In Collaboration with McKinsey & Company

Pathways for airports to develop into energy hubs

APRIL 2025

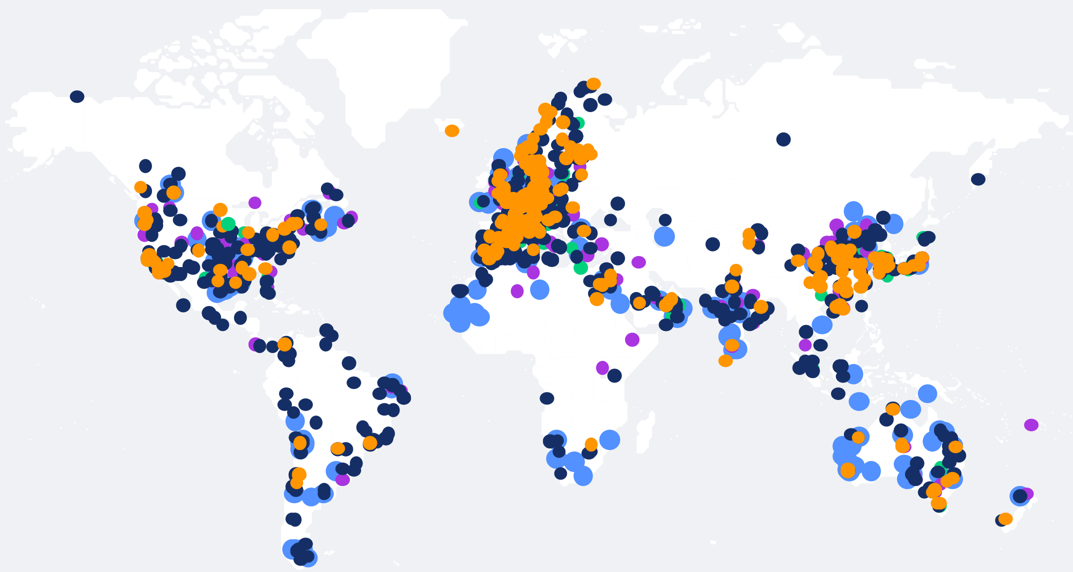
In partnership with Airports Council International (ACI) World, the Airports of Tomorrow initiative seeks to address the energy, infrastructure and financing needs of the aviation industry's transition to net-zero carbon emissions by 2050. This initiative is part of the World Economic Forum's Centre for Nature and Climate.

One of Airports of Tomorrow's core focus areas is exploring the role of airports as energy hubs, building off a previous Forum initiative, Target True Zero,[1] which defined the infrastructure required for hydrogen and battery-powered flight. The insights in this paper are informed by the Airports of Tomorrow community from key convenings and industry roundtables in Farnborough, Atlanta, Riyadh, Brazil and Japan during 2024, as well as discussions with ACI World and previous work on the Target True Zero and Clean Skies for Tomorrow Forum initiatives.

In exploring airports' role as energy hubs, hydrogen has emerged as a next-generation, low-carbon energy. Hydrogen is gaining momentum, with more than 1,500 large-scale hydrogen projects announced globally across industries and all types of hydrogen, according to the 2024 McKinsey Global Energy Perspective Report.[2] By 2050, under the Sustainable Transformation scenario of the 2024 McKinsey Global Energy Perspective Report,[3] there is expected to be 400+ Mt p.a. H_2 equivalent demand, primarily driven by China, North America and Europe. The world supply is expected to match demand in 2050, primarily coming from North America, the Middle East and China.

The purpose of this paper is to identify the pathways for airports to test and scale hydrogen solutions by outlining potential hydrogen use cases and the airport archetypes that may be best positioned across them. Identifying pathways for specific use cases by identifying suitable airport archetypes will be crucial for successfully integrating hydrogen solutions into airports.

For the purposes of this paper, whenever we refer to hydrogen, we are specifically focusing on hydrogen for aviation that is produced through renewable or low-carbon methods (i.e., not "grey" hydrogen).



As of May 2024

1,572+ project[1]

186
Giga-scale production

783
Large-scale industrial use

268
Transport

190
Integrate H_2 economy

138
Infrastructure projects

Note: 1. Project announcements below 1 MW are excluded. 7 projects have not announced project type

Source: Hydrogen Council & McKinsey Project & Investment Tracker, as of May 2024

The role of airports in the economic and energy landscape

Airports have a unique role to play in the economic and energy landscape at this crucial time, with a potential for outsized impact. Both the aviation and energy sectors have set targets and started to mobilize to decarbonize, impacting airports as both consumers of energy and critical infrastructure for aviation. By serving as energy hubs, airports could potentially open new opportunities to advance the energy transition for themselves, their customers and the surrounding communities.

Technologies to decarbonize aviation that will need to be developed include electricity, SAF and hydrogen. For all three, funding should be in place to develop these technologies, and the cost of delaying climate action continues to grow. Airports can play a key role in advancing these technologies in aviation through their convening power, regional economic development power, flexibility to use land and obtain permits in certain cases and public profile in the surrounding community.

As the global energy transition accelerates, there is growing demand for low-carbon energy to power homes, businesses and transport through a range of sources including hydrogen. Hydrogen is well positioned to deliver in multiple use cases in the aviation, ground transport and power sectors.[4] In partnership with aviation, transport and energy industries, airports can be positioned to begin deploying hydrogen solutions in key sectors.

Exemplary hydrogen use cases at airports

Aviation: Hydrogen can be used as battery-electric aircraft fuel for combustion and fuel cells for electric motors, providing a low-carbon footprint, extended range versus electric aircraft and noise reduction. Furthermore, the sector can leverage hydrogen for eSAF (e.g., power-to-liquid). Shifting to alternative propulsion will require a capital investment of $700 billion-$1.7 trillion by 2050.[5] However, only 10% of this investment will be for on-airport infrastructure.

Ground transport: Hydrogen can be leveraged in fuel cells to power vehicles' electric motors. Hydrogen provides reduced tailpipe emissions, fast refuelling and a longer range than battery electric vehicles. As a result, ground support equipment can also use hydrogen fuel cells. At airports, hydrogen can be used in baggage tugs, cargo loaders and pushback tractors to reduce carbon footprint and noise pollution where electric alternative may not be viable.

Power: Hydrogen can be used for fuel cell microgrids generating electricity by converting hydrogen into electrical energy. Hydrogen provides build flexibility to reduce reliance on the grid and avoid peak pricing and enables load shaving when the grid is under stress due to increased intermittent renewable energy production capacity.

Sequence to scale hydrogen at airports

Scaling hydrogen solutions for broader airport applications can be broken down into a systematic approach that can help ensure its viability and demand.

1	**Feasibility study**	Conduct a feasibility study to assess the techno-economic viability of hydrogen production, supply, storage and distribution
2	**Identify and secure offtakers**	Identify and secure core offtakers in potential use cases. Secured demand can help derisk continued investment in hydrogen infrastructure and solution deployment
3	**Test end uses in non-aviation context**	Test a subset of hydrogen use cases (e.g., parts of Ground Service Equipments (GSE), microgrids). Given the relative nascency of aviation-specific use cases (e.g., hydrogen aircraft), early deployment may focus on non-aviation specific use cases
4	**Pilot a test case at an airport**	Collaborate to begin piloting aviation-specific use cases at airports as use cases mature (e.g., hydrogen aircraft)
5	**Scale solutions for aviation**	Scale use cases for aviation through collaboration, partnership and continued investment

Spotlight: Hydrogen fuel feasibility studies with airports and airlines[6]

> To help meet its goal of zero-emission commercial flights, Airbus has begun hydrogen feasibility studies at airports worldwide. The studies will examine the opportunities and barriers to hydrogen supply, infrastructure and equipment development. These studies are typically conducted across the wider airport ecosystem, where not only are the OEMs and the airports participating but also energy producers, ground handling service providers and airlines. These feasibility studies are happening already in Canada, France, Germany, Japan, New Zealand, Singapore, Spain and the United States where major airports are driving hydrogen adoption for the industry. Most of these studies are intended to be completed in the coming years.

Spotlight: Rotterdam The Hague Airport enhancing logistics and transport efficiency[7]

> The collaboration between Rotterdam The Hague Airport and the Port of Rotterdam is advancing hydrogen infrastructure for various use cases. Hydrogen is a good fit for the airport, which has 16,000 flights a year and 90% of those connections are point-to-point routes that align with the potential future hydrogen aircraft ranges. Currently, hydrogen can be delivered by trucks, allowing the airport to start testing initial use cases to explore safety and certification concerns. A 8.6kg hydrogen storage facility is set for the summer of 2025, to be placed airside for testing drone operations and safety protocols, and will be open for research institutes and R&D purposes. Additionally, a hydrogen aircraft concept is being tested at the airport and ground support equipment (GSE) operations are transitioning to hydrogen, supported by EU funding. A delivery contract has been established with Air Products for the transportation of liquid hydrogen (LH2) from the Port of Rotterdam to the airport. Additionally, the hydrogen ground power unit (GPU), initially tested at Amsterdam Schiphol as part of the TULIPS project, will also be piloted at the airport in Q4 of 2025. The gaseous hydrogen will be supplied through the gaseous hydrogen refuelling station that is currently under development. Safety measures involve close cooperation with fire services, simulating emergency hydrogen flight scenarios.

Hydrogen use cases at airports

The scope of this section focuses on "on-airport" use cases, which excludes other potential use cases, such as local energy generation, ground vehicles for local industry and fuel cell rental cars.

<table>
<tr><th colspan="2">Use case</th><th>Potential offtaker</th><th>Core requirements for implementation</th></tr>
<tr><td colspan="2">Microgrids</td><td>– Airport operators
– Utility companies
– Energy service companies
– Airlines
– Facility and infrastructure owners
– Public-private partnerships
– Government agencies</td><td>– Technology: Microgrid integration (e.g., through advanced energy management systems)
– Policy: Streamlined permitting and licensing frameworks, incentives and subsidies to scale hydrogen solutions
– Economics: Increased cost-competitiveness of fuel cell microgrids
– Education: Stakeholder engagement on the benefits and safety of fuel cell microgrids
– Partners: Strong supporting ecosystem include energy suppliers, federal agencies and infrastructure providers</td></tr>
<tr><td rowspan="2">Aircraft</td><td>Small business and regional flights (i.e., fewer than 100 seats)</td><td rowspan="2">– Airlines
– Leasing companies
– Cargo operators
– Corporate buyers
– Private owners</td><td>– Technology: Hydrogen storage and distribution infrastructure, streamlined certification processes
– Policy: Safety regulations, incentives and subsidies, mandates
– Economics: Cost-reduction strategies, TCO (total cost of ownership) analysis
– Education: Pilot and crew training, ground service equipment (GSE) workforce development
– Partners: Governments to certify aircraft, airlines to procure and add aircraft to fleet</td></tr>
<tr><td>100-300 seater</td><td>– Technology: Research and development to make feasible, long-term offtake agreements to signal demand
– Policy: Safety regulations, incentives and subsidies, mandates
– Education: R&D to confirm feasibility and advance latest technology
– Partners: Government, airlines, OEMs and universities to advance R&D</td></tr>
</table>

Ground service equipment (GSE)	– Airlines – Airports – Ground handling companies – Fixed-base operators – MRO providers – Cargo-handling companies	– **Technology:** Hydrogen refuelling infrastructure, hydrogen storage and distribution systems – **Policy:** Streamlined permitting and licensing frameworks, incentives and subsidies to scale hydrogen solutions – **Economics:** Cost-reduction strategies, competitive TCO, funding and financing options (e.g., Public Private Partnerships (PPP), green bonds) – **Education:** Technical training for staff, awareness and outreach, certification programmes for technical operators – **Partners:** Governments, manufacturers, airlines, infrastructure providers
Buses	– Airport authorities – Airlines – GSE providers – Car park operators – Car rental companies – Local transit agencies	– **Technology:** Fleet development, refuelling infrastructure, storage and distribution systems, safety systems – **Policy:** Standards and safety codes, incentives and subsidies to scale hydrogen solutions – **Economics:** Cost-reduction strategies, TCO analysis, funding and financing options (e.g., PPPs, green bonds) – **Education:** Technical training for staff, awareness and outreach, certification programmes for technical operators – **Partners:** Federal agencies, airlines, local transit agencies, car rental companies, car park operators

Note: PtL SAF is another key use case for hydrogen at airports; however, SAF is not in scope for this analysis

Conditions and actors that must be in place for airports to successfully serve as energy hubs

Ten levers related to demand and supply can help airports develop into energy hubs.

Demand levers

Adjacency to and critical mass of "offtakers" of likely energy products (i.e., H_2, SAF, electricity) and ability to adopt to new technologies for future takers

Regional demand for centralized green energy with willingness to pay green premium vs fossil fuels

Signed commercial partnerships with operators using sustainable fuels (e.g., SAF) and other potential ecosystem players (e.g., OEMs)

Existing logistics infrastructure (e.g., access to maritime port, rail lines, capacity for truck traffic) with ability to scale

Solutions to space constraints at international and regional airports

Supply levers

Capabilities to generate utility-level energy on-airport or adjacency to energy producers off-airport

Competitive unit economics for production and/or distribution of green energy vs local alternatives, including a defined "last-mile" premium

Competitive advantage in non-production elements of the value chain (e.g., energy storage, transmission)

Capabilities and funding to scale to meet regional needs before market is saturated by other players

Incentive and policy regime that enables the required unit economics

Drivers that could impact hydrogen pathways

The adoption of hydrogen in aviation will depend on different parameters such as the development of aircraft and non-aircraft R&D projects, the timing for certification, the roll-out of the associated infrastructure and, ultimately, the specific dynamics of supply and demand at different types of airports. The most significant drivers are likely to be the individual characteristics of the airport and its local and regional policy environment.

Three main airport archetypes have been identified from the Target True Zero report[8].

- **Intercontinental hubs**, which comprise roughly 40 of the largest commercial and cargo airports in the world, such as Dubai International Airport and Changi in Singapore.
- **Major regional airports**, comprising approximately 200 medium-sized airports acting as domestic hubs, such as Dallas Fort Worth or Hamburg in Germany.
- **Small regional airports**, including all other airports with regularly scheduled services that act primarily as spokes in the larger aviation network.

Intercontinental hub

Airports that handle significant international traffic (e.g., 100+ international destinations, 50m+ annual passengers) and serve as major transfer points for global travellers (e.g., 500k-900k annual aircraft movements)

Examples: DXB, LHR

Major regional airport

Airports that serve important business regions and focus on regional and some international traffic (e.g., focus on connecting regional hubs, 20m-50m annual passengers, 300k-600k annual aircraft movements)

Examples: DFW, BRU

Small regional airport

Airports that primarily handle domestic flights and serve as feeders for larger hubs (e.g., primarily domestic routes, 5m-25m annual passengers, 150k-400k annual aircraft movements)

Examples: Westchester County Airport (HPN), Birmingham Airport (BHX)

Three policy archetypes have been identified – subsidy-based environment, mandate-based environment and limited climate policy. Although large regions can be generalized by their climate policy archetype, it must be noted that individual countries within regions may not fit into the archetype (e.g., Japan does not have limited climate policies).

Subsidy-based policy environment

Climate policy focused on government incentives through tax credits, direct funding, rebates or grants

Example*: North America

Mandate-based policy environment

Climate policy that implements strict regulations and legally binding targets to force emission reductions through cap-and-trade programmes, quotas and outright bans

Example*: Europe

Limited climate policy environment

Do not prioritize aggressive climate action or are in the early stages of implementing climate strategy. May have climate goals but lack the frameworks required to drive change

Examples*: Asia, Middle East, Latin America, Africa

Note: *Not all countries within a region may fit under one archetype

Drivers that could impact hydrogen testing and scaling

Factors that could impact hydrogen uptake and deployment at airports centre around global hydrogen dynamics and economics, enabling infrastructure and airport characteristics. The research identified five key hydrogen accelerators and five key hydrogen enablers. Accelerators are indicators that have a strong impact on the rate of hydrogen adoption at airports. These indicators have the most significant impact on accelerated hydrogen uptake. Enablers are indicators that address the broader unlocks required for hydrogen adoption to scale.

Although they may have a relatively weaker impact on accelerated development, they play a crucial role in the successful implementation and deployment of hydrogen technologies. The relative impact of hydrogen drivers differs across archetypes, as individual airport and policy characteristics directly impact the role and impact of each driver.

	Lever	Materiality/impact
Accelerators	**Net-zero policy**	Net-zero policies (e.g., carbon prices, mandates, subsidies, renewable portfolio standards) are a strong indicator for hydrogen development given their ability to influence supply and demand for hydrogen in a region
	H_2 production	Sufficient hydrogen production is critical to accelerated uptake – regions that are expected to have strong pipelines of hydrogen production will uptake at an accelerated rate
	H_2 demand (other)	Given relatively nascent use-cases for hydrogen in aviation, non-aviation use cases could be a stronger accelerator of hydrogen development at airports in the near term as aviation use cases continue to mature
	Ground fleet composition	Given relatively nascent use-cases for hydrogen in aviation, ground fleet with mature use cases could strongly influence hydrogen development at airports in the near term
	Short-range flight density	Given relatively nascent use cases for hydrogen in aviation, short-range flight density represents a proxy for use case of aviation hydrogen
Enablers	**H_2 demand (aviation)**	Impacts hydrogen development at airports – however, relatively nascent use cases currently available do not drive significant demand
	Transport network	Facilities to transport hydrogen can be a key unlock for airports, but given other use cases in the near term it is not a significant factor
	Energy infrastructure	Critical to the deployment of hydrogen, but largely captured and mirrors net-zero policy
	Airport infrastructure	Airport infrastructure can be a key unlock for airports, but given other use cases in the near term it is not a significant factor
	H_2 cost	Not a critical lever and largely covered through supply and demand of hydrogen

Ingredients for testing and scaling hydrogen

Given the current landscape of airports and the environment in which they operate, a number of future developments could impact hydrogen pathways at airports.

1. **Subsidies could be relevant by reducing key financial barriers and encouraging broad industry participation.**[9]

   Policy levers such as direct financial support, tax incentives and grants can reduce early-stage barriers associated with clean hydrogen development and implementation. By reducing key early-stage barriers, subsidies increase the financial feasibility of hydrogen deployment by derisking company investment in hydrogen infrastructure, fuel production and the development of hydrogen-powered aircraft.

   Subsidies (e.g., US hydrogen hubs investments) can also derisk critical early-stage R&D by reducing upfront costs and guaranteeing returns. Subsidies, for example, can fund pilot projects, demonstration plants and technology incubators, accelerating the refinement and scaling of hydrogen technologies.

   Furthermore, policies that provide tax breaks, reduced land costs or financial incentives for building hydrogen production and refuelling facilities can stimulate investment and market competition.

   However, subsidies are typically timebound or designed to decrease as time progresses and technologies scale and develop. At these critical points, technologies must be able to stand on their own financially. Without continued support, technologies can stall if cost reductions and market demand have not reached sustainable levels. Further, institutional investors and private companies may hesitate to continue expanding hydrogen development and infrastructure if it becomes economically unviable without government subsidies and aid.

2. **Regional airports could provide an environment to implement hydrogen technologies because of their relatively high short-range flight density, less complex infrastructure and smaller scale of operations.**[10]

   Regional airports primarily serve shorter origin and destination routes, which are well-suited to the range and performance of emerging hydrogen aircraft models.

   Additionally, the smaller scale of operations at regional airports requires less significant investment in infrastructure changes needed to support hydrogen, such as hydrogen production, storage, and refuelling facilities.

   Regional airports can serve as early adopters and pilot grounds for hydrogen technology, regulation and standards, demonstrating its feasibility and unlocking pathways for broader adoption in the aviation industry.

   However, regional airports typically have fewer resources and less influence than larger hubs, making collaboration with airlines, energy providers and government agencies essential[11]. Partnerships with broader stakeholders can provide the technical expertise, financial investment and policy support to overcome key early challenges such as high initial costs and regulatory and safety compliance. By working together with industry stakeholders, regional airports can create a more robust and scalable hydrogen network, ensuring long-term success.

3. **It may be difficult to adopt hydrogen solutions at large intercontinental hubs due to the complexity of their operations and infrastructure, unless they can leverage strong existing infrastructure.**

   Implementing hydrogen in the near term at large-scale airports presents significant logistical and financial challenges, slowing the pace of development. However, in certain cases, intercontinental hubs may be more likely to have the enabling infrastructure in place due to their relatively larger footprint near significant locations (e.g., with strong industry concentration, port location). This could propel hydrogen development forward in the near term, as airports can capitalize on currently viable use cases

   High traffic volumes, high number of airlines and a wide range of operations require substantial modifications to accommodate hydrogen fuel.

   Developing a reliable hydrogen supply chain at such a scale may involve large investments in production, storage and distribution facilities, as well as extensive safety measures.

   Intercontinental hubs could face considerable pressure from stakeholders and customers to develop hydrogen infrastructure. Passengers and clients may prefer airlines and airports that demonstrate a strong commitment to reducing carbon emissions, putting pressure on large hubs to develop the required enabling environment for hydrogen deployment.

   Although long-haul flights are unable to be supported by novel propulsion in the short term, a growing sentiment for sustainable solutions could push major hubs to take initial steps towards building a hydrogen-supportive infrastructure sooner rather than later.

4. **A strong net-zero policy and growing demand for hydrogen in non-aviation sectors can accelerate hydrogen adoption in the near term.**[12]

   Strict carbon reduction targets and supportive regulation can create the enabling environment required for disruptive technologies to scale and commercialize (e.g., funding renewable hydrogen production methods, aligning regulations to promote cleaner alternatives).

   Growing demand for hydrogen in non-aviation sectors such as transport and power can drive rapid hydrogen development. As sectors such as trucking and power adopt hydrogen solutions more broadly, economies of scale can lower costs and promote infrastructure expansion in other sectors such as aviation. The shift of non-airport ground fleets to hydrogen also encourages the development of airport hydrogen infrastructure, making it easier to ultimately adopt hydrogen-powered aircraft.

   However, as hydrogen demand grows in other sectors, the aviation sector may need to be diligent to quantify and advocate for energy and hydrogen needs to avoid being carved out and deprioritized for hydrogen access.

5. **Workforce development, education and outreach can accelerate hydrogen development and deployment.**

   The public sector can also mobilize collaboration across stakeholder groups to strengthen technical expertise and provide the enabling foundational structure to succeed (e.g., US Regional Clean Hydrogen Hubs that promote the production, use and distribution of clean hydrogen, the European Clean Hydrogen Alliance aimed at identifying investment needs, bottlenecks and opportunities to scale hydrogen technology).

   Education, awareness building, and outreach (e.g., with key stakeholders at airports, federal agencies, the broader community) can help inform stakeholders about the benefits, challenges, and safety of potential hydrogen use cases. This can ensure the proper capabilities are in place, reduce overall scepticism and facilitate project implementation.

Next steps for airport energy ecosystem players

Moving forward, as airports develop into energy hubs, actions, suggestions and areas to track vary by stakeholder.

1. **Hydrogen producers and energy suppliers**

   – Effectively forecast demand: Utilize historical data and predictive analytics to accurately forecast hydrogen demand at airports

   – Optimize transport: Develop efficient logistics for transporting hydrogen from production sites to airports

   – Demonstrate viable supply chains: Validate the feasibility of fully scaled hydrogen supply chains including cost-competitive plant designs and transport

   – Evaluate on-site production: Assess the feasibility of hydrogen production to meet demand effectively

2. **Airports**

   – Integrate hydrogen into operations: Assess the impact of hydrogen deployment on daily operations and logistics

   – Drive synergies: Have a consistent approach to airport energy transitions that includes TCO considerations

   – Enhance safety protocols: Establish and maintain robust safety protocols to support large-scale hydrogen deployment

   – Develop the workforce: Support initiatives (i.e., training, recruitment) that grow the number of skilled workers in hydrogen

   – Scale investments profitably: Strategize on scaling hydrogen infrastructure investments while ensuring profitability and sustainability

3. **Infrastructure planners**

   – Collaborate with energy suppliers: Foster strong partnerships with energy suppliers to ensure seamless integration of hydrogen infrastructure

   – Plan financially and timely: Develop comprehensive financial plans and timelines for large-scale hydrogen infrastructure projects within airport ecosystems

   – Develop the workforce: Support initiatives (i.e., training, recruitment) that grow the number of skilled workers in H_2

   – Assess technological readiness: Evaluate the readiness of key infrastructure components to support hydrogen deployment

4. **Investors**

   – Compare long-term returns: Analyse long-term returns of hydrogen compared to other sustainable aviation solutions and sectors

   – Support aviation transition: Invest in initiatives that facilitate the rapid transition of aviation to hydrogen

   – Advocate for favourable policies: Engage with policy-makers to promote policies for hydrogen as an attractive long-term investment

5. **Aviation offtakers (e.g., OEMs, airlines, service providers)**

   – Accelerate technological readiness: Invest in research and development to advance the technological readiness of hydrogen-powered flight

   – Foster effective collaboration: Develop collaborative projects, such as pilot technologies and proofs of concept, to accelerate hydrogen uptake

   – Contribute to regulation: Help standardize regulation of hydrogen aircraft handling at airports (i.e., refuelling)

   – Integrate hydrogen aircraft: Plan for the seamless integration of hydrogen aircraft into existing fleets

6. **Non-aviation offtakers (e.g., logistics and shipping)**

   - Deploy hydrogen today: Identify opportunities for immediate hydrogen deployment and establish conditions necessary for a broader shift to hydrogen energy

   - Promote supportive policies: Advocate for policies that signal a broader shift to hydrogen energy

   - Leverage airport hydrogen hubs: Explore ways to utilize airport hydrogen hubs for broader applications and benefits

7. **Policy-makers**

   - Standardize safety and sustainability: Develop and harmonize safety and sustainability standards for hydrogen deployment

   - Accelerate key policies: Implement and accelerate policies and regulations to maintain momentum in hydrogen development

   - Facilitate cross-border collaboration: Establish cross-border policies to leverage hydrogen in various use cases effectively

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Endnotes

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