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Innovative research impulses shaping the future of logistics

Green Hydrogen Applications for Sustainable Airport Ground Operations

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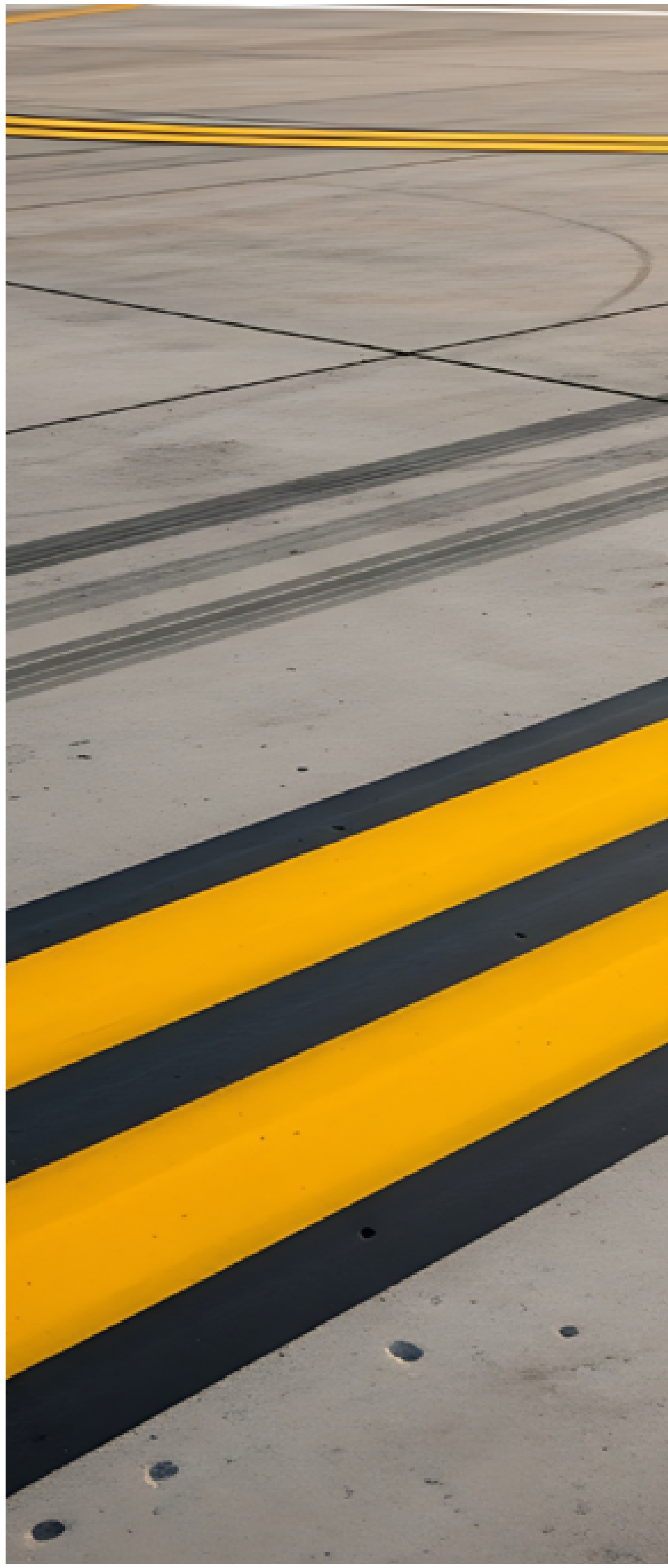
Preambel

Innovative research impulses shaping the future of logistics

The white paper series "Innovative research impulses shaping the future of logistics" addresses current challenges and future trends in logistics, highlights new technologies and business models, and thus advances the discussion in science and management practice.

The editions of the white paper series inspire fundamental developments within the framework of an innovative, efficient, and sustainable vision of the future of logistics systems as the core elements of an innovative economy, which benefits from the exchange between actors from research, practice, and other stakeholders. In this form, the IML serves as a network hub for technology, knowledge, and innovation in international value chains, true to the motto "100% logistics!".

In an era characterized by unpredictable global challenges, the strategic resilience transformation of value-added networks is becoming increasingly important. Experience from past crises has shown that supply chain resilience can no longer be considered an optional element. This white paper addresses the current challenges and provides supply chain management stakeholders with tools to make their networks more resilient and adaptable. It offers practical recommendations for action that have been successfully implemented by resilience researchers at the Dortmund Science Park and supports companies in operating in a future-proof manner in a complex and volatile environment.



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Management Summary
/ Managementzusammenfassung

This whitepaper examines the integration of hydrogen-powered ground support equipment (GSE) into sustainable airport ground operations, with a focus on determining the conditions under which hydrogen GSE could be effectively deployed. Innovative concepts in this field are becoming increasingly important as the need to quickly reduce the climate impact of global transport systems grows. For the aviation sector, progress towards zero-emission practices remains particularly challenging, and it has remained unclear to what extent green hydrogen could play a role in this clean energy transition. Therefore, it is essential to understand the challenges and requirements associated with green hydrogen-based processes, such as hydrogen production and distribution logistics, high-pressure storage and plane refuelling procedures, integration into airport infrastructure or hydrogen-specific operational protocols, and relevant strategic decisions in this regard.

Hydrogen GSE is part of a broader mix of technologies necessary for achieving zero-emission airside operations, complementing existing solutions rather than merely replacing them. This includes specific airport characteristics that need to be considered when assessing the economic and environmental suitability of green hydrogen integration, for example operational demands, existing infrastructure capabilities, and commitment to sustainability objectives. By reviewing case studies and best practices from successful hydrogen projects at leading airports, the paper provides actionable insights for airports considering the adoption of hydrogen solutions. This includes strategic considerations regarding an implementation of hydrogen-powered GSE, aligned with airport circumstances and broader objectives of sustainable aviation.

Context & Rationale

- Aviation faces urgent decarbonisation needs
- Hydrogen seen as complementary zero-emission enabler

Research Focus

- Integration of hydrogen-powered GSE
- Conditions for effective deployment

Key Challenges

- Limited supply and infrastructure
- High costs and regulatory gaps

Strategic Insights

- Hydrogen complements electric GSE
- Feasibility depends on airport context

Best Practices & Lessons Learned

- Pilots show technical feasibility
- Collaboration is crucial for scaling

Outlook & Recommendations

- Develop airport hydrogen roadmaps
- Combine hydrogen with other clean solutions

Figure 1: Management Summary - Key Points

/ Dieses Whitepaper untersucht die Integration von grünem wasserstoffbetriebenem Ground Support Equipment (GSE) in nachhaltige Bodenabfertigungsprozesse an Flughäfen, mit besonderem Fokus auf die Bedingungen, unter denen Wasserstoff-GSE sinnvoll eingesetzt werden kann. Innovations¬konzepte in diesem Bereich gewinnen zunehmend an Bedeutung, da die Ziele zur Minderung der negativen Auswirkungen globaler Transportsysteme auf das Klima nur dann relevante Wirkungen entfalten, wenn sie rasch umgesetzt werden. Für den Luftfahrtsektor ist der Weg zu emissionsfreien Betriebsabläufen besonders anspruchsvoll – und es ist nach wie vor offen, in welchem Umfang grüner Wasserstoff zu diesem Übergang beitragen kann. Umso wichtiger ist es, die Herausforderungen und Voraussetzungen für wasserstoffbasierte Prozesse zu verstehen, von der Produktion und Distributionslogistik über die Hochdruckspeicherung und Betankung bis hin zur Integration in die Flughafeninfrastruktur und zu spezifischen Betriebsprotokollen.

