic impulses but also brings new challenges for energy supply and value chains [17].

2.2. Market and Demand

The market potential for hydrogen-powered aviation is examined in several studies. Oesingmann et al. (2024) examined the development of demand, price dynamics, and CO₂

reduction potential and showed that there is considerable market potential, particularly in the short- and medium-haul sector, assuming that the infrastructure is provided. They analyzed that the global demand for liquid hydrogen in aviation could rise to approximately 17 million tons in 2050. This could lead to a 9% reduction in CO₂ emissions [18]. Grimme and Braun (2022) estimated the global hydrogen demand potential and CO₂ savings in passenger air traffic in 2050. They emphasized that technological and infrastructural challenges still exist that hinder the widespread introduction of hydrogen aircraft and that the market entry of hydrogen aircraft, in particular, has the highest sensitivity regarding future hydrogen demand [19]. Schenke et al. (2023) quantified the resources required for the global introduction of hydrogen-powered aviation and made it clear that the expansion of renewable energies and the provision of large quantities of green hydrogen are key prerequisites. It was found out that the choice of supply route has significant impacts on the economic viability and energy efficiency of hydrogen use in aviation [20]. Adler and Martins (2023) and Yusaf et al. (2025) provided an overview of the technological fundamentals, environmental impacts, and economic framework conditions for hydrogen aircraft. They emphasized that, in addition to technological breakthroughs, economic incentives and political framework conditions are also crucial for market penetration [21,22]. Akbiyik et al. (2025) conducted an economic analysis of current applications and showed that the costs of hydrogen aircraft are currently still significantly higher than those of conventional aircraft but could decrease with economies of scale and technological progress [23]. A holistic comparison of hydrogen-powered aviation with alternative net-zero pathways (Hoelzen 2024) revealed that, when considering both fuel supply and aircraft-related costs, operating hydrogen aircraft could be approximately 3% less expensive than flying with synthetic kerosene [24]. Bridgelall (2025) analyzed patent data in the field of hydrogen-powered aviation and identified key technological trends and innovation priorities. The analysis made it clear that the development of hydrogen technologies for aviation is gaining momentum worldwide and holds great potential for innovation [25]. Rau et al. (2024) modeled the effects of the introduction of hydrogen-powered narrowbody aircraft on the European passenger air transport network. The results showed that the use of these aircraft leads to changes in the route structure and network utilization, with shorter routes and larger airports benefiting in particular [26].

2.3. Research Gap

Despite the significant number of research publications in the field of hydrogen potential in aviation, there have been no comprehensive studies or publications on the specific potential of hydrogen-powered aircraft connections between European airports in close proximity to seaports. The combination of airport and seaport infrastructure could offer synergies in hydrogen logistics, particularly with regard to the maritime import of liquid hydrogen (LH₂). Shared use of import terminals, storage facilities, and distribution systems may enhance overall efficiency. This has not yet been sufficiently analyzed on a European level, although it could be of great importance for the efficient scaling of hydrogen in aviation. This paper therefore addresses a relevant research gap and positions itself in the current research field of hydrogen-based aviation by analyzing the potential of hydrogen flight connections between European airports in the proximity of seaports.

3. Hydrogen in Aviation and Seaports as Hydrogen Hubs

To achieve emission reductions, hydrogen (H₂), next to battery-electric propulsion systems and Sustainable Aviation Fuels (SAF), is increasingly gaining attention as a potential energy carrier for aviation. Hydrogen can be produced renewably through electrolysis and is therefore not dependent on fossil fuels. This makes hydrogen a promising candidate

for the use in aviation, as the use of hydrogen propulsion can not only contribute to the avoidance of CO₂ emissions but also eliminates soot emissions, which contribute to contrail formation [27,28]. Furthermore, the gravimetric energy density of H₂ is almost three times higher than that of kerosene. This makes it particularly attractive for applications where weight plays a crucial role, such as aircraft. The high density of liquid hydrogen (LH₂) compared to gaseous hydrogen opens up advantageous applications for aviation, as significantly larger quantities can be stored at low pressure. On the other hand, a heavy, complex tank system will be necessary for storing LHLH₂ on the aircraft. Hydrogen can be used in aviation in a variety of ways, with the use of fuel cells or direct combustion being the most frequently discussed methods. Although the direct combustion of hydrogen in an aircraft engine does not generate soot emissions like kerosene, the formation of contrails can still occur, albeit significantly reduced. Furthermore, nitrogen oxides (NO_x) are still emitted due to the high combustion temperature [29]. An alternative to combustion is the use of hydrogen in fuel cells, which in turn generate electrical power for the electric powertrain. This approach enables nearly emission-free flight operations but is limited in terms of the aircraft's range due to the heavy weight of the fuel cells and the large tank volume [30]. The development of lighter and more efficient fuel cells is therefore a key research area to expand the application of this technology in aviation. An analysis of emissions by range segment shows that over two-thirds of aviation emissions come from medium-haul flights with ranges of less than 4000 km [30]. Of these, short-haul flights with ranges of less than 1500 km alone account for half of the CO₂ emissions [30]. Hydrogen technology, therefore, has enormous potential to reduce emissions in aviation, despite the comparatively short range in the short- and medium-haul segments. In contrast, long-haul flights are more difficult to optimize technologically. Although they account for a smaller share of aviation CO₂ emissions, they pose a greater challenge in the development of new technologies.

Despite the many advantages of hydrogen as an energy carrier, its use in aviation presents significant challenges. The low density of hydrogen compared to kerosene results in a larger tank volume, which negatively impacts aerodynamics and flight efficiency. In addition, storing liquid hydrogen at cryogenic temperatures requires special tanks to minimize heat input and control evaporation. These characteristics impact not only aircraft design but also supply chains, infrastructure requirements, operational procedures, and airport handling processes.

Since the delivery of LHLH₂ is only possible to a limited extent using conventional truck trailers due to its low volumetric density, the construction of hydrogen liquefaction plants in combination with gaseous delivery via a pipeline requires significant intervention in airport infrastructure, resulting in very high investment costs for airports.

The transport of liquid hydrogen by pipeline also presents enormous technical challenges. Unlike for gaseous hydrogen, cryogenic LHLH₂ pipelines currently exist only in special cases over relatively short distances. Examples include LHLH₂ pipelines within industrial facilities for refueling rockets or from seagoing vessels to port terminals [31]. A long-distance pipeline for liquid hydrogen has not yet been realized, as heat losses and evaporation drastically reduce efficiency over long distances. However, pipelines for liquefied natural gas (LNG) exist worldwide, which present similar technical challenges to pipelines for liquid hydrogen and are therefore comparable to a certain extent. However, a possible future innovative solution for the transport of liquid hydrogen in pipelines could be achieved through the use of innovative "hybrid pipelines." These utilize the cold temperature level of liquid hydrogen to simultaneously cool a superconductor. This allows liquid hydrogen and electricity to be transported highly efficiently to regions with high demand via a single pipeline. Initial considerations and calculations for hybrid pipelines for distances between 10 and 20 km have already been carried out, and the assessment of

their future potential is part of current research, for example, by KIT in the context of the TransHyDE project AppLHy! [31–33].

