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Published

2023

Journal Title

Sustainability

Version

Version of Record (VoR)

DOI

10.3390/su152115539

sustainability

MDPI

Review

Hydrogen-Powered Aircraft at Airports: A Review of the Infrastructure Requirements and Planning Challenges

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Abstract: Hydrogen-fueled aircraft are a promising innovation for a sustainable future in aviation. While hydrogen aircraft design has been widely studied, research on airport requirements for new infrastructure associated with hydrogen-fueled aircraft and its integration with existing facilities is scarce. This study analyzes the current body of knowledge and identifies the planning challenges which need to be overcome to enable the operation of hydrogen flights at airports. An investigation of the preparation of seven major international airports for hydrogen-powered flights finds that, although there is commitment, airports are not currently prepared for hydrogen-based flights. Major adjustments are required across airport sites, covering land use plans, airside development, utility infrastructure development, and safety, security, and training. Developments are also required across the wider aviation industry, including equipment updates, such as for refueling and ground support, and supportive policy and regulations for hydrogen-powered aircraft. The next 5–10 years is identified from the review as a critical time period for airports, given that the first commercial hydrogen-powered flight is likely to depart in 2026 and that the next generation of short-range hydrogen-powered aircraft is predicted to enter service between 2030 and 2035.

Keywords: sustainable aviation; airport planning; hydrogen; airport strategy; airport operations

Citation: 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. https://doi.org/10.3390/su152115539

Academic Editor: Marinella Giunta

Received: 27 September 2023
Revised: 26 October 2023
Accepted: 31 October 2023
Published: 1 November 2023

1. Introduction

The primary energy source in aviation is kerosene. The combustion engines in aircraft emit CO_2 emissions, nitrogen oxides (NOx), water vapor, and soot at high altitudes. CO_2 emissions can last in the upper atmosphere for 50 to 100 years, and the other exhaust gases can disrupt the balance of naturally occurring ozone and form contrails, contributing to global warming [1–3]. With environmental challenges high on the agenda, particularly surrounding climate change, there is an increasing focus on net-zero CO_2 emissions in aviation. The International Civil Aviation Organization (ICAO) has established several programs, such as the Global Coalition for Sustainable Aviation and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), to promote sustainable international aviation [4]. The Air Transport Action Group (ATAG) has set a goal for the global aviation industry to reduce its CO_2 emissions by 50% by 2050 relative to 2005 levels [5]. To achieve this ambitious goal, the industry will have to rely on the development of alternatives to petroleum-based fuels, such as hydrogen, but also sustainable aviation fuels (SAFs), electric propulsion, and hybrid solutions, along with improvements through the energy efficiency of aircraft and air traffic management [6,7].

Hydrogen (H2) is a sustainable alternative fuel for aircraft, facilitating full decarbonization in aviation if generated by renewable energy, so-called green hydrogen. Hybrid-electric propulsion systems, a combination of hydrogen fuel cells and batteries, produce no emissions or emission-related effects in flight [8,9]. In addition to hydrogen fuel cells, hydrogen can be burned in hydrogen combustion engines to power aircraft. The combustion of hydrogen does not produce any CO_2 or soot, and in turn, allows for substantial reductions in NOx emissions [10,11]. However, some research into contrails produced by H_2O emissions during hydrogen flight is ongoing [12].

The gravimetric energy density of hydrogen is three times higher than kerosene, while liquid hydrogen's volumetric density is lower than kerosene. To perform the same mission, aircraft need to carry a volume of cryogenic liquid hydrogen four times larger than the volume of kerosene [11,13]. This shortcoming can lead to larger and heavier fuel tanks on aircraft and lead to new aircraft designs [14]. From a fuel-supply perspective, the costs of production of renewable hydrogen are currently significantly greater than conventional kerosene due to the limited production facilities. As the demand for hydrogen increases across many sectors, economies of scale are expected to reduce costs [7]. Hydrogen has the potential to expand to all aircraft segments and is seen as the preferred solution for long-haul flights in the future.

Airlines and aircraft manufacturers have invested in research and development for alternative fuels, such as biofuels and hydrogen, for short-, medium-, and long-distance travel. It is hoped that the first hydrogen-powered commercial aircraft will be certified by 2025. For instance, Skytrans Airlines plans to have Australia's first hydrogen-powered flight in 2026 [15]. However, considering the increased space requirement for tanks on hydrogen-powered flights in comparison to traditional aeroplanes and accompanied design challenges, it is expected that first hydrogen flights will be short-haul flights. Over time, and with manufacturers such as Boeing and Airbus working on designs for long-haul hydrogen aircraft, an increasing number of flights (likely after 2035) will be powered with hydrogen. With increasing demand, demand for hydrogen volume storage at airports and infrastructure will also need to be developed. Some airports partner with manufacturers, such as Changi Airport with Airbus and Edmonton International Airport with ZeroAvia. These partnerships facilitate airports starting to assess the hydrogen infrastructure and supply solutions needed to facilitate hydrogen flights and airport operations [16,17]. However, efforts and the development of strategic roadmaps need to meet the timeline of hydrogen-driven aircraft operation.

Airport planners plan to develop well-prepared airports that can accommodate existing and future air traffic demand. To enable hydrogen-powered flights, airports must realize the long lead time decisions that are necessary to enable hydrogen flights from airports. This awareness must align with the airports' vision and reflect the development objectives to maintain focus on them throughout the master planning effort. With the first commercial hydrogen flights expected in less than five years, this paper reviews airport preparation for hydrogen flights. In particular, it investigates the requirements for airports to enable hydrogen-powered flights and how such requirements should be integrated into the airport master-planning process. This paper's objectives can be broken down into the following two research questions (RQ):

1. How are major airports prepared to support hydrogen flights?
2. What are the primary challenges in airport planning for enabling hydrogen-powered flights?

To answer the research questions, the paper is structured as follows. In Section 2, the methodology is presented. Thereafter, preparations of major airports for hydrogen-powered flights and the infrastructure requirements and planning challenges are discussed in Section 3: Results. While a possible timeline for meeting the identified requirements is proposed in Section 4: Discussion; conclusions and future directions are derived in Section 5.

2. Methods

To analyze the progress of major airports worldwide regarding hydrogen flight preparation (RQ 1), we identified the busiest airport by international passenger volume in each of the seven regions of Africa, Asia-Pacific and Middle East, Europe, Latin America and the Caribbean, North America, and Oceania to ensure global representation. The airports were selected based on the number of international passengers that embarked and disembarked at the airports and are listed in alphabetical order along with their passenger volume in Table 1. To avoid the impact of COVID-19, numbers from 2019 are used. The authors reviewed published online resources from all seven airports, including airport websites, airport master plans, environmental and sustainable planning documents, and news articles. The relative information has been identified and summarized.

Table 1. Annual international passenger numbers of the seven busiest airports for international flights from/to Oceania, Africa, Asia Pacific, Latin America, the Middle East, and North America in 2019.

Airport	Annual International Passenger Numbers in 2019
Cairo International Airport (CAI)	18,955,450
Dubai International Airport (DXB)	86,396,757
Hong Kong International Airport (HKG)	71,542,000
London Heathrow Airport (LHR)	80,886,671
Mexico City Juarez International Airport (MEX)	50,308,049
New York John F Kennedy International Airport (JFK)	62,551,072
Sydney Kingsford Smith Airport (SYD)	16,898,000

Note. The information is from [18].

RQ 2 investigates the primary challenges for airports to enable hydrogen-powered flights and where these requirements should be reflected in the airport planning process. The research team conducted a systematic literature review (SLR) to comprehensively search for literature that focuses on requirements for airports to enable hydrogen flight by following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [19]. The authors used 'Hydrogen' and 'Airport' to search in the Scopus database. The keywords appeared in the titles, keywords, or abstracts of 226 papers in the database. Then, the 215 papers that were not written in English and that had no clear relevancy by title and abstract were removed. The research team reviewed the remaining 11 peer-reviewed papers and found that only four of them had significance and are thus used in this study [20–23]. The selection process is shown in Figure 1.

Since it is not sufficient to answer RQ2 based on these four studies, the research team further investigated industrial studies and reports on infrastructure, technologies, and policies required to support the operation of hydrogen aircraft. Required changes were systematically collected from the documents under review. In the second step, these requirements were categorized in relation to airport infrastructure areas such as the terminal, airside, and landside. Then, we looked in depth at airport master plans and analyzed where those changes to airport infrastructure areas would need to be addressed in an airport master-plan strategic document. By combining the findings, the research team identified the requirements and gaps that should be filled. These requirements and gaps are summarized and presented under the relative sections based on the typical structure of airport master plans. The related sections are Airport Land Use Plan, Terminals and Aviation Development Plan, Utility Infrastructure Development Plan, and Safety, Security, and Training. The research explored and identified the challenges in airport planning for enabling hydrogen-powered flights, assuming that airports will need to adopt hydrogen operations in the future, given the need for sustainable aviation fuel. However, it was acknowledged that crucial timelines are different for the various requirements. A possible timeline for meeting the identified requirement is presented and discussed. The technical barriers and costs associated with infrastructure updates have not been studied.

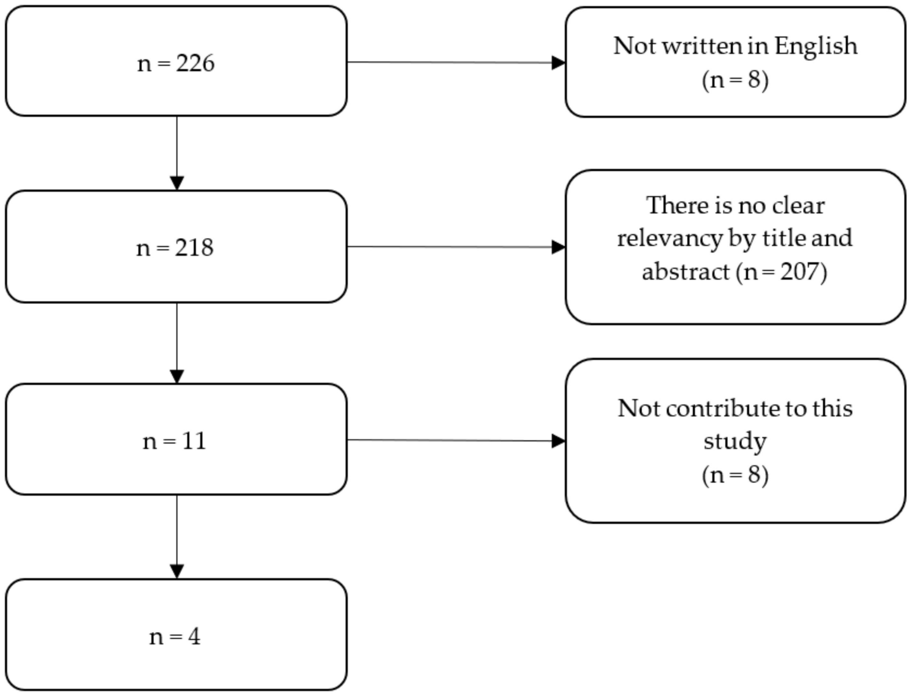

Figure 1. Literature review selection process.

3. Results

In the following sections, we review the planning documents of major international airports and analyze their preparation for hydrogen flights. In the second stage, we examine the major changes to airport infrastructure to enable hydrogen flight, and develop a timeline for necessary implementation depending on the volume of hydrogen flights.

3.1. Research Question 1: Preparations and Opportunities for Hydrogen in Major Airports

The authors reviewed published online resources from all seven airports, including airport websites, airport master plans, environmental and sustainable planning documents, and news articles. All the airports have existing environmental programs and established sustainability initiatives to reduce their impacts on climate change. Some of them, such as London Heathrow Airport, acknowledge the trend towards sustainable biofuels but stop short of having a more comprehensive sustainability strategy that encompasses hydrogen flight preparation. However, none of the programs or plans of the seven airports involve major airport master-planning exercises to enable hydrogen-powered flights at the airports, as shown in Table 2. The sustainable goals and initiatives tend to focus on percentage reductions in emissions, sustainability slogans (e.g., Hong Kong International Airport's 'Towards the Greenest Airport'; Make Heathrow a 'great place' to live and work), and onsite renewable energy solutions such as solar power (e.g., Cairo Airport) [24,25]. On the other hand, most of the airports plan to increase onsite renewable energy production, which could be used to produce green hydrogen in the future.

Table 2. Existing hydrogen infrastructure and planning of the seven busiest airports for international flights from/to Oceania, Africa, Asia Pacific, Latin America, the Middle East, and North America.

Airport	Plans for Hydrogen Application	Examples of Sustainable Goals and Initiatives Regarding Energy and Emission
Cairo International Airport	No evidence	• Intend to use solar energy for operations. • Install 300-kilowatt-capacity solar plant.
Dubai International Airport	No evidence	• Carbon-neutral growth by 2020. • Install 15,000 solar planes, which can produce 7,483,500 kilowatt hours of energy per year.
Hong Kong International Airport	• The airport plans to have a pilot program for hydrogen-powered applications at the airport. • Hong Kong Aircraft Engineering Company plans to upgrade to hydrogen-powered ground support equipment at the airport.	• Achieve net zero carbon by 2050. • Use renewable diesel in vehicles and ground services equipment.
London Heathrow Airport	• Heathrow and its partners are "stablishing a blueprint for zero carbon aviation by modelling the introduction of low or zero emissions aircraft into regional and short-haul aviation, such as those with hydrogen or electric propulsion [25].	• Introduce SAF in landing charges from 2022. • Transitioned most ground fleet to electric vehicles. • Reduce emissions by 50% by 2030. • Achieve zero carbon by 2050.
Mexico City Juarez International Airport	No evidence	No evidence
New York John F. Kennedy International Airport	• Shell opens two hydrogen refueling stations for hydrogen fuel-cell vehicles at JFK	• Vehicles at JFK International Air Terminal will be fully electric or hybrid-engine by 2023. • 35% GHG reduction by 2035 and 80% by 2050.
Sydney Kingsford Smith Airport	No evidence	• Achieve a 50% reduction in emissions per passenger by 2025. • Equipment around the airport powered by low emissions fuels and renewable energy.

Note. The information is from [24–32].

No evidence

Through exploring the online resources of the seven airports, the authors also found that, with the exception of Mexico City Juarez International Airport, the airports are making commitments to reduce their carbon emission footprints and use renewable energy. Furthermore, there are two hydrogen refueling stations for cars located at New York John F. Kennedy International Airport. Hong Kong International Airport also plans to have hydrogen-powered applications [26]. London Heathrow Airport collaborates with its partners to establish a blueprint for zero-carbon aviation by modelling the introduction of low- or zero-emissions aircraft into regional and short-haul aviation, such as those with hydrogen or electric propulsion [24]. Information about hydrogen applications at the remaining three airports was not found in the investigation. In terms of enabling hydrogen-powered flights at the airports, none of the seven major airports have existing programs or published plans.

3.2. Research Question 2: Challenges in Airport Planning for Enabling Hydrogen Flights

While much recent research focuses on aircraft technologies [9,33–36], the requirements to enable alternative-powered flights from an airport planning perspective are not often analyzed. As early as 1976, the National Aeronautics and Space Administration (NASA) sponsored two case studies on the requirement to enable hydrogen-powered flight at San Francisco International Airport and Chicago O'Hare International Airport in the United States. These studies state that economics is the primary determinant and presented preliminary requirements of the infrastructure and facilities at airports to support hydrogen-powered flights, and also confirmed the feasibility of the hydrogen-powered flights [21,37]. The Ad Hoc Executive Group (AHEG) also tested the feasibility of hydrogen-powered flights at Zurich Airport in Switzerland and found that the airport infrastructure needs to be updated and expanded to accommodate the hydrogen facilities [20]. Recently, several reports from industrial and governmental organizations looked at hydrogen supply to airports and delivery to aircraft. For example, CleanSky2 found that the utilization of hydrogen (H2) combustion during flight has the potential to decrease its environmental impact by 50 to 75 percent [7]. The Aerospace Technology Institute (ATI) outlined the challenges and solutions for implementing liquid hydrogen as a sustainable aviation fuel [6]. In contrast, studies investigating the requirements to enable hydrogen-powered flights at airports are very limited. Hoelzen et al. presented an overview of H2 infrastructure for aviation and found that the availability of low-cost, green hydrogen is crucial for the economy of hydrogen-powered aviation, and the use of hydrogen could significantly increase direct operating costs [38]. Another recent study led by the same author compared and evaluated the potential liquid hydrogen refueling systems from an economic perspective [39]. It concluded that for airports with 125 kt-LH2 annual demand, an LH2 refueling truck setup is more cost-effective, while airports with higher LH2 demands may benefit from an LH2 pipeline and hydrant system.

Recent research on hydrogen aircraft technologies tended not to analyze the requirements to enable hydrogen-powered flights from an airport planning perspective. However, as essential parts of the air transport system, airports need to be ready for hydrogen-powered aviation to enable net zero goals of the future.

An airport master plan that reflects the long-term strategy of an airport is the most appropriate document to present the potential efforts needed to support hydrogen-powered aviation at airports. In our analysis, we list the requirements and gaps related to both infrastructure and policy that should be filled under the relative sections of a typical airport master plan structure. This should help airport operators consider these challenges in future planning stages. The relevant sections are Airport Land Use Plan, Terminals and Aviation Development Plan, Utility Infrastructure Development Plan, and Safety, Security, and Training. A possible timeline for meeting the identified requirement is presented, discussed, and summarized in the Discussion section. The technical barriers and costs associated with infrastructure updates and their impact on the timeline presented have not been studied.

3.2.1. Airport Land Use Plan

The land use plan is a key element of the entire planning process. To serve hydrogen aircraft, airports may need to accommodate new infrastructure such as liquefaction facilities, hydrogen storage tanks, hydrogen production plants, and potentially duplicate terminal and runway systems if hydrogen and traditional aircraft systems are used in parallel. The following three elements are airport-land-use challenges associated with hydrogen.

1. Storage. Hydrogen can be stored either in gaseous or liquid forms. Yet, liquefied hydrogen storage tanks would be more appropriate for airports due to space availability [40]. Even for liquid hydrogen, the volume is nearly four times more than Jet A-1 for the same amount of energy. The largest storage tank (20-m diameter) that is currently used by NASA can hold approximately 220 tons (850,000 gallons or 4000 m^3) of liquid hydrogen [41]. This amount of hydrogen could potentially support the operations of 200 short-range turboprop aircraft flights or 40–50 narrowbody medium-haul aircraft flights [7,21,37]. In some cases, storage tanks and liquefiers may not be necessary if the cistern truck can directly refuel the aircraft [6,42]. Alternatively, certain locations may be suitable for underground storage of several orders of magnitude more hydrogen. However, this would only be possible where certain geological features coincide with the airport location and cannot be assumed on a general basis. However, in actual operations, airports need to hold a certain amount of buffer in case of disruption to the hydrogen supply.
2. Liquefaction. Hydrogen can be transported to airports via trucks, trains, and pipelines, or produced at airports. If hydrogen arrives at airports in gaseous form or is produced

on-site, a liquefaction process is needed before storage or refueling. This process requires a series of infrastructure elements, including liquefiers, cooling towers, air separators, and control rooms [21,37]. Those footprints can vary from 25 to as much as 300 m^2/ton [42].

3. Hydrogen production plants. As the demand for hydrogen increases, the ultimate solution for hydrogen supply would be to produce hydrogen using electrolysis at the airport or nearby. A 50 tons/day electrolysis hydrogen production plant using state-of-the-art production technologies would require 5000–10,000 m^2 of space [40]. This footprint is similar to the 8500 m^2 quoted in 1976 [37] and is hence unlikely to significantly reduce with technological improvements, despite anticipated efficiency improvements of up to 10% by 2030 [40].

In summary, the production, liquefication, and storage tanks associated with hydrogen production each have significant footprints. ATI estimates that if an airport needs to supply 700,000 L (around 50 tons, catering for about 50 short-haul turboprop aircraft or 8–12 medium-haul narrowbody aircraft) of liquid hydrogen per day, it would need a further 13,000 m^2 of space to install the hydrogen production plant and associated liquefaction and storage facilities [6]. This does not include provisions for renewable electricity generation or infrastructure required to purify water for electrolysis.

Busy hub airports are usually very space-constrained, and these four elements show it is paramount that planning for hydrogen flights is incorporated early in any master plan update. By way of example, Sydney Kingsford Smith Airport has a daily kerosene-based jet fuel demand of approximately 10 million liters [43]. Replacing this with hydrogen produced on-site may require approximately 1.3 million m^2—or 130 ha—which would equate to nearly 15% of that airport's land area [44].

3.2.2. Airside Development Plan

The airside development plan discusses the essential need to provide for future aircraft movements. This section describes potential infrastructure and facilities updates to support hydrogen aircraft at the airside according to three elements.

1. Terminals. Airports may need to have two separate terminal systems for hydrogen-powered aircraft and aircraft using kerosene fuel due to the potential differences in operations and infrastructure requirements. The fuselage of hydrogen aircraft will be longer than that of current aircraft. If the new aircraft applies a revolutionary design, such as a blended-wing-body design, the wingspan may also change. To accommodate those hydrogen aircraft, airports may need to redesign and reconstruct their terminals. CleanSky2 estimates that hydrogen-powered aircraft will be 5–15 m longer than current aircraft. Not all airport boxes (airport parking areas for aircraft at gates) are able to accommodate this additional space requirement [7]. The turnaround time for hydrogen aircraft may be longer than the current aircraft because the required hydrogen fuel safety zone is much larger than Jet A's [6]. For example, the refueling safety exclusion zone could be 20 m which is larger than the existing requirement. This new requirement may disrupt other activities such as passenger boarding and catering, increasing turnaround time and reducing the capacity of the terminal unless new refueling procedures are used [23]. Airport operators need to realize the potential conflict between the operations of hydrogen aircraft and traditional aircraft. As the number of hydrogen-powered flights increases, airports may need an additional terminal system to service hydrogen aircraft.
2. Refueling equipment. Another area that would require a major update is aircraft refueling equipment. Like refueling conventional aircraft, delivering hydrogen to aircraft can use both trucks and hydrants. Since technical requirements for refueling hydrogen are different (e.g., hydrogen needs to be insulated and kept in liquid form), there is no existing equipment that can be directly used at airports [45], although equivalent technologies and technical standards do exist for both gaseous and liquid hydrogen transfer (e.g., ISO 19880.5:2019, "Gaseous hydrogen—Fueling stations, Part

5: Dispenser hoses and hose assemblies” [46], and ISO 13984:1999, “Liquid hydrogen—Land vehicle fueling system interface” [47]). In addition, it is impossible to replace all conventional aircraft with hydrogen aircraft in the short term. Therefore, airports likely need two separate refueling systems for an extended period.

3. Ground support equipment. There are two design concepts. The conservative one is based on the current tube-and-wing design of commercial aircraft. While this concept of design requires slight changes in the fuselage and airframe to accommodate larger and heavier fuel tanks, the new aircraft will still be 5–15 m longer than the current ones [7]. The revolutionary concept adapts new aerodynamic concepts (blended-wing-body designs), which are more efficient but much different from the current designs [7]. The current ground support equipment, such as towing trucks, may not meet future operation requirements.

On the airside, therefore, not only is more space needed in the future to support hydrogen flights, but also significant financial investment is needed for new ground support and refueling equipment.

3.2.3. Utility Infrastructure Development Plan

Another challenge airports face is managing their utility infrastructure to ensure the security and efficiency of the storage, liquefaction, and production of hydrogen, requiring sufficient electricity and water supply.

1. Electricity and Water Supply. Intensive energy consumption is required to produce or liquefy large amounts of hydrogen. For example, Haglind et al. estimated that the energy to produce and liquefy 50 tons of hydrogen is seven times the daily energy consumption of Arlanda Airport [48]. ATI estimated that the energy consumption for liquifying or producing hydrogen could be at least as much as the current energy consumption for all other purposes at the airports [45]. In order to ensure zero carbon emissions, the electricity used for hydrogen production needs to be from renewable energy, such as solar and wind, making a stable energy supply at airports even harder. For example, providing a substantial airport with the electricity needed for electrolysis might necessitate the installation of several dedicated 400 kV overhead power lines, in contrast to just a single pipeline required to deliver an equivalent amount of hydrogen to the airport [22]. In addition, hydrogen production via electrolysis requires a large amount of high-purity water [49]. Therefore, securing a sustainable water source that does not significantly impact water security or the local environment is another main challenge for airports to produce hydrogen onsite. If hydrogen is to be produced on-site, airports will need to meet the increased demand for electricity, which may leave a gap for renewable energy as a source.

This section makes it clear that long-term planning is key to enabling hydrogen flight, either because significant investment in infrastructure is needed or intense stakeholder management is required to secure resources needed for hydrogen flight.

3.2.4. Safety, Security, and Training

The transition to hydrogen as aviation fuel poses a broad range of potential safety and security challenges to airports, of which the main four are listed below.

1. Aircraft refueling. One of the most apparent technical changes to operating aircraft with hydrogen fuel would be the refueling process. Whether the fuel is transported to the aircraft or gate in a refueling vehicle or via a hydrant system, hydrogen would need to be transferred into the cooled tanks within the aircraft to maintain the hydrogen in its cryogenic liquid state. This requires maintaining temperatures below 20 K for hydrogen in a liquid state at atmospheric pressure. Temperatures may be closer to 100 K for pressurized supercritical hydrogen, however, which has similar properties. Above these temperatures, the evaporation of hydrogen and hence pressurization of any hydrogen storage vessels, is significant and must be accounted for in system

design [50]. All tanks, storage vessels, and piping in this system would, therefore, need to be held at significantly higher pressures than kerosene or gasoline fuels, which are only pumped to overcome the pressure differences in height between the vehicle/hydrant and the aircraft, on the order of 1–5 atm. This equates to increasing the line pressure by a factor of 100–200. According to the International Air Transport Association (IATA), a 3 m-radius fuel safety zone extends from the aircraft fuel tank required during refueling operations. In this zone, no ignition sources are allowed [51]. For fueling liquid hydrogen, the fuel safety zone needs to expand to 30–60 m wide under the current standard, and potentially reduce to 20 m during connection and disconnection and 8 m during fuel flow after 2030 [39]. This standard change will significantly impact aircraft ground operations and the passenger boarding process.

2. Airport rescue and firefighting. Since many of the physical characteristics of hydrogen, such as the flammability, diffusivity, density, flame speed, and evaporation rate, are very different to Jet A fuel, the airport rescue and firefighting procedures need to be reviewed and adapted to accommodate the new challenges associated with hydrogen. New specialized equipment and training will be required.
3. Employee training. Once the airports adopt hydrogen operations, airport staff need to receive appropriate safety training for operating the new equipment and working in the new environment. The staff involved in hydrogen operations must be familiar with new procedures and be able to recognize the potential risks associated with the new fuel. They will need to be able to protect themselves and others from potential accidents and incidents involving hydrogen production.
4. Policy and regulations. Currently, some efforts are being made to establish regulatory frameworks and technical guidelines for the safe development, testing, and certification of hydrogen fuel systems [52]. As the hydrogen aircraft certification progresses, regulatory frameworks, and standards for hydrogen aircraft to safely operate in the airport environment need to be developed. The airports interested in supporting hydrogen flights may participate in the development process and update their policies accordingly once the new official regulations are available.

Therefore, the various safety, security and training requirements emphasize the long lead time required for airports to adapt to hydrogen flight.

4. Discussion

As demonstrated in the previous section, the challenges involved in airport planning to enable hydrogen flights are mainly from airport land use, airside infrastructure development, utilities supply security, and safety and security. To enable hydrogen-powered flights, there are some factors that decide the complexity and difficulty level of the challenges that airports face beyond current master-plan challenges in those categories. These determinants are on the scale of demand for hydrogen, the location of airports, and the availability of relevant regulations and procedures.

In the initial years of the hydrogen operation, the scale of demand would be low enough to be supplied by road tankers to the airport. Since the capital cost of road transportation of hydrogen is lower than the options of gas pipeline and production onsite, airports would be more likely to choose the use of road trucks. This situation will continue until the increasing demand and the deliveries cause congestion in traffic to-and-from airports, affecting the supply of hydrogen. For some small airports that only have a few flights per day, there is no motivation for them to choose hydrogen supply methods other than road trucks [6]. In this case, airports must decide if and when to build new infrastructure based on the forecast of their aviation traffic increase, developing their airport land use plan. For major airports such as those discussed in this paper, new infrastructure would need to be ready by 2030 in order to achieve the aviation net zero goal by 2050.

Within airport land-use-plan challenges, the plan for storage and liquefaction equipment should be considered first. However, the storage tanks and liquefaction equipment needed are uncertain, since the number of hydrogen flights will be very limited before

2030. As an increasing number of hydrogen aircraft come into service, airports will have to address these challenges in their plans. Regarding hydrogen production plants, there is no need to generate hydrogen before 2035. Even after the second time segment, airports may not choose to produce hydrogen onsite due to the large capital investments, unless the airport plays the role of a hydrogen hub in the region [6]. However, major airports around the world should investigate the possibility now, as capital-intensive projects such as building a hydrogen production plant need some major lead time and plans need to be incorporated in current and future master plans.

In addition, the production of green hydrogen requires a large amount of renewable energy, such as solar and wind power. Airports located in regions with abundant renewable resources have an advantage in hydrogen production. For the same reason, these airports will have less pressure from the utilities supply security for producing hydrogen onsite. Otherwise, there will be a huge gap in the renewable energy supply. Regarding the production of hydrogen at airports, a feasibility study on individual airports is recommended based on future demand for hydrogen, the availability of renewable resources, and the cost of ownership. If airports need to address the challenges in the utilities infrastructure development plan depending on the decision to generate hydrogen onsite, they need to consider it in their master planning in the near future to be ready by 2035. Planning for the scaling up of renewable energy sources on airport land would need to start now.

The challenges involved in airside infrastructure development are related to the design of hydrogen aircraft as well as regulation changes. The characteristics of hydrogen aircraft will be different from the current aircraft in the same category. For instance, hydrogen aircraft are expected to be longer and heavier than conventional aircraft, in order to carry more hydrogen. With the two new design concepts mentioned in the results, the current refueling equipment (both trucks and hydrants) needs to be redesigned, and the current ground support equipment may also need to be replaced. The regulations and procedures of aircraft ground operations should also be redeveloped. Airports need to update their infrastructure (refueling, terminal, maybe even runway system) and group support equipment based on the new types of hydrogen aircraft and the relevant regulations and procedures. Among the challenges involved in an airside development plan, the refueling and ground support equipment should be addressed in airport plans before 2025 to serve hydrogen flights. It is uncertain if the terminals will need to be redesigned and updated since the characteristics of hydrogen aircraft are not settled yet. Discussions between airport master planners, architects, aircraft manufacturers, and hydrogen specialists should be initiated in due course to appropriately plan for the hydrogen airport of the future.

There are many safety considerations in ground handling, refueling, rescue, and firefighting for hydrogen aircraft. It is impossible to perform these tasks safely and efficiently without proper regulations and procedures. Airports also need to identify the relevant qualifications and provide enough training for their staff based on the official regulations. However, there are currently no established regulations and procedures on hydrogen aircraft ground operations. The challenges in safety, security, and training need to be addressed in the 2022–2025 plans. In particular, the development of relevant operating procedures should be a top priority. The development process should run in parallel to the development of hydrogen aircraft and support equipment, and requires collaboration and integration across the whole aviation industry, including aircraft manufacturers, ground equipment providers, airports, and aviation authorities. Otherwise, it will be impossible to safely and efficiently implement hydrogen operations at airports.

The timeline to address the challenges in the airport planning process can be divided into three segments. The first segment is from the present to 2025, given that the first commercial hydrogen-powered flight is likely to depart in 2026 [7]. The second segment is from 2025 to 2035, as it is expected that the next generation of short-range aircraft to enter service will be around 2030–2035 [7]. An increase in hydrogen-powered flights, especially for long-haul flights, is expected after this time period. Therefore, the third segment is from 2035 to 2050. In order to achieve zero-carbon emissions, there will need to be a large number of hydrogen aircraft in operation at that time, and that is, therefore, the time by which major airports need to be ready for hydrogen flights. Table 3 shows a possible timeline to address the identified challenges in the airport planning process.

Table 3. Timeline to address the challenges in the airport planning process.

		Timeline		
	Challenge	**2023–2025**	**2025–2035**	**2035–2050**
Airport Land Use Plan	Storage	uncertain	✓	✓
	Liquefaction	uncertain	✓	✓
	Hydrogen production plants	×	×	uncertain
Airside Development Plan	Terminals	×	uncertain	uncertain
	Refueling equipment	✓	✓	✓
	Ground support equipment	✓	✓	✓
Utility Infrastructure Development Plan	Electricity and Water Supply	×	×	uncertain
Safety, Security, and Training	Aircraft refueling	✓	✓	✓
	Airport rescue and firefighting	✓	✓	✓
	Employee training	✓	✓	✓
	Policy and regulations	✓	✓	✓

Note. The symbol '✓' presents a need to address the relative challenge in the timeframe. The symbol '×' shows no need to address the relative challenge in the timeframe.

Considering the long lead times for the various capital-intensive infrastructure projects, as well as training and regulation requirements as outlined in the review, we call on airports to act now and incorporate the discussed requirements in their master plans. Depending on the size of the airport, the number of hydrogen flights expected, and vacant airport land available, planning can be undertaken in stages, but it is critical that airports start the planning process now to enable the scaling up of hydrogen flights by 2035. Only when hydrogen flights are widely available, by 2035, can net zero for the aviation industry be likely achieved by 2050.

There is little motivation for airports to update their infrastructure to promote hydrogen-powered aircraft, as long as it is not demanded by the airlines. The level of funding available and competing concerns are two of the barriers that airports face when seeking to implement improvement projects [53]. Airports have large facilities and other fixed costs, while the incomes are variable and based on the volume of use [48]. Airports have a typical economic profit margin of 3% [54]. Low-profit margins have the effect of limiting budgets. For longer-term projects, airports may seek Government funding (federal or state) or may also seek approval for bond packages. Longer-term planning is undertaken through Airport Master Plans or Airport Sustainability Plans, but these are limited as available options to fund longer-term projects. Therefore, to motivate airports, it is necessary for the airlines to get serious about net zero goals in aviation and acknowledge that SAFs alone will not reach those goals. Furthermore, investments from other sectors and special funding for promoting hydrogen flights coming from governments are in desperate need.

5. Conclusions and Future Directions

This study investigated the preparation of major international airports for hydrogen-powered flights and identified the planning challenges involved in enabling the operation of hydrogen flights in an airport context. In terms of enabling hydrogen-powered flights at the airports (RQ1), none of the seven major airports have existing programs or published plans. Major adjustments and challenges (RQ2) in airport planning are expected in areas such as airport land use, airside development, utility infrastructure development, safety, security, and training. The difficulties in airport land use and utility infrastructure development will increase as the demand for hydrogen flights accelerates. The challenges in airside development and operations, as well as safety, security, and training, should be overcome first, in order to enable the first hydrogen flights at airports in the very near future.

Meeting these tight timelines will require collaboration and integration across the whole aviation industry, including aircraft manufacturers, ground equipment providers, airports, and aviation authorities. Given that the first commercial flights are expected to be introduced in 2026, it is surprising that a review of major international airport master plans found very little preparation for the technology. Although, recent industry news suggests that airports, airlines, and manufacturers are starting to form alliances, such as Singapore Changi Airport and Airbus [16]. However, much more needs to be undertaken in order to enable hydrogen flights to be a key part of net-zero aviation.

This preliminary investigation identifies the challenges in airport management and planning on hydrogen operations and gives airport planners a roadmap to help speed up the process. This paper assists airports in planning ahead in terms of updating their infrastructure, enabling the future aviation energy transition, and contributing to a reduction in the climate impact of the aviation sector.

While many previous studies focused on conceptual analysis of the requirements for hydrogen flights, future studies should consider case studies on the assessment of potential land use requirements, energy demand, and refueling requirements at specific airports, as well as pilot tests on the new technologies and procedures. In addition, future studies should look at airport requirements for the parallel accommodation of hydrogen-, electric-, and SAF-powered aircraft. This will be for the mix of the alternatives available to enable the aviation industry to reach net zero in 2050. The different roles of airports and associated geographies are adding to the complexity, and so more research is needed to systematically plot the challenges of airport master planning for the years to come.

Author Contributions: Conceptualization, Y.G. and M.W.; methodology, Y.G., M.W. and M.E.J.; validation, Y.G.; formal analysis, Y.G.; writing—original draft preparation, Y.G., M.W. and M.J.E.; writing—review and editing, Y.G., T.R., M.W., M.E.J. and M.J.E. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

References

1. Arrowsmith, S.; Lee, D.S.; Owen, B.; Faber, J.; van Wijngaarden, L.; Boucher, O.; Celikel, A.; Deransy, R.; Fuglestvedt, J.; Laukia, J.; et al. *Updated Analysis of the Non-CO_2 Climate Impacts of Aviation and Potential Policy Measures Pursuant to the EU Emissions Trading System Directive Article*; European Union Aviation Safety Agency (EASA): Cologne, Germany, 2022.
2. Graver, B.; Rutherford, D. *CO_2 Emissions from Commercial Aviation: 2013, 2018, and 2019*; International Council on Clean Transportation Working Paper; International Council on Clean Transportation: Washington, DC, USA, 2020.
3. Lee, D.S.; Fahey, D.W.; Skowron, A.; Allen, M.R.; Burkhardt, U.; Chen, Q.; Doherty, S.J.; Freeman, S.; Forster, P.M.; Fuglestvedt, J.; et al. The contribution of global aviation to anthropogenic climate forcing from 2000 to 2018. *Atmos. Environ.* **2021**, *244*, 117834. [CrossRef] [PubMed]
4. ICAO Global Coalition for Sustainable Aviation. Available online: https://www.icao.int/environmental-protection/SAC/Pages/learn-more.aspx (accessed on 22 September 2022).
5. Air Transport Action Group (ATAG). *Fact Sheet #3–Tracking Aviation Efficiency*; Air Transport Action Group (ATAG): Geneva, Switzerland, 2019.
6. Aerospace Technology Institute (ATI). *Hydrogen Infrastructure and Operations: Airports, Airlines and Airspace*; Aerospace Technology Institute (ATI): London, UK, 2022.
7. CleanSky2. *Hydrogen-Powered Aviation, A Fact-Based Study of Hydrogen Technology, Economics and Climate Impact by 2050*; Publication Office of European Union: Luxembourg, 2020. [CrossRef]
8. Hepperle, M. *Electric Flight–Potential and Limitations*; German Aerospace Center: Braunschweig, Germany, 2012.

9. Misra, A. *Technical Challenges and Barriers Affecting Turbo-Electric and Hybrid Electric Aircraft Propulsion*; NASA Glenn Research Center: Cleveland, OH, USA, 2017.
10. Agarwal, P.; Sun, X.; Gauthier, P.Q.; Sethi, V. Injector design space exploration for an ultra-low NOx hydrogen micromix combustion system. In Proceedings of the ASME Turbo Expo: Power for Land, Sea, and Air, Phoenix, AZ, USA, 17–21 June 2019. [CrossRef]
11. Baharozu, E.; Soykan, G.; Ozerdem, M.B. Future aircraft concept in terms of energy efficiency and environmental factors. *Energy* **2017**, *140*, 1368–1377. [CrossRef]
12. Airbus to Take Up the Hydrogen Contrail Characterization Challenge. Available online: https://www.airbus.com/en/newsroom/press-releases/2022-07-airbus-to-take-up-the-hydrogen-contrail-characterisation-challenge#:~:text=The%20project%2C%20named%20%E2%80%9CBlue%20Condor,of%20significant%20interest%20to%20Airbus (accessed on 22 March 2022).
13. Verstraete, D. The Potential of Liquid Hydrogen for Long Range Aircraft Propulsion. Ph.D. Thesis, Cranfield University, Cranfield, UK, April 2009.
14. Colozza, A.J.; Kohout, L. *Hydrogen Storage for Aircraft Applications Overview*; NASA: Washington, DC, USA, 2002.
15. Khawaldeh, A.K. Queensland Airline Skytrans Unveils Plans for Australia's First Hydrogen-Fuelled Plane. *The Guardian*, 30 June 2022.
16. Airbus Signs Agreement to Study Hydrogen Hub in Singapore. Available online: https://www.airbus.com/en/newsroom/press-releases/2022-02-airbus-signs-agreement-to-study-hydrogen-hub-in-singapore (accessed on 22 March 2023).
17. ZeroAvia & Edmonton International Airport Tie Up to Bring Hydrogen-Electric Flights to Canada. Available online: https://www.zeroavia.com/eia-collaboration (accessed on 22 September 2022).
18. Airport Rankings. Available online: https://centreforaviation.com/data (accessed on 1 June 2022).
19. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G.; Prisma Group. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *Int. Surg. J.* **2009**, *8*, 336–341. [CrossRef] [PubMed]
20. Alder, H.P. Hydrogen in air transportation. Feasibility study for Zurich airport, Switzerland. *Int. J. Hydrog.* **1987**, *12*, 571–585. [CrossRef]
21. Brewer, G.D. *LH2 Airport Requirements Study*; NASA: Washington, DC, USA, 1976.
22. Degirmenci, H.; Uludag, A.; Ekici, S.; Karakoc, T.H. Analyzing the hydrogen supply chain for airports: Evaluating environmental impact, cost, sustainability, viability, and safety in various scenarios for implementation. *Energy Convers. Manag.* **2023**, *293*, 117537. [CrossRef]
23. Mangold, J.; Silberhorn, D.; Moebs, N.; Dzikus, N.; Hoelzen, J.; Zill, T.; Strohmayer, A. Refueling of LH2 Aircraft—Assessment of Turnaround Procedures and Aircraft Design Implication. *Energies* **2022**, *15*, 2475. [CrossRef]
24. New Aviation Propulsion Knowledge and Innovation Network. Available online: https://www.heathrow.com/company/about-heathrow/future-flight-challenge/napkin (accessed on 14 March 2022).
25. Nassar, M. *Cairo Airport Going Solar with Support of UNDP*; CSR Egypt: Agouza, Egypt, 2021.
26. HNO International Partners with HAECO to make Hong Kong International Airport's Ground Support the World's First Hydrogen Upgraded Fleet. Available online: https://hnointernational.com/news/pr018-hno-international-partners-with-haeco-to-make-hong-kong-international-airports-ground-support-the-worlds-first-hydrogen-upgraded-fleet (accessed on 14 May 2022).
27. Corporate Responsibility. Available online: https://www.dubaiairports.ae/corporate/about-us/csr/ (accessed on 14 May 2023).
28. Energy Shell Opens Second Hydrogen Station in, N.Y.C. Energy. 2020. Available online: https://energydigital.com/renewable-energy/shell-opens-second-hydrogen-station-nyc (accessed on 14 May 2022).
29. Frangoul, A. *Dubai International Airport Installs 15,000 Solar Panels*; CNBC: Englewood Cliffs, NJ, USA, 2019.
30. Aviation Underpins the Global Economy, Delivering Trade and Tourism to All Corners of the Globe. Available online: https://www.heathrow.com/latest-news/sustainable-aviation-fuel (accessed on 14 May 2022).
31. Kingsford Smith Airport. *2021 Sustainability Report*; Sydney Kingsford Smith Airport: Sydney, NSW, Australia, 2021.
32. John F. Kennedy International Airport. *T4 2019 Sustainability Report*; John F. Kennedy International Airport: New York, NY, USA, 2019.
33. Monkam, L.K.; von Schweinitz, A.G.; Friedrichs, J.; Gao, X. Feasibility analysis of a new thermal insulation concept of cryogenic fuel tanks for hydrogen fuel cell powered commercial aircraft. *Int. J. Hydrogen Energy* **2022**, *47*, 31395–31408. [CrossRef]
34. Barton, D.I.; Hall, C.A.; Oldfield, M.K. Design of a Hydrogen Aircraft for Zero Persistent Contrails. *Aerospace* **2023**, *10*, 688. [CrossRef]
35. Karpuk, S.; Ma, Y.; Elham, A. Design Investigation of Potential Long-Range Hydrogen Combustion Blended Wing Body Aircraft with Future Technologies. *Aerospace* **2023**, *10*, 566. [CrossRef]
36. Janovec, M.; Babčan, V.; Kandera, B.; Šajbanová, K.; Škultéty, F.; Halvoň, L'. Performance and Weight Parameters Calculation for Hydrogen- and Battery-Powered Aircraft Concepts. *Aerospace* **2023**, *10*, 482. [CrossRef]
37. Hanks, G.W.; Andrews, D.G.; Brende, B.; Eckert, E.E.; Hamamoto, M.; Kimble, R.H.; Kreitinger, R.L.; Miyatake, H.J.; Momenthy, A.M.; Taylor, R.A.; et al. *An Exploratory Study to Determine the Integrated Technological Air Transportation System Ground Requirements of Liquid-Hydrogen-Fueled Subsonic, Long-Haul Civil Air Transports*; NASA: Washington, DC, USA, 1976.

38. Hoelzen 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]
39. Hoelzen 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.* **2022**, *14*, 100206. [CrossRef]
40. IEA. *The Future of Hydrogen*; IEA: Paris, France, 2019.
41. Sempsrott, D. *Kennedy Plays Critical Role in Large-Scale Liquid Hydrogen Tank Development*; NASA: Washington, DC, USA, 2021.
42. ACI. *Integration of Hydrogen Aircraft into the Air Transport System: An Airport Operations and Infrastructure Review*; Airports Council International (ACI): Montreal, QC, Canada, 2021.
43. Jet Fuel. Available online: https://www.sydneyairport.com.au/corporate/planning-and-projects/jet-fuel (accessed on 14 August 2023).
44. Sydney Kingsford Smith Airport. *Sydney Airport Master Plan 2039*; Sydney Kingsford Smith Airport: Sydney, NSW, Australia, 2019.
45. A.T.I. *Primary Energy Source Comparison Selection*; A.T.I.: London, UK, 2022.
46. *ISO 19880.5:2019*; Gaseous Hydrogen—Fueling Stations, Part 5: Dispenser Hoses and Hose Assemblies. ISO: Geneva, Switzerland, 2019.
47. *ISO 13984:1999*; Liquid Hydrogen—Land Vehicle Fueling System Interface. ISO: Geneva, Switzerland, 1999.
48. Haglind, F.; Hasselrot, A.; Singh, R. Potential of reducing the environmental impact of aviation by using hydrogen Part I: Background, prospects and challenges. *Aeronaut. J.* **2006**, *110*, 553–565. [CrossRef]
49. C.S.I.R.O. *Opportunities for Hydrogen in Commercial Aviation*; C.S.I.R.O.: Canberra, Australia, 2020.
50. Faye, O.; Szpunar, J.; Eduok, U. A critical review on the current technologies for the generation, storage, and transportation of hydrogen. *Int. J. Hydrogen Energy* **2022**, *47*, 13771–13802. [CrossRef]
51. IATA. *Standard into-Plane Fueling Service Levels and Safety*; International Air Transport Association (IATA): Montreal, QC, Canada, 2020.
52. EUROCAE WG-80 Hydrogen Fuel Cell Systems—Call for Participation. Available online: https://www.eurocae.net/news/posts/2018/march/eurocae-wg-80-hydrogen-fuel-cell-systems-call-for-participation/ (accessed on 14 May 2022).
53. NASEM. *Airport Sustainability Practices Drivers and Outcomes for Small Commercial and General Aviation Airports*; National Academies of Sciences, Engineering, and Medicine (NASEM): Washington, DC, USA, 2016. [CrossRef]
54. Bouwer, J.; Krishnan, V.; Saxon, S.; Tufft, C. *Taking Stock of the Pandemic's Impact on Global Aviation*; McKinsey & Company: Chicago, IL, USA, 2022.