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Hydrogen applications in airport operations: a review using the Port Authority of New York and New Jersey as an illustrative airport system

Veronika Semchukova, Kevin Topolski and Zainul Abdin *

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Airports combine aircraft propulsion, ground operations, stationary power systems, and fuel logistics in ways that make emissions reduction technically and operationally complex. Existing studies often assess hydrogen applications in these areas separately, limiting understanding of the shared infrastructure, safety, and operational constraints that shape airport deployment. This review evaluates hydrogen across three airport-relevant operational domains: aviation propulsion, ground support equipment and vehicles, and stationary power systems. Within aviation propulsion, the review examines sustainable aviation fuel production and hydrogen-powered aircraft as two distinct hydrogen-relevant pathways. The Port Authority of New York and New Jersey is used as an illustrative airport system to relate the literature to a real operating context. Drawing on peer-reviewed studies, technical reports, demonstration projects, and public operational information, the review also includes screening-level calculations of hydrogen demand and potential CO_2e reductions for selected applications. The findings show that hydrogen's role is highly application-specific. Near-term opportunities are strongest where hydrogen serves as a low-carbon process input, supports selected high-utilization ground equipment, or contributes to resilient stationary power-system configurations. Hydrogen-powered aircraft remain a longer-term option because storage, fueling infrastructure, certification, cost, and NO_x management continue to constrain deployment. Across all domains, infrastructure readiness, fuel logistics, safety requirements, and leakage management emerge as recurring determinants of viability. Future research should focus on cross-domain infrastructure planning, comparative assessment of hydrogen against alternative pathways, improved treatment of leakage and non-CO_2 effects, and clearer safety and regulatory frameworks for airport deployment.

1 Introduction

Airports are critical infrastructure within the global transportation network, supporting passenger mobility, freight movement, and regional and international economic activity. At the same time, airport operations generate carbon dioxide equivalent (CO_2e) emissions through multiple pathways, including aircraft movements, ground support equipment (GSE), on-site energy use, and supporting infrastructure. The Port Authority of New York and New Jersey (PANYNJ), which operates John F. Kennedy International Airport (JFK), Newark Liberty International Airport (EWR), LaGuardia Airport (LGA), New York Stewart International Airport (SWF), and Teterboro Airport (TEB), manages one of the busiest airport systems in North America. Using PANYNJ as an illustrative airport system, this review identifies findings that are relevant to other large commercial airports facing comparable emissions and infrastructure challenges. In 2021, aircraft operations alone accounted for approximately 56% of total reported CO_2e emissions across these airports,[1] underscoring the dominant contribution of aviation propulsion relative to other emission sources. Fig. 1 shows the geographic footprint of the PANYNJ airport system within the New York and New Jersey region.

Globally, governments and industry are advancing fuel innovation and operational reforms as part of broader aviation transition strategies. The United Arab Emirates has outlined a long-term goal for hydrogen-powered commercial aircraft within its national aviation framework.[2] India is pursuing market-based approaches for aviation emissions management that are informed by the European Union Emissions Trading System.[3] The Netherlands has proposed a transition toward CO_2-free energy carriers in aviation by 2050 through alignment of national energy and transportation policies.[4] In China, major urban airports are promoting fleet modernization and fuel switching for GSE to improve local air quality and reduce reliance on fossil fuels.[5] Open-access datasets integrating aircraft movement, energy use, and technology adoption have also been developed to support analysis of airport emissions strategies.[6] Together, these developments show that airport emissions

National Laboratory of the Rockies, Golden, CO, USA. E-mail: zainul.abdin@nlr.gov

Fig. 1 PANYNJ airports and regional footprint. Geographic layout of JFK, EWR, LGA, SWF, and TEB airports with major transportation infrastructure and surrounding urban context.

reduction is increasingly being approached as a systems challenge involving fuel innovation, infrastructure adaptation, and operational change.

Among the technical options under consideration, sustainable aviation fuels (SAFs) and hydrogen-based technologies are especially prominent. SAFs have been widely studied as near-term alternatives because they can be introduced with limited modification to existing aircraft and fueling infrastructure. Kozakiewicz and Ludwiczak[7] examined turbine engine adaptations that support SAF combustion and reported emissions benefits without major mechanical overhauls. Bauen *et al.*[8] evaluated SAF and electrification strategies across aircraft categories and identified differentiated potential based on flight distance and operational context. Duarte *et al.*[9] used bibliometric methods to map emerging SAF technologies, industry collaboration, and policy alignment. Gan *et al.*[10] assessed SAF deployment constraints related to certification, safety, and regulatory uncertainty. Despite considerable progress, these studies consistently indicate that long-term SAF deployment will depend on continued improvements in production scale, cost, feedstock availability, and policy support.

Hydrogen technologies have also received growing attention for their longer-term role in both propulsion and supporting airport systems. Vajdová *et al.*[11] reviewed hydrogen use in aviation and outlined prospective deployment pathways, technical barriers, and infrastructure requirements. Hydrogen-powered aircraft, particularly fuel cell electric concepts, are under development for regional applications, although commercial readiness remains limited.[12] Hydrogen combustion is also being explored for longer-range operations, but unresolved issues related to nitrogen oxides (NO_x), storage volume, and volumetric energy density continue to affect its competitiveness.[13] Broader airport integration will also require investment in on-site production, compression, storage, and refueling infrastructure,[14] and original equipment manufacturers (OEMs), airport operators, and national laboratories are actively examining these systems as part of longer-term low-emission transition strategies.[15] Taken together, the literature suggests that hydrogen propulsion is better understood as a complementary pathway alongside SAFs, with its long-term role dependent on progress in cost, logistics, infrastructure, and technology maturity.

Hydrogen also has an important role in SAF production as a low-carbon process input. SAF pathways such as hydroprocessed esters and fatty acids (HEFA), Fischer–Tropsch (FT) synthesis, and alcohol-to-jet (ATJ) conversion are already certified and used commercially.[16] Incorporating hydrogen, especially from renewable or other low-emission sources, can reduce the life cycle CO_2e intensity of these fuels.[17] However, large-scale SAF deployment will require regional production expansion, supply-chain integration, and more efficient fuel logistics.[17] The literature therefore indicates that long-term SAF viability remains closely linked to feedstock availability, production economics, and durable policy support.[18,19] These findings also show that SAFs and hydrogen should not be treated as isolated pathways, but as interdependent components of a broader airport and aviation energy transition.

A recurring limitation in the airport-hydrogen literature is that propulsion, ground operations, and stationary energy systems are often assessed in isolation. That approach can obscure the fact that airport deployment is shaped by shared constraints, including hydrogen supply pathways, storage and refueling requirements, safety compliance, siting limitations, fuel-handling compatibility, and interaction with existing electrical and thermal infrastructure. A cross-application perspective is therefore necessary to identify where hydrogen is most credible, where alternative pathways may remain more practical, and how infrastructure choices in one domain may influence another.

This review addresses the identified need by synthesizing hydrogen applications within airport operations across three operational domains: aviation propulsion, ground support equipment and vehicles, and stationary power systems. Within aviation propulsion, the analysis considers two distinct hydrogen-relevant pathways: sustainable aviation fuel production and hydrogen-powered aircraft. PANYNJ is used as an illustrative airport system rather than as a standalone case study, providing a real multi-airport operating context through which cross-domain findings can be interpreted. Both gaseous and liquid hydrogen (LH_2) are considered where relevant to the application under discussion, since storage form, delivery mode, and infrastructure requirements differ across aircraft propulsion, ground support equipment, and stationary power systems. The analysis examines technology readiness, infrastructure requirements, safety considerations, fuel-handling compatibility, and comparison with incumbent and emerging electrification pathways.

To support interpretation of the literature, the manuscript also includes screening-level estimates of hydrogen demand and potential CO_2e reduction for selected airport applications using PANYNJ's 2021 operating context as a reference baseline. These calculations are intended to clarify scale, infrastructure implications, and comparative deployment conditions rather than to substitute for project-specific engineering design, techno-economic optimization, or full-system life-cycle analysis.

This review is intended to provide an application-focused analytical assessment of the evidence most relevant to hydrogen deployment in airport operations. The evidence base was assembled through targeted searching and selection of peer-reviewed journal articles, airport and government technical reports, standards, documented demonstration projects, manufacturer disclosures, and publicly available institutional and operational sources. Sources were selected when they contributed substantive information on technology status, infrastructure requirements, safety considerations, emissions implications, operational performance, or deployment readiness. The review does not aim to provide an exhaustive statistical synthesis of all published material; rather, it evaluates the most relevant evidence across airport energy domains to identify cross-domain constraints, enabling conditions, and research needs.

Hydrogen leakage is treated throughout the review as an environmental and operational issue rather than as a secondary detail. Although hydrogen can eliminate direct CO_2 emissions at the point of use, leakage during production, storage, distribution, and end use can weaken overall climate benefit through indirect atmospheric effects. In airport settings, where hydrogen may be handled across multiple pressure regimes, storage conditions, and equipment classes, credible environmental performance depends on effective containment, leak detection, and emissions accounting alongside the fuel-switching strategy itself.

The manuscript is organized as follows. Section 2 establishes the baseline by analyzing 2021 CO_2e emissions across airports managed by PANYNJ. Section 3 is organized around three operational domains: aviation propulsion, ground support equipment and vehicles, and stationary power systems. Within aviation propulsion, two distinct hydrogen-relevant pathways are examined, namely sustainable aviation fuel production and hydrogen-powered aircraft. Section 4 synthesizes cross-sector findings, identifies key implementation barriers, and outlines enabling conditions for hydrogen deployment. Section 5 concludes with implications for airport planning, infrastructure development, and future research.

2 Major contributors to emissions at PANYNJ airports

Airports operated by PANYNJ, including JFK, EWR, LGA, SWF, and TEB, are major passenger and freight hubs whose scale and operational complexity generate significant CO_2e emissions. This section establishes the 2021 emissions baseline used to frame the subsequent discussion of hydrogen applications. The baseline is drawn from PANYNJ's GHG and Criteria Air Pollutant Emissions Inventory (2023), which also outlines the agency's targets to reduce CO_2e emissions by 35% by 2025 and to reach net-zero emissions by 2050.[1]

In 2021, aircraft operations were the largest source of total CO_2e emissions, accounting for 56% of the inventory. Passenger-attracted travel contributed 12%, purchased electricity 11%, air cargo 8%, and GSE 6%. The remainder arose from auxiliary power units, on-site energy production, shadow-fleet vehicles, purchased thermal energy, and stationary combustion, as shown in Fig. 2.[1] Although these values are specific to the PANYNJ airport system, the overall pattern is broadly consistent with other large international hubs, where aircraft activity dominates total emissions while passenger access, freight movement, and facility energy use remain important secondary contributors.

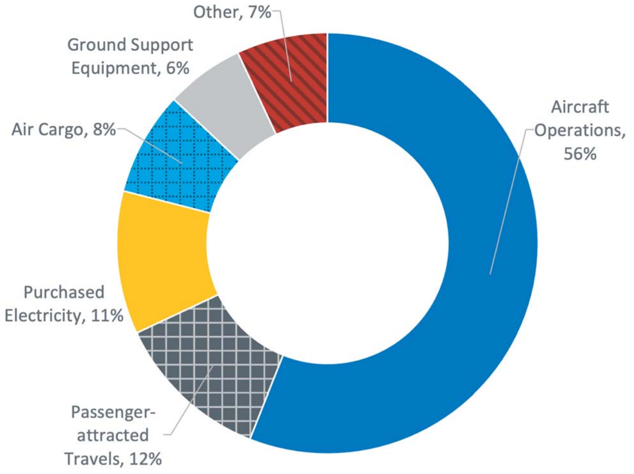

Fig. 2 Proportional contributions of major CO_2e emissions sources at PANYNJ airports in 2021. Source data: PANYNJ 2021 GHG and Criteria Air Pollutant Emissions Inventory.[1]

For the purposes of this review, the main emission sources are discussed through three operational groupings that are most relevant to hydrogen deployment: aircraft operations; vehicles and equipment; and electricity and stationary energy systems. Together, these categories account for approximately 92% of total reported CO_2e emissions across PANYNJ airports in 2021.[1] Most of these emissions are associated with tenants and customers rather than PANYNJ's direct operations, which has important implications for implementation authority, investment decisions, and the allocation of mitigation responsibilities.

2.1 Aircraft operations

Aircraft operations remain the dominant source of CO_2e emissions across PANYNJ airports. In the inventory, this category is based on the landing and takeoff (LTO) cycle†, which includes approach, taxi-in, startup, taxi-out, takeoff, and climb-out, and covers aircraft activity below 3000 feet within Federal Aviation Administration (FAA) boundaries. Emissions were estimated using the Aviation Environmental Design Tool based on operational volume, aircraft type, and performance characteristics.[1] This approach is consistent with FAA and ICAO inventory practice, but it also means that a single flight contributes LTO emissions to both its origin and destination airport inventories.

Within the PANYNJ system, JFK accounted for nearly half of aircraft-operational emissions, followed by EWR at 33%, LGA at 14%, TEB at 5%, and SWF at 2%.[1] These differences reflect airport-specific traffic volume and fleet composition. JFK, for example, serves a larger share of long-haul wide-body operations, whereas TEB is dominated by business aviation. Because aircraft operations account for more than half of the total inventory, they provide the primary reference point for evaluating the relative contribution and practical significance of lower-emission alternatives discussed later in the manuscript.

† Landing and takeoff (LTO) cycle includes six modes: approach, taxi in, startup, taxi out, takeoff, and climb out.

2.2 Vehicles and equipment

Vehicles and equipment constitute the next major group of emission sources and include passenger-attracted travel, air-cargo transport, GSE, and other mobile sources. Their importance lies not only in their aggregate contribution, but also in the fact that several of these segments are more directly amenable to airport-level operational and infrastructure interventions than aircraft propulsion itself.

Passenger-attracted travel was the second-largest individual source in the 2021 inventory, accounting for approximately 12% of total CO_2e emissions.[1] This category includes passenger access to airports, which is dominated by light-duty personal vehicles, taxis, and ride-hailing services. PANYNJ has already begun supporting electrification of this segment through electric-vehicle charging deployments, including fast-charging stations at JFK and planned installations at EWR and LGA.[20]

Air-cargo vehicle activity accounted for 8% of total CO_2e emissions in the 2021 inventory. JFK handled 65% of cargo tonnage and EWR the remaining 35%.[1] Emissions from this segment depend on truck class, trip frequency, and average hauling distance, which typically ranges from 12 to 130 miles. Cargo activity includes both combination and all-cargo carriers as well as integrators such as FedEx and UPS.