Against this background, airports located close to seaports have significant locational advantages with regard to a future cost-effective and sustainable hydrogen supply for the use of hydrogen in aviation.

One key advantage is the possibility of efficiently utilizing a shared hydrogen infrastructure and pooling infrastructure investments. The shared use of hydrogen facilities leads to synergies and economies of scale, making areas such as distribution, liquefaction, transshipment, and storage more cost-effective because larger volumes can be handled. Geographical proximity also facilitates collaboration between players in the aviation, shipping, and energy sectors. This accelerates innovation and facilitates joint pilot projects and demonstration flights, such as those already planned in Hamburg and Rotterdam [34].

Spillmann et al. suggest that a distance of 20 km between a hydrogen hub and a customer site is required for the economic use of a shared hydrogen infrastructure in order to realize synergies and cost advantages [35]. Another study also assumes a distance of 20 km as the maximum distance for the economical supply of hydrogen to companies via truck trailers [36]. For specific applications such as hydrogen refueling stations, another study also considers a distance of up to 50 km between the hydrogen hub and the customer site [37]. In general, it can be concluded that the closer an airport is to a hydrogen hub, the more economically advantageous the hydrogen supply becomes, primarily due to reduced transport and infrastructure costs.

4. Methods and Assumptions

This section explains the methodological approach and the assumptions used for the potential analysis. In order to conduct a corresponding potential analysis for Europe, a tool was created in which various assumptions, in particular the maximum distance between airports and seaports and the range of a hydrogen aircraft, can be varied and their influence on the results can be analyzed.

The DLR Air Transport Forecast [38] was used as the central data basis for the projected air traffic connections and air passenger numbers in Europe for the year 2050. This forecast provides projected passenger numbers at the airport-pair level for all air traffic routes worldwide. The IMF Port Watch port database, which contains 1648 seaports and covers 99 percent of maritime trade [39], was used as source for geocoordinates for all seaports worldwide. The major seaports used in this study are listed in Table 1. A primary reason for selecting this source was that its geocoordinates provide better or, rather, more central coverage of a seaport's area than other available free databases. Furthermore, this database provides additional information on the cargo handling of the respective seaports.

After filtering the air connections, airports, and seaports to only include European ones, the nearest seaport had to be determined for each airport. For this purpose, a spatial distance analysis was performed using GIS resulting in a list of all European airports and the nearest seaport, along with the air distance in kilometers. For this step, the “Distance to Nearest Hub” algorithm of QGIS (Version 3.38) was used. All input datasets (coordinates of airports and seaports) were screened before the distance analysis to ensure spatial accuracy and completeness.

Using this data, a tool was finally developed that allows the parameters “maximum airport–seaport distance” and “range of hydrogen-powered aircraft” to be varied, resulting in the output of corresponding European air connections that match the respective parameters. This allows for in-depth analysis of the corresponding market potential and sensitivities. With the aim of also being able to make statements regarding emission reduc-

tions, hydrogen demand, and feasibility, the following assumptions were made, which are embedded in the tool.

Table 1. Major seaports in Europe ranked by average total vessel count per year with information about the share of the country's maritime import and export share. Based on IMF Port Database [39].

Seaport	Vessel Count per Year	Share of Country's Maritime Import	Share of Country's Maritime Export
Rotterdam	23,374	74%	64%
Antwerp	13,942	68%	82%
Hamburg	6992	35%	32%
Immingham	6368	14%	9%
Algeciras	5796	15%	19%
Piraeus	5504	42%	45%
Bremerhaven	5043	14%	29%
Zeebrugge	4676	11%	12%
Barcelona	4634	9%	11%
Las Palmas (de Gran Canaria)	4616	7%	9%
Amsterdam	4596	9%	15%
Terneuzen	4172	4%	8%
Valencia	3938	8%	15%
Le Havre	3761	26%	24%
Klaipeda	3701	64%	99%
London Gateway	3580	8%	6%
Gothenburg	3557	15%	32%
Genova	3497	9%	15%
Constanta	3435	87%	92%
Gravesend	3126	5%	1%

To determine the potential emission savings, CO₂ emissions of 90 g per passenger-kilometer (pkm) were assumed [40]. The average consumption of a modern aircraft is approximately 3.52 L of JET-A1 per 100 passenger kilometers [41]. This corresponds to approximately 2.82 kg of kerosene or an energy of approximately 31.3 kWh per 100 pkm.

Based on a hydrogen energy content of 33.3 kWh/kg, the corresponding hydrogen consumption is 0.94 kg H₂ per 100 pkm, assuming the same energy demand. Although hydrogen-electric propulsion systems, particularly when fuel cells are used in the powertrain, can achieve significantly higher efficiencies than today's turbines [42], the following analysis assumes identical energy requirements per pkm. The reason for this lies in several structural limitations that relativize the efficiency potential of hydrogen-powered aircraft. In particular, high-volume requirements of the LHLH₂ tanks lead to an increase in the size of the aircraft fuselage and a reduction in available passenger capacity. Since liquid hydrogen has a very low volumetric energy density, the tanks must usually be cylindrical and located in the rear of the aircraft. Although the gravimetric energy content of LHLH₂ is around three times that of kerosene, this advantage is partially reversed in the overall system due to the factors mentioned above. Against this background, a conservative yet realistic value of 1 kg of H₂ per 100 pkm (10 g per passenger-kilometer) is assumed for the

hydrogen demand estimation. This value takes into account the potential efficiency gains on the propulsion side as well as the mass- and volume-related disadvantages at the structural level and can be considered as a reasonable benchmark for hydrogen consumption in future air transport. Furthermore, this value is also assumed in other studies for hydrogen aircraft [43].

To determine the required number of hydrogen deliveries by truck, an estimated transport capacity of 4 tons of liquid hydrogen per truck was assumed [31]. If an airport's hydrogen demand exceeds 50 tons per day, a switch from truck deliveries to a pipeline was assumed, as above this daily volume, a pipeline is considered more economical in any case [44], and the supply traffic to the airport, with 13 truck deliveries per day, does not cause any major impacts or restrictions on road traffic and airport logistics.

Finally, a minimum demand of 7000 passengers per year was assumed for considering a route in the potential analysis for hydrogen air connections. For a hydrogen aircraft with 150 seats, this would correspond to approximately one flight per week. Furthermore, it is assumed that there is no limit to the maximum passenger demand per route. Accordingly, it is assumed that any potential demand per route can be met by purely hydrogen-powered aircraft, and that previously used (conventional, SAF-powered) aircraft are being moved to other routes serving domestic airports or to routes that are only domestic. The geographical scope of the analysis is limited to Europe (excluding Turkey and Russia).