Dies ist die Basis für strategische Entscheidungen, die eine erfolgreiche Umsetzung unterstützen – mit Wasserstoff-GSE als einem Teil eines breiten Technologie-Mixes, der für emissionsfreie Vorfeldoperationen erforderlich ist. Darüber hinaus beschreibt das Whitepaper zentrale Merkmale, die bei einer Beurteilung der wirtschaftlichen und ökologischen Eignung der Wasserstoffintegration berücksichtigt werden müssen. Dazu zählen unter anderem betriebliche Anforderungen, Stand der Infrastruktur sowie spezifische Nachhaltigkeitsziele. Anhand von Fallstudien und Best Practices führender Flughäfen liefert das Whitepaper praxisorientierte Erkenntnisse als erste Orientierung für strategische Überlegungen bei der Einführung wasserstoffbetriebener GSE mit dem Ziel, den Übergang passgenau auf die individuellen Gegebenheiten eines Flughafens abzustimmen und gleichzeitig den übergeordneten Zielen einer nachhaltigen Luftfahrt Rechnung zu tragen.

Kontext & Begründung

- Luftfahrt steht unter hohem Dekarbonisierungsdruck
- Wasserstoff als komplementäre Schlüsseltechnologie

Forschungsschwerpunkt

- Integration wasserstoffbetriebenem GSE
- Bedingungen für effektiven Einsatz

Herausforderungen

- Begrenzte Verfügbarkeit und Infrastruktur
- Hohe Kosten, regulatorische Unsicherheiten

Strategische Erkenntnisse

- Ergänzt elektrische Lösungen
- Sinnhaftigkeit & Machbarkeit standortabhängig

Praxisbeispiele

- Pilotprojekte zeigen Umsetzbarkeit
- Kooperation als Erfolgsfaktor

Ausblick & Empfehlungen

- Entwicklung von Wasserstoff-Roadmaps
- Kombination mit anderen sauberen Energien

Figure 2: Hauptpunkte Managementzusammenfassung

Introduction

Airports are significant contributors to greenhouse gas (GHG) emissions within the global transport system, accounting for approximately 15% of total emissions from the aviation industry (Roland Berger, 2023). Airports are under increasing pressure from regulators, communities, and industry partners to cut emissions in all areas as part of broader transport decarbonisation efforts (ACI EUROPE, 2022).

Growing air travel demand makes this challenge harder, as more flights directly increase emissions (International Air Transport Association, 2023). In this context, ground operations, particularly through the deployment of sustainable GSE, present an immediate and practical opportunity to cut emissions, improve local air quality, and modernise ageing fleets. In contrast, other segments of the air transport value chain often require significantly longer transition periods (European Commission, 2019).

Adopting zero-emission technologies such as battery-electric or hydrogen-powered GSE can deliver multiple benefits: enhanced environmental performance, reduced long-term operating costs, and greater readiness for future regulatory requirements (European Commission, 2021a; U.S. Department of Energy, 2022). Beyond meeting compliance standards, these investments strengthen operational resilience, stimulate innovation, and build stakeholder confidence (World Economic Forum, 2024/2025). Airports that move early can make a meaningful contribution to climate targets while positioning themselves as preferred partners in an increasingly sustainable aviation ecosystem (Airports Council International Europe, 2023a).

While airports follow similar national and international rules, their local conditions, infrastructure, and location create unique challenges. These differences create unique challenges and opportunities in the transition to zero-emission airside operations. This paper examines the key factors that support the adoption of such practices, with a particular focus on hydrogen-powered GSE as part of the broader clean-energy transition.

Importance of Zero-Emission Practices for Airports

Airports are expected to support global climate goals like net-zero by 2050, making airside operations key for achieving quick and measurable emission cuts (Destination 2050, 2023). Among the available measures, the electrification of GSE is particularly impactful, as it eliminates tailpipe emissions entirely and significantly reduces GHG output. This directly improves both Scope 1 emissions from airport-owned assets and Scope 3 emissions linked to the wider value chain (IATA, 2025).

Regulatory and policy frameworks are accelerating this shift. Initiatives such as the Federal Aviation Administration (FAA)'s zero-emissions grants in the United States, as well as similar EU-level and national programmes, are incentivising airports to replace diesel fleets with electric or other zero-emission GSE, ensuring compliance with tightening environmental standards while reducing future regulatory risk (FAA, 2021; European Union, 2023).

Beyond compliance, zero-emission GSE delivers tangible local benefits. Electric equipment improves air quality and reduces noise pollution, creating healthier and safer working conditions for ground crews and improving the quality of life for surrounding communities (ICAO, 2020a; Aviation Pros, 2025). The operational advantages are equally significant: transitioning from diesel to electric GSE can cut carbon emissions by more than 90%, while lowering fuel and maintenance costs and improving operational reliability (Akande, 2025).

Visible zero-emission projects can reinforce an airport's "social licence to operate," boosting its reputation with passengers, investors, and nearby communities (Enterprise Mobility, 2024). Strategically, airports with electrified GSE and other green infrastructure are better positioned to attract sustainability-focused airlines and logistics partners, turning environmental performance into a competitive advantage (Aviation Pros, 2025).

Background on Hydrogen in Aviation

As the aviation industry accelerates towards decarbonisation, hydrogen is emerging as a pivotal enabler of long-term sustainability. While hydrogen-powered aircraft, such as Airbus' ZEROe concepts and ZeroAvia's hydrogen-electric test flights, attract significant attention, near-term applications are already materialising on the ground, specifically within airport ground operations (RMI, 2024).

For GSE applications, compressed gaseous hydrogen is often preferred over liquid hydrogen because it requires less extreme storage conditions, has simpler handling protocols, and can be refuelled using compact, modular systems (Anand et al., 2025). Traditional GSE, such as baggage tractors, aircraft tow tractors, and Ground Power Units (GPUs), are predominantly diesel-powered, resulting in substantial local emissions. Transitioning to zero-emission GSE, particularly those powered by green hydrogen, offers a concrete opportunity to reduce CO_2, NO_x, particulate pollution, and noise, especially at large, high-utilisation airports (NREL, 2025).

Hydrogen-powered GSE also benefits from zero tailpipe emissions, faster refuelling times and extended operational ranges comparable to or exceeding diesel performance, making it a compelling alternative to battery-electric solutions in high-utilisation or grid-constrained contexts (World Economic Forum, 2024/2025; Singh et al., 2024). In terms of energy density, hydrogen contains approximately 33 kWh/kg, compared to ~0.25 kWh/kg for conventional lithium-ion batteries, enabling lighter equipment and longer duty cycles between refuelling (Singh et al., 2024 Anand et al., 2025).

Several airports are already piloting hydrogen-based GSE. Amsterdam Airport Schiphol (AMS), for instance, is conducting the world's first live test of a hydrogen-powered GPU (Schiphol, 2024; European Hydrogen Observatory, 2024; Dynell, 2024). Further hydrogen GSE projects and examples are presented later in this paper.

Despite these advances, significant regulatory and infrastructure hurdles remain. Deploying hydrogen GSE requires investment in refuelling infrastructure compliant with safety codes, hazard classification systems, and additional workforce training for hydrogen handling. Additionally, integration with wider hydrogen strategies, such as the EU Green Deal, the Alternative Fuels Infrastructure Regulation, and national hydrogen roadmaps, will be essential to ensure interoperability and scalability (European Union, 2023; UNECE, 2022).

While widespread hydrogen-powered flight is at least a decade away, hydrogen GSE is already delivering measurable results in real-world airport environments. It serves as a critical stepping stone towards fully zero-emission aviation, offering both operational insights and environmental benefits as part of a scalable transition pathway.

Hydrogen Fuel Cells vs. Hydrogen ICE

Hydrogen can be used to power vehicles in two fundamentally different ways: via fuel cells or internal combustion engines (ICEs) adapted to burn hydrogen. Both offer a path to significant emission reductions in airport ground operations, but they differ in terms of energy efficiency, hydrogen purity requirements, operational characteristics, and technological maturity. Maintenance requirements may also differ, but reliable comparative data is still lacking due to the limited operational history of hydrogen GSE at airports.