GSE operations accounted for 6% of total CO_2e emissions in 2021, with 84% of these emissions concentrated at JFK and EWR.[1] The fleet includes tugs, belt loaders, aircraft tractors, and related service vehicles powered by diesel, gasoline, electricity, or compressed natural gas. Although GSE contributes less than passenger-attracted travel, purchased electricity, and air-cargo movement in the baseline inventory, it remains an operationally important category because it is directly tied to airport activity and is comparatively accessible for technology transition. PANYNJ has already supported electrification through a partnership with the New York Power Authority and JetBlue to install 38 charging stations at JFK, enabling conversion of 116 baggage tugs and belt loaders to electric operation.[21] In addition, PANYNJ has announced that it will no longer renew registrations for non-zero-emission core-fleet GSE beginning in 2027, with the requirement extending to all GSE with tailpipe emissions by 2030 unless exemptions are justified.[22] Although these measures postdate the 2021 baseline, they provide important context for the transition trajectory.

Other mobile sources, including security vehicles, shuttle buses, and employee business travel, each accounted for less than 1% of total CO_2e emissions.[1] The shadow fleet, defined as PANYNJ-owned vehicles operated and refueled by contractors, accounted for about 1%.[1] PANYNJ's Central Automotive Division manages approximately 3000 on-road and non-road vehicles and portable equipment; however, vehicle-level data specific to airport activities remain limited.

2.3 Purchased electricity and stationary combustion

Purchased electricity and stationary combustion are important emissions sources associated with terminal operations, heating and domestic hot water, and on-site energy production within airport boundaries. These sources are especially relevant to

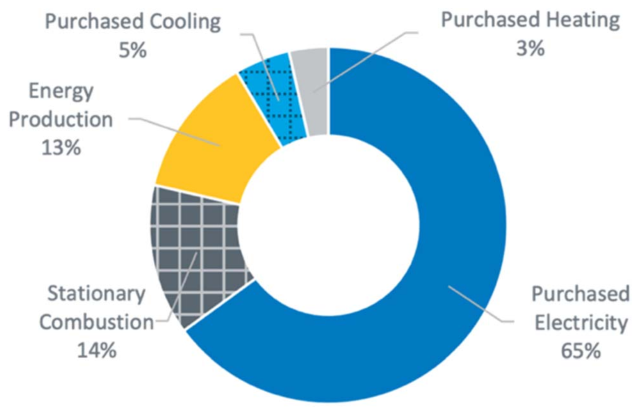

Fig. 3 Proportional contributions of CO_2e emissions associated with purchased electricity, stationary combustion, and on-site energy production at PANYNJ airports in 2021. Source data: PANYNJ 2021 GHG and Criteria Air Pollutant Emissions Inventory.[1]

hydrogen because they intersect directly with discussions of fuel switching, combined heat and power, co-firing, and microgrid design.

Stationary combustion includes Scope 1 emissions from on-site fuel use and Scope 3 upstream emissions associated with natural gas, heating oil, and propane. Natural gas is the dominant fuel, with limited heating-oil use at JFK and LGA, while propane is used only for fire training at JFK. In 2021, EWR accounted for 55% of Scope 1 and 59% of Scope 3 stationary-combustion emissions, followed by JFK with 36% and 31%, respectively.[1]

Purchased electricity from PANYNJ and tenant operations accounted for 65% of emissions within this energy-related category, measured as Scope 2 and Scope 3 emissions.[1] At JFK, a large share of electricity and thermal energy is supplied by the 121 MW Kennedy International Airport Cogeneration (KIAC) plant, which includes two General Electric LM6000 combustion turbines with heat-recovery steam generators.[23] The KIAC plant operates as a dedicated microgrid fueled primarily by natural gas, with Jet A as a secondary feedstock. Because of this configuration, the emissions factor associated with purchased electricity at JFK is 1.5 times the regional average reported in eGRID, which reflects substantial non-emitting generation from nuclear and hydropower.[1]

The KIAC facility is owned by PANYNJ and operated under a long-term lease with a third-party provider. It supplies electricity and thermal energy to airport facilities and tenants, sells excess electricity to the grid, and distributes surplus thermal energy locally. The 2020 lease renewal reaffirmed its central role in meeting JFK's energy needs while also maintaining its importance in the airport's emissions profile.[23]

Fig. 3 shows the proportional breakdown of emissions associated with airport energy use and on-site energy production in 2021. Purchased electricity accounted for 65% of emissions within this category, followed by stationary combustion at 14% and on-site energy production at KIAC at 13%.[1]

This baseline provides the reference framework for evaluating hydrogen applications in Section 3 across aircraft propulsion, ground support equipment and vehicles, and stationary power systems, and for identifying the airport activities in which hydrogen deployment is most likely to have material operational and emissions relevance.

3 Integration of hydrogen technologies in airport operations

Hydrogen technologies are being explored as part of broader airport energy transition strategies, with potential applications spanning aviation propulsion, ground support equipment and vehicles, and stationary power systems. Each domain presents distinct technical, operational, and infrastructure requirements shaped by energy demand, fuel handling, safety compliance, and technology readiness. This section reviews the current status of hydrogen integration across these areas, with emphasis on near- and medium-term deployment opportunities informed by recent demonstrations, pilot projects, and collaborative initiatives. Although hydrogen eliminates direct CO_2 emissions at the point of use, its overall benefits depend on production pathway, infrastructure design, and effective leakage management. Safety risks associated with flammability and handling, together with environmental considerations such as indirect atmospheric effects from leakage and air-quality implications in combustion-based applications, therefore require careful engineering and operational oversight. Combustion-based hydrogen applications are addressed in two distinct airport contexts in this review: direct hydrogen combustion in aircraft propulsion and hydrogen blending or co-firing in stationary gas turbines, with the discussion organized by end use rather than by hydrogen production pathway.

3.1 Low-carbon aviation propulsion pathways

Reducing emissions from aviation propulsion requires distinguishing between pathways with near-term deployment potential and those that remain longer-term options. This subsection examines sustainable aviation fuel (SAF), including E-fuels where relevant, and hydrogen-powered aircraft as the two main hydrogen-related routes discussed in the current aviation literature. For each pathway, it reviews production and conversion routes, hydrogen requirements where applicable, integration and infrastructure needs, safety considerations, and near- to medium-term deployment prospects. The discussion also highlights the coordination required among airport authorities, fuel suppliers, OEMs, and regulators to support implementation.

3.1.1 Sustainable aviation fuel and hydrogen's role in production. SAF is a lower carbon-intensity alternative to conventional Jet A. Under Internal Revenue Service guidance, eligible SAF must achieve at least a 50% reduction in life cycle CO_2e, corresponding to a maximum carbon intensity of 44.5 g CO_2e per MJ.[24] SAF is generally treated as a drop-in fuel because it can be blended with Jet A without requiring modification to aircraft or fueling infrastructure. As of 2023, ASTM International had approved 11 production pathways with allowable blends of up to 50%, depending on the process.[25] Some pathways, however, lack aromatic hydrocarbons needed for lubrication and seal swelling, which limits blend ratios. Pathways under review, such as synthesized aromatic kerosene, may eventually support full substitution. In late 2023, Virgin Atlantic completed a transatlantic flight using 100% SAF synthesized to meet aromatic content requirements.[26,27]

In addition to stand-alone SAF routes, coprocessing of SAF feedstocks along with conventional crude fractions is permitted under ASTM D1655 specifications at up to 5% by volume.[28] This provides a potential near-term route for incremental deployment because it can reduce capital requirements and leverage existing refinery assets. For example, BP launched a task force to examine coprocessing at levels of up to 30%, although ASTM-certified deployment remains subject to the current specification limit.[29]

Among currently recognized pathways, hydroprocessed esters and fatty acids (HEFA) dominates near-term commercial deployment. HEFA uses lipid feedstocks such as waste and vegetable oils, and benefits from relatively mature processing routes, favorable conversion efficiency, and lower production costs than most alternatives, although long-term feedstock scalability remains a constraint.[30] As of early 2024, about 66% of announced U.S. SAF capacity was expected to rely on HEFA.[31]

Fischer–Tropsch (FT) synthesis converts gasified biomass or waste into liquid fuels. While the original coal-based FT route does not satisfy current carbon-intensity thresholds, more recent attention has shifted to biomass and municipal solid waste feedstocks.[32] These feedstocks can be abundant and comparatively low cost, but they typically require additional preprocessing and may deliver lower overall yields.[30] Capital intensity, gas-cleanup requirements, and process complexity therefore continue to limit FT's near-term contribution to SAF supply.[33]

Alcohol-to-jet (ATJ) conversion upgrades sugars, starches, or cellulosic biomass to ethanol or isobutanol, followed by dehydration, hydrogenation, oligomerization, and hydrotreatment to produce jet fuel.[34] Although ATJ broadens the potential feedstock base, feedstock cultivation can increase land and energy requirements, and corn ethanol may not meet the 50% life cycle reduction threshold unless paired with carbon capture or renewable electricity.[34,35] LanzaJet's commercial facility, which uses sugarcane ethanol and on-site electrolysis for hydrogen, illustrates how low-carbon hydrogen can be integrated into this pathway.[36,37]

E-fuels, produced through FT- or ATJ-type synthesis using renewable electricity, hydrogen, and captured CO_2, offer a potentially scalable route that is not constrained by finite lipid or biomass resources.[38] Their near-term deployment, however, remains limited by high electricity demand,[39] as well as by the slow build-out of low-cost renewable electricity and CO_2 capture, transport, and handling infrastructure.[40] Although direct air capture, electrolysis, and synthetic fuel synthesis have all been demonstrated at small scale,[41] integrated commercial deployment remains limited.

Hydrogen is a critical input across SAF pathways, particularly where chemical upgrading or synthetic-fuel production is involved. In the United States, hydrogen is still produced predominantly from natural gas reforming, so wider use of low-carbon hydrogen is important for reducing the overall carbon intensity of SAF.

In HEFA, hydrogen is required for hydrogenation, hydrodeoxygenation, decarboxylation, decarbonylation, hydroisomerization, and hydrocracking. Reported demand varies with feedstock composition; processing plant-based oil feedstocks typically requires about 0.08 to 0.11 kg H_2 per gallon of SAF.[42] FT upgrading can also require substantial hydrogen input. In one RWGS-assisted power-to-liquid FT configuration,

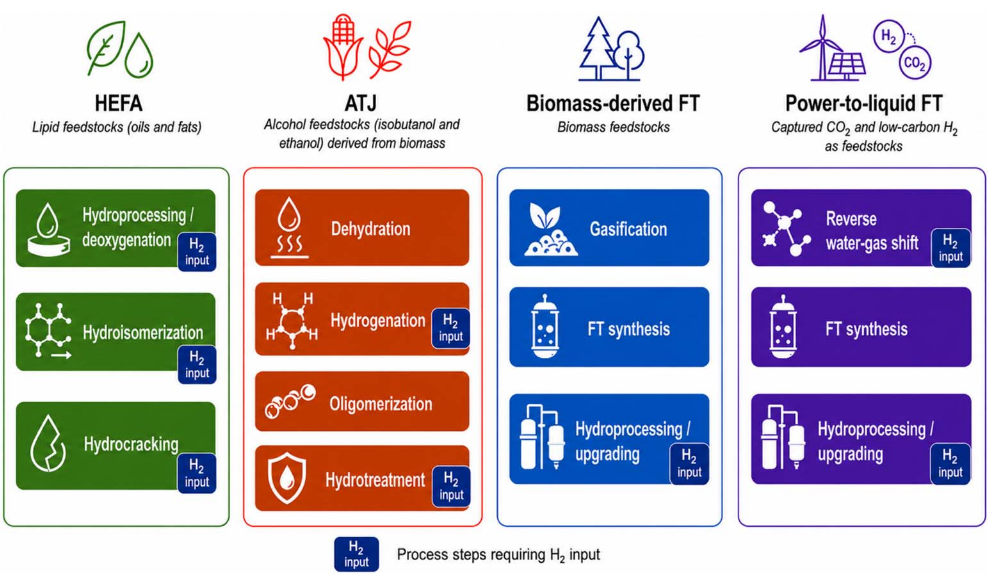

Fig. 4 Schematic of selected hydrogen-relevant process steps in SAF production for HEFA, ATJ, biomass-derived FT, and power-to-liquid FT pathways. H_2 input labels indicate process steps requiring hydrogen input.

hydrogen and CO_2 are first converted through reverse water–gas shift to produce syngas, corresponding to an estimated 1.38 kg H_2 and 8.56 kg CO_2 per gallon of FT-derived product‡.[43] In a separate modeling study of two CO_2 pathways, total electricity demand was approximately 100 to 115 kWh per gallon of product, with electrolytic hydrogen production accounting for approximately 59% to 93% of the total electricity requirement.[39] For ATJ, Fig. 4 identifies hydrogen input at the hydrogenation and hydrotreatment steps. These values are reported on different bases across the literature and should therefore be interpreted as indicative rather than directly comparable without additional normalization. Integrating low-carbon hydrogen at these stages can materially reduce life cycle CO_2e across multiple SAF pathways.

Fig. 4 identifies selected hydrogen-relevant process steps in HEFA, ATJ, biomass-derived FT, and power-to-liquid FT pathways.

