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Qualitative risk assessment for future hydrogen-enabled airports

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Abstract

Introducing hydrogen infrastructure at airports is a key element in achieving net-zero emission aviation and, at the same time, a major challenge for the aviation industry. The operational and infrastructure enhancements required to support the ground handling of alternative-powered aircraft as well as the deployment of zero-emission ground service equipment will require significant future investment and a clear roadmap for implementation. Adapting the existing operational processes and capability levels at the airport to support hydrogen-powered flight, including refuelling and safety requirements, causes challenges but also opportunities. In addition to presenting an exemplary hydrogen deployment roadmap for a mid-sized airport, the authors present a risk register and airport strategies for managing risks to the roadmap by analysing and prioritising airport requirements.

Keywords: hydrogen; airport management; roadmap; risk assessment

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1. Introduction

The transition from kerosene to alternative propulsion aircraft (battery-electric, hydrogen-powered, or hybrid variants thereof) imposes major challenges for all stakeholders of the aviation industry. According to World Economic Forum (2023), these new aircraft could represent up to one third of all operated aircraft flying in 2050. The uptake of alternative-powered aircraft is also a contributor to long-term net zero emission roadmaps (EUROCONTROL, 2022). One major challenge is to provide sufficient hydrogen infrastructure at airports. This includes hydrogen storage tanks, liquefaction facilities to produce liquid hydrogen, and an effective hydrogen supply chain supported by road transport

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or pipelines to the airport. Yet, another major challenge is to adapt the airport operations to enable ground handling, refuelling and turnaround of alternative-powered aircraft. This requires changes of ground service equipment (GSE) fleets, for example, introducing bowsers to support liquid hydrogen refuelling, but also introduction of and adherence to new safety procedures. New regulations and standards will be established as part of the transition, leading to a change of the current regulatory framework.

In addition, new airport infrastructures must coexist with today's kerosene-based infrastructures that are required for handling current aircraft and for using sustainable aviation fuel types (SAF) as part of the transition to net-zero aviation (Grimme and Braun, 2022) by 2050. SAFs are hydrocarbon drop-in fuels reducing lifecycle emissions and can be used with existing infrastructure and aircraft. Handling different types of fuels and infrastructures at the airport increases complexity, congestion and risk of failure, e.g., due to human factors. Also, new value chains for both battery-electric and hydrogen (combustion and fuel cell) aviation are emerging, leading to a variety of new business partners, suppliers, and customers for airports and airlines alike.

For these reasons, it is important to develop clear and robust future roadmaps to enable the transition towards zero-emission aviation. Roadmaps can differ according to airport size, location, business case, or individual airport requirements. Further, decarbonizing roadmaps need to be supported by a thorough risk assessment to address key challenges and avoid delays in implementation or even failure. This paper addresses these issues by providing a qualitative risk assessment of a preliminary hydrogen roadmap for a mid-sized airport to contribute to zero carbon emission aviation. The focus is on airports that will support handling and turnaround of liquid hydrogen-powered aircraft, see Adler (2023), with direct combustion equivalent to the size of A321/Boeing 757 type aircraft. Market entry of these future types is expected in 2030 to 2040, expecting 2% of hydrogen combustion aircraft of the global aircraft fleet in 2040, and increasing up to 6% in 2050 (World Economic Forum, 2023). The risk assessment is based on a literature review and consolidated inputs from an airport roadmap research project that involved a mid-sized real-world airport. Results are presented in terms of risk registers that are grouped into three different categories: The first is related to refuelling, ground handling, and turnaround of hydrogen-powered aircraft at the airport. Safety rules regarding frostbite, rescue and firefighting are also addressed. The second captures maintenance and repair including certification and training of respective personnel. The third captures the regulatory landscape including the introduction of government incentives and standards for hydrogen-powered aviation (European Commission, 2022).

One of the main concerns for aviation industry stakeholders is how to source the vast amount of green energy required for the transition to zero-emission aviation. Moreover, aviation competes with other industries for renewable energy sourcing. Therefore, the success of a wider adoption of hydrogen infrastructure and operations for European airports also depends on the EU's energy transition policy (European Commission, 2019). For example, the rapid expansion of offshore and onshore wind parks would strongly increase supply capacity of renewable energy (International Energy Agency, 2021). This sustainable energy could then be used to produce green hydrogen either off- or onsite of airports, and for feeding the hydrogen supply chains.