In the baseline scenario, a maximum distance of 20 km was defined between an airport and a seaport. This maximum distance offers significant potential for shared use of a hydrogen infrastructure and is considered ideal for ensuring an efficient and economical supply of hydrogen to the airport [35,36]. A value of 2250 km was assumed as the maximum range of the hydrogen-powered aircraft in the baseline scenario. This value lies between the range of Airbus' planned short-/medium-haul concept aircraft (1850 km) and EXACT-2's (DLR design study) planned short-/medium-haul concept aircraft with a range of 2778 km [45,46].

In addition to the baseline scenario, the following section also analyses variations in the key parameter assumptions (maximum airport–seaport distance and hydrogen aircraft range) and examines their impact on the market potential and emission savings potential through sensitivity analyses.

5. Results

In this section, the results will be described and discussed. Based on the assumptions of the baseline scenario—a maximum airport–seaport distance of 20 km and maximum range of the hydrogen-powered aircraft of 2250 km—a total of 625 routes in Europe can be identified in 2050 on which hydrogen-powered aircraft would operate. Of these, 39 routes are very highly frequented, with at least 1000 passengers per day in each direction, which would mean more than six flights per day in each direction for a 150-seat hydrogen aircraft. 230 routes also have a significant flight frequency, with at least 150 passengers per day in each direction, which would mean one flight per day in each direction for a 150-seat hydrogen aircraft. The remaining 356 routes represent very low-frequency routes, ranging from one to a maximum of seven flights per week in each direction. Exemplary routes are shown in Table 2.

The identified potential route network of the baseline scenario includes a total of 129 airports across Europe from which hydrogen-powered flights are operated. As can be seen in Figure 1, the airports in this network have a different importance. With over 50 connections each and more than 30,000 passengers per day, Amsterdam (AMS) and Barcelona (BCN) are the largest airport hubs in the described hydrogen-powered air traffic route network in Europe. Dublin (DUB), Copenhagen (CPN), Palma de Mallorca (PMI),

Lisbon (LIS), Malaga (AGP), Helsinki (HEL), Edinburgh (ADI), Alicante (ALC), Bristol (BRS), and Hamburg (HAM) also represent significant and important airport hubs in the identified European route network, each with more than 7000 passengers per day and 19–45 connections.

Table 2. Exemplary routes with high and low flight frequency in the identified hydrogen-powered flight network in Europe in 2050, with the number of daily passengers per route and the respective flight distance between the airports.

Flight Frequency	Origin Airport	Destination Airport	Pax/Day	Flight Distance (km)
High min. 1000 Pax/Day	BCN	AMS	3365	1241
	AMS	CPH	2668	633
	HEL	OUL	2511	513
	SVQ	BCN	2127	809
Low max. 150 Pax/Day	VCE	HAM	148	919
	BGO	KSU	143	342
	RIX	BRE	140	1057
	DUB	BIO	137	1152

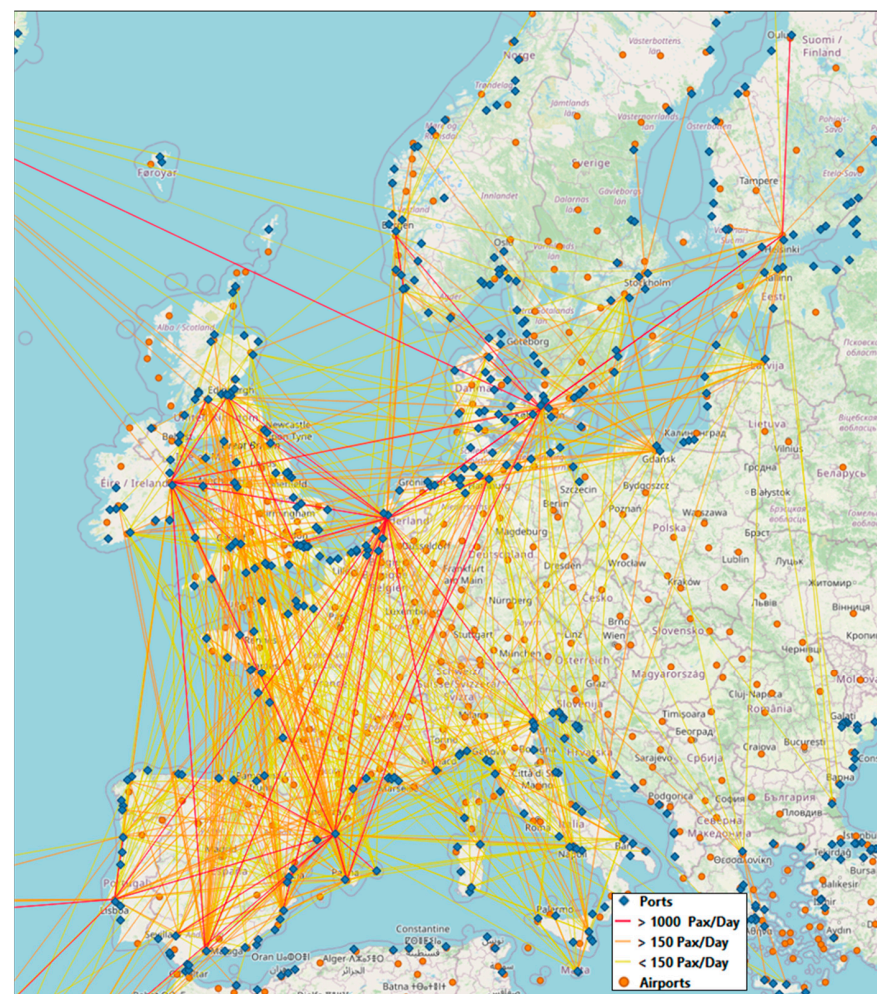


Figure 1. Potential hydrogen-powered flight network in Europe in 2050 with number of daily passengers per route; assumed maximum airport–seaport distance: 20 km; and assumed maximum range of hydrogen-powered aircraft: 2250 km.

In total, more than 135 million passengers would be transported by hydrogen-powered aircraft on the identified routes in 2050, corresponding to approximately 11 percent of total air transport passengers in Europe. The total amount of CO₂ emissions saved amounts to 11.7 million tons, which in turn corresponds to approximately 10 percent of all air transport emissions in 2050. The total hydrogen demand for this route network amounts to 1.3 million tons in 2050.

Figure 2 shows the hydrogen demand of the 40 airports with the highest hydrogen demand in the identified route network and also provides an overview of the share of emissions saved at airport level in relation to all intra-European traffic relations at the respective airports. The aforementioned high-frequency hubs of the transport network are also reflected in the hydrogen demand of the individual airports. Accordingly, the airports in Amsterdam (just under 400 tons/day), Barcelona (approximately 300 tons/day), and Dublin (just under 250 tons/day) have by far the highest hydrogen demand. These airports, along with the corresponding hydrogen demand, number of passengers, and distance to the nearest seaport, are summarized in Table 3.

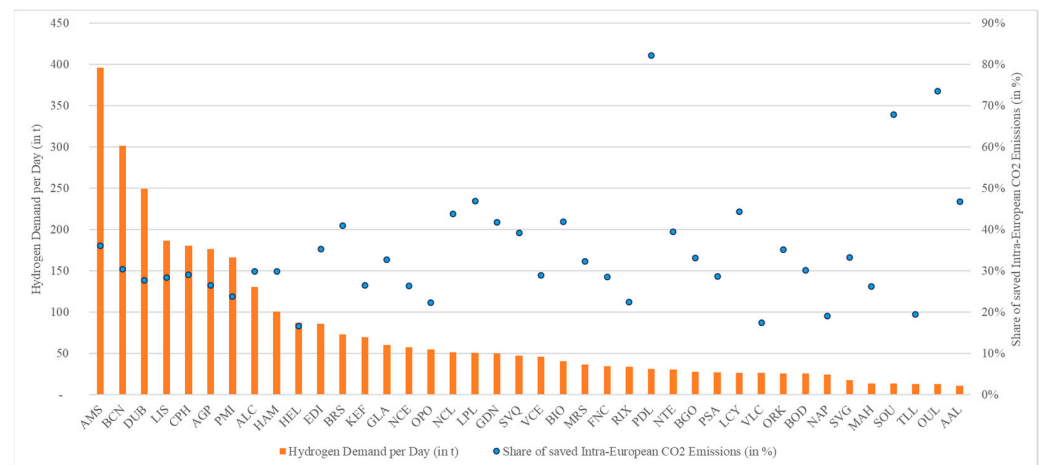


Figure 2. Hydrogen demand per day (in t) and share of saved intra-European CO₂ emissions (in %) at airport level; only top 40 airports ranked by hydrogen demand in the hydrogen-powered flight network (see Figure 1) in Europe in 2050.

Table 3. Overview of the top 10 airports in the identified hydrogen-powered flight network in Europe in 2050 ranked by hydrogen demand per day and with information about number of passengers per day and distance (in km) to the nearest seaport.

Airport Code	Hydrogen Demand/Day (in t)	Number of Hydrogen Air Traffic Relations	Number of Pax/Day	Distance to Seaport (in km)
AMS	396	53	38,492	12
BCN	301	54	31,729	7
DUB	249	45	24,339	10
LIS	187	29	15,563	12
CPH	181	33	18,989	9
AGP	177	34	11,770	8
PMI	166	41	16,853	9
ALC	130	30	8862	8
HAM	101	28	7678	13
HEL	87	19	10,783	15

A total of 19 airports has a hydrogen demand of more than 50 tons per day. For these airports, a pipeline connection to the seaport would therefore certainly make economic sense due to the high, continuous demand for hydrogen. At the remaining 110 airports, the daily demand for hydrogen is less than 50 tons. For these airports, a delivery of liquid hydrogen from the seaport by truck would make more sense or, rather, a pipeline connection would not (yet) be worthwhile for every airport. The share of emissions saved at airport level in relation to all intra-European traffic at the respective airport shows significant savings potential. The average of emissions saved for all 129 airports is 39 percent. Figure 2 also shows a clear concentration of emission-saving potentials in the range of 20–50 percent for the 40 airports shown there.

A change in the key input parameters—maximum seaport–airport distance and range of a hydrogen aircraft—leads to a significant impact on the overall emission savings potential, as illustrated by a sensitivity analysis in Table 4. Accordingly, the intra-European emission savings potential would decrease from 10 percent (baseline scenario) to 3 percent if the assumed maximum distance from seaports to airports was reduced from 20 km to 10 km.

Table 4. Sensitivities of potential saved intra-European CO₂ emissions; * base case.

Saved Intra-European CO ₂ Emissions (in %)		Maximum Airport–Seaport Distance				
		10 km	20 km	30 km	40 km	50 km
H₂ Aircraft Range	1000 km	1%	3%	4%	6%	8%
	1800 km	2%	7%	8%	13%	18%
	2250 km	3%	10% *	11%	18%	24%
	2800 km	4%	11%	12%	21%	29%
	3700 km	4%	12%	14%	24%	32%

At the same time, the emission savings potential would increase to 24 percent as soon as the assumed maximum distance between seaports and airports was increased to 50 km. An increase in the range of the hydrogen aircraft would only result in minor increases in potential emission savings compared to the baseline scenario.

Accordingly, the savings potential would increase from 10 percent (baseline scenario) to only 11 percent (increase in range to 2800 km) or 12 percent (increase in range to 3700 km). Reducing the assumed range to 1800 km or 1000 km, however, has a very strong impact on the emission savings potential, with a reduction to 7 percent and 3 percent, respectively. With very progressive assumptions (maximum seaport–airport distance of 50 km and range of 3700 km), an intra-European emission savings potential of 32 percent would theoretically be possible.

Figure 3 illustrates the sensitivities of the baseline scenario (range of 2250 km) with changing assumptions regarding the maximum distance between seaports and airports only. As the assumed maximum distance increases, the number of airports in Europe located within this distance rises significantly from 129 (baseline scenario) to over 200 (maximum distance of 50 km). At the same time, a sharp increase in the share of emissions saved from intra-European air traffic can be observed.

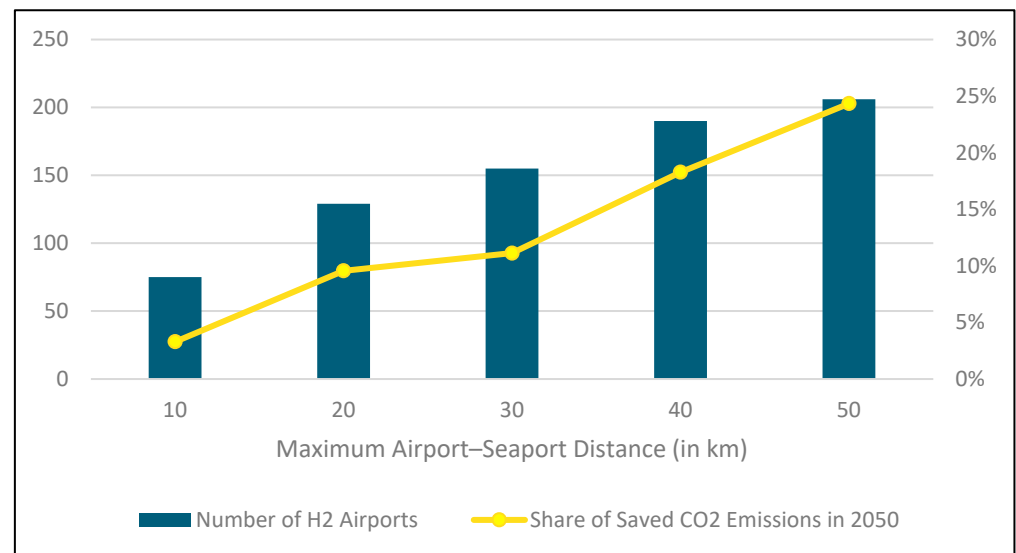


Figure 3. Sensitivity analysis for the base scenario; impact of changed maximum airport–seaport distance on results (number of airports and share of saved CO₂ emissions).

Finally, Figure 4 can be used to conduct more detailed assessments of airports regarding the general suitability of hydrogen-powered air connections. In addition to the actual distance to the nearest seaport, the potential total absolute emission savings potential for intra-European air connections—assuming a maximum distance of 50 km between the seaport and airport—is shown for each airport. Accordingly, airports in the lower right quarter have the greatest potential, as they are very close to the nearest seaport (some even less than 10 km) and have many air connections (and, therefore, a high absolute emission savings potential) to other European airports located near seaports. Thus, in addition to the airports of Amsterdam (AMS) and Barcelona (BCN), the airports in Dublin (DUB), Copenhagen (CPH), Malaga (AGP), Lisbon (LIS), Palma de Mallorca (PMI), and Alicante (ALC) are the airports with the greatest emission reduction potential while being very close to the nearest seaport.

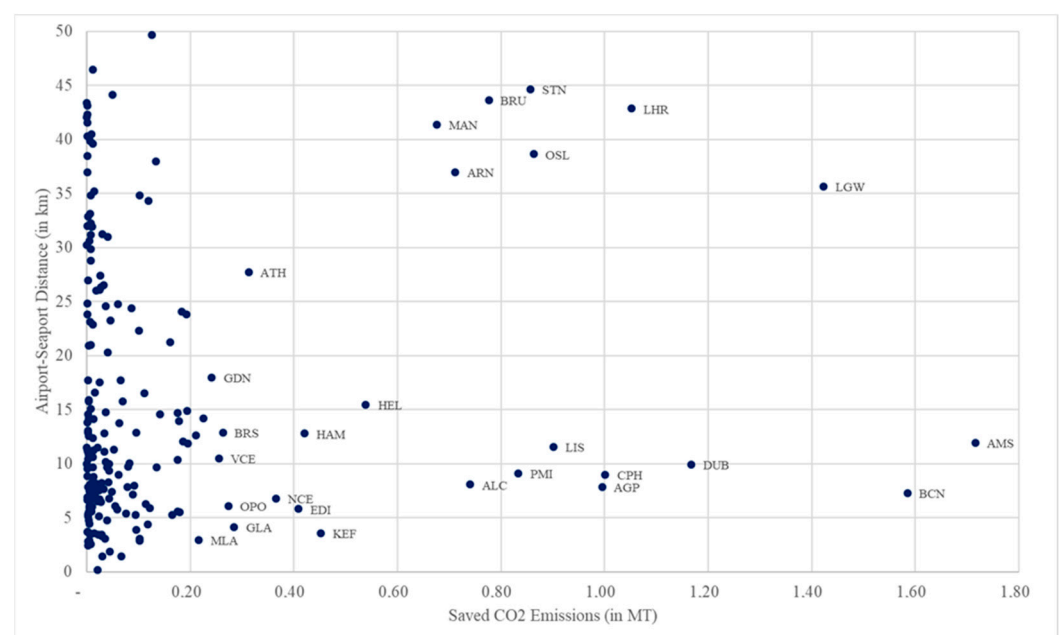


Figure 4. Emission reduction potential at airport level in a maximum 50 km airport–seaport distance use case and overview of actual distance of airport to the next seaport.

Other airports such as London Gatwick (LGW), London Heathrow (LHR), Oslo (OSL), London Stansted (STN), Brussels (BRU), Stockholm (ARN), or Manchester (MAN) also have very a high absolute emission savings potential but are relatively far away from the nearest seaport, with over 35 km between them. Airports like Malta (MLA), Glasgow (GLA), or Porto (OPO) are in turn very close to the next seaport but have only a comparable moderate absolute emission savings potential.

6. Discussion

The results discussed in the previous section have shown that air transport connections for hydrogen aircraft in Europe between airports located close to seaports represent significant potential for reducing emissions in the aviation sector. In particular, due to their geographical proximity to seaports and corresponding future maritime hydrogen hubs, these airports could benefit from the efficient use of a shared hydrogen infrastructure. The supply of liquid hydrogen via maritime transport requires the construction of LH₂ terminals for loading and unloading operations. Such a terminal typically consists of a liquefied hydrogen storage tank, a loading arm system to transfer the hydrogen between the carrier and the shore, and various ancillary facilities [47].

The highly capital-intensive investments in a completely new hydrogen infrastructure at airports could therefore be significantly reduced through synergies in hydrogen storage, logistics, and distribution in cooperation with a nearby seaport.

The identified potential route network provides an overview of air transport connections and airports in Europe that have a high potential for this possible use case. In addition to the significant emission reduction potential for air transport in Europe—approximately 10 percent emission reduction in all intra-European traffic—the very high emission reduction potential at airport level—on average, a 40 percent emission reduction for intra-European transport connections—is a particularly interesting result. Such a transport network could represent a first phase of hydrogen transport connections, particularly at the beginning of the entry into the service of hydrogen aircraft. As demonstrated in the case of Rotterdam Airport, the proximity to a major hydrogen hub with existing and planned import and liquefaction capacities allows for significantly lower investment, logistics, and transport costs compared to inland locations [12]. The pan-European findings of this paper could therefore also be interesting for other international research projects in the field of hydrogen use in aviation, such as “BSR HyAirport”, where airports in the Baltic Sea region are already being prepared for the handling of hydrogen-powered aircraft [48].

The introduction of hydrogen aircraft connections could therefore initially be limited to such logistically advantageous airport locations (e.g., Barcelona, Amsterdam, or Hamburg) before airports further inland in Europe can also be supplied with cost-effective green hydrogen. As the sensitivity analyses have shown, the emission savings potential of hydrogen-powered aircraft connections continues to increase significantly when airports further away from seaports are included in the hydrogen route network. For these airports further inland, sustainable aviation fuels and (hybrid) electric aircraft will initially be of greater importance than purely hydrogen-powered aircraft concepts.

In addition to logistical feasibility, the economic attractiveness of hydrogen in aviation can increase significantly, particularly in the context of CO₂ abatement costs. Projections for the development of allowance prices within the European Union Emissions Trading System (EU ETS) indicate that certificate prices may already reach EUR 91 to EUR 188 per ton of CO₂ by 2030 [49]. On a global level, MSCI Carbon Markets estimates that CORSIA-eligible offset credits will range between USD 18 and USD 51 per tCO₂e during Phase I (up to 2032), and between USD 27 and USD 91 per tCO₂e during Phase II (2033–2035) [50]. This development

positions the CO₂ price as a central economic lever for the future competitiveness of hydrogen-powered propulsion in aviation.

Another cost advantage emerges from the potential avoidance of non-CO₂ effects, which are significantly lower when using hydrogen compared to hydrocarbon-based fuels such as fossil fuels or synthetic fuels. If such non-CO₂ climate effects were to be integrated into the EU ETS in the future, this would create an additional economic incentive in favor of hydrogen propulsion.

Assuming an LH₂ price of USD 2.60 per kilogram, a regional aircraft would have CO₂ abatement costs of approximately USD 90 to USD 135 per ton of CO₂ [30]. The assumed liquid hydrogen price of USD 2.60 per kilogram used in this analysis is consistent with a range of international cost projections. Recent studies estimate global average production costs for low carbon hydrogen in 2050 to range between USD 1.00 and USD 3.20 per kilogram, with total supply chain costs including liquefaction, transport, storage, and refueling estimated at USD 2.20 to USD 3.70 per kilogram [16].

In addition to the presented results and identified potentials, this paper can also be used as a starting point for further possible future studies and research directions on this topic. Accordingly, more detailed region-specific analyses of the maximum distance between a hydrogen hub (seaport) and an airport could be conducted in order to benefit from a shared hydrogen infrastructure. Thus, even in some regions, longer distances with minimal additional costs and minimal efficiency losses might be conceivable in the future. An analysis of seaports in Europe with regard to their suitability as future hydrogen import hubs would also be useful in order to identify which seaports will actually be locations for hydrogen imports in the future.

Furthermore, it would be valuable to compare the situation in Europe with other global regions, such as North America, the Middle East, or East Asia, where hydrogen import strategies and energy infrastructures differ significantly. East Asia, in particular, is likely to have significant potential due to its geographical proximity to major hydrogen-exporting countries like Australia, and the fact that hydrogen exports from Australia are expected to be transported by LH₂ ships [47]. This form of transport aligns well with the needs of the aviation sector, as the hydrogen arrives already liquefied in the form required for aircraft use, thereby avoiding further energy-intensive conversion steps and reducing overall supply chain losses. Another advantage is the coastal location of major East Asian airport hubs such as Tokyo Haneda, Seoul Incheon, Shanghai Pudong, and Hong Kong International. In comparison, Europe appears particularly well suited for this approach due to its dense network of seaports and airports and its ambitious climate goals. In other regions, such as North America, major airports are often located farther inland, which limits the potential for shared hydrogen infrastructure and increases transport complexity and cost. Furthermore, some regions like South America have significantly better climatic conditions for producing green hydrogen locally, which may reduce their future dependence on imports altogether.

Another important research topic would be an economic analysis and evaluation of the actual feasibility of such a concept. Here, it could also be analyzed which identified airports would be suitable for implementation and which airports would be problematic due to space requirements and hydrogen demand. In this context, a more detailed economic analysis could also be conducted regarding the optimal logistics solution—truck, train, inland waterway vessel, or pipeline, as well as liquid or gaseous hydrogen—for supplying hydrogen to the identified airports. Here, it could also be investigated in which regions in Europe, and from which year, local hydrogen production at airports with its own liquefaction plant would make more economic sense than supplying from seaports or hydrogen hubs.

7. Conclusions

Air connections for hydrogen-powered aircraft between European airports located near seaports offer a promising opportunity for the further decarbonization of air transport. The shared use of hydrogen infrastructure by air and sea transport can bring economic and ecological benefits. The proximity of airports to seaports, therefore, opens up significant opportunities to accelerate the transformation toward climate-friendly hydrogen-powered air mobility. Joint infrastructure projects reduce costs, increase efficiency, and accelerate innovation, which is a significant advantage for the sustainable development of both transport sectors.

Modeling results for 2050 show that such a hydrogen-powered route network of 625 intra-European routes could serve over 135 million passengers annually, reduce approximately 11.7 million tons of CO₂ emissions, and account for around 10 percent of total intra-European air traffic. Sensitivity analyses show that extending the assumed seaport–airport distance from 20 km to 50 km could raise the emissions savings potential from 10 percent to 24 percent, based on an assumed maximum hydrogen aircraft range of 2250 km. Especially at airport level, significant emission savings potentials of an average of 40 percent for intra-European flight connections have been identified.

Key airports such as Amsterdam, Barcelona, Dublin, Copenhagen, and Malaga are identified as particularly promising candidates for early adoption. These airports are well positioned to lead the rollout of a hydrogen-powered aviation network.

Current initiatives, such as the establishment of the northern German “Hanseatic Hydrogen Center for Aviation and Maritime” (H₂AM), which is intended to advance hydrogen research in aviation and shipping at three locations [51], underline the future relevance of a joint use of hydrogen for aviation and shipping as examined in this paper.

Further research should examine regional variations, the technical limits of infrastructure (e.g., feasible distances for liquid hydrogen pipelines), and the comparative feasibility of similar concepts in other global regions. Given that aviation could become a major consumer of liquid hydrogen, infrastructure planning must begin early and be aligned with anticipated demand.

Coordinated investments in infrastructure and political support are essential for its actual implementation. Integration into existing logistics and energy systems, and the consideration of other future alternatives such as fully electric aircraft concepts—with appropriate charging infrastructure—and sustainable aviation fuels, also play a crucial role. Overall, the results in this paper confirm the significant potential of such an approach for a sustainable, low-emission air transport system in Europe.

Author Contributions: Conceptualization, N.F. and T.S.; methodology, N.F. and T.S.; software, N.F.; validation, N.F. and T.S.; formal analysis, N.F. and T.S.; investigation, N.F. and T.S.; resources, N.F. and T.S.; data curation, N.F. and T.S.; writing—original draft preparation, N.F. and T.S.; writing—review and editing, N.F., T.S., A.L., and M.G.; visualization, N.F.; supervision, N.F. and T.S.; project administration, N.F. and T.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within this article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. ICAO. ICAO Environmental Report. 2025. Available online: <https://www.icao.int/environmental-protection/Pages/envrep2025.aspx> (accessed on 10 July 2025).
2. Clean Aviation Joint Undertaking. Clean Sky 2 Technology Evaluator—Second Global Assessment. 2024. Available online: https://www.clean-aviation.eu/sites/default/files/2024-11/CS2_TE_25.11.2024_FINAL.pdf (accessed on 10 July 2025).

3. Reuters. Airbus Postpones Development of New Hydrogen Aircraft. 2025. Available online: <https://hydrogen-central.com/airbus-postpones-development-of-new-hydrogen-aircraft/> (accessed on 5 May 2025).
4. Fraunhofer ISI. How Much Green Hydrogen Will Europe's Industry Need in 2050? 2023. Available online: <https://www.isi.fraunhofer.de/en/blog/2023/europa-energiesystem-2050-wasserstoff-industrie.html> (accessed on 5 May 2025).
5. Wietschel, M.; Zheng, L.; Arens, M.; Hebling, C.; Ranzmeyer, O.; Schaadt, A.; Hank, C.; Sternberg, A.; Herkel, S.; Kost, C.; et al. *Metastudie Wasserstoff—Auswertung von Energiesystemstudien. Studie im Auftrag des Nationalen Wasserstoffrats*; Fraunhofer ISI: Karlsruhe, Germany; Fraunhofer ISE: Freiburg, Germany; Fraunhofer IEG: Cottbus, Germany, 2021.
6. Clean Hydrogen Partnership. Study on Hydrogen in Ports and Industrial Coastal Areas—Report 1. 2023. Available online: https://www.clean-hydrogen.europa.eu/document/download/9fef29ac-6f95-465b-bb6e-1365526f43c4_en?filename=Study%20on%20hydrogen%20in%20ports%20and%20industrial%20coastal%20areas.pdf (accessed on 5 May 2025).
7. Gu, Y.; Wiedemann, M.; Ryley, T.; Johnson, M.E.; Evans, M.J. Hydrogen-powered aircraft at airports: A review of the infrastructure requirements and planning challenges. *Sustainability* **2023**, *15*, 15539. [CrossRef]
8. Braun, M.; Classen, A. Qualitative risk management for future hydrogen-enabled airports. *Transp. Res. Procedia* **2023**, *75*, 86–95. [CrossRef]
9. Scheelhaase, J.; Oesingmann, K.; Classen, A.B. Roadmap for Implementing Hydrogen Technology at Medium-Sized European Airports. *Transp. Res. Procedia* **2024**, *81*, 155–166. [CrossRef]
10. Hoelzen, J.; Silberhorn, D.; Zill, T.; Bensmann, B.; Hanke-Rauschenbach, R. Hydrogen-powered aviation and its reliance on green hydrogen infrastructure—Review and research gaps. *Int. J. Hydrogen Energy* **2022**, *47*, 3108–3130. [CrossRef]
11. Hoelzen, J.; Flohr, M.; Silberhorn, D.; Mangold, J.; Bensmann, A.; Hanke-Rauschenbach, R. H₂-powered aviation at airports—Design and economics of LH₂ refueling systems. *Energy Convers. Manag. X* **2022**, *14*, 100206. [CrossRef]
12. Van Dijk, D.; Ebrahim, H.; Jooss, Y.; Bødal, F.; Hjorth, I. Integrating liquid hydrogen infrastructure at airports: Conclusions from an ecosystem approach at Rotterdam The Hague Airport. *J. Airt. Manag.* **2024**, *18*, 367–396. [CrossRef]
13. Takaoka, Y.; Mizumukai, K.; Kamenno, Y. Suiso Frontier, the First LH₂ Carrier—Demonstration of Technologies and Operational Phase. *Int. J. Offshore Polar Eng.* **2023**, *33*, 225–233. [CrossRef]
14. Zhang, T.; Uratani, J.; Huang, Y.; Xu, L.; Griffiths, S.; Ding, Y. Hydrogen liquefaction and storage: Recent progress and perspectives. *Renew. Sustain. Energy Rev.* **2023**, *176*, 113204. [CrossRef]
15. Degirmenci, H.; Uludag, A.; Ekici, S.; Karakoc, T.H. Challenges, prospects and potential future orientation of hydrogen aviation and the airport hydrogen supply network: A state-of-art review. *Prog. Aerosp. Sci.* **2023**, *141*, 100923. [CrossRef]
16. Jaffary, Z.; Wiedemann, M. Towards net zero aviation: Exploring safe hydrogen refuelling at airports. *J. Air Transp. Res. Soc.* **2025**, *4*, 100048. [CrossRef]
17. Gronau, S.; Hoelzen, J.; Mueller, T.; Hanke-Rauschenbach, R. Hydrogen-powered aviation in Germany: A macroeconomic perspective and methodological approach of fuel supply chain integration into an economy-wide dataset. *Int. J. Hydrogen Energy* **2025**, *48*, 5347–5376. [CrossRef]
18. Oesingmann, K.; Grimme, W.; Scheelhaase, J. Hydrogen in aviation: A simulation of demand, price dynamics, and CO₂ emission reduction potentials. *Int. J. Hydrogen Energy* **2024**, *64*, 633–642. [CrossRef]
19. Grimme, W.; Braun, M. Estimation of potential hydrogen demand and CO₂ mitigation in global passenger air transport by the year 2050. *Transp. Res. Procedia* **2022**, *65*, 24–33. [CrossRef]
20. Schenke, F.; Hoelzen, J.; Minke, C.; Bensmann, A.; Hanke-Rauschenbach, R. Resource requirements for the implementation of a global H₂-powered aviation. *Energy Convers. Manag. X* **2023**, *20*, 100435. [CrossRef]
21. Adler, E.J.; Martins, J.R. Hydrogen-powered aircraft: Fundamental concepts, key technologies, and environmental impacts. *Prog. Aerosp. Sci.* **2023**, *141*, 100922. [CrossRef]
22. Yusaf, T.; Mahamude, A.S.F.; Kadirgama, K.; Ramasamy, D.; Farhana, K.; Dhahad, H.A.; Abu Talib, A.R. Sustainable hydrogen energy in aviation—A narrative review. *Int. J. Hydrogen Energy* **2025**, *52*, 1026–1045. [CrossRef]
23. Akbiyik, T.; Öztürk, O.; Yıldız, M.; Kale, U.; Kilikeyičius, A. The future of hydrogen fuel in aviation: Economic analysis of current applications. *Int. J. Hydrogen Energy* **2025**, *143*, 650–658. [CrossRef]
24. Hoelzen, J. Hydrogen-Powered Aviation—Techno-Economics of Flying with Green Liquid Hydrogen. 2024. Available online: <https://repo.uni-hannover.de/items/8c77a2f3-ee78-4726-a031-ffb85de3ec9> (accessed on 3 June 2025).
25. Bridgelall, R. Hydrogen-Powered Aviation: Insights from a Cross-Sectional Scientometric and Thematic Analysis of Patent Claims. *Appl. Sci.* **2025**, *15*, 5555. [CrossRef]
26. Rau, A.; Stumpf, E.; Gelhausen, M.C. Modelling the impact of introducing first-generation narrowbody hydrogen aircraft on the passenger air transportation network in Europe. *J. Air Transp. Res. Soc.* **2024**, *3*, 100029. [CrossRef]
27. Bräuer, T.; Voigt, C.; Sauer, D.; Kaufmann, S.; Hahn, V.; Scheibe, M.; Schlager, H.; Huber, F.; Le Clercq, P.; Moore, R.H.; et al. Reduced ice number concentrations in contrails from low-aromatic biofuel blends. *Atmos. Chem. Phys.* **2021**, *21*, 16817–16826. [CrossRef]

28. Märkl, R.S.; Voigt, C.; Sauer, D.; Dischl, R.K.; Kaufmann, S.; Harlaß, T.; Hahn, V.; Roiger, A.; Weiß-Rehm, C.; Burkhardt, U.; et al. Powering aircraft with 100 % sustainable aviation fuel reduces ice crystals in contrails. *Atmos. Chem. Phys.* **2024**, *24*, 3813–3837. [CrossRef]
29. Palies, P.P. Hydrogen Thermal-Powered Aircraft Combustion and Propulsion System. *ASME J. Eng. Gas Turbines Power* **2022**, *144*, 101007. [CrossRef]
30. Fuel Cells and Hydrogen 2 Joint Undertaking. Hydrogen-Powered Aviation—A Fact-Based Study of Hydrogen Technology, Economics, and Climate Impact by 2050. Publications Office. 2020. Available online: <https://data.europa.eu/doi/10.2843/471510> (accessed on 5 May 2025).
31. Alexander, A.; Tabea, A.; Christoph, H.; Thomas, J.; Dirk, L.; Sebastian, P.; Astrid, P.; Paul, S.; Camelia, S.; Klaus-Peter, W.; et al. Hydrogen Liquefaction, Storage, Transport and Application of Liquid Hydrogen. 2023. Available online: <https://publikationen.bibliothek.kit.edu/1000168281> (accessed on 5 May 2025).
32. Fuhry, F.; Neumann, H.; Weiss, K.-P.; Wolf, M.J. Transport und Nutzung von flüssigem Wasserstoff: Leitprojekt TransHyDE—Projekt AppLHy!, “Wasserstoff”. *Chem. Ing. Tech.* **2024**, *96*, 1–11. [CrossRef]
33. Trevisani, L.; Fabbri, M.; Negrini, F. Long distance renewable-energy-sources power transmission using hydrogen-cooled MgB2 superconducting line. *Cryogenics* **2007**, *47*, 113–120. [CrossRef]
34. Hamburg Airport. Hamburg und Rotterdam Geben Kollaboration Bekannt, um eine Wasserstoff-Flugroute zu Etablieren. 2022. Available online: <https://www.hamburg-airport.de/de/unternehmen/presse/hamburg-und-rotterdam-geben-kollaboration-bekannt-um-eine-wasserstoff-flugroute-zu-etablieren-72044> (accessed on 5 May 2025).
35. Spillmann, T.; Nolden, C.; Ragwitz, M.; Pieton, N.; Sander, P.; Rublack, L. *Wasserstoff-Verteiloptionen 2035—Versorgungsmöglichkeiten Von Verbrauchsstandorten in Deutschland Mit Importiertem Wasserstoff*; Fraunhofer-Einrichtung für Energieinfrastrukturen und Geothermie IEG: Cottbus, Germany, 2024.
36. Neuman & Esser GmbH. Engpassfaktor Wasserstoff. Anforderungen an Die Wasserstoffversorgung für Die Industrie in Nordrhein-Westfalen. 2024. Available online: <https://www.ihk.de/hagen/servicemarken/presse/pressemeldungen/mai2024/engpassfaktorwasserstoff-6163202> (accessed on 5 May 2025).
37. NOW GmbH. Versorgung der H2-Tankstelleninfrastruktur in Deutschland über ein H2-Pipeline-Netz. 2024. Available online: https://www.now-gmbh.de/wp-content/uploads/2024/11/Studie_H2-Pipeline-Netz_2024-11-26.pdf (accessed on 5 May 2025).
38. DLR. Air Transport Forecast. 2025. Available online: <https://www.dlr.de/en/lv/research-transfer/air-transport-forecast> (accessed on 5 May 2025).
39. IMF. IMF Port Watch. 2025. Available online: <https://portwatch.imf.org/> (accessed on 5 May 2025).
40. ICCT. CO₂ Emissions from Commercial Aviation: 2013, 2018, and 2019, International Council on Clean Transportation, October 2020. Available online: <https://theicct.org/wp-content/uploads/2021/06/CO2-commercial-aviation-oct2020.pdf> (accessed on 5 May 2025).
41. Lufthansa. Sustainability 2023—Fact Sheet. 2023. Available online: <https://www.lufthansagroup.com/media/downloads/en/responsibility/LH-Factsheet-Sustainability-2023.pdf> (accessed on 5 May 2025).
42. Durkin, K.; Khanafer, A.; Liseau, P.; Stjernström-Eriksson, A.; Svahn, A.; Tobiasson, L.; Andrade, T.S.; Ehnberg, J. Hydrogen-Powered Vehicles: Comparing the Powertrain Efficiency and Sustainability of Fuel Cell versus Internal Combustion Engine Cars. *Energies* **2024**, *17*, 1085. [CrossRef]
43. ICCT. Quick Pit Stops: A Challenge for Zero-Emission Planes?—International Council on Clean Transportation. 2023. Available online: <https://theicct.org/quick-pit-stops-a-challenge-for-zero-emission-planes/> (accessed on 5 May 2025).
44. Emcel. Wann Lohnt Sich Der Transport Von Wasserstoff Per Wasserstoffpipeline. 2025. Available online: <https://emcel.com/de/wann-lohnt-sich-der-transport-von-wasserstoff-per-wasserstoffpipeline/> (accessed on 5 May 2025).
45. DLR. EXACT2: Short-, Mid-, and Long Range Aircraft—Configuration Overview. 2024. Available online: https://elib.dlr.de/208836/1/EXACT2-SMR_AC_Config_Overview.pdf (accessed on 5 May 2025).
46. Flight Global. Airbus Pushes Back ZEROe Timeline and Ditches A380 Fuel Cell Flight-Test Plan. 2025. Available online: <https://www.flightglobal.com/air-transport/airbus-pushes-back-zeroe-timeline-and-ditches-a380-fuel-cell-flight-test-plan/161718.article> (accessed on 5 May 2025).
47. Kawasaki Heavy Industries, Ltd. Kawasaki Technical Review—Special Issue on Hydrogen Energy Supply Chain. 2021. Available online: <https://global.kawasaki.com/en/corp/rd/magazine/182/pdf/n182en.pdf> (accessed on 10 July 2025).
48. H2 News. Energiewende in der Luftfahrt: Internationales Projekt Plant Wasserstoff-Flüge im Ostseeraum. 2024. Available online: <https://h2-news.de/wirtschaft-unternehmen/energiewende-in-der-luftfahrt-internationales-projekt-plant-wasserstofffluege-im-ostseeraum/> (accessed on 10 July 2025).
49. Kopernikus-Projekt Ariadne. MSR Through 2030: Impact on Market Liquidity and Considerations for the 2026 Reform. 2023. Available online: https://ariadneprojekt.de/media/2023/12/Ariadne-Dokumentation_ETSWorkshopBruessel_December2023.pdf (accessed on 10 July 2025).

50. MSCI. CORSIA: Costs and Implications for the Airline Industry. 2024. Available online: <https://www.msci.com/research-and-insights/paper/corsia-costs-and-implications-for-the-airline-industry> (accessed on 10 July 2025).
51. Hamburg Aviation. Wenn die Luftfahrt mit der Schifffahrt: Gemeinsame Wasserstoff-Forschung am Hamburger ZAL. 2025. Available online: <https://www.hamburg-aviation.de/aktuelles/detail/wenn-die-luftfahrt-mit-der-schifffahrt-gemeinsame-wasserstoff-forschung-am-hamburger-zal/> (accessed on 10 July 2025).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.