Scaling SAF depends on both feedstock availability and the commercialization of emerging conversion routes. Progress from demonstration to first-of-a-kind and then commercial-scale facilities remains slow and capital-intensive. In 2021, the U.S. Departments of Energy, Transportation, and Agriculture launched the SAF Grand Challenge to expand supply, improve performance, and lower costs, with targets of 3 billion gallons annually in the near term and full displacement of U.S. jet fuel demand by 2050. Achieving 3 billion gallons will likely depend on rapid deployment of near-commercial pathways such as HEFA and ATJ together with use of existing refinery infrastructure.[44] Achieving 35 billion gallons by 2050 will require more diversified feedstocks and additional conversion routes, including pathways with potentially carbon-negative characteristics.[33]

Regional supply chains that connect local feedstocks to major airports can improve both logistics and delivered cost.[33,45] Studies have identified substantial cellulosic biomass potential in the Rocky Mountain region and in Indiana.[31,46] Within 50 to 200 miles of Chicago O'Hare, woody biomass, municipal solid waste, and crop residues could displace up to 55% of jet fuel use.[45] At the same time, competition from renewable diesel and biodiesel can constrain feedstock availability, as shown in the Seattle–Tacoma context.[47]

For PANYNJ airports, selected organic municipal solid waste and woody biomass were evaluated as potential regional FT feedstocks, although the high capital requirements of FT facilities remain a major barrier. Ref. 48 used baseline feedstock costs of $88 per dry tonne for both sorted organic municipal solid waste and woody biomass. For the municipal-solid-waste cases, the analysis assumed sorting before delivery to the plant and did not include transportation cost. Under the study assumptions, the modeled minimum fuel selling prices for total hydrocarbon output were \$2.24–\$2.53 gge^{-1} for municipal solid waste and \$2.06–\$2.44 gge^{-1} for woody biomass across the 50-, 100-, and 200-mile cases. For HEFA, the used-cooking-oil cases used a feedstock price of \$0.55 kg^{-1} and resulted in modeled minimum fuel selling prices of \$3.07–\$3.44 gge^{-1}. The soybean-oil case, which was available only within the 200-mile assessment radius, used a feedstock price of \$0.64 kg^{-1} and resulted in a modeled value of approximately \$3.74 gge^{-1}.[48] These estimates are reported in 2017 U.S. dollars for total hydrocarbon output and depend on the assumptions of the underlying techno-economic analysis.

Integration with existing jet-fuel logistics is another key requirement. Depending on production volume and blending location, SAF distribution may rely on pipelines, rail, barges, ships, or trucks.[49] The Buckeye Linden terminal supplies Jet A to EWR, JFK, and LGA but does not currently blend SAF. However, eight upstream terminals connected by pipeline could potentially support SAF storage and blending.[48] Because many U.S. pipelines already operate near capacity, alternative distribution channels may still be required.[49]

Overall, expanding SAF will require commercial progress across multiple pathways, reliable and affordable feedstocks, and integration with regional fuel logistics. Low-carbon hydrogen is relevant to reducing life cycle CO_2e in HEFA, ATJ, FT, and E-fuel routes, but its role differs markedly by pathway and by the metric used to describe hydrogen demand. HEFA is currently the most mature route, while long-term scaling will depend on overcoming feedstock, infrastructure, and cost constraints. Region-specific analyses, including those relevant to PANYNJ, therefore point to both near-term opportunities and structural limitations.

3.1.2 Hydrogen-powered aircraft: technology, infrastructure and economic considerations. There are two principal routes for using hydrogen in aircraft: electrochemical conversion in fuel cells and direct hydrogen combustion.[50] Each route presents distinct technical requirements, infrastructure implications, certification challenges, and cost drivers. Fuel cell electric concepts currently appear more relevant to commuter and regional applications, whereas hydrogen combustion remains a longer-term option for larger aircraft because of unresolved challenges related to combustor design, cryogenic integration, and emissions control.

3.1.2.1 Fuel cell electric propulsion. Fuel cell electric (FCE) aircraft use hydrogen to generate electricity that powers electric motors. At the point of use, these systems avoid direct CO_2 emissions and combustion-related NO_x formation, but their implications for contrail formation and broader atmospheric effects remain uncertain.[50] These systems are not yet commercial and are best characterized as advanced demonstrators, with technology readiness around TRL 5–6 for regional-scale applications.[51] One advantage of fuel cells is that the oxidant and fuel remain physically separated until electrochemical conversion, which reduces some combustion-related hazards. However, fuel cells generate substantial waste heat and therefore require robust onboard thermal-management systems.[51]

Hydrogen storage remains a central design constraint. The two main storage forms currently considered for aircraft are compressed gaseous hydrogen and LH_2. Compressed gaseous hydrogen can simplify fuel conditioning and is more compatible with smaller demonstrator platforms and short-range missions, but its low volumetric energy density imposes

‡ Note that FT fuel here is not a final SAF product but an intermediate, which includes naphtha (35%), jet fuel (42%), and diesel (23%).

substantial tank-volume penalties. Liquid hydrogen provides higher volumetric energy density than gaseous storage and is therefore the more plausible option for larger aircraft and longer-range operation, but it introduces cryogenic requirements, including insulation, boil-off management, and more complex tank integration. Even in liquid form, hydrogen has much lower volumetric energy density than kerosene, which affects aircraft layout, payload, and range. Tank mass and system performance depend on storage state, pressure rating, materials, insulation, and integration strategy, with direct implications for aircraft configuration and operating economics.[51,52]

FCE viability also depends strongly on specific power. Industry targets generally exceed 1 kW kg^{-1}, and demonstrations have reported values near 1.5 kW kg^{-1}.[53] Because aircraft performance is highly weight-sensitive, this parameter has major implications for airframe mass, range, and operating economics. Battery-electric aircraft remain more constrained by range and payload, whereas hydrogen fuel cells may offer a broader envelope for commuter and regional operations, particularly where rapid turnaround and higher daily utilization are required.[54]

3.1.2.2 Direct hydrogen combustion propulsion. Hydrogen combustion in modified gas turbines is technically feasible but currently less mature than fuel cell electric propulsion for aviation.[55] Hydrogen combustion does not emit CO_2 at the point of use, but higher flame temperatures can increase NO_x formation unless controlled through combustor design, dilution strategies, and operating controls.[56] Water vapor emissions are also higher than for Jet A on an energy-equivalent basis, and the absence of soot changes contrail microphysics in ways that remain under active study.[57] Under the ZEROe program, engine concepts and contrail effects are being investigated as part of the broader hydrogen-aircraft development pathway.[58,59]

Medium-haul hydrogen combustion concepts are expected to rely on LH_2 because gaseous storage would impose excessive volume penalties.[60–62] This introduces additional requirements for cryogenic tanks, boil-off management, insulation, structural integration, and fuel conditioning before combustion. As a result, hydrogen combustion is generally viewed as a longer-term option for larger aircraft, contingent on further progress in both engine and storage technologies.

3.1.2.3 Technological readiness and safety considerations. FCE platforms currently lead development compared to hydrogen combustion aircraft, particularly in the commuter and regional segments. ZeroAvia has targeted 9–19-seat retrofits, including the Dornier 228 and Cessna 208B, using gaseous-hydrogen storage, while larger regional aircraft, including the ATR 42/72 and DHC Dash 8 classes, would likely require LH_2 to extend range and remain at lower readiness levels.[63,64] Airbus has also tested an integrated six-unit, approximately 1.2 MW fuel cell concept for a 100-seat regional aircraft.[55] Universal Hydrogen ceased operations in 2024 after several flight tests that nevertheless provided useful early technical evidence.[65] Recent studies have also examined configuration, performance, and cost implications of fuel cell propulsion for regional and single-aisle aircraft, helping clarify the challenges associated with scaling beyond commuter platforms.[66]

Hydrogen combustion aircraft are likely to enter later because they require new combustor architectures and tighter control of NO_x, flame stability, thermal loading, and fuel-system integration.[67] Their earliest practical role is more likely to be in selected short-haul to medium-haul applications, while SAF is expected to remain the dominant lower-emission pathway for much of the existing fleet over the coming decades.[54]

Safety is central to certification for both approaches. Hydrogen's wide flammability range, low ignition energy, and high diffusivity require rigorous leak prevention, detection, ventilation, and shutdown strategies.[55] Additional risks include flame invisibility, boil-off overpressure, and hydrogen embrittlement of metals.[68] Cryogenic storage introduces further complexity because LH_2 expands by about 1 : 848 on vaporization, requiring robust insulation, pressure-relief systems, vent management, and materials compatibility.[69] In practice, safety evaluation for hydrogen aircraft and associated fueling systems relies on structured hazard identification together with quantitative or semi-quantitative assessment of leak, dispersion, ignition, and overpressure scenarios.[70] These approaches are important for informing tank placement, ventilation, emergency procedures, and certification planning in both onboard and airport-side systems. Certification frameworks must therefore address crashworthiness, redundancy, fuel containment, thermal protection, structural durability, and maintainability, while international harmonization of standards will also be necessary as hydrogen aircraft move toward commercial deployment.

Table 1 compares the principal technical, emissions, infrastructure, and safety characteristics of fuel cell electric and hydrogen combustion aircraft.

3.1.2.4 Airport hydrogen fueling systems and supply pathways. Refueling requirements depend strongly on hydrogen state and aircraft size. Early FCE operations may rely on mobile 350–700 bar gaseous-hydrogen fueling units supplied from off-site production, which can support pilot operations without immediate investment in permanent airport-wide infrastructure.[64] At larger scales, however, commercial operations are more likely to depend on LH_2 supplied by road tankers, gaseous hydrogen delivery by pipeline with on-site centralized liquefaction, or on-site electrolysis coupled with liquefaction. Because hydrogen has low volumetric energy density, delivery frequency and storage requirements increase rapidly with demand.[72] Pipeline supply from hydrogen hubs could reduce unit costs but would require major investment, permitting, and materials qualification, while repurposing natural-gas pipelines remains constrained by embrittlement, code compliance, and operating-pressure limits.[73]

On-site electrolysis offers a modular and potentially low-emission supply option, but it is both electricity- and space-intensive. At Chicago O'Hare, an estimated 719 tonnes per day of LH_2 would require about 44.5 GWh per day and more than 1.5 GW of renewable generation, while liquefaction can consume up to 30% of hydrogen's energy content.[60] Electrolyzers, liquefiers, and cryogenic storage systems also require substantial

Table 1 Comparison of fuel cell electric and hydrogen combustion aircraft by technical, emissions, and infrastructure characteristics

Parameter	Fuel cell electric (FCE) aircraft	Hydrogen combustion aircraft
Propulsion route	Electrochemical conversion in fuel cells powering electric motors	Modified gas turbines or turbofans using hydrogen combustion
Primary hydrogen form	Compressed gaseous hydrogen for short range; LH_2 for extended range	LH_2 generally required
Development horizon	Nearer-term focus for commuter and regional demonstrators[63,64,71]	Longer-term option for larger aircraft classes[54,67]
Technology readiness	Approximately TRL 5–6 for regional aircraft demonstrators[55]	Lower maturity, commonly around TRL 3–4 for conceptual and component-level development[55,67]
NO_x emissions at point of use	None from the propulsion conversion process	Potentially significant unless mitigated through combustor design and controls[56]
CO_2 emissions at point of use	None	None
Water vapor and contrail implications	Lower direct combustion-related effects; uncertainty remains[54]	Higher water-vapor emissions and contrail effects remain under study[57]
Particulate matter emissions	None from combustion	Negligible soot-related particulate emissions
Powertrain efficiency	High, typically about 45–60%	Moderate, typically about 30–45%
Storage requirements	Gaseous or cryogenic hydrogen with integration of tanks, fuel cells, power electronics, and cooling systems	Cryogenic hydrogen tanks, fuel conditioning, combustion-system redesign, and thermal management
Airport infrastructure implications	Hydrogen storage, quality control, fueling, electrical integration, and thermal-support systems	LH_2 fueling, cryogenic handling, higher-throughput delivery, and combustion-system support
Main safety considerations	Leak detection, thermal management, electrical integration, flame invisibility, and containment of gaseous or cryogenic hydrogen	Cryogenic handling, boil-off management, combustion stability, NOx control, phase-change hazards, and pressure-relief requirements
Most plausible early applications	Commuter and regional routes	Longer-term short-haul to medium-haul concepts
Example programs	ZeroAvia Dornier 228 and Cessna 208B retrofits; Airbus fuel cell demonstrator	Airbus hydrogen combustion concepts

physical footprint and must comply with NFPA 2 separation distances.[74] Geological storage options such as salt caverns are geographically limited.[75,76] Where pipelines are not available, multiple LH_2 tanks would be needed. For context, the largest active LH_2 tank at Kennedy Space Center holds about 1.25 million gallons, whereas Jet A storage at JFK exceeds 26 million gallons.

NFPA 2 also introduces practical siting constraints. The listed setback distances apply to aggregate LH_2 quantities up to 75 000 gallons, and larger airport-scale systems typically require additional engineering review and permitting scrutiny.[77] As traffic grows, refueling systems would likely need to transition from mobile bowsers to more permanent hydrant-based systems. LH_2 hydrants are more complex than conventional Jet A systems because of cryogenic conditions, insulation requirements, leakage risk, material compatibility, and the need for redundancy and continuous monitoring.[55,78]

Preventing oxidizer ingress is a critical issue in cryogenic fueling operations. Systems typically maintain positive pressure and purge residual gases to prevent contamination and freezing.[78] Nitrogen is generally unsuitable for LH_2 purging because it can condense under cryogenic conditions, whereas helium is technically preferable but costly and supply-constrained.[79] Clean-break disconnect systems may reduce purging demand, but these designs still require validation for routine aviation use.[60]

Fueling rate strongly affects aircraft turnaround time. Gaseous hydrogen fueling rates of about 14–21 kg min^{-1} have been demonstrated in heavy-duty vehicle applications.[73] NASA shuttle operations achieved LH_2 transfer rates of roughly 580 kg min^{-1}, but even that may be insufficient for future wide-body aviation needs, indicating that further advances in cryogenic flow management, pressure control, and real-time monitoring will be necessary.[80–82]

3.1.2.5 Total cost of ownership. Commercial viability ultimately depends on total cost of ownership (TCO), including propulsion capital cost, hydrogen and electricity prices, maintenance, infrastructure, and operational effects. For FCE aircraft, major cost drivers include the fuel cell stack, hydrogen storage system, thermal management, and specific power. Higher specific power can reduce airframe mass and fuel use, while longer stack life and lower stack cost improve lifecycle economics.[53] Sensitivity studies indicate that specific power is among the most influential variables in FCE-dominant architectures, together with storage mass, gravimetric efficiency, stack cost per kilowatt, and annual utilization.[83]

For battery-dominant hybrids, TCO is more sensitive to battery specific energy, cycle life, and annual utilization because higher use accelerates degradation and replacement cost.[83] For hydrogen combustion aircraft, propulsion-system capital cost may benefit from partial use of modified turbine architectures, but cryogenic storage, fuel-system complexity, and high-throughput fueling requirements add significant cost, while lower conversion efficiency increases fuel consumption per unit thrust.[56] Operating cost also depends on LH_2 price, NO_x-compliance requirements, and thermal-management demands.[67]

At the airport level, TCO extends beyond the aircraft to include storage, distribution, fueling systems, permitting, and safety compliance. Hydrogen infrastructure generally requires more space, higher upfront capital, and more stringent regulatory review than conventional Jet A systems. Economic assessments therefore need to include boil-off losses, turnaround-time impacts, maintenance of safety systems, and the cost implications of nonroutine permitting pathways.[77,78] Limits on gaseous fueling rates and logistics can also increase labor and scheduling costs.[73]

Competitive TCO will require simultaneous gains in propulsion performance, reductions in hydrogen and infrastructure cost through scale, and operational optimization. Early adoption is most plausible where missions are predictable, utilization is high, and emissions or air-quality objectives justify higher upfront cost, such as regional passenger services, short-haul cargo operations, or other centralized fleet applications. Comparative assessment against battery-electric and SAF pathways across mission types and distance classes therefore remains essential.