	Hydrogen Fuel Cell	**Hydrogen ICE**	**Diesel ICE**
Principle of Operation	Converts hydrogen gas to electricity through an electrochemical reaction	Burns hydrogen instead of fossil fuels	Burns diesel fuel for energy
Energy Efficiency	40-60%	30-40%	30-40%
Hydrogen Purity Requirement	99,5% purity	85% purity	Does not apply
Emissions	Only water vapor	Small amounts of NOx and water vapour?	High GHG emissions (NO_x, CO_2, particulates)
Noise Level	Low	Low-Moderate	High
Ideal Environments	Indoors, semi-closed, and outdoors	Outdoors, heavy duty applications	Outdoors, heavy-duty applications
Operational Considerations	Potentially higher costs because of new technology	Easier to retrofit, vehicles could be reused	Well-established and proven, widely accessible
Compliance with zero-emission targets	Yes	Not under current legislation	No

Table 1: Comparison of Hydrogen Fuel Cell, Hydrogen ICE & Diesel ICE Technologies (Halder et al., 2024; Wang & Fulton, 2024)

In principle, fuel cell technology is often better suited for airport GSE due to its higher efficiency and cleaner operation, especially where zero-emission mandates are strict. By contrast, hydrogen ICEs can act as an interim solution in cases where durability, lower upfront cost, or compatibility with existing platforms is prioritised over maximum efficiency. Both technologies can play complementary roles in the decarbonisation of airport ground operations, depending on operational context and infrastructure readiness.

The Spectrum of Hydrogen: From Gray to Green

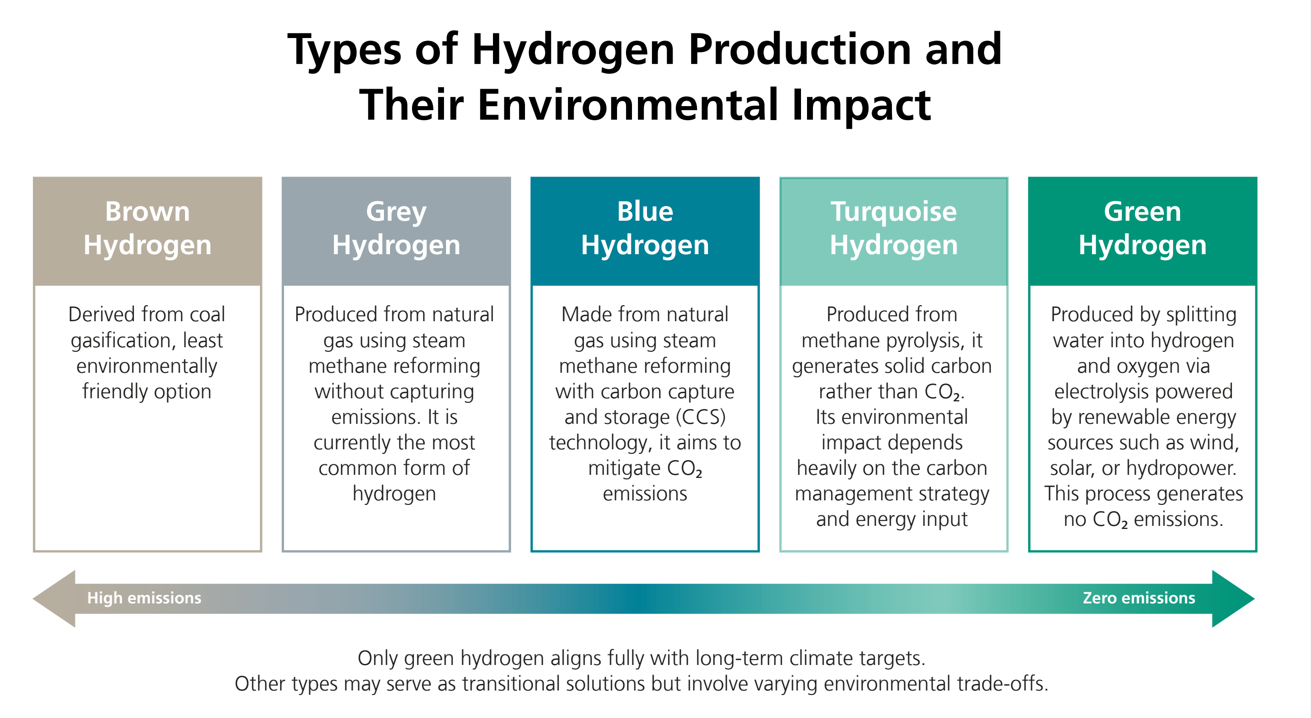
Hydrogen is a versatile energy carrier that can support the decarbonisation of various sectors, including aviation. However, not all hydrogen is created equal. The environmental footprint of hydrogen depends on how it is produced, which has led to the widespread use of a colour code classification system. Understanding these types is essential for airports and aviation stakeholders aiming to make informed choices aligned with climate goals.

Within the European Union, hydrogen is officially categorised according to its production method and associated greenhouse gas emissions. The European Parliament Research Service (EPRS) currently defines three principal categories:

- Renewable hydrogen: Produced via electrolysis using electricity from renewable sources. This category corresponds to what is commonly referred to as green hydrogen (EPRS, 2025).
- Low-carbon hydrogen: Produced from fossil fuels (e.g., natural gas) but coupled with carbon capture and storage (CCS) technologies to reduce CO_2 emissions. This is often associated with blue hydrogen (EPRS, 2025).
- Fossil-based hydrogen without CCS: Produced from fossil fuels such as natural gas or coal without carbon capture. This category encompasses grey, brown, or black hydrogen, depending on the feedstock (EPRS, 2025).

These definitions are embedded in EU policy documents such as the EPRS briefings on renewable and low-carbon hydrogen and align with the European Commission's hydrogen strategy. (European Commission, 2019 & 2024b, EPRS, 2025)

In addition to these formal definitions, an informal colour code classification is widely used in public and industry discourse. This colour system links production methods with environmental impact and, while not formally standardised, offers an accessible way to communicate differences (UNECE, 2022):



Types of Hydrogen Production and Their Environmental Impact

Brown Hydrogen	Grey Hydrogen	Blue Hydrogen	Turquoise Hydrogen	Green Hydrogen
Derived from coal gasification, least environmentally friendly option	Produced from natural gas using steam methane reforming without capturing emissions. It is currently the most common form of hydrogen	Made from natural gas using steam methane reforming with carbon capture and storage (CCS) technology, it aims to mitigate CO_2 emissions	Produced from methane pyrolysis, it generates solid carbon rather than CO_2. Its environmental impact depends heavily on the carbon management strategy and energy input	Produced by splitting water into hydrogen and oxygen via electrolysis powered by renewable energy sources such as wind, solar, or hydropower. This process generates no CO_2 emissions.

Only green hydrogen aligns fully with long-term climate targets.
Other types may serve as transitional solutions but involve varying environmental trade-offs.

Figure 3: Types of Hydrogen Production and Their Environmental Impact (UNECE, 2022)

By linking the EU's official terminology with the more widely known colour code, stakeholders can ensure that communication remains policy-aligned and accessible to diverse audiences, from policymakers to operational teams.

While various forms of hydrogen may play transitional roles, green hydrogen stands apart as the only option that fully aligns with aviation's climate targets, airport net-zero commitments, and regulatory trends. Its application in ground operations offers immediate decarbonisation potential and serves as a foundational element for a more sustainable airport energy ecosystem. As production costs decline and renewable energy becomes more accessible, green hydrogen is expected to become increasingly viable, not only as a clean fuel but also as a strategic asset in the aviation sector's energy transition.

At present, however, large-scale green hydrogen production and distribution remain limited. Most hydrogen in Europe is still produced from fossil sources, with renewable hydrogen accounting for less than 5% of total output (Hydrogen Europe, 2024; IEA, 2024). Expanding electrolysis capacity, supported by initiatives such as the EU Hydrogen Bank and national funding schemes, will therefore be crucial to ensure reliable supply for airports and other transport hubs (European Commission, 2024).

Currently, some forward-looking airports are exploring on-site electrolysis systems, allowing them to generate green hydrogen locally using solar or wind energy, enhancing energy independence and reducing supply chain emissions (CINEA, 2024).

National and International Hydrogen Strategies

The German National Hydrogen Strategy, first published in June 2020 (BMWK, 2020) and amended in July 2023 (BMWK, 2023), aims to accelerate the market ramp-up of green hydrogen and its applications by 2030. The domestic electrolysis capacity goal has been raised from 5 GW to at least 10 GW, with 50-70% of hydrogen products expected to be imported as the total hydrogen demand is estimated to be around 95 to 130 TWh in 2030 (BMWK, 2023; Bundesnetzagentur, 2025).

To build a robust hydrogen infrastructure, over 1,800 km of pipelines are planned by 2027/2028 as part of a "starter network" (Bundesnetzagentur, 2025). The national core network connecting major production and storage centres is targeted for completion by 2032. Hydrogen is aimed to be deployed across industrial applications, heavy-duty transport, and as a feedstock for H_2-ready power plants and electrolysers (Bundesnetzagentur, 2025).

While the core network could provide links to all major German TEN-T airports, establishing a direct connection from the core network to airports is not included in the scope of the core network concept. The primary objective of the core network is to serve as a foundational element rather than the final stage of Germany's hydrogen infrastructure. Future connections from the core network to airports may be feasible through a potentially developed downstream hydrogen infrastructure.

The TEN-T (Trans-European Transport Network) is a European Union program designed to connect major transport routes, by road, rail, water, and air, across member states. Its purpose is to improve cross-border mobility, promote sustainability, and boost economic integration. The plan is split into two layers: the Core Network, targeted for completion in 2030, and the Comprehensive Network, due by 2050. (European Commission, 2021).

Additionally, existing or planned storage facilities are influenced by geological conditions, which are more prevalent in the northwest than in the vicinity of the major German airports, meaning that reliable hydrogen supply to airports remains a challenge (Bundesnetzagentur, 2025).

On a European level, the European Hydrogen Backbone (EHB) initiative is developing a dedicated hydrogen pipeline transport network throughout Europe, with Germany's national hydrogen core network forming an integral part of it due to the country's central geographical location. The goal is to establish a 58,000 km pipeline network by 2040, promoting a liquid hydrogen market, enabling the buying and selling of hydrogen among various parties, and reducing transportation costs across the continent (European hydrogen Backbone Initiative, 2024).

The integration of green hydrogen GSE into airport operations primarily targets environmental benefits. Replacing fossil fuels with alternative fuels such as hydrogen aims to reduce GHG emissions and noise, in line with the EU's aspirational targets for sustainable aviation targets at airports (European Commission, 2019; Destination 2050, 2023). However, it is also important to consider that airports are complex environments comprising multiple interlinked processes and stakeholders. Growing demand and strict safety regulations leave little room for disruption or delay; airports generally strive to maximise capacity utilisation in order to remain profitable. Against this backdrop, the integration of new technologies must be assessed in terms of their environmental and social benefits, as well as their operational reliability and profitability.

Impact of Green Hydrogen GSE on the Existing Airport Ecosystem

While the technical feasibility of hydrogen-powered systems is a key criterion for certification and initial implementation, their actual uptake by the industry will depend on how well they align with existing processes within the targeted ecosystem. The introduction of this technology affects vehicle propulsion, operational workflows, infrastructure planning, energy supply models, safety considerations, and stakeholder relations.

This is particularly relevant to airports with limited capacity for modification or extension, a situation common in much of Europe. Of the 37 certified commercial airports in Germany, most were built decades ago, under very different infrastructure, regulatory, and demand conditions. Opportunities like those at Germany's youngest commercial airport, Berlin Brandenburg Airport (BER), which opened in 2020 using largely new construction methods, are rare in Europe (Flughafen Berlin Brandenburg GmbH, 2020). Even in cases of greenfield construction, which provide a significant opportunity to embed sustainability from the design phase, an airport must remain network-compatible in terms of both internationally standardised procedures and competitiveness influenced by local ground-handling fees.

Almost every commercial airport in the EU faces limitations when implementing substitutes for fossil fuels in its operations. The likelihood of adopting technologies that support this transition increases when the proposed solution closely resembles the systems around which existing operational processes were designed. This consideration has three principal dimensions:

i) **Compatibility with international standards** (e.g. a GPU must deliver 400 Hz of power using the same plug as a conventional GPU);

ii) **Operability under local regulations and infrastructural conditions;** and

iii) **Market support**, including compatible equipment costs and hydrogen supply. In some cases, local regulations can override market insufficiencies. Based on these three dimensions, EU airports are likely to choose substitutes that comply with current EU regulations. Currently, options to replace GSE are limited to electrification or alternative (bio)fuels, with hydrogen providing options for both, either via fuel cells or direct combustion (ICE) (IATA, 2025; ICAO, 2020b).

From an operational perspective, hydrogen-powered GSE can offer significant advantages in high-utilisation contexts due to shorter refuelling times compared to battery-electric alternatives (NREL, 2025). This can lead to greater operational flexibility, particularly in time-sensitive turnaround scenarios. That said, these benefits must be weighed against the current limitations in hydrogen infrastructure and supply chains. Airports must consider whether green hydrogen can be reliably sourced, via pipelines, delivered by trucks, or produced on-site through electrolysis powered by renewable energy (European Hydrogen Backbone initiative, 2024; HEAVENN, 2021a&b).

Infrastructure-wise, the transition to hydrogen GSE will necessitate new investments in refuelling stations, storage facilities, and safety systems. Such developments will require coordination with regulatory bodies, fire safety authorities, and utility providers. Additionally, staff training and, in some jurisdictions, certification will be mandatory depending on the specific hydrogen infrastructure installed. Safety zoning and hazard classification requirements differ from those for electric charging stations and may affect airport layouts (UNECE, 2022).

The shift also affects stakeholder dynamics. Airlines, ground handling companies, fuel suppliers, airport operators, and public authorities must collaborate closely to determine the most appropriate technological pathways. Access to government incentives and decarbonisation funds may also shape the pace and direction of adoption, influencing procurement strategies and investment cycles (Roland Berger, 2023).

As hydrogen solutions scale, the airport's role may evolve from being a consumer of fuel to becoming a shareholder in its production and distribution, particularly in cases where on-site electrolysis is economically viable. This opens opportunities for new business models and cross-sector collaboration, especially in regions with strong renewable energy potential. For example, Pittsburgh International Airport has partnered with CNX Resources and KeyState Energy to develop a USD 1.5 billion facility on airport grounds, aiming to produce up to 68,000 tonnes of hydrogen annually or approximately 70 million gallons of sustainable aviation fuel (SAF) (Power-to-X, 2025).

Under current conditions, the primary choice for GSE decarbonisation is likely to be electrification using battery-electric versions of GSE (IATA, 2025). A minority of airports in the EU are already actively working on solutions to integrate hydrogen-powered GSE in their regular commercial operations, driven by stricter local regulations, a progressive management mindset, or both. While these airports currently represent a niche market for hydrogen-powered GSE, adoption is likely to grow with improved market conditions. To determine whether hydrogen-powered GSE represents a suitable economic and operational choice compared to electric alternatives, airports should conduct site-specific evaluations based on a set of critical factors.

Evaluation Criteria for Economic Suitability of Hydrogen vs. Electric GSE

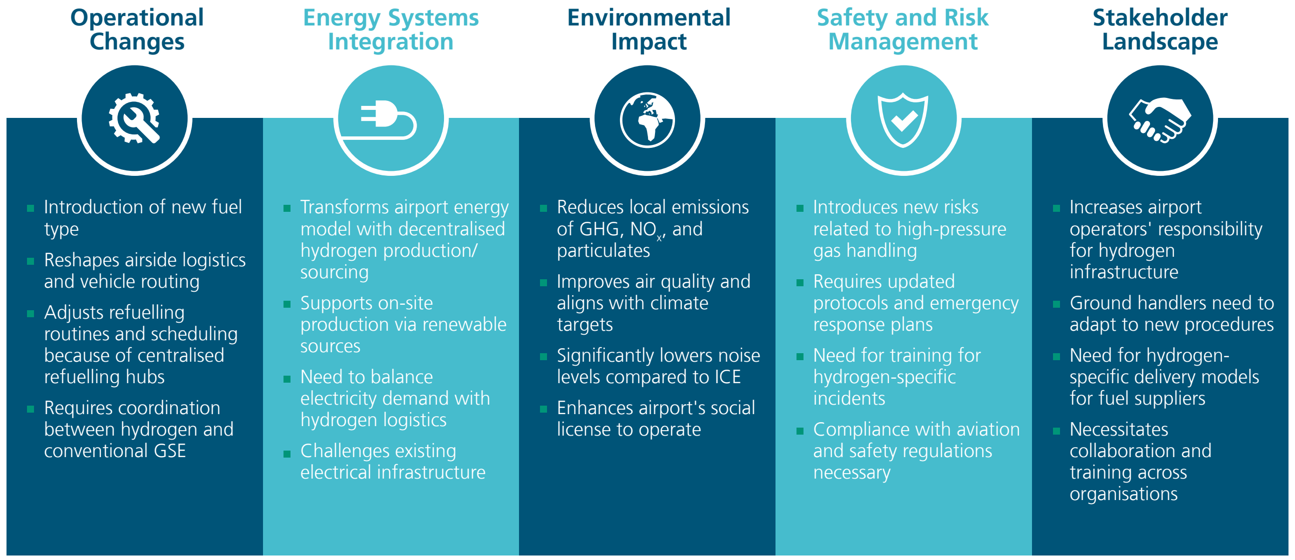
As airports pursue the decarbonisation of ground operations, choosing the most appropriate propulsion technology, whether hydrogen or electric, requires a context-specific, evidence-based approach. While both technologies offer zero-emission potential, their suitability varies depending on operational, environmental, financial, and infrastructural factors unique to each airport site (Anand et al., 2025; NREL, 2025). The introduction of green hydrogen GSE involves higher complexity in terms of infrastructure and supply logistics but may offer strategic advantages in specific high-utilisation or grid-constrained contexts (Roland Berger, 2023). Applying such a framework enables airport stakeholders to align procurement choices.

Understanding the broader effects of hydrogen-powered GSE integration is essential for managing the transition effectively and ensuring that hydrogen serves as a strategic enabler of airport decarbonisation (UNECE, 2022; NREL, 2025). While current hydrogen GSE are mainly at pilot stage, broader market availability and robust cost data are expected as technology and supply chains mature.

Hydrogen GSE Implementation: Operational Considerations and System Requirements

Successfully introducing hydrogen-powered GSE at airports requires a coordinated strategy that addresses infrastructure readiness, workforce capabilities, regulatory compliance, and financial feasibility (Roland Berger, 2023; ICAO, 2020a&b). Unlike drop-in replacements, hydrogen GSE introduces systemic changes that must be addressed across technical, operational, and institutional dimensions.

Core considerations include a phased fleet transition aligned with replacement cycles (IATA, 2025), the design of infrastructure that meets safety zoning and hazard classification requirements (UNECE, 2022), and comprehensive workforce training and certification for high-pressure hydrogen systems. In addition,



Operational Changes

- Introduction of new fuel type
- Reshapes airside logistics and vehicle routing
- Adjusts refuelling routines and scheduling because of centralised refuelling hubs
- Requires coordination between hydrogen and conventional GSE

Energy Systems Integration

- Transforms airport energy model with decentralised hydrogen production/sourcing
- Supports on-site production via renewable sources
- Need to balance electricity demand with hydrogen logistics
- Challenges existing electrical infrastructure

Environmental Impact

- Reduces local emissions of GHG, NO_x, and particulates
- Improves air quality and aligns with climate targets
- Significantly lowers noise levels compared to ICE
- Enhances airport's social license to operate

Safety and Risk Management

- Introduces new risks related to high-pressure gas handling
- Requires updated protocols and emergency response plans
- Need for training for hydrogen-specific incidents
- Compliance with aviation and safety regulations necessary

Stakeholder Landscape

- Increases airport operators' responsibility for hydrogen infrastructure
- Ground handlers need to adapt to new procedures
- Need for hydrogen-specific delivery models for fuel suppliers
- Necessitates collaboration and training across organisations

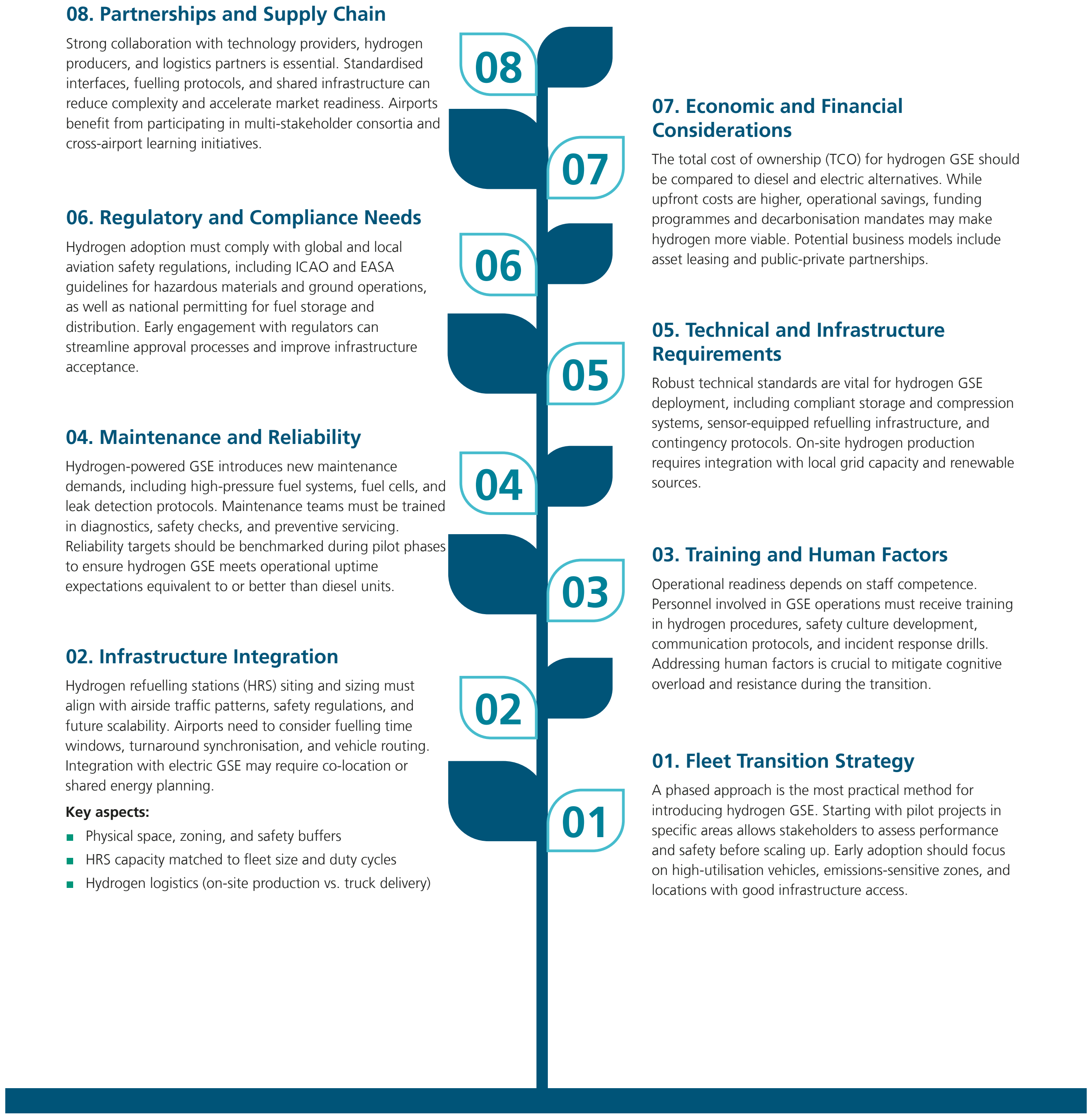
Figure 4: Systemic Impacts of Hydrogen GSE Integration in Airport Operations (own illustration based on Roland Berger, 2023; ICAO, 2020b, and learnings from TULIPS, 2025)

Evaluation Criteria	Description
Utilisation Intensity	Frequency and duration of GSE use per shift; hydrogen suits high-intensity operations.
Ambient Temperature	Hydrogen fuel cells outperform batteries in extreme temperatures, particularly cold conditions.
Refuelling / Charging Time Windows	Hydrogen offers faster refuelling, which is critical for time-sensitive operations.
Electric Infrastructure Availability	Electric GSE depends on a reliable and sufficient power supply; limited capacity can be a barrier or lead to high CapEx, affecting the business case.
Hydrogen Availability (On-site or Regional)	Feasibility and reliability depend on access to green hydrogen via pipelines, delivery, or on-site production.
Available Space for Infrastructure	Both hydrogen and electric infrastructure require space; hydrogen needs specific safety zoning and risk assessments.
Local Capital Expenditure (CapEx)	Purchase and infrastructure costs vary by airport scale and market maturity.
Access to Funding / Incentive Programs	Availability of funding and subsidies can influence choice; incentive programs may differ by region and technology. Subsidies or grants may be technology-specific.
Local Operating Costs (OPEX)	Consider regional costs and price volatility of hydrogen vs. electricity in long-term planning.
Age and Replacement Cycle of GSE Fleet	Timing of GSE renewal influences transition feasibility, aligns with long-term climate strategy and capital planning.
Local and National Regulations	Local regulations can be a limiting factor in the decision on the technology that can be used.
Technological Readiness, Certification, and Insurance	Electrification may have advantages in development cycles from the automotive industry, easing the implementation at airports.
Maintenance and Repair Complexity	Hydrogen GSE are mostly in prototype or pilot stages, so maintenance requirements remain uncertain. New skills and safety procedures are needed, though standardisation may simplify maintenance as the technology matures.

Table 2: Evaluation Criteria for Economic Suitability of Hydrogen vs. Electric GSE (adapted and sourced from Anand et al., 2025; Singh et al., 2024; NREL, 2025; UNECE, 2022; Roland Berger, 2023; ICAO, 2020b)

integration with renewable energy projects is essential to ensure long-term fuel sustainability (HEAVENN, 2021a&b), while effective multi-stakeholder coordination can help standardise interfaces and distribute infrastructure costs more efficiently. These interdependencies are summarised in Figure 3: Hydrogen GSE Implementation – Operational Considerations and System Requirements.

Collaboration with technology providers, hydrogen producers, and logistics partners is essential. Standardised interfaces and shared infrastructure can simplify the process and enhance market readiness. Airports should engage in multi-stakeholder consortia and cross-airport learning initiatives. This integrated perspective shall support airports' moves from vision to execution, ensuring that hydrogen-powered GSE implementation is safe, scalable, and strategically aligned with their long-term sustainability and operational objectives.



08. Partnerships and Supply Chain

Strong collaboration with technology providers, hydrogen producers, and logistics partners is essential. Standardised interfaces, fuelling protocols, and shared infrastructure can reduce complexity and accelerate market readiness. Airports benefit from participating in multi-stakeholder consortia and cross-airport learning initiatives.

07. Economic and Financial Considerations

The total cost of ownership (TCO) for hydrogen GSE should be compared to diesel and electric alternatives. While upfront costs are higher, operational savings, funding programmes and decarbonisation mandates may make hydrogen more viable. Potential business models include asset leasing and public-private partnerships.

06. Regulatory and Compliance Needs

Hydrogen adoption must comply with global and local aviation safety regulations, including ICAO and EASA guidelines for hazardous materials and ground operations, as well as national permitting for fuel storage and distribution. Early engagement with regulators can streamline approval processes and improve infrastructure acceptance.

05. Technical and Infrastructure Requirements

Robust technical standards are vital for hydrogen GSE deployment, including compliant storage and compression systems, sensor-equipped refuelling infrastructure, and contingency protocols. On-site hydrogen production requires integration with local grid capacity and renewable sources.

04. Maintenance and Reliability

Hydrogen-powered GSE introduces new maintenance demands, including high-pressure fuel systems, fuel cells, and leak detection protocols. Maintenance teams must be trained in diagnostics, safety checks, and preventive servicing. Reliability targets should be benchmarked during pilot phases to ensure hydrogen GSE meets operational uptime expectations equivalent to or better than diesel units.

03. Training and Human Factors

Operational readiness depends on staff competence. Personnel involved in GSE operations must receive training in hydrogen procedures, safety culture development, communication protocols, and incident response drills. Addressing human factors is crucial to mitigate cognitive overload and resistance during the transition.

02. Infrastructure Integration

Hydrogen refuelling stations (HRS) siting and sizing must align with airside traffic patterns, safety regulations, and future scalability. Airports need to consider fuelling time windows, turnaround synchronisation, and vehicle routing. Integration with electric GSE may require co-location or shared energy planning.

Key aspects:

- Physical space, zoning, and safety buffers
- HRS capacity matched to fleet size and duty cycles
- Hydrogen logistics (on-site production vs. truck delivery)

01. Fleet Transition Strategy

A phased approach is the most practical method for introducing hydrogen GSE. Starting with pilot projects in specific areas allows stakeholders to assess performance and safety before scaling up. Early adoption should focus on high-utilisation vehicles, emissions-sensitive zones, and locations with good infrastructure access.

Figure 5: Hydrogen GSE Implementation: Operational Considerations and System Requirements (own illustration based on learnings from TULIPS, 2025)

Assessing Hydrogen GSE Deployment: A Strategic Airport Typology

Hydrogen-powered GSE offers a promising pathway towards zero-emission airside operations. However, it should be considered as one of several complementary technologies, alongside battery-electric systems, SAF, and renewable diesel options such as HVO100, that collectively contribute to the decarbonisation of airport environments (ICAO, 2022; European Commission, 2021a&b). Its deployment potential depends on airport-specific operational, economic, and regulatory contexts, making it essential to assess strategic fit before large-scale implementation.

This chapter presents a structured decision-making framework to help airport operators, policymakers, and industry stakeholders determine whether a given airport is well-suited for early adoption or scaling of hydrogen GSE. It identifies the key determinants of suitability, while recognizing that future airside energy systems will likely integrate a tailored mix of technologies adapted to local conditions (WEF, 2024&2025; Roland Berger, 2023).

Criteria for Airport Selection

Selecting airports for hydrogen deployment requires an integrated assessment of operational capacity, infrastructure availability, environmental ambition, and policy support. Hydrogen is most impactful in settings with high-intensity duty cycles, limited charging windows, and grid or space constraints that restrict battery-electric scaling (NREL, 2025; Anand et al., 2025).

Dimension	Description
Airport Size and Traffic Volume	Large hubs with high aircraft movements benefit from fast refuelling and continuous duty capability, while smaller or cargo-focused airports can serve as low-risk pilots (NREL, 2025; IATA, 2025).
Fleet Characteristics	Best suited for long-runtime assets with minimal downtime; advantageous for fleets with high proportions of aging diesel units or limited charging infrastructure (Roland Berger, 2023; ICAO, 2020b).
Infrastructure Space and Infrastructure	Requires sufficient space for HRS and supply access; hybrid layouts can integrate both hydrogen and electric infrastructure (UNECE, 2022; European Commission, 2024c).
Environmental Ambition	Aligns with airports pursuing net-zero targets and innovation-driven procurement strategies (ACI Europe, 2023).
Regulatory Context	Favourable in regions with clear hydrogen strategies, incentives, and streamlined permitting; participation in hydrogen valleys or industrial clusters improves feasibility (European Union, 2023; EPRS, 2025).

Table 3: High-Level Considerations for Assessing Hydrogen GSE Potential at Airports (adapted from industry and policy sources)

Analysis of Operational Conditions

Hydrogen viability is shaped by local operational profiles, climatic factors, and workforce readiness. Its integration must complement existing zero-emission solutions rather than compete with them (Anand et al., 2025; NREL, 2025).

Dimension	Description
Climatic Conditions	Fuel cells maintain performance in cold conditions where batteries may degrade; in hot and humid climates, effective thermal control and ventilation are required (Anand et al., 2025; ICAO, 2020).
Duty Cycles and Usage Intensity	Competitive for continuous or high-intensity operations; electric alternatives may be preferable for low-utilisation or short-shift assets (NREL, 2025; IATA, 2025).
Logistical and Spatial Factors	Efficient refuelling depends on optimal HRS placement, mobile supply routing, and integration into airside traffic; multi-energy operations must balance competing spatial needs (UNECE, 2022; EHB, 2024).
Workforce Readiness and Organisational Maturity	Hydrogen handling expertise is essential; airports with a strong safety culture and prior alternative-fuel experience are better positioned for multi-technology transitions (ICAO, 2020; IATA, 2025).

Table 4: Key Operational and Organisational Considerations for Hydrogen Adoption (adapted from industry and policy sources)

Economic and Environmental Impacts

Hydrogen's long-term viability depends on its ability to deliver both environmental and economic benefits. Although capital expenditure for hydrogen GSE and infrastructure is typically higher, total cost of ownership can be favourable in high-utilisation environments, particularly where grid constraints or high electricity prices limit battery-electric adoption (Roland Berger, 2023; Enterprise Mobility, 2024). Coordinated infrastructure development and joint procurement can further reduce costs (WEF, 2024&2025).

Environmentally, hydrogen delivers zero local emissions and reduces airside noise, complementing e-GSE and SAF initiatives (ICAO, 2022). It is particularly relevant for airports facing air quality compliance challenges or occupational health risks where battery-electric solutions fall short (NREL, 2025). Strategic planning should be based on comparative scenario analyses across technologies. For example, a major hub might deploy electric baggage tractors, hydrogen pushback tractors, SAF for aircraft, and HVO100 for backup, while a cargo-focused airport could pilot hydrogen tugs, electrify belt loaders, and integrate SAF into logistics (ICAO, 2022; WEF, 2024&2025). Hydrogen's role will ultimately depend on regional conditions, fuel price trajectories, and funding availability, embedded within a multi-energy strategy that enhances resilience and flexibility (European Union, 2023; CINEA, 2024).

Hydrogen Suitability Assessment for Airports

The hydrogen suitability assessment offers a simple, structured way for airports to deliberate hydrogen's role in ground operations. It uses a set of seven broad criteria, covering operational patterns, fleet replacement needs, infrastructure availability, supply access, environmental policy, regulatory context, and workforce readiness, each scored from 0 (low) to 3 (high). Adding the scores provides a general indication of suitability, with higher totals suggesting that hydrogen may merit further exploration and lower totals pointing towards other fuels as a current priority.

To support strategic decision-making, airports can use the following scoring matrix. Each category is rated from 0 (low suitability) to 3 (high suitability). A total score of >14 indicates a strong candidate for hydrogen adoption.

Criteria	0 – Low	1 – Moderate	2 – Good	3 – High
Traffic Volume and Duty Cycles	Low utilisation	Seasonal peaks	Moderate utilisation	High utilisation, continuous ops
Fleet Replacement Need	Mostly new electric fleet	Few diesel units	Diesel fleet partly due for replacement	Diesel-dominated fleet near end of life
Infrastructure Space	No space for HRS	Limited space	Space available with adjustments	Dedicated HRS site available
Hydrogen Supply Access	No local supply	Trucked-in only	Regional supply	Pipeline or on-site production
Environmental Policy	No targets	General green policy	Net-zero by 2050	Net-zero by 2030 or earlier
Regulatory Support	No incentives	Some support	Regional strategy in place	Funding and streamlined permitting
Workforce Readiness	No experience	Limited alt-fuel experience	Electric GSE experience	Hydrogen-specific training
SUM				

Table 5: Scoring Matrix for Assessing Hydrogen GSE Deployment Suitability (own illustration)

Interpretation (total sum):

- 0–8 points: Low suitability, focus on electric or other fuels first
- 9–14 points: Transitional suitability, consider pilots in specific areas
- 15–21 points: High suitability, plan for scaling hydrogen GSE

This scoring tool provides a high-level snapshot for local decision makers to gain an initial understanding of how a hydrogen strategy can be deployed, without needing to delve into the operational, financial, and technical factors that influence real-world feasibility. For instance, it does not account for detailed total cost of ownership, site-specific operational modelling, or the varying importance of different criteria.

For airports interested in exploring hydrogen further, the matrix can be complemented with more detailed analyses, such as economic modelling, lifecycle emission comparisons, operational trials, and stakeholder consultations. These additional steps can provide the depth and evidence needed to make well-founded investment decisions, while the scoring matrix remains a way to frame initial discussions.

While all criteria are currently treated equally for simplicity and comparability, their relative importance may vary depending on the airport context. In future applications, weighting or distinguishing between critical and secondary factors, such as secure hydrogen supply or strong regulatory support, could further enhance the predictive value of the tool. Airports and policymakers may therefore adapt the matrix by assigning higher relevance to criteria that most strongly influence local feasibility and investment priorities.

Experiences from other transport sectors, including logistics and heavy-duty mobility, also offer valuable lessons for hydrogen deployment. Nevertheless, this whitepaper focuses on the specific operational and infrastructural context of airports, where some of these insights may prove transferable in future applications.

Existing Hydrogen Projects and Demonstrations at Airports

Across Europe, multiple large-scale initiatives are advancing the integration of hydrogen into airport operations, ranging from aircraft refuelling demonstrations to hydrogen-powered GSE pilots. These projects typically combine technology development, infrastructure deployment, and regulatory standardisation, positioning hydrogen as a key enabler of zero-emission airport ecosystems. To move beyond a descriptive listing, Table 6 systematises the projects by focus area, scope, and key learnings. This highlights how each initiative contributes specific insights to the collective European knowledge base.

Figure 6: Airport Demonstrations Involving Hydrogen Applications (own illustration)

Project	Focus / Demonstration	Airports Involved	Funding / Timeline	Key Learning
ALRIGH$_2$T (ALRIGH$_2$T, 2024; European Commission, 2024)	Liquid hydrogen (LH$_2$) aircraft refuelling and tank swap logistics	MXP, CDG, ORY, LBG	€10m (2024–2027)	Demonstrates operational feasibility of LH$_2$ refuelling under real airport conditions.
GOLIAT (Airbus Research, 2024; European Commission, 2024a; H2FLY, 2024)	Large-scale LH$_2$ refuelling, certification and standardisation	BUD, STR, RTM	€10m (2024–2028)	Addresses certification hurdles and sets standards for LH$_2$ infrastructure across multiple EU states.
HEAVENN (European Commission, Clean Hydrogen Partnership, 2024b; CORDIS, 2020; HEAVENN, 2021a&b, 2024; NXT Airport, 2022)	Hydrogen valley integration (production, storage, distribution, airport link)	GRQ	€20m (2020–2027)	Provides a replicable model for regional hydrogen valleys as multi-sector energy ecosystems.
OLGA (OLGA, 2021)	Integration of SAF and hydrogen into existing fuel infrastructure	CDG, MXP, ZAG	€25m (2021–2026)	Explores hybrid fuel infrastructures, bridging short- and long-term decarbonisation pathways.
STARGATE (STARGATE, 2022)	Hydrogen GSE pilots (baggage tractors), digital twin technology	BRU, ATH	€25m (2021–2026)	Proves hydrogen GSE deployment can be embedded within broader smart-airport frameworks.
TULIPS (Schiphol, 2024; TULIPS Green Airports, 2022)	Hydrogen GPU and tow tractor pilots	AMS, RTM, TRN	€25m (2022–2025)	Demonstrates hydrogen's viability for intensive-duty GSE in live operational environments.
Hydrogen Hubs at Airports (Airbus) (Airbus, 2024)	Global network for hydrogen production, storage, refuelling	LGW, HAM, plus airlines	Industry-driven	Pushes alignment between airports and airlines for a harmonised hydrogen ecosystem.
Exeter Airport (Exeter Airport, 2025)	First full hydrogen turnaround with GSE (GPU, tug, tractor)	EXT	Industry-led (2025)	Demonstrates technical readiness of a 100% hydrogen turnaround under live operational conditions.
Glasgow Airport (Glasgow Airport, 2024)	Feasibility study for hydrogen production, storage, refuelling	GLA (AGS group)	Industry-led (to 2027)	Offers blueprint for scalable hydrogen solutions at regional airports.

Table 6: Selected European Hydrogen Initiatives in Aviation – Profiles and Key Learnings[1]

Collectively, these initiatives illustrate a multi-track European approach to hydrogen adoption in aviation within the following streams:

- Infrastructure readiness (e.g. HEAVENN, OLGA)
- Operational pilots (e.g. STARGATE, TULIPS, Exeter)
- Certification and standardisation (e.g. GOLIAT, ALRIGH$_2$T)
- Cross-sector and global collaboration (e.g. Hydrogen Hubs, Glasgow blueprint)

Conclusions and Outlook

This whitepaper has analysed the role of green hydrogen in advancing the decarbonisation of airport ground operations, with particular attention to the technological, operational, and systemic factors shaping its adoption. A critical finding is the distinction between hydrogen fuel cell systems and hydrogen ICEs. While ICE technology may act as a bridging technology on the path towards lower emissions, fuel cells offer a more sustainable route to achieving long-term zero-emission GSE operations. Furthermore, hydrogen's environmental performance is directly linked to its production method. Only green hydrogen, produced through electrolysis powered by renewable energy, delivers the full climate benefit required to align with aviation's net-zero targets.

Infrastructure emerges as both a barrier and an enabler. Expanding European and German hydrogen pipeline networks, with many TEN-T airports situated close to planned core corridors, offers a strategic opportunity for future integration. Although most airports are not yet connected to these systems, their geographic positioning could facilitate scalable, secure supply in the medium term. However, operational integration will require substantial change: safety protocols must be updated, emergency procedures adapted, and staff trained to manage hydrogen-specific hazards. This transition will also reshape stakeholder roles, with airport operators potentially taking on more responsibility for centralised fuel infrastructure and ground handlers adjusting operational workflows accordingly.

From an energy systems perspective, hydrogen adoption redefines airports as decentralised energy hubs. This transformation enables integration with on-site renewable generation while introducing new logistical, electrical, and spatial considerations. Centralised hydrogen refuelling stations will require adjustments to GSE scheduling, ramp layout, and traffic flows, with implications for turnaround efficiency and operational resilience.

Despite positive momentum in technology development and promising results from pilot projects, significant challenges remain. These include supply chain bottlenecks, the high cost and limited availability of green hydrogen, incomplete refuelling infrastructure, and technical uncertainties related to standardisation, certification, and interoperability in multi-airport operations. Operationally, mixed-fleet environments will demand careful planning to manage maintenance schedules, safety protocols, and inter-airport equipment compatibility.

The future of hydrogen in airport ground operations is promising, but its success will depend on sustained investment, regulatory harmonisation, and integration into broader hydrogen and climate action strategies. Crucially, hydrogen should not be seen as a standalone solution but as part of a diversified zero-emission technology mix. While battery-electric GSE remains the preferred option in many scenarios, hydrogen offers distinct advantages in high-utilisation, rapid-turnaround, and long-range contexts where battery limitations become operational constraints.

Pathways for Future Research

Further research may extend the findings of this whitepaper to address remaining gaps and support evidence-based decision-making regarding hydrogen GSE deployment as outlined below:

1. Systems integration analysis exploring synergies between hydrogen GSE, hydrogen-powered aircraft, and airport-based renewable energy hubs.
2. Comparative lifecycle assessments of hydrogen and battery-electric GSE in varying operational contexts, including regional and seasonal variability.
3. Techno-economic modelling of hydrogen infrastructure investment under different market conditions, fuel price trajectories, and policy incentive frameworks.
4. Standardisation studies to develop interoperable equipment interfaces and harmonised safety protocols across airports and jurisdictions.
5. Human factors research examining training needs, safety culture evolution, and operational resilience in hydrogen-integrated ground operations.

Requirements for Airports, Ground Handlers, Regulators, and Industry Associations

The transition to zero-emission ground operations requires coordinated efforts across the full ecosystem.

Airport management must plan and invest in multi-energy infrastructure, adapt procurement strategies, and ensure adequate space and safety systems for hydrogen and electric GSE. Ground handling companies, as the primary operators of GSE, need to adapt fleet strategies, engage in workforce training, and align daily operations with emerging zero-emission standards. Regulators and industry associations such as IATA, ICAO, and regional authorities must provide clear and harmonised safety frameworks, accelerate permitting and certification, and enable scaling through incentives and funding mechanisms.

In conclusion, airports must take decisive steps in infrastructure and investment planning, ground handlers must operationalise new technologies through fleet renewal and training, and regulators and industry bodies must deliver the standards, policies, and incentives that collectively enable a sustainable and safe zero-emission ramp.

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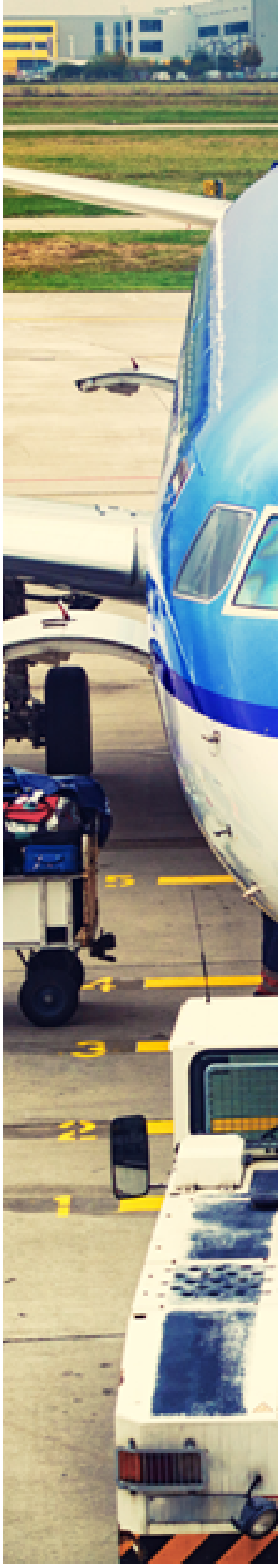

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