Following this introduction, section 2 gives an overview of literature regarding roadmaps and hydrogen adoption at airports. Section 3 introduces an exemplary roadmap for a mid-sized airport and respective assumptions used for the risk assessment. Section 4 provides first results in terms of risk registers for hydrogen-enabled airport roadmaps. Section 5 concludes with final remarks and an outlook.

2. Literature Review: Hydrogen adoption at European airports

The introduction of hydrogen as an aviation fuel has long been discussed in literature, with early publications dating back to the 1970s, see NASA (1976) and Brewer (1982). Regarding airport infrastructure and operations, more recent publications include e.g., Bruce et al. (2020), Baroutaji (2019), World Economic Forum (2023), and others.

The Aerospace Technology Institute (2022) investigated hydrogen roadmaps based on the FlyZero project which was backed by the UK government to investigate zero carbon emission commercial flight. The authors estimate that more than 70 million tons of liquid hydrogen (LH_2) could be required to meet global aviation demand in 2050. They further estimate that the production of this amount in terms of green hydrogen (produced with renewable energy in contrast to blue or grey hydrogen) would require about 3,800 TWh of electricity.

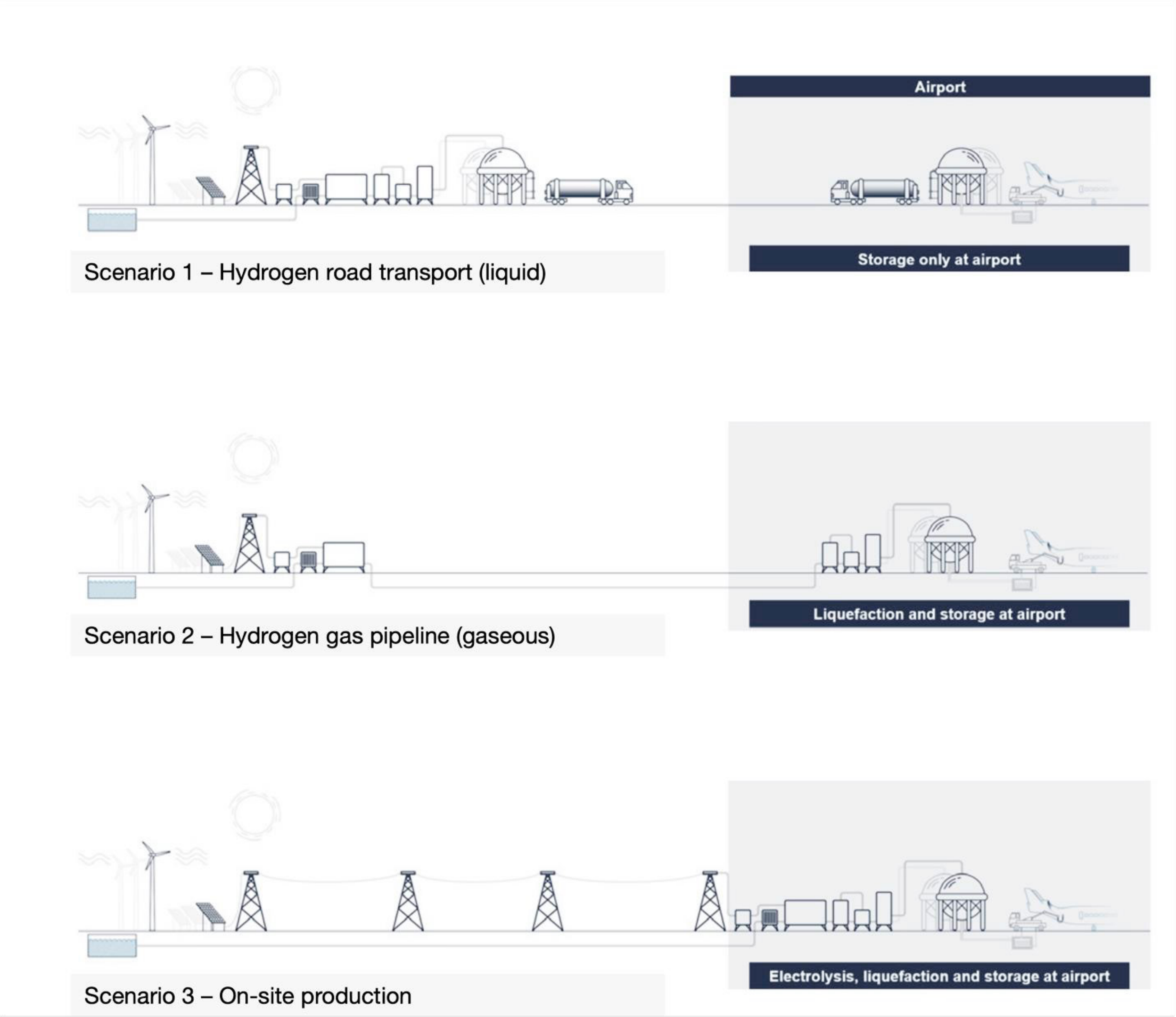

Fig. 1. Overview of future hydrogen supply chain options. Renewable electricity is required for producing green hydrogen. Source: Adopted from Aerospace Technology Institute (2022) and European Commission (2022).

For hydrogen supply of an airport, the authors distinguish between three scenarios shown in Fig. 1. In scenario 1, hydrogen is generated and liquefied off-site and then transported to the airport by bowsers. Scenario 1 would be preferred by most airports in the first years of the hydrogen transition due to lower capital requirements for hydrogen infrastructure and shorter lead times. The second scenario assumes that hydrogen is generated off-site and supplied to the airport in gaseous form by gas pipelines, which is then both liquefied and stored at the airport (Scenario 2). This option is likely if bowser operations will cause road congestion at major airports or if demand increases. Scenario 3 assumes that hydrogen is produced and liquefied (Tang, 2023) at the airport site. However, this option would require significant amounts of renewable electrical energy not available at most airports.

The study concludes that distribution of hydrogen at airports and aircraft refuelling will basically be comparable to current kerosene-based airport operations, which means that bowsers will be used for hydrogen aircraft refuelling. According to the study, maintaining existing aircraft turnaround times for liquid hydrogen aircraft will be challenging due to the specific properties of hydrogen, but almost similar turnaround times will be feasible. Also, safety exclusion zones during refuelling at the aircraft will likely be larger due to safety requirements for liquid hydrogen, ranging from 8 to 20 meters according to some estimations (Catapult, 2022).

The Zero Emission Flight Infrastructure (ZEFI) roadmap (Catapult, 2022) was developed as part of the UK funded zero-emission flight infrastructure project. It considers different elements of an airport to support battery-electric and hydrogen-powered aircraft in the range of 1 up to 250+ seats. The general roadmap was designed for small airfields up to major international airports. The intention was to provide a time-based view of zero-emission airport infrastructure for the time horizon of 2025 to 2050.

The roadmap distinguishes between four capability levels for airports to provide the required infrastructure and operations. These levels capture the basic handling and safety operations and handling of possible emergencies, the capability of enabling operations in limited capacity and with lower financial commitment. More comprehensive capabilities allow for scaled-up operations of a greater number of electric and hydrogen-powered aircraft. They also considered future advanced airport infrastructure, e.g., renewable power generation at airports to increase supply chain resilience, or on-site hydrant distribution and battery swap technologies. The ZEFI methodology was based on literature review, stakeholder identification, and review of existing infrastructures.

Results suggest that gaseous hydrogen refuelling vehicles will be available before 2025 with further investment needed. On-site production of hydrogen via electrolysis is already possible. However, hydrogen refuelling stations are technically complex and require longer lead times than refuelling GSE vehicles. With respect to both gaseous and liquid hydrogen storage, the respective technologies are mature at small scale.

Moradi and Groth (2019) give an overview of the current state-of-the-art on hydrogen storage and delivery with respect to safety and reliability. They also provide a risk and reliability analysis capturing key parts of the hydrogen economy.

To conclude, several roadmaps and studies of hydrogen infrastructure and required technologies have been developed, however, little has been published on necessary changes of the regulatory framework for alternative-powered aviation. In addition, risk assessments of future hydrogen roadmaps for airports to support hydrogen-based operations need to be further discussed. This paper provides a contribution to fill this gap.

3. Methodology: Qualitative risk assessment for hydrogen roadmaps

As a starting point for the risk assessment, we elaborated a tangible hydrogen roadmap for a mid-sized European airport comparable to airports such as, Hamburg (DE), Nice (FR), or London Stansted (UK). Based on stakeholder consultations and internal model calculations, an exemplary roadmap was compiled to illustrate the transformation from a state-of-the-art European airport to a future hydrogen-enabled airport. The roadmap then serves as a reference for the qualitative risk assessment presented in the next section.

The concrete hydrogen topology for these kinds of airports depends on several factors. As outlined in Fig. 1, the supply chain scenario has a direct impact on the required infrastructure at the specific airport. This includes not only the need for the additional vehicles but will also consume additional parking space on the apron, including access roads and required safety clearances. An estimation for the resulting space requirements, based on estimates of the considered airport, showed that in a positive liquid hydrogen (LH_2) uptake scenario up to 15 LH_2-bowsers will be needed by 2040, thus, requiring about 3,000 square meters of additional space on the apron or the airport's immediate vicinity.

Referring to scenario 1 (see Fig. 1) for the hydrogen supply chain, which is very likely for most airports in the early years of the transition, it is assumed that hydrogen bowsers will deliver liquefied hydrogen to the airport. The capacity of these trucks is estimated at about 4 tons of hydrogen per truckload.

Table 1 quantifies the supply chain scenario of the roadmap based on DLR model calculations, with an estimated hydrogen demand of 5,000 tons per year in 2035 up to 60,000 tons in 2050. This projection assumes an equal distribution and does not consider traffic peaks. As a result, we can expect an average of about 30 bowsers per day in 2045 or over 11,000 bowsers per year for hydrogen delivery alone. Depending on the location and general traffic load at the airport, these numbers may already lead to congestion effects – even more at peak days.

Table 1. Exemplary hydrogen roadmap (year 2035-2050) for a typical mid-sized airport. Source: Stakeholder consultations, literature review, and internal modelling results. Estimations of hydrogen demand represent upper limits.

Year	Estimated demand for liquid hydrogen (LH_2) in tons per year at the airport	Estimated number of bowsers per day needed for the hydrogen supply chain to the airport	Assumptions
2035	5,000	4	market entry of hydrogen-powered aircraft expected in year 2035
2040	25,000	17	
2045	45,000	30	1-1.5 tons of liquid hydrogen are required for each departing flight of hydrogen-powered aircraft (LH_2)
2050	60,000	40	

With regard to hydrogen storage at the airport, it is roughly estimated that a hydrogen tank with an external diameter of about 25m and a capacity of 4,700m^3 would require ground space of about 900 square meters at the airport. This assumes a total height of the tank of 28 meters. According to expert interviews, the airport would prefer fewer hydrogen tanks with greater height, rather than using a larger number of smaller tanks requiring more ground space. Further, two storage scenarios are considered, including a two-day hydrogen storage buffer and a three-day storage buffer, respectively. The resulting storage capacities and space requirements were estimated for both scenarios.

The hydrogen required for buffering depends on the number of movements at the specific airport in question. Here, the number of flights to be taken as a basis for hydrogen buffering at the airport is about 250 flights per day (assuming 450-500 movements during peak hour; of which 275-300 are departing flights). Depending on the year and the expected uptake, up to 80% of departures will be LH_2-affine, whereas in 2035 only 5.5% of departures will be LH_2-affine.

If the airport were to move to supply scenario 2 (Fig. 1) a liquefaction plant would need to be built and financed at the airport. The resulting additional space consumption would be significant. This can be illustrated by the demonstration example of a liquefaction plant within the “idealhy.eu" project, which is designed for a quantity of 40 tons of LH_2 per day. However, the order of magnitude of the required capacity required for the airport roadmap in 2050 is likely to be about four times higher.

Considering the ground service equipment (GSE) fleet, Testa et al. (2014) studied the potential of hydrogen as an alternative fuel for GSE vehicles. However, the roadmap presented here assumes a GSE fleet only consisting of conventional vehicles, battery-electric vehicles, or optionally, gaseous hydrogen-powered vehicles, also see Johnson (2017). In addition, the estimated number of mobile and fixed chargers for the handling of battery-electric aircraft has not yet been defined as the main focus of the roadmap is on enabling airport capabilities for liquid hydrogen operations, which would support the commercial operation of larger hydrogen-powered aircraft as opposed to smaller regional aircraft types based on electric or hybrid propulsion.

4. Risk assessment results for a mid-sized airport

This section presents the results of a qualitative risk assessment in form of risk registers grouped into three categories: The first category covers risks related to airport ground handling operations including hydrogen infrastructure. The second relates to maintenance and repair, including certification and training of necessary personnel. The third considers the regulatory environment and incentives for future investment. For each identified risk the associated probability and impact are assessed in terms of expected losses at the airport or the risk of a delay or failure of hydrogen implementation. The following qualitative risk registers for a mid-sized airport have been identified and grouped into three different categories. The identified risks are based on a literature review of existing roadmaps, own assessments and stakeholder consultations in relation to the roadmap presented in the previous section.

4.1. Refuelling, ground handling, and turnaround

For airline stakeholders, hydrogen-powered aircraft need to be turned-around as quickly as conventional aircraft fleets to avoid cost premiums and under-utilization of aircraft. Current average turnaround times are 60-90 minutes for mid-size aircraft, 25-30 minutes for narrow-body aircraft, and 20-25 minutes for regional aircraft (Aerospace Technology Institute, 2022).

At each airport, several ground handling activities are carried out, partly in parallel, during the aircraft turnaround, e.g., refuelling, baggage loading and unloading, catering and galley services, etc. These activities are supported by proper ground service equipment, i.e., several different vehicles operating in the immediate vicinity of the aircraft.

For future hydrogen-powered aircraft, refuelling with liquid hydrogen can be carried out using mobile bowsers, principally similar to those used for kerosene refuelling (see Salehi, 2022). However, due to the low volumetric density of hydrogen, the volume of fuel required to refuel the aircraft will increase by a factor of approximately four compared to aircraft using conventional kerosene or SAF fuels for a given range. To ensure refuelling in the same time as conventional fuels, the flow during refuelling needs to be increased, e.g. by using larger or additional aircraft hoses.

In addition, the low boiling point of liquid hydrogen and the risk of fire due to its flammability may require extended safety zones for refuelling, as well as specific training and certification of ground handling personnel. Additional steps may also be required for the refuelling connection process, e.g., to dissipate heat and hydrogen boiling prevention. This may require additional time.

It is generally assumed that hydrogen refuelling will have no significant impact on aircraft turnaround time. However, there are risks that can lead to delays in ground operations or, in the worst case, lead to delays or even failure of enabling hydrogen aviation at airports (indicated as implementation delay / failure in Table 2).

Table 2. Risk register for airport infrastructure and ground handling operations for hydrogen-enabled airports.

	Identified risk	Probability (low, medium, high)	Impact (1 = minimal loss/delay; 5 = implementation failure)	Airport policy for managing the risk
1	Bowsers required for hydrogen refuelling cause vehicle congestion at the airport or apron	medium	2 = low commercial loss / delay	Check on space requirements and develop a robust GSE fleet replacement strategy
2	New safety procedures to mitigate the risks of frostbite or fires caused by hydrogen cannot be established or approved	low	5 = implementation delay / failure	Develop the organizational capabilities to establish and test new safety, emergency planning, and rescue and firefighting procedures
3	Safety rules and exclusion zones for refuelling liquid hydrogen aircraft extend A/C turnaround time	low	4 = significant commercial loss	Engage with regulators and industry associations to ensure that safety rules can evolve with hydrogen technology
4	Required ground service equipment for hydrogen is not sufficiently available on the market	medium	5 = implementation delay / failure	Build coalitions with industry partners across the value chain to ensure market readiness at sufficient scale
5	Interruption of the hydrogen supply chain to the airport, e.g., due to road congestion or unexpected increase in demand	medium	4 = significant commercial loss	Develop robust hydrogen supply chain strategy, partner with other hydrogen-dependent industries near the airport, increase storage capacity for buffering
6	Adequate insurance for hydrogen infrastructure (storage tanks, equipment, hazards, etc.) is not available at reasonable cost	low	5 = implementation delay / failure	Negotiate with insurance providers, or engage with hydrogen-related industries for insurance deals

4.2. Certification, maintenance, and repair

Compared to conventional kerosene (Jet A-1) aircraft, the fuel system for future hydrogen-powered aircraft will be inherently different. Like kerosene, liquid hydrogen can directly be combusted in future engines but does not produce any carbon emissions. However, due to its low boiling point, liquefied hydrogen must be cooled down to -253°C. Such low temperatures require different fuel tanks, cooling, and fuel systems (Hoelzen, 2022) for both aircraft and airport infrastructure. Additional or changed operational strategies and procedures for aircraft maintenance and repair will be required. The critical function of the fuel system to maintain hydrogen fuel in liquid form and to prevent pressure and boiling imposes significant technological and operational challenges (Tzimas, 2002). LH_2 fuel tanks must be thermally efficient and able to withstand multiple take-off and landing rotations.

Table 3 provides an overview of the identified risks associated with maintenance and servicing at the airport, as well as the certification of the respective personnel. To give an example: Technological issues, such as materials becoming brittle at low temperatures, can pose a risk.

Table 3. Risk register for maintenance and repair including certification and training of personnel for hydrogen-enabled airports.

	Identified risk	Probability (low, medium, high)	Impact (1 = minimal loss/delay; 5 = roadmap failure)	Airport policy for managing the risk
1	Maintenance and repair cycles for hydrogen-powered aircraft increase unexpectedly	low	2 = low commercial loss / delay	Develop effective MRO strategy with OEMs and maintenance service providers.
2	Maintenance procedures at the airport to solve ad-hoc problems related to the storage, transport, and refuelling of hydrogen cannot be established, or are immature	medium	3 = commercial loss / delay	Establish effective maintenance and procedures by collaborating with stakeholders such as OEMs, airports, and airlines
3	Insufficient capacity for maintenance and repair related to the hydrogen fuel system or ground service equipment at the airport	low	3 = commercial loss / delay	Collaborate with OEMs, maintenance, and hydrogen infrastructure service providers to avoid unexpected delays
4	Certification cannot be granted, or certified and trained ground personnel are not available	high	5 = implementation delay / failure	Ensure effective training and certification programs, hire certified personnel, and work closely with certification and regulatory bodies

Regarding training and certification, an enhanced certification program is likely to be required to evaluate the impacts of hydrogen fuel on aircraft handling and maintenance (Schmidtchen, 1997). In particular, liquid hydrogen can cause severe frostbite and/or hypothermia injuries for ground personnel handling the equipment at airports. There is also an increased risk of fire as hydrogen is more flammable compared to kerosene. If there is a hydrogen leak, the liquid hydrogen will form a gas cloud due to its low boiling point. The cloud can move for some distance until the gas heats up and mixes with air, resulting in a flammable gas mixture that, if ignited, causes explosions or fires.

Also, condensed air on non-insulated LH_2 equipment can lead to oxygenation and explosive conditions in the vicinity of an LH_2 system. These safety risks need to be resolved by proper trained and certified handling personnel and must be backed up by an appropriate regulatory framework.

4.3. Regulatory framework and incentives

A key role for a successful hydrogen roadmap is related to regulation and government incentives. Such are crucial, as the industry alone cannot realize the transition to zero-carbon-emission flying. Substantial investments are needed and market maturity must be achieved in time to deliver on the net zero roadmap. Industry stakeholders also need planning certainty for their major investments, which policymakers should create and ensure. Best practices learned from hydrogen demonstration projects could support the introduction of effective regulations (Hall and Bromaghim, 2014) and standards to accelerate hydrogen introduction at European airports and beyond (Finger et al., 2021; Apak et al., 2012). Table 4 shows examples of associated risks and recommendations.

Table 4. Risk register on regulations, government incentives, and standards for hydrogen-enabled airports.

	Identified risk	Probability (low, medium, high)	Impact (1 = minimal loss/delay; 5 = roadmap failure)	Airport policy for managing the risk
1	No binding EU (safety) regulations for liquid hydrogen for airports to allow effective ground handling	low	5 = implementation delay / failure	Engage with regulatory bodies and industry associations to ensure that necessary regulations are established
2	Aviation standards (technical, commercial, etc.) for H_2 cannot be set by official bodies, or they are immature or unrecognized	medium	3 = commercial loss / delay	Create de-facto standards in collaboration with other airports, airlines, and relevant stakeholders
3	International cooperation fails to achieve agreement on cross-border H_2-powered flights, e.g., related to CORSIA or safety requirements	low	4 = significant commercial loss	Invest to cultivate international cooperation for alternative-powered flights across national borders
4	Incentives to subsidize investments in airport hydrogen infrastructure are proving ineffective, insufficient, or misaligned	high	3 = commercial loss / delay	Develop a robust investment and financing strategy in collaboration with external partners to meet future needs

Regulation is further important to increase public trust. Some surveys suggest that public's main concerns about hydrogen are related to safety and regulation (Parfomak, 2021). Aviation stakeholders must proactively collaborate to ensure that safety is guaranteed across the battery-electric and hydrogen value chains, including production, transport, storage, last-mile delivery and use on aircraft. Otherwise, public acceptance may become a market barrier to the commercialization of hydrogen aviation.

5. Conclusion

Depending on the risk management and business strategy, airports need to decide where they position themselves on the hydrogen roadmap to zero carbon emission flight, i.e., whether they want to be early adopters, market leaders, or followers. If they decide to be early adopters, they will need to start planning and investing in hydrogen infrastructure within the next few years.

In terms of hydrogen infrastructure, some airports may want to be early adopters to support new aircraft types, such as battery-electric, hydrogen-powered, or hybrid variants, to increase market share if they can build and maintain a competitive position. However, others may decide to wait until hydrogen infrastructure and operations are well established and proven to be mature before making investment decisions. A lower risk approach may reduce capital requirements but may also result in missed opportunities for market share and growth due to a lower level of capabilities developed at these airports compared to others.

In addition, the hydrogen transition is likely to be a catalyst for the emergence of new and disruptive business models, for example – in relation to infrastructure – leasing or the provision of an 'energy as a service' business model where customers pay for an energy service without any upfront capital investment.

This paper introduced a preliminary hydrogen roadmap and risk assessment for a mid-sized airport to help developing the capabilities for alternative-powered aircraft operations at airports. The roadmap was developed for the years 2035 up to 2050. The presented risk registers of the risk assessment reveal that there are risks that may delay facilitation of hydrogen aviation at airports. Identified risks include incentives for investment in airport hydrogen infrastructure proving misaligned or ineffective. There is also a risk that effective ground handling and maintenance procedures for liquid-hydrogen equipment cannot be established at airports, or that respective ground service equipment is not sufficiently available on the market. In terms of regulation, there is a risk that public confidence in the use of hydrogen in aviation may not be sufficient, e.g., due to a lack of regulation or engagement with local communities. Furthermore, if the hydrogen supply chain to airports is not robust enough to ensure continuous supply and buffering, e.g. due to lack of production capacity, renewable energy, or geopolitical risks, significant losses for airports would be expected.

While the exemplary risks discussed above are not exhaustive, they could cause significant economic losses for airports and airlines or could even jeopardize the entire hydrogen roadmap.

Proposed actions for airports to address the identified issues include, but are not limited to, building effective coalitions with industry associations, regulators, and other stakeholders in the aviation and battery-electric / hydrogen value chains. In addition to the initial investment in airport hydrogen infrastructure, it is also necessary to assess the replacement cycles and the associated costs for infrastructure and ground service equipment fleets. The future scalability of airport operations in terms of alternative-powered aircraft and supply chains will remain a challenge. Future scalability may require advanced airport infrastructure and additional investments, e.g. onsite liquefaction plants. Governments and regulators need to provide the right incentives to encourage market readiness and also to ensure that stakeholders deliver on hydrogen roadmaps, e.g., by setting mandates for hydrogen-powered flight operations. In addition, low public acceptance could become a market barrier to the commercialization of the hydrogen aviation ecosystem, requiring safety regulations and verification to increase public confidence.

Future research could look at a quantitative risk assessment, human factors in risk mitigation, and European airports' compliance with international regulations and incentive policies. Further research could further address the cost-benefit analysis of investment initiatives to develop hydrogen capacity at airports.

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