Hydrogen aviation timelines will ultimately depend on coordinated progress in propulsion technology, refueling infrastructure, safety assurance, and certification. Fuel cell electric aircraft appear to be the medium-term hydrogen option for aviation, whereas hydrogen combustion is likely to remain a later pathway for larger aircraft. The implications of hydrogen for ground support equipment and stationary power systems are discussed further in Sections 3.2 and 3.3.

3.2 Ground support equipment (GSE) and vehicles

GSE and associated airport vehicles, including airside baggage tractors, belt loaders, tow tractors, and landside shuttles, represent an important airport emissions segment because they are closely tied to routine airside and landside functions and are more directly accessible to airport-level operational and infrastructure interventions than aircraft propulsion. These fleets typically operate with predictable duty cycles, repeated daily use, and equipment-specific performance requirements, which makes them a useful testbed for comparing hydrogen and battery-electric technologies. This subsection reviews technology status, field demonstrations, and integration barriers for hydrogen-powered GSE and airport vehicles and evaluates scaling pathways and infrastructure needs. It also compares hydrogen with battery-electric options to assess feasibility, cost, and readiness across equipment classes.

3.2.1 Technology status, demonstrations, and integration barriers. Integrating hydrogen technologies into airport GSE offers a potential route to reduce on-site emissions, diversify energy supply, and address operational constraints in equipment classes that are difficult to electrify under all duty conditions. The transition remains challenging because GSE fleets are heterogeneous, with equipment-specific operational characteristics and duty cycles that complicate technology choice and scheduling.[84] In addition, airport-specific data on equipment utilization and energy demand are often limited, and replacement timing and total-cost information are not consistently available in public sources.[85] As a result, cost effectiveness depends strongly on equipment type, duty cycle, fueling access, and local electricity constraints. High-utilization assets appear to offer the strongest operational case for hydrogen, but they also impose demanding runtime and refueling requirements.

3.2.1.1 Feasibility studies and demonstrations. Ground power units that supply electricity to parked aircraft are among the more suitable candidates for hydrogen fuel cell integration. Their fixed location, relatively steady load, and high utilization, often exceeding 15 hours per day, favor fuel cell electric retrofits.[86] Additional assessments report reliable operation and potential cost effectiveness, although total cost of ownership remains a barrier because of higher capital cost and infrastructure requirements.[87]

At Albany International Airport, plug power converted Charlatte baggage tow tractors to fuel cells. The units met performance targets, including a top speed of 10 mph, operation over three to four shifts, and cargo-handling capacity of 40 000 lb, but the planned deployment was reduced from 15 to 2 units because of infrastructure constraints and single-shift scheduling.[88] A U-30 aircraft tow tractor retrofit at a U.S. Air Force base in Hawaii incorporated a 30 kW fuel cell, 10 kg hydrogen storage system, and a 22 kWh plug-in battery, enabling an operating range of about 12 hours and a maximum drawbar pull of 72 000 lb.[89] In Europe, Groningen Airport Eelde supported certification of a 40 kW fuel cell ground power unit with 10 kg of hydrogen storage at 350 bar and a 70 kWh battery, partly in response to long charging times and charger bottlenecks observed in earlier battery-electric trials at Amsterdam Schiphol.[90]

Demonstration projects involving logistics operators also highlight cargo-related applications. A U.S. Department of Energy-supported deployment of hydrogen fuel cell hybrid-electric UPS delivery vans in disadvantaged communities demonstrated operational feasibility in urban delivery settings and highlighted emissions reduction potential.[91]

3.2.1.2 Market acceptance and economic considerations. Despite moderate to high technological readiness in several equipment classes, hydrogen-powered GSE faces significant barriers to commercial uptake. Battery-electric equipment remains the preferred option for many airport operators because of lower capital costs, simpler infrastructure, and stronger current policy support. By 2023, American Airlines, Delta, Southwest, and United reported fleet electrification levels of 23%, 31%, 37%, and 35%, respectively.[92–95] PANYNJ has also mandated that, by 2030, only zero-emission airside vehicles can be newly registered unless alternatives are not commercially available or operationally feasible.[22]

Table 2 Comparison of representative hydrogen fuel cell GSE with diesel counterparts, including operational metrics and technology readiness

Application	H_2 FCE TRL[a]	Average H_2 demand[b] (diesel gallon equivalent per day per unit)	Average diesel demand (gal per day per unit)
Aircraft tractor[c]	7	43	61
Cargo/baggage tractor[d]	7	20	28
Forklift[e]	—	6	9
Ground power unit[f]	6	20	28

[a] TRL is based on OEM activities to date. FCE forklifts for Classes I–III are commercially available; however, the representative model refers to heavy-duty forklifts, where demonstrations have not yet been conducted.[101] [b] To convert kilograms to diesel gallon equivalent, values were multiplied by the ratio of lower-heating-value energy densities of hydrogen (120 MJ kg^{-1}) and ultra-low-sulfur diesel (134.47 MJ per gal).[102] These values support energy-equivalent comparison only and do not imply equivalent storage, fueling rate, or infrastructure requirements. [c] Representative model: JBT B1200 Push Back Tractor (DBP, 72 000 lb). The JBT B1200 aircraft tractor can accommodate aircraft with a maximum takeoff weight from 75 to 590 metric tons, including wide-body aircraft such as B747 and A380.[103] [d] Representative model: TUG MT (MDP, 12 000 lb). The MT can be used as a heavy-duty cargo/baggage towing tractor and as a pushback for narrow-body and regional aircraft.[104] [e] Representative model: Toyota High-Capacity IC Pneumatic (45 000–72,000 lb).[105] [f] Representative model: TLD 28 VDC.[106]

Battery-electric models are now widely available and often function as drop-in replacements for conventional equipment.[96] For many airports, this makes battery-electric GSE the most practical near-term pathway because the technology is commercially established, infrastructure requirements are comparatively straightforward, and current regulatory momentum already favors fleet electrification.[97] The main limitations arise in high-utilization applications, where maintaining shift coverage may require larger batteries, spare units, or opportunity charging.[98] Under such conditions, fuel cell systems can offer longer runtime and faster refueling, which may reduce operational disruption where charger congestion, peak-demand charges, space limitations, or delayed utility upgrades constrain further battery-electric expansion. Available analyses further suggest that authority-owned light-duty vehicles are relatively straightforward to electrify, whereas vocational assets such as sweepers and snowplows have higher fuel use despite lower annual operating hours and therefore remain more difficult to transition in the near term.[22]

Hydrogen may also serve as a bridging option where electrification is constrained by delayed grid upgrades. One proposed approach uses hydrogen-powered mobile chargers for electric vehicles to reduce reliance on diesel generators and support phased electrification.[99] Platform modularity can further reduce transition risk: some OEMs now offer equipment compatible with lead-acid batteries, lithium-ion batteries, or fuel cells, allowing powertrain selection to evolve with site conditions and infrastructure readiness.[100] In this context, hydrogen is better understood as a selective complement to battery-electric deployment rather than a universal replacement, with the strongest case in demanding duty cycles or at airports where electrical-infrastructure constraints remain unresolved.

Hydrogen-powered GSE also introduces distinct safety requirements. High-pressure hydrogen storage, invisible flames, and leak-management risks require equipment-specific safety protocols, operator training, ventilation measures, and appropriate gas-detection systems. These requirements are not peripheral considerations; they are prerequisites for commercial-scale deployment.

Overall, hydrogen-powered GSE is technically feasible and approaching deployment readiness in several equipment categories, but commercialization remains constrained by capital cost, fueling infrastructure, and safety-compliance requirements. Battery-electric equipment remains the primary near-term pathway across much of the sector, while hydrogen appears most relevant for high-utilization applications, duty cycles that strain battery-only operation, or airports facing grid and charging limitations.

3.2.2 Scaling pathways and infrastructure readiness. Scaling hydrogen use at airports requires coordinated integration across vehicles, fueling systems, site layout, safety procedures, and longer-term aviation demand. Estimating hydrogen consumption is therefore important for infrastructure planning and prioritization. Table 2 summarizes indicative hydrogen demand for representative GSE relative to diesel baselines using duty-cycle assumptions of 12 hours per day for aircraft tractors, cargo and baggage tractors, and ground power units, and 6 hours per day for forklifts. Actual usage will vary with landing and takeoff activity, aircraft mix, cargo *versus* passenger operations, equipment dispatch patterns, and carrier-specific practices. Detailed assumptions and calculations are provided in Appendix A.

Despite the limitations discussed in the previous subsection, a growing number of airports now operate hydrogen refueling stations for ground vehicles.[107] These deployments build practical familiarity with hydrogen handling, refueling logistics, safety management, and permitting, while also creating a foundation for larger future uses. Demonstrations involving baggage tractors, ground power units, and airside shuttles are frequently described as first steps toward broader airport hydrogen hubs.[72,108,109]

At Toulouse–Blagnac Airport, Airbus and its partners installed on-site electrolysis with a production capacity of 400 kg per day together with two hydrogen stations. One station serves airside applications such as ground power units and aircraft tractors, while the other supports landside buses and light-duty vehicles.[110] This example illustrates how early airport hydrogen systems are more likely to emerge through staged

Table 3 Comparative combustion properties of hydrogen and methane and implications for turbine operation

Properties	Hydrogen	Methane	Implications for equipment	References
Lower heating value, Btu per scf	290	983	Higher volumetric flow is required for equivalent energy input	111–113
Adiabatic flame temperature, °F	4089	3565	Higher temperatures can alter combustion dynamics and thermal loading	111 and 114
Flame speed, cm s^{-1}	200–300	30–40	Higher flashback and instability risk; potential hardware damage if not controlled	111, 112 and 114

multi-use deployment rather than through immediate aviation-scale supply.

Longer-term planning scenarios anticipate that, if hydrogen-powered aircraft are deployed, aircraft refueling would dominate hydrogen demand by a wide margin. Infrastructure would then need to be sized for peak aviation demand and, where feasible, coordinated with ground-vehicle demand while accounting for operational conflicts and reliability requirements.[72] Under such conditions, on-site electrolysis alone is unlikely to satisfy the needs of medium and large airports.[73] Larger-scale supply would more likely depend on a combination of delivered hydrogen, centralized production, liquefaction capacity, and airport-specific storage and distribution systems. At the same time, projections for aircraft adoption remain uncertain and, in some scenarios, extend well into the 2050s.[72]

In the near term, battery-electric GSE remains the most practical route for meeting 2030 zero-emission targets at many airports, including PANYNJ, because it aligns with current equipment availability, existing charging deployments, and near-term regulatory direction. Continued battery-electric deployment does not eliminate a role for hydrogen, however. Instead, it may clarify where hydrogen offers the greatest incremental value, particularly in high-utilization applications, in locations affected by charger congestion or peak-demand penalties, or where utility upgrades lag behind fleet-transition goals. In that sense, battery-electric deployment and hydrogen adoption should not be viewed only as competing pathways. Early electrification can reduce the number of equipment classes that require hydrogen, while also helping define the narrower but potentially durable roles in which hydrogen may support operational flexibility and future shared airport energy infrastructure.

Overall, hydrogen integration into airport vehicles and GSE remains at an early stage. Demonstrations and initial fueling stations are valuable because they provide operational experience with logistics, permitting, and safe handling while revealing cost, siting, and scalability constraints. Long-term success will depend on aligning infrastructure build-out with actual demand growth across both ground and aviation applications, supported by clear regulatory pathways and sustained investment in scalable hydrogen supply systems.

3.3 Stationary power systems

Airports face rising electricity demand from the electrification of ground operations, expanding terminal and facility loads, and the need for high-reliability energy supply. These trends increase interest in resilient, lower-emission stationary power systems. This section evaluates hydrogen in stationary power systems through two pathways: co-firing with natural gas in existing gas turbines and integration into microgrids using fuel cells. It reviews technology readiness, emissions implications, operational challenges, and infrastructure requirements for both applications, drawing on demonstration projects and a site-specific case study at JFK.

3.3.1 Technology status and challenges of hydrogen co-firing in gas turbines. Hydrogen co-firing in gas turbines represents a transitional approach for reducing CO_2e emissions in airport power systems while continuing to use existing thermal assets. Partial substitution of natural gas with hydrogen in combined heat and power (CHP) plants can provide incremental emissions reduction without full system replacement. For airports with substantial thermal loads and stringent reliability requirements, such as JFK's Kennedy International Airport Cogeneration (KIAC) facility, this offers an intermediate pathway that can complement electrification and renewable integration. This subsection reviews the technological basis of hydrogen co-firing, turbine-compatibility issues, emissions implications, operational constraints, and airport-specific deployment considerations.

3.3.1.1 Combustion properties and turbine compatibility. Hydrogen differs substantially from methane in ways that directly affect gas-turbine hardware, control systems, and emissions performance. Key differences include lower volumetric energy content, higher adiabatic flame temperature, and much higher flame speed. Table 3 summarizes selected thermophysical properties and their implications for turbine operation.

Hydrogen's lower volumetric energy density requires higher fuel flow rates for equivalent heat input and may necessitate resizing or redesign of fuel-delivery hardware. Its faster flame speed and higher reactivity require more precise fuel–air mixing and tighter combustor control to avoid flashback, blowout, and unstable flame anchoring, especially in lean premixed systems originally optimized for natural gas.[114] These characteristics can also require changes to combustor geometry, materials, and cooling strategies.

Compatibility depends strongly on combustor design. Lean premixed systems, which are widely used to limit NO_x emissions, are often sensitive to fuel-composition changes and may require substantial modification to accommodate hydrogen

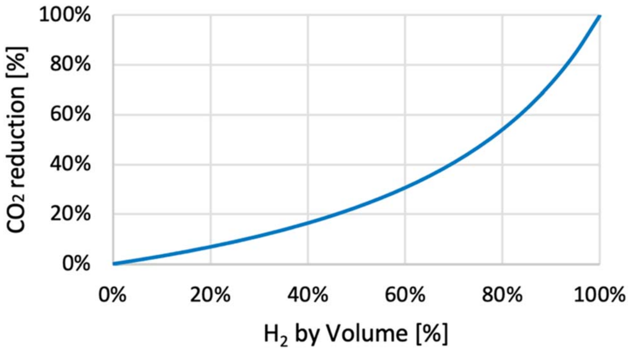

Fig. 5 CO_2 emissions reduction potential as a function of volumetric hydrogen co-firing with natural gas.

blends.[114] Diffusion combustors are generally more tolerant of variable fuel composition, but they tend to produce higher NO_x and may therefore require more extensive downstream emissions control.[115] OEM retrofit options have nevertheless emerged. For example, PSM's FlameSheet system has demonstrated co-firing up to 50 vol% hydrogen while managing combustion stability and NO_x through tailored mixing and flame anchoring.[116] Retrofit scope typically includes new fuel nozzles, liners, controls, skids, and safety instrumentation, with modification requirements increasing as blend fraction rises.[112] Elevated combustion temperatures also increase thermal-fatigue risk and strengthen the need for enhanced cooling and high-temperature materials. Computational modeling and targeted testing therefore remain necessary to validate performance across load ranges and blend conditions.

3.3.1.2 Emissions implications and control strategies. Hydrogen blending lowers CO_2 emissions in proportion to the amount of natural-gas-derived energy displaced, but the relationship is not linear with volumetric blend fraction because hydrogen has lower volumetric energy density than methane. For example, 5 vol% hydrogen corresponds to only about a 1.5% reduction in CO_2 emissions, whereas 35 vol% corresponds to about 13.7%, assuming constant thermal input, as illustrated in Fig. 5. The principal technical challenge is NO_x. Hydrogen's higher adiabatic flame temperature, approximately 4089 °F (2254 °C), increases the tendency for thermal NO_x formation under conventional combustion conditions,[111,114] and uncontrolled combustion can yield substantially higher NO_x than natural gas firing.[111]

Mitigation strategies include lean premixed combustion, water injection, flame dilution, and selective catalytic reduction (SCR). Hydrogen combustion also produces negligible sulfur and particulate matter, which can reduce some catalyst-fouling concerns. However, because stationary gas turbines operate with oxygen-rich exhaust, three-way catalysts are not applicable. NO_x control therefore depends on a combination of combustor strategies, such as lean premix or water/steam injection, and downstream SCR, with separate oxidation catalysts used where needed for CO and unburned hydrocarbons. At JFK's KIAC plant, diffusion combustors with water injection and downstream SCR currently meet the U.S. Environmental Protection Agency NO_x limit of 9 ppm at 15% O_2 for combined-cycle plants larger than 50 MW fired on natural gas.[117,118]

Recent demonstrations indicate that permit-compliant NO_x performance is achievable at moderate hydrogen-blend levels when control strategies are matched to combustor type. On GE LM6000 and Mitsubishi M501G platforms, NO_x remained within applicable limits at roughly 20 to 44 vol% hydrogen, using lean premixed combustion on premix-capable systems and proportional water injection on diffusion systems.[119,120] These results also show important tradeoffs, including increased water demand, modest efficiency penalties during water-injected operation, and the need for carefully tuned SCR systems to limit ammonia slip. Performance remains platform specific.

3.3.1.3 Demonstration projects and case studies. At the Brentwood Power Station in New York, a 45 MW simple-cycle GE LM6000 turbine co-fired hydrogen at 5 to 44 vol%. CO_2 emissions were reduced by up to 20% relative to 100% natural-gas firing, and stable combustion was achieved without hardware changes. Operation, however, was limited to approximately 12 hours because hydrogen was supplied by tube trailers with manual pressure regulation.[120]

At the McDonough–Atkinson Power Station in Georgia, a Mitsubishi M501G combined-cycle unit operated with up to 20.9 vol% hydrogen. At the highest blend, CO_2 emissions were reduced by about 7%, accompanied by a modest efficiency penalty. Permit compliance was maintained through lean premixed combustion and downstream SCR.[119]

Additional OEM demonstrations report NO_x concentrations between 25 and 50 ppm at 15% O_2 for blends up to 50 vol%, depending on combustor design and the effectiveness of water injection and fuel-air mixing.[121]

The Brentwood demonstration is particularly relevant to JFK because Brentwood and KIAC share several important characteristics, including single-annular combustors, water injection, SCR, and aeroderivative LM6000 cores. Brentwood therefore provides a useful analogue for assessing technical feasibility at KIAC. At the same time, the results should not be treated as directly transferable. NO_x formation depends on flame temperature, equivalence ratio, residence time, turbulence intensity, mixing uniformity, combustor geometry, and operating conditions. Longer-duration field data would be needed before defining a reliable operating envelope for KIAC under sustained hydrogen blending.

3.3.1.4 Challenges and future outlook. Key technical challenges include combustion instability, NO_x control at higher blend levels, and reliable hydrogen supply. Hydrogen's fast reaction kinetics increase the risk of flashback and dynamic instability, particularly in lean premixed systems that achieve low NO_x on natural gas but have more limited fuel flexibility.[111,114] Although retrofits up to about 50 vol% have been demonstrated on selected platforms, higher blends often require major redesign of combustors, fuel-delivery systems, and controls.[112]

Maintaining emissions compliance requires robust integration of premixing strategies, water or steam injection, and SCR. Long-term effects on catalyst durability, thermal loading, maintenance intervals, and overall plant efficiency also require further monitoring and optimization under varying load conditions and blend fractions.[118,120]

Hydrogen supply remains a practical constraint. Even relatively low blend levels can require frequent deliveries when hydrogen is supplied by tube trailer, suggesting that large-scale deployment would likely depend on LH_2 storage, pipeline supply, or on-site production.[112,120] Balance-of-plant upgrades, including sensors, enclosures, ventilation, and fuel skids, will also vary by turbine model, target blend level, and permitting environment.[112]

Overall, hydrogen co-firing offers a practical near-to mid-term pathway for reducing CO_2e emissions in airport stationary power systems while reusing existing generation assets. Demonstrations on platforms relevant to KIAC indicate that moderate blend levels are technically feasible when accompanied by appropriate combustion control and NO_x-mitigation strategies. Broader deployment will require platform-specific retrofit design, validated emissions-control performance, and reliable hydrogen logistics. Progress in airport settings will therefore depend on coordinated efforts among OEMs, utilities, regulators, and airport operators, together with longer-duration operation to define stable performance envelopes, assess long-term catalyst durability, and inform cost-effective implementation strategies.

3.3.2 Hydrogen-enabled microgrids for airport power and resilience. This subsection examines hydrogen-enabled microgrids as a decentralized energy solution for airports, with emphasis on their capacity to provide resilient, fuel-flexible, and lower-emission power. In contrast to centralized cogeneration systems, microgrids can integrate distributed generation, fuel cells, storage, and controllable thermal assets to serve localized loads under both grid-connected and islanded operation. In airport settings, this architecture is particularly relevant because critical loads such as terminal systems, control infrastructure, security functions, and essential thermal services require high reliability under both normal and contingency conditions. Hydrogen's role in these systems, particularly through stationary fuel cells, creates a pathway toward modular expansion, improved resilience, and lower-emission operation.

3.3.2.1 Microgrid integration with hydrogen. Hydrogen-enabled microgrids are emerging as a flexible architecture for localized generation, storage, and distribution at airports. These systems can operate either in parallel with the main grid or independently during disruptions, thereby maintaining service during outages and peak-load events. Their core characteristics include proximity of supply and demand, integration of multiple generation sources, and the ability to isolate from the grid when necessary.[122]

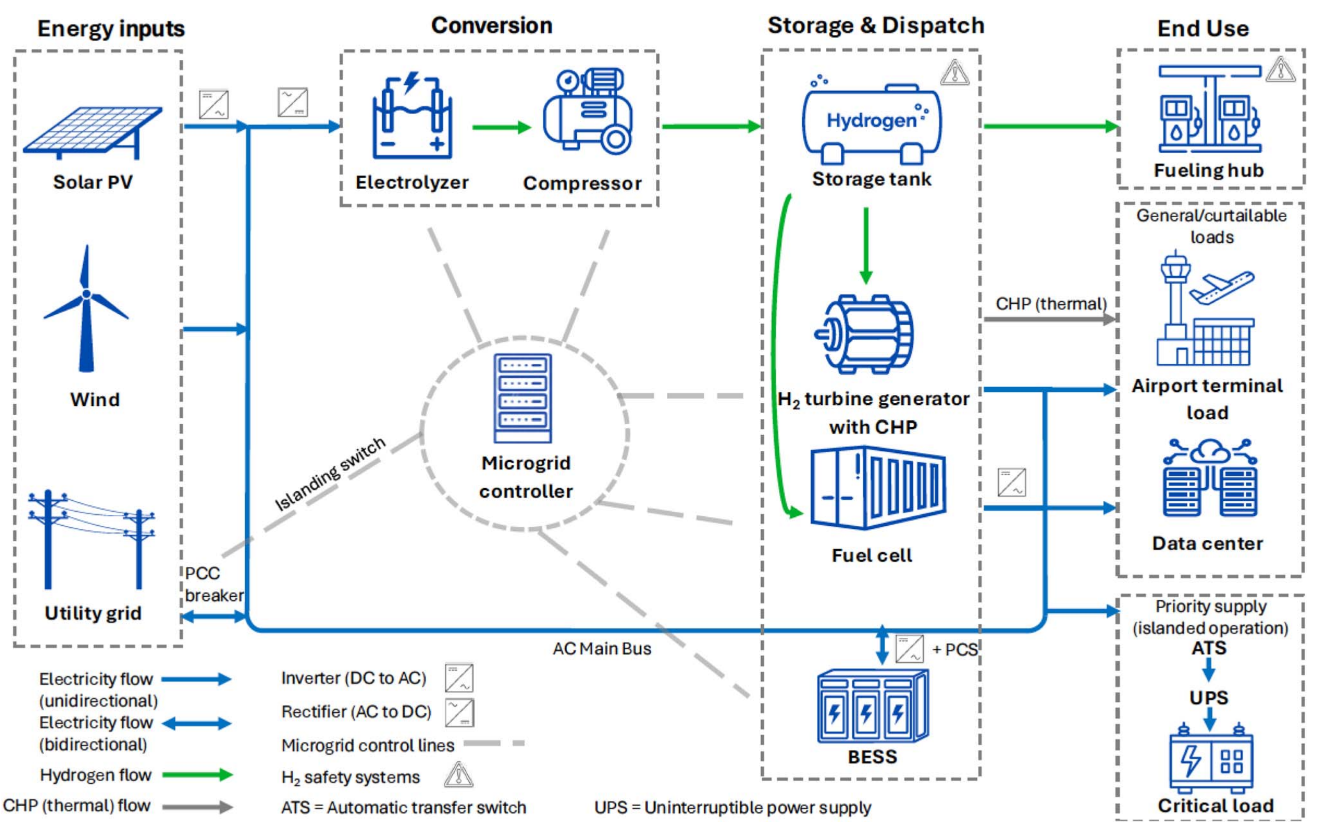

Fig. 6 Illustrative schematic of a hydrogen-enabled airport microgrid. The configuration combines solar PV, wind, and utility-grid inputs with electrolysis, compression, hydrogen storage, a fuel cell, a hydrogen turbine generator with CHP, and battery energy storage. Coordinated dispatch supports airport terminal loads, a fueling hub, a data center, and priority critical loads under both grid-connected and islanded operating conditions.

Integrating hydrogen, particularly through stationary fuel cells, expands the set of lower-emission and dispatchable generation options while improving operational flexibility. Depending on fuel cell type and system configuration, hydrogen can be supplied directly or produced on site through reforming of natural gas or biogas. Relative to diesel backup systems, hydrogen fuel cells can provide continuous power with no direct NO_x or particulate emissions at the point of use. This makes them especially attractive in airport environments where air quality, reliability, and operational continuity are all important.

As illustrated in Fig. 6, one hydrogen-enabled airport microgrid configuration can integrate solar PV, wind, and utility-grid electricity with an electrolyzer-compressor train, hydrogen storage, a fuel cell, a hydrogen turbine generator with combined heat and power (CHP), and battery energy storage. A microgrid controller coordinates conversion, storage, and dispatch across the AC main bus, while automatic transfer switch and uninterruptible power supply arrangements support priority islanded operation for critical loads. In this configuration, the system can serve airport terminal loads, a fueling hub, data-center demand, and other critical services, while also providing usable thermal output from the CHP unit where required.

3.3.2.2 Fuel cells in microgrids. Fuel cells are central to hydrogen-enabled microgrids because they provide continuous, lower-emission electricity and can support CHP. When supplied with hydrogen, fuel cells produce electricity, water, and usable heat at the point of use without combustion-related NO_x or particulate emissions. High-temperature systems can also operate on reformed natural gas or biogas, in which case emissions characteristics depend on fuel and system configuration. Several fuel cell types are relevant to airport microgrids.[123]

Proton exchange membrane fuel cells operate at approximately 80 °C, offer rapid startup, and are well suited to dynamic load following and responsive backup or peaking roles. Their relatively compact footprint can be advantageous where space is constrained. Solid oxide fuel cells operate at roughly 500 to 1000 °C, provide high electrical efficiency, and can use hydrogen, natural gas, or biogas, making them attractive where fuel flexibility and high-grade waste heat are valuable. Phosphoric acid fuel cells operate at approximately 150 to 200 °C, are commercially mature for stationary baseload service, and can tolerate fuel impurities under continuous operation. Molten carbonate fuel cells operate at around 600 to 700 °C, offer high fuel flexibility and strong CHP performance, but their deployment remains more limited because of thermal-integration complexity and larger system requirements.[123,124]

Fuel flexibility is a major advantage of the high-temperature systems, particularly solid oxide and molten carbonate fuel cells, which can use on-site reformed fuels. By contrast, proton exchange membrane systems generally require high-purity hydrogen. Load-following capability in proton exchange membrane and phosphoric acid systems can also improve dispatch under variable demand and time-of-use electricity pricing, which is relevant for airport facilities with both critical and flexible loads.[124]

3.3.2.3 New Terminal One microgrid at JFK. The New Terminal One project at JFK provides a useful example of an integrated airport microgrid designed to enhance resilience while creating a pathway toward lower-emission power. The planned 12 MW on-site microgrid combines 6.63 MW of rooftop photovoltaics, 3.84 MW of phosphoric acid fuel cells, and a 1.5 MW/3.34 MWh lithium-ion battery energy storage system to serve critical loads and support islanded operation during disturbances or peak events.[125]

The fuel cells are initially configured to operate on natural gas in CHP mode, but the design includes a pathway toward lower-emission operation through fuel flexibility. The baseline configuration supports up to a 30% hydrogen blend in the natural gas stream. Full conversion would require upgrades to internal fuel processing, reformer configuration, thermal management, and control logic before enabling operation on 100% hydrogen or renewable natural gas.[126] This project therefore illustrates a staged integration strategy rather than immediate full-hydrogen deployment. It also demonstrates how airports can combine legacy and emerging technologies in a modular format to improve reliability, reduce emissions, and preserve optionality as hydrogen supply evolves.

3.3.2.4 Operational flexibility and resilience. Hydrogen-enabled microgrids can materially improve continuity of service in airport settings. Unlike centralized power systems, microgrids can island during grid outages and continue supplying critical functions such as air traffic support systems, terminal HVAC, lighting, communications, and security infrastructure.[127] Fuel cells provide modular and dispatchable output with stable frequency and voltage regulation, which can improve local power quality and reduce dependence on external grid support. Proton exchange membrane and phosphoric acid systems can also follow load, allowing operators to reduce peak purchases from the grid and optimize internal dispatch.

When supplied with low-carbon hydrogen, fuel cells can operate with very low life-cycle emissions while eliminating direct CO_2, NO_x, and particulate emissions at the point of use, and they may displace more carbon-intensive gas turbines or diesel backup systems.[128] CHP operation can raise overall energy conversion efficiency above 80% by utilizing waste heat, thereby improving site energy performance and reducing reliance on separate thermal generation. In principle, coupling fuel cells with renewable electricity and electrolysis also creates an opportunity for longer-duration or seasonal energy balancing, although this remains more prospective than routine in current airport applications.

3.3.2.5 Challenges and future directions. Despite their promise, airport-scale deployment of hydrogen-enabled microgrids faces several important constraints. Capital costs for fuel cells, hydrogen storage, reformers, and supporting balance-of-plant equipment remain higher than those of conventional backup systems. As a result, airport-specific techno-economic assessment is necessary to determine whether lifecycle value justifies deployment under different load profiles, resilience objectives, and fuel-supply conditions.

Technical integration is also complex. Effective operation requires coordinated control of photovoltaics, batteries, electrolyzers, fuel cells, and thermal loads. Advanced energy-management systems must support real-time balancing, adaptive dispatch, and stable islanded operation under variable conditions, while existing platforms may not yet provide that level of integrated control capability in all airport contexts.

Regulatory and institutional factors remain equally important. Airports operate within overlapping utility, air-quality, safety, and permitting frameworks at federal, state, and local levels. Clear guidance on hydrogen safety, emissions accounting, interconnection, and permitting will be necessary to support wider deployment. Alignment with regional hydrogen strategies and public incentives may further improve project viability.

Supply-chain readiness is another foundational issue. Reliable and cost-competitive hydrogen production, delivery, and storage are prerequisites for sustained operation. Early systems may rely on natural-gas reforming, with a gradual transition toward electrolytic hydrogen as availability and economics improve. Coordination with possible future hydrogen use in aircraft and GSE, discussed in Sections 3.1 and 3.2, will also be important for coherent infrastructure planning across the airport system.

Stakeholder acceptance and operational confidence will matter as well. Airports will require robust fire protection, ventilation, leak detection, and emergency-response protocols, together with sustained engagement among airport authorities, regulators, utilities, tenants, and surrounding communities.

Priority research areas include improving fuel-cell durability and efficiency under variable load, developing hybrid design and planning tools for airport microgrids, and establishing performance benchmarks and operational standards for hydrogen-integrated systems. More explicit comparison with alternative resilience strategies, including battery-dominant microgrids, renewable-backed CHP, and advanced grid services, would also strengthen decision-making in future studies.

Overall, stationary hydrogen technologies, particularly microgrids and fuel-cell-based CHP systems, offer airports a flexible and resilient pathway toward lower-emission power. Hydrogen co-firing in gas turbines can help leverage existing assets as a transitional option, whereas fuel-cell-based microgrids represent a more modular longer-term approach with stronger resilience benefits. Planned deployments such as the New Terminal One microgrid show how staged deployment can combine fuel flexibility, distributed generation, and infrastructure learning. Realizing this potential will depend on continued progress in cost reduction, systems integration, regulatory alignment, and scalable hydrogen supply.

Table 4 Annual hydrogen demand for the KIAC plant as a function of volumetric hydrogen co-firing (metric tons per year)

H_2 vol %							
Year of operation	5%	10%	15%	20%	25%	30%	35%
2021	616	1278	1993	2767	3606	4521	5521
2022	717	1487	2319	3219	4196	5260	6424
2023	550	1142	1781	2472	3222	4039	4933

Table 5 Projected hydrogen demand and fuel-input CO_2 reduction for the New Terminal One microgrid under selected hydrogen blend scenarios

H_2 vol%	Hydrogen blends up to 30 vol%			Hydrogen 100%
Operating metrics	5%	20%	30%	100%
H_2 demand, kg per year	31 755	143 080	233 965	1 834 125
CO_2 reduction, %	1.5%	6.9%	11.2%	100%

3.3.3 Infrastructure requirement for large-scale hydrogen sourcing. Integrating hydrogen into airport energy systems requires infrastructure that is reliable, scalable, and sufficiently flexible to serve different end uses over time. For stationary power systems applications, this means not only securing hydrogen supply, but also designing delivery, storage, blending, and control systems that can operate safely under variable load and evolving fuel pathways. This subsection evaluates these requirements using the KIAC plant and the New Terminal One microgrid at JFK as case studies. The discussion covers projected hydrogen demand, delivery logistics, on-site blending and storage, and the feasibility of hydrogen transport through existing gas infrastructure. Technical, regulatory, and economic considerations are examined together because infrastructure feasibility depends on their interaction rather than on engineering factors alone.

3.3.3.1 Hydrogen demand estimation. Quantifying hydrogen demand is a prerequisite for infrastructure planning. For KIAC, annual hydrogen demand was estimated from historical hourly unit-level heat-input data from the U.S. Environmental Protection Agency's Clean Air Markets Program Data.[129] The analysis assumes hydrogen blending of up to 35 vol%, consistent with the gas-turbine OEM limit,[130] and reflects observed capacity-factor variation from 46% to 59% between 2021 and 2023. Table 4 summarizes the resulting annual hydrogen demand, which ranges from 550 to 6424 metric tons depending on operating year and blend level. Detailed assumptions and calculations are provided in Appendix B.

For the New Terminal One microgrid, hydrogen demand was estimated under two operating modes: blended operation at 5, 20, and 30 vol% in the natural-gas stream, and full conversion to 100% hydrogen. Because the facility remains under construction, the estimates are based on the maximum installed fuel-cell capacity reported by the manufacturer.[126] As shown in Table 5, projected hydrogen demand ranges from about 32 to 1834 metric tons per year. The associated reduction in fuel-input CO_2 increases with hydrogen fraction, from 1.5% at 5 vol% to 11.2% at 30 vol%, while 100% hydrogen eliminates fuel-input CO_2. Assumptions and methods are provided in Appendix C §.

§ These estimates were developed by the authors based on publicly available information and may not match New Terminal One project specifics.

These estimates show that even moderate hydrogen blending in airport stationary power systems can create substantial annual fuel demand. They also highlight the difference in scale between transitional co-firing and full hydrogen conversion. As a result, infrastructure planning cannot be separated from expected adoption pathway, blend target, and operating regime.

3.3.3.2 On-site hydrogen mixing and storage. If hydrogen is supplied separately from natural gas, on-site blending, storage, and fuel-delivery systems become essential. For KIAC, sustained co-firing at up to 35 vol% would require both continuous high-volume hydrogen supply and tightly controlled mixing to remain within combustion-stability limits and OEM operating tolerances.[112] The Brentwood Power Station demonstration illustrates the limitations of trailer-based supply under these conditions. In that case, a GE LM6000 operated for about 12 hours on blends ranging from 5 to 44 vol%, but manual regulation of individual tube trailers was required, which is not practical for routine commercial service.[120]

At KIAC, even a 5 vol% blend corresponds to roughly 1687 kg of hydrogen per day. Using representative delivery capacities of about 300 kg per tube trailer and 4000 kg per LH_2 tanker, this would require approximately five trailer deliveries per day or one LH_2 tanker delivery every two days.[131,132] Delivery frequency increases substantially at higher blend levels. On-site LH_2 storage can reduce supply interruptions and provide operational buffering, but the required storage footprint is significant. A very large LH_2 tank on the order of 335 000 kg would still provide only limited operating coverage, depending on plant load and target blend level, while siting would be constrained by setback distances, fire-code requirements, and airport land-use limitations.[112]

These constraints make pipeline delivery increasingly attractive as hydrogen demand rises. At steady-state demand on the order of tens of thousands of kilograms per week, pipeline transport may reduce reliance on high-frequency trucking and improve operational continuity. Repurposing or interconnecting with existing gas infrastructure could also reduce some capital requirements, but only if material compatibility, pressure constraints, metering, and permitting issues can be resolved.[133]

3.3.3.3 Hydrogen sourcing pathways. Hydrogen sourcing strategy should reflect both technology type and duty profile. Baseload CHP systems, such as phosphoric acid or solid oxide fuel-cell applications, benefit from steady and predictable hydrogen supply, potentially through pipelines, dedicated delivered hydrogen, or reforming of natural gas with a later transition toward lower-carbon sources. By contrast, intermittent or rapid-response applications, such as backup service within microgrids, may be better suited to modular supply options including trailers, on-site electrolysis, or third-party delivered hydrogen.

Because real-time loads will vary with renewable generation, weather, dispatch logic, and site-specific operational conditions, procurement strategy should remain flexible. A robust airport hydrogen architecture may therefore combine fixed infrastructure with modular options such as on-site reformers, electrolyzers, and external supply agreements. This flexibility is especially important during early deployment, when hydrogen demand remains uncertain and future coupling with aircraft or GSE applications is still evolving.

3.3.3.4 Hydrogen blending in natural gas pipelines. Blending hydrogen into existing natural-gas pipelines can provide an incremental pathway with lower initial capital cost than dedicated new hydrogen infrastructure, but feasibility remains highly case specific. PANYNJ does not control the gas infrastructure serving airport facilities, so any blending strategy would depend on cooperation from utility operators such as National Grid.[134] Acceptable hydrogen concentration depends on pipeline materials, compressor and valve compatibility, operating pressure, metering systems, and overall network configuration.[114]

Transmission infrastructure can present greater technical challenges than lower-pressure distribution systems because of material-performance requirements and hydrogen embrittlement concerns in some steel assets. Polyethylene-based distribution assets may also require case-specific evaluation because hydrogen permeation, code compliance, and utility operating standards can limit allowable use conditions. As a result, practical blending strategies may require targeted material replacement, upgraded leak-detection systems, revised operating protocols, and compressor modifications to address hydrogen's lower volumetric energy density. Most demonstrations to date have focused on lower-pressure distribution networks rather than transmission-scale systems. Because KIAC is supplied through a transmission pipeline, compatibility assessment would likely face a higher technical and regulatory threshold.[135]

3.3.3.5 Economics of fuel delivery. Delivered cost depends on hydrogen production pathway, natural-gas price, pipeline compatibility, delivery mode, and target blend level. A recent techno-economic analysis found that, even at blends up to 50 vol%, transportation is a relatively small component of levelized energy cost compared with the cost of electrolytic hydrogen production itself.[136] At 50 vol%, delivered energy cost can approach about 12 USD/MMBtu, reflecting the large cost difference between hydrogen and natural gas.

Cost tolerance varies by application. Distributed generation at airports can sometimes justify higher delivered fuel costs because resilience, peak-shaving capability, and operational continuity have value beyond energy alone. In New York and New Jersey, peak electricity prices are often observed during midday rather than evening hours. As renewable penetration increases, the timing and frequency of peak-price periods may change, which could alter the economic value of hydrogen-fueled assets. To reduce near-term cost, many projects continue to prioritize low-carbon hydrogen from natural-gas reforming because it can leverage existing infrastructure and may align more readily with transitional policy incentives.[137]

3.3.3.6 Infrastructure requirements and future research. Reliable supply at airport scale will likely require either substantial on-site LH_2 storage with code-compliant siting or access to pipeline-based hydrogen delivery. Storage improves resilience and operational flexibility, but it faces land-use, siting, and safety constraints near critical airport infrastructure.[112] Pipeline repurposing or interconnection may offer long-term cost advantages where compatibility and regulatory approvals can be secured.[133] Site-specific techno-economic assessment is therefore essential to compare capital cost, operating cost, emissions benefit, storage requirement, delivery frequency, and coverage of peak or contingency loads for both KIAC and the New Terminal One.

Several research needs remain. Advanced NO_x-control strategies tailored to hydrogen combustion are still needed for co-firing applications. Hydrogen-integrated microgrids require stronger energy-management and dispatch frameworks. Long-term material effects of hydrogen blending on pipelines, valves, seals, and related components also remain an important concern. Collaboration with OEMs is necessary to define turbine modifications, allowable operating envelopes, and performance implications across hydrogen concentrations. Continued airport-based demonstrations will also be important for refining siting strategies, safety protocols, permitting pathways, and interoperability standards.

Overall, large-scale hydrogen integration in airport stationary power systems presents a combined infrastructure, logistics, and planning challenge. The KIAC and New Terminal One case studies show that projected demand can range from hundreds of metric tons to more than 1800 metric tons per year depending on technology pathway and blend level. Meeting that demand will require some combination of on-site storage, reliable delivery logistics, controlled blending, and possibly future pipeline adaptation. Economic viability remains central and depends on hydrogen price, blend fraction, delivery mode, and end-use value. Scalable deployment will therefore depend on coordinated infrastructure planning, OEM engagement to ensure equipment readiness, and continued research on safety, emissions control, and material compatibility.

Taken together, the pathways examined across SAF production, hydrogen-powered aircraft, ground support equipment, and stationary power systems indicate that hydrogen integration at airports is inherently crosscutting, with shared infrastructure needs, operational synergies, and overlapping policy drivers. Common requirements include reliable low-carbon hydrogen supply, on-site storage, safe and efficient refueling or fuel-delivery systems, and harmonized safety and permitting frameworks. Infrastructure developed for one domain may also support others. For example, cryogenic storage and distribution systems sized for future aircraft applications could also serve stationary fuel cells or high-utilization GSE, improving overall capital efficiency. Conversely, earlier deployment in stationary power systems or ground operations can help build institutional familiarity, refine safety procedures, and reduce implementation risk ahead of possible aircraft adoption. SAF pathways are also linked to this broader system because several production routes depend on low-carbon hydrogen that may be sourced through the same regional supply chains supporting direct airport applications. Recognizing these interdependencies can reduce infrastructure redundancy, support phased investment, and improve alignment between technology deployment, regulatory requirements, and market conditions. Hydrogen integration at airports should therefore be approached as a multi-domain systems transition rather than as a sequence of isolated projects.

4 Cross-domain synthesis, implementation barriers, and research priorities

This section synthesizes the cross-domain findings of the review and examines the main barriers, enabling conditions, and research needs associated with hydrogen integration in airport operations. Rather than treating airport applications as isolated pathways, the discussion compares sustainable aviation fuel production, hydrogen-powered aircraft, ground support equipment and vehicles, and stationary power systems through a common analytical lens that includes deployment horizon, infrastructure intensity, operational fit, emissions implications, and implementation constraints. The aim is to clarify where hydrogen is most likely to provide near-term value, where it remains a longer-term option, and what technical, regulatory, and institutional conditions will shape its practical adoption at airports.

4.1 Cross-domain comparison of hydrogen applications at airports

International airport examples show that hydrogen integration is advancing through differentiated pathways rather than through a single deployment model. The current landscape includes operational pilots for ground vehicles, on-site hydrogen production and refueling systems, phased infrastructure roadmaps for future aircraft use, and feasibility studies aimed at long-term hub development. Taken together, these examples help clarify where hydrogen is already technically and operationally credible, where infrastructure remains preparatory, and which implementation strategies appear most transferable across airport contexts.

The most mature airport applications are concentrated in ground operations rather than in aircraft propulsion. Toulouse–Blagnac provides one of the clearest operational examples, with a green hydrogen production and distribution station commissioned in early 2023 that produces approximately 400 kg per day through on-site electrolysis and fuels about 50 ground service vehicles.[110] The project also shows how hydrogen deployment can be integrated across landside and airside operations while being supported by coordinated public financing, safety compliance, and scalable station design.[138] Its importance lies not in demonstrating airport-wide hydrogen readiness, but in showing that a bounded, multi-vehicle ground-operations model can be implemented under current regulatory and technical conditions.

Hamburg Airport illustrates a broader systems-readiness model. Its participation in Airbus's "Hydrogen Hub at Airports" initiative, the hydrogen infrastructure roadmap developed with the German Aerospace Center, deployment of hydrogen-powered baggage tractors, coordination of the BSR HyAirport network, and use of a decommissioned Airbus A320 as a hydrogen ground-handling test platform together indicate a more comprehensive preparation strategy.[139–143] However, Hamburg is better understood as a test bed for infrastructure planning, operational familiarization, maintenance readiness, and regional coordination than as evidence that hydrogen-powered aircraft operations are close to routine commercial implementation.

Lyon–Saint Exupéry represents an intermediate model centered on phased infrastructure development. Its initial emphasis on gaseous hydrogen distribution for ground support vehicles and heavy-duty ground transport, followed by a road-map toward LH_2 capability for future aircraft refueling through 2030, reflects a sequencing strategy that matches infrastructure intensity to expected demand growth.[144] This approach is analytically important because it recognizes that immediate airport-scale LH_2 deployment is difficult to justify where aircraft demand remains uncertain. Lyon therefore highlights the value of preserving optionality while avoiding premature overbuilding of airport hydrogen systems.

A different category is represented by George Bush Intercontinental Airport and Hartsfield–Jackson Atlanta International Airport, where current activity remains at the feasibility-assessment stage. In both cases, the focus is not yet on direct deployment, but on defining technical requirements, siting options, fueling logistics, safety alignment, and links with wider regional hydrogen ecosystems.[145,146] These studies are valuable because they recognize that airport hydrogen integration depends on more than airport boundaries alone. Supply-chain connectivity, utility interfaces, industrial demand, and institutional coordination may all shape viability. At the same time, these examples also underline a current limitation of the field: in major U.S. hubs, planning activity is progressing faster than physical implementation.

Glasgow Airport provides a regional-airport example in which hydrogen is framed as part of a broader innovation-hub strategy. The project combines feasibility assessment for green hydrogen production, storage, and distribution with a multi-partner structure involving technology firms, academic institutions, utilities, and airline operators.[147] Its relevance lies in showing how smaller or regional airports may use hydrogen initiatives to build demonstration value and align with national hydrogen strategies. At the same time, the Glasgow case remains prospective. Its transferability will depend heavily on policy support, regional coordination, and the economics of green hydrogen supply.[148]

Across these examples, several cross-domain patterns emerge. First, hydrogen deployment at airports is currently most credible in bounded, high-control segments such as GSE fleets and localized vehicle fueling. Second, airports that appear furthest advanced generally rely on phased implementation, beginning with ground operations and small-scale infrastructure before considering future aircraft applications. Third, public-private coordination is a recurring enabling condition, particularly where projects require joint action among airport operators, OEMs, hydrogen suppliers, utilities, and regulators. Fourth, most airport examples still emphasize readiness, pilot operations, or feasibility analysis rather than fully scaled commercial hydrogen systems. This distinction is important because it suggests that, although technical feasibility has been demonstrated in selected contexts, large-scale airport hydrogen deployment remains contingent on stronger infrastructure economics, clearer permitting pathways, and more reliable low-carbon hydrogen supply.

The airport case examples also reinforce the broader findings of Section 3. Applications with lower infrastructure intensity and more predictable duty cycles, especially GSE and localized stationary uses, are moving first. By contrast, applications requiring cryogenic handling, high-throughput fueling, or airport-wide distribution networks remain less mature and more capital intensive. The case evidence therefore supports a staged transition logic in which early hydrogen deployment is most plausible in selected operational niches, while broader aviation-scale integration depends on longer-term progress in supply, storage, safety assurance, and system-wide planning.

4.2 Key implementation barriers and enabling conditions

Hydrogen integration at airports is constrained less by any single technical issue than by the interaction of supply, infrastructure, safety, institutional coordination, and economics. Although the relative importance of these factors differs across sustainable aviation fuel production, hydrogen-powered aircraft, ground support equipment, and stationary power systems, several barriers recur consistently across the applications examined in this review.[73]

A first barrier is the scale and reliability of hydrogen supply. Early airport applications, particularly in ground operations, can often be supported by localized fueling systems or modest on-site production, as demonstrated at Toulouse–Blagnac.[144] However, infrastructure requirements increase sharply as hydrogen use expands toward stationary power systems or future aircraft refueling, where demand becomes more continuous, volumetrically intensive, and operationally sensitive. The KIAC and New Terminal One case studies illustrate this shift clearly, with projected demand rising from pilot-scale requirements to hundreds or thousands of metric tons per year depending on technology pathway and blend level. An important enabling condition is therefore phased infrastructure development that begins with bounded, lower-volume uses while preserving flexibility for later expansion.

A second barrier is the uneven operational and economic fit of hydrogen across airport applications. The review shows that hydrogen is not equally attractive in all segments. In GSE, battery-electric systems remain the primary near-term pathway for many fleets because of lower capital cost, wider equipment availability, and simpler charging infrastructure, while hydrogen appears more relevant in high-utilization or charging-constrained niches. In stationary power systems, hydrogen co-firing can provide a transitional emissions-reduction pathway using existing assets, but its effectiveness depends on hydrogen cost, NO_x control, and fuel logistics. In aviation propulsion, hydrogen-powered aircraft remain less mature and more infrastructure-intensive than SAF-based pathways for near-term deployment. The corresponding enabling condition is selective rather than universal deployment. Airports are more likely to make credible progress by prioritizing applications where hydrogen provides a clear operational advantage.

A third barrier concerns safety, codes, and regulatory approval. Hydrogen's low ignition energy, wide flammability range, leakage sensitivity, and, in some applications, cryogenic handling requirements make safety and permitting central determinants of deployment pace. These issues are especially significant at airports because operations occur in dense, highly regulated environments where siting, ventilation, setback distances, emergency response, and interoperability with existing fuel systems must all be managed carefully. The case studies suggest that early coordination among airport authorities, technology providers, fuel suppliers, and regulators is one of the most important enabling conditions for reducing permitting delays and clarifying infrastructure responsibilities.

A fourth barrier is institutional and organizational readiness. Airports typically do not control all of the assets, networks, or investment decisions required for hydrogen deployment. Utility operators, OEMs, tenants, third-party service providers, and public regulators all shape what can be implemented, at what pace, and under what conditions. This fragmentation is evident across multiple domains, including gas-network compatibility, hydrogen blending, GSE procurement, and future aircraft fueling infrastructure. An enabling condition is therefore the creation of multi-actor implementation frameworks that link airport planning with regional hydrogen strategies, utility participation, OEM roadmaps, and external funding programs. The airport examples reviewed in this manuscript show that public-private coordination is not peripheral to hydrogen deployment. It is one of its core preconditions.

Operational readiness is another enabling condition that deserves explicit emphasis. Hydrogen integration depends not only on infrastructure and equipment, but also on trained personnel, tailored safety protocols, routine audits, and organizational familiarity with hydrogen handling and fueling procedures. Demonstration projects involving hydrogen-powered GSE, fueling stations, and infrastructure planning are valuable not only because they test equipment, but also because they generate institutional learning and expose practical issues in maintenance, dispatch, and emergency response before larger-scale deployment is attempted.

Finally, robust monitoring and performance evaluation remain essential. Routine assessment of equipment reliability, fueling logistics, utilization, emissions reduction, and operating cost helps identify performance gaps and provides the evidence base needed for scaling decisions. This is particularly important in a field where many airport hydrogen projects remain at pilot or feasibility stage rather than mature commercial scale. Without credible performance data, it is difficult to compare hydrogen with electrification or SAF-based alternatives or to determine where infrastructure expansion is justified.

Taken together, these findings indicate that hydrogen adoption at airports will depend less on any single technological breakthrough than on the coordinated resolution of supply, infrastructure, safety, institutional, and economic challenges. The strongest enabling conditions identified across the reviewed cases are phased implementation, multi-stakeholder coordination, adaptable infrastructure design, operational preparedness, and evidence-based performance monitoring. These conditions do not remove the core barriers, but they materially improve the likelihood that hydrogen deployment can proceed in a technically credible, economically defensible, and operationally manageable manner.

4.3 Stakeholder coordination and governance for airport hydrogen deployment

The airport examples reviewed in this manuscript show that hydrogen deployment is not simply a technical decision about fuel choice or equipment replacement. In practice, progress depends on how effectively airports coordinate infrastructure planning, fuel supply, technology integration, regulatory approval, financing, and public communication. Across cases such as Hamburg, Toulouse–Blagnac, Lyon–Saint Exupéry, George Bush Intercontinental, and Hartsfield–Jackson Atlanta, stakeholder alignment emerges as a defining condition that shapes whether projects advance beyond feasibility analysis toward pilot or operational deployment.

Airport operators play the central coordinating role in this process. Their responsibilities extend beyond hosting hydrogen infrastructure to include integrating new systems into airside and landside operations, managing safety and permitting interfaces, sequencing infrastructure investment, and overseeing operational logistics. The case examples indicate that airports function most effectively when they act not only as deployment sites but also as conveners that connect airlines, OEMs, hydrogen suppliers, utilities, regulators, and local stakeholders around a common implementation pathway. This coordinating role is especially important where early infrastructure decisions for GSE, stationary power systems, or fueling systems may influence the cost and feasibility of later expansion.

Airlines and aircraft developers become particularly important where airport hydrogen planning is linked to future propulsion transition. Their expected fleet requirements, operational procedures, turnaround constraints, and fueling concepts directly influence demand profiles and infrastructure design. The feasibility studies conducted under Airbus's Hydrogen Hub at Airports initiative in Hamburg, Houston, and Atlanta illustrate that airport planning cannot be separated from assumptions about future aircraft class, storage requirements, and fueling logistics. At the same time, these examples also show that airline engagement alone is insufficient if supporting hydrogen supply, safety, and permitting conditions are not in place.

Hydrogen suppliers and technology providers shape both the technical and economic credibility of airport hydrogen systems. Suppliers influence production pathway, purity, delivery mode, and logistics reliability, while technology providers determine the maturity, interoperability, and maintainability of fueling stations, fuel cells, storage systems, and control equipment. In the stronger cases, these actors are engaged early enough to

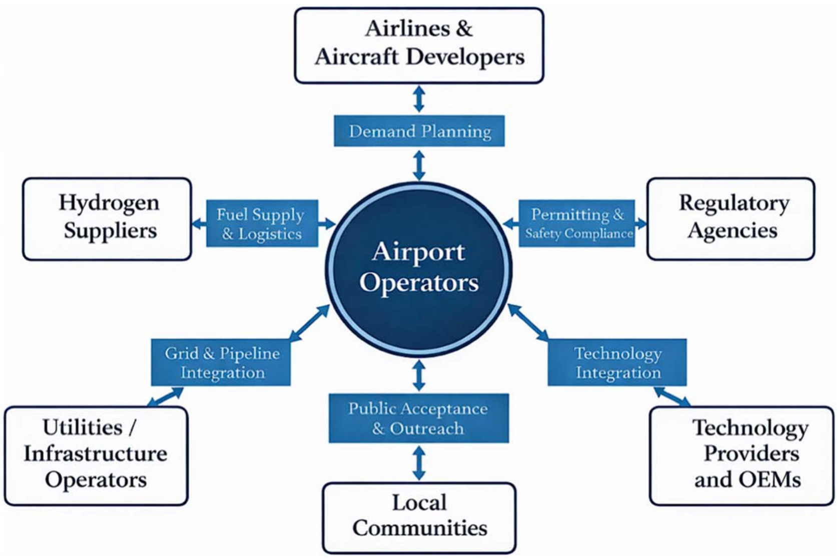

Fig. 7 Stakeholder coordination framework for hydrogen integration in airport operations. Airport operators act as the central coordinating entity linking airlines and aircraft developers, hydrogen suppliers, utilities and infrastructure operators, technology providers, regulatory agencies, and local communities. The framework illustrates how supply-chain coordination, technology deployment, and public acceptance interact to shape hydrogen implementation outcomes at airports.

align technology selection with airport-specific operating conditions rather than adapting systems only after major site and planning decisions have already been made. This is particularly important in airports, where space constraints, fueling geometry, safety setbacks, and duty-cycle variation can materially affect system performance and cost.

Regulatory agencies also play a decisive enabling role. Hydrogen deployment at airports introduces requirements related to siting, safety distances, fueling procedures, emergency response, and interpretation of existing codes. The case examples suggest that early regulator engagement improves implementation quality by clarifying expectations before design choices are fixed, thereby reducing the risk of delay, redesign, or procedural uncertainty later in the project cycle. This is especially relevant where airport hydrogen applications intersect with utility regulation, transport safety, industrial gas handling, and local land-use constraints.

Local communities and surrounding institutions influence project trajectory as well, even when they are less visible in technical planning documents. Public acceptance depends on perceived safety, environmental value, and local relevance. Demonstrator projects, public outreach, and visible early-use cases can therefore help reduce uncertainty and strengthen confidence in airport hydrogen initiatives, particularly where airports seek to expand activity beyond bounded pilot deployments. In this sense, community engagement is not peripheral to implementation. It is part of the broader institutional environment that affects legitimacy and scalability.

Fig. 7 summarizes these stakeholder interdependencies by positioning airport operators as the central coordinating entity linking airlines and aircraft developers, hydrogen suppliers, utilities and infrastructure operators, technology providers, regulatory agencies, and local communities. The figure highlights three interrelated dimensions of implementation, namely supply-chain coordination, technology deployment, and public acceptance, which together shape project outcomes. As the case examples indicate, airport hydrogen projects progress most credibly when these relationships are aligned through shared planning assumptions, coordinated governance, and phased decision-making.

Taken together, the case evidence shows that airport hydrogen deployment is an institutional and operational transition as much as a technical one. Projects that progress most effectively tend to combine phased infrastructure development with early stakeholder coordination, transparent governance, and implementation structures capable of linking supply, operations, safety, and public communication. This helps explain why some airports are moving toward pilot deployment while others remain at the feasibility stage despite similar strategic interest. For an illustrative multi-airport system such as PANYNJ, these governance implications suggest that hydrogen planning would need to be coordinated across airports, tenants, utilities, regulators, and infrastructure partners rather than pursued through isolated decisions within individual asset classes.

4.4 Priority research and demonstration needs

The evidence reviewed in this manuscript indicates that airport hydrogen deployment is constrained less by the absence of candidate technologies than by limited integration of evidence across demand, infrastructure, operations, safety, and economics. Future research should therefore move beyond isolated technology assessments toward airport-scale studies that evaluate hydrogen as part of an interacting system of fuels, vehicles, stationary power systems assets, and logistics networks. This is particularly important because planning decisions at airports depend not only on the performance of

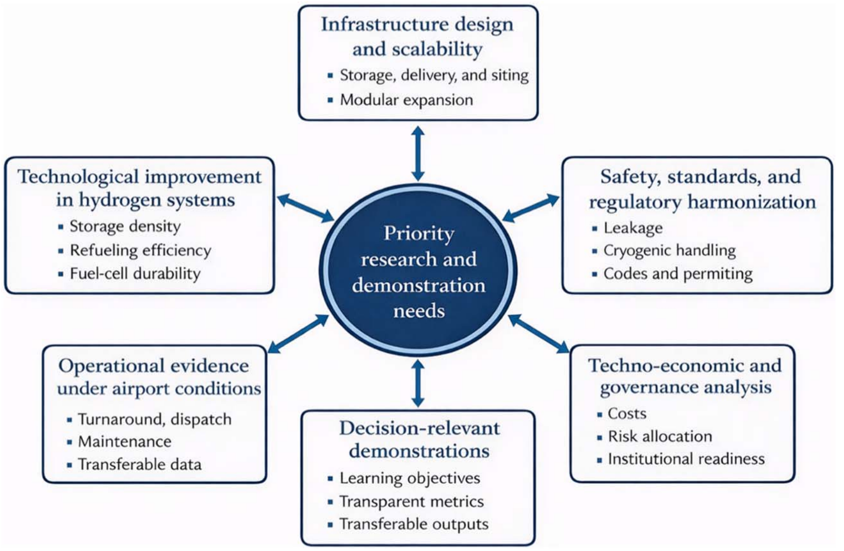

Fig. 8 Priority research and demonstration needs for hydrogen integration in airport operations. The framework summarizes six interrelated domains requiring continued investigation: infrastructure design and scalability, safety, standards, and regulatory harmonization, technological improvement in hydrogen systems, operational evidence under airport conditions, techno-economic and governance analysis, and decision-relevant demonstrations. Together, these domains highlight the need for integrated research that supports scalable, safe, and economically credible hydrogen deployment across airport energy systems.

individual technologies, but also on how hydrogen demand from SAF production, aircraft, GSE, and stationary power systems may overlap in time, location, required fuel state, and infrastructure intensity.

A first research priority is infrastructure design and scalability. Future work should examine how gaseous and LH_2 fueling systems can be designed as modular, staged, and reconfigurable assets across different airport sizes and operational profiles. This includes the integration of on-site electrolysis, delivered hydrogen, liquefaction, storage, and grid or pipeline interfaces within space-constrained airport environments. Research is also needed on land-use requirements, siting tradeoffs, and risk-informed design for large-scale storage and distribution systems, especially where hydrogen deployment must coexist with existing fuel networks, terminal operations, and safety buffers. More rigorous airport-scale demand modeling would improve storage sizing, delivery frequency, utility coordination, and phased investment planning.

A second priority concerns safety, standards, and regulatory harmonization. Although individual projects have established localized safety procedures, broader deployment will require more consistent treatment of hydrogen leakage, cryogenic handling, fueling-system siting, emergency response, setback interpretation, and compatibility with existing airport and utility infrastructure. Research should therefore support the development of harmonized safety frameworks, airport-specific code interpretation, and clearer regulatory pathways for integrating hydrogen systems into highly regulated operational environments. This is particularly important where hydrogen deployment intersects with aviation safety, industrial gas handling, utility oversight, and local land-use regulation.

A third priority is longer-duration operational evidence under representative airport conditions. For aviation propulsion, demonstration needs extend beyond proof-of-concept flight activity to include fueling turnaround, dispatch reliability, ground handling, and lifecycle operating implications for different aircraft classes. For GSE, more comparative evidence is needed on duty-cycle suitability, refueling frequency, maintenance requirements, and the operational boundary between battery-electric and hydrogen systems under high-utilization conditions. For stationary power systems, future work should focus on longer-duration co-firing trials, catalyst durability, emissions-control performance, and the real operating behavior of hydrogen-enabled microgrids under airport-specific load conditions. Demonstrations should therefore be designed not only to show feasibility, but also to generate transferable evidence on operational performance and infrastructure requirements.

A fourth priority is continued technological improvement in hydrogen systems. Advancing deployment readiness will depend on improvements in storage density, fueling efficiency, refueling throughput, hybrid system integration, fuel-cell durability, and diagnostics under demanding operational cycles. In airport applications, these issues are especially relevant because turnaround time, equipment utilization, and resilience requirements can be more restrictive than in many other transport or stationary settings. Research on lightweight storage systems, high-throughput dispensing, battery–hydrogen hybrid architectures, and robust performance monitoring will therefore remain important across both mobile and stationary applications.

A fifth priority concerns techno-economic and governance analysis. Airport-specific assessments are needed to compare hydrogen credibly with competing pathways, including battery-electric systems, renewable-backed microgrids, and SAF-centered strategies, rather than evaluating hydrogen in isolation. These analyses should examine not only capital and operating cost under different fuel-price and utilization assumptions, but also the allocation of risk, responsibility, and decision authority among airport operators, airlines, OEMs, utilities, hydrogen suppliers, and regulators. This is essential because several airport examples reviewed in this manuscript show that planning activity is advancing faster than large-scale deployment, making decision-quality institutional and economic analysis as important as technical feasibility.

A final priority is the design of demonstrations that produce decision-relevant evidence rather than only symbolic first-mover visibility. Pilot projects are most valuable when they reduce uncertainty about infrastructure sizing, operational performance, workforce needs, regulatory feasibility, and cross-domain coordination. In airport settings, this means that demonstrations should be linked to explicit learning objectives, transparent performance metrics, and outputs that inform later deployment phases. Projects that combine operational monitoring with comparative assessment across alternative pathways are likely to generate more durable value than demonstrations designed primarily to signal ambition.

Fig. 8 summarizes six interrelated research and demonstration priorities for hydrogen integration in airport operations: infrastructure design and scalability; safety, standards, and regulatory harmonization; technological improvement in hydrogen systems; operational evidence under airport conditions; techno-economic and governance analysis; and decision-relevant demonstrations. Together, these priorities reinforce that future airport hydrogen research must remain interdisciplinary, linking engineering design, systems analysis, regulatory interpretation, and implementation governance rather than treating hydrogen adoption as a purely technical transition.

Taken together, these priorities indicate that the next phase of airport hydrogen research should emphasize integrated planning, longer-duration field evidence, safety and standards maturation, and comparative techno-economic assessment. The most valuable future projects may therefore be not those that deploy the most hydrogen, but those that most clearly reduce uncertainty about where hydrogen provides durable value within airport energy systems.

5 Conclusion

Hydrogen integration in airport operations presents a credible but highly differentiated pathway for reducing emissions across aviation-related energy systems. This review has examined hydrogen across three operational domains in airport energy systems: aviation propulsion, ground support equipment and vehicles, and stationary power systems. Within aviation propulsion, two distinct hydrogen-relevant pathways were assessed: sustainable aviation fuel production and hydrogen-powered aircraft. Across these domains, the evidence shows that hydrogen is neither a universal substitute nor a single-track transition pathway; its relevance depends on end use, infrastructure requirements, safety constraints, and deployment context.

In aviation propulsion, the review shows that hydrogen-related pathways differ substantially in maturity and implementation horizon. SAF remains the most compatible near-term route for reducing emissions from the existing fleet, but its long-term contribution depends on feedstock availability, production scale-up, cost reduction, and the availability of low-carbon hydrogen in pathways such as HEFA, FT, ATJ, and E-fuels. Hydrogen-powered aircraft offer a longer-term pathway with stronger direct emissions-reduction potential at the point of use, but they remain constrained by storage volume, infrastructure requirements, certification, and, in combustion-based systems, NO_x control. Fuel cell electric concepts currently appear more plausible for commuter and regional applications, whereas hydrogen combustion remains a later option for larger aircraft classes.

For ground support equipment and vehicles, hydrogen can play a useful but selective role. Hydrogen-powered equipment has demonstrated technical feasibility in several high-utilization applications and may offer operational advantages where battery-electric systems face limitations related to charging time, duty cycle, or grid constraints. At the same time, battery-electric equipment remains the primary near-term route for much of this segment because of greater commercial availability, lower infrastructure complexity, and stronger present-day deployment momentum. In this part of airport operations, hydrogen is therefore best understood as a targeted complement rather than a universal replacement.

In stationary power systems, hydrogen provides both transitional and longer-term possibilities. Co-firing in gas turbines can reduce CO_2 emissions while extending the use of existing assets, but performance depends on hydrogen supply, combustor compatibility, NO_x mitigation, and the economics of delivered fuel. Hydrogen-enabled microgrids and fuel-cell-based CHP systems offer a more modular and potentially lower-emission longer-term pathway for airports with critical loads and resilience requirements. Their practicality, however, depends on coordinated infrastructure planning, appropriate technology selection, and reliable hydrogen sourcing at scales that are often far greater than those required for early pilot projects.

Taken together, the review shows that hydrogen deployment at airports is fundamentally cross-domain. Infrastructure requirements for supply, storage, delivery, safety, and permitting are shared across multiple use cases, and decisions in one application can influence the cost and feasibility of others. This creates both opportunity and constraint. Early deployment in stationary power systems or GSE may help build operational familiarity and justify initial infrastructure, while future aircraft applications could eventually dominate demand and reshape infrastructure requirements. Airports must therefore evaluate hydrogen not as a series of isolated projects, but as part of an integrated energy-transition strategy.

The review also shows that environmental credibility depends on full-system assessment rather than end-use technology alone. Hydrogen eliminates direct CO_2 emissions at the point of use in fuel cells and avoids carbon emissions in combustion, but overall performance depends on production pathway, upstream emissions, and leakage management. Because hydrogen leakage can weaken net climate benefit through indirect atmospheric effects, credible deployment requires attention not only to fuel switching, but also to containment, monitoring, and emissions accounting across the supply chain. Safety, institutional coordination, and infrastructure governance are equally central, particularly in airports where hydrogen storage, high-pressure delivery, cryogenic handling, and fuel-system integration must coexist with public access, mission-critical operations, and overlapping regulatory responsibilities.

For PANYNJ, used here as an illustrative airport system, these findings suggest that the most credible near-term hydrogen roles lie not in immediate aviation-scale aircraft refueling, but in applications that align more closely with existing operational control points and infrastructure-readiness conditions. In practical terms, this includes hydrogen's role in SAF production and supply, selected high-utilization GSE applications, and staged stationary-power uses linked to resilience or transitional emissions reduction. Broader aircraft-scale deployment remains a longer-term prospect that would depend on major progress in aircraft technology, fuel supply, storage and fueling infrastructure, safety assurance, and cost reduction.

Airports provide an important proving ground for hydrogen because they combine concentrated energy demand, centralized logistics, regulated governance, and multiple candidate applications within a single operational environment. The evidence reviewed here indicates that hydrogen can contribute meaningfully to lower-emission airport operations when evaluated and deployed in a deliberate, coordinated, and application-specific manner. Its long-term role, however, will depend on integrated planning across fuels, infrastructure, operations, and policy rather than on any single technological breakthrough.

Conflicts of interest

The authors declare no competing interests.

Abbreviations

APU	Auxiliary power unit
ATJ	Alcohol-to-jet
CHP	Combined heat and power
CO_2e	Carbon dioxide equivalent
DGE	Diesel gallon equivalent
E-fuels	Electricity-derived synthetic fuels
eGRID	Emissions and Generation Resource Integrated Database
EWR	Newark Liberty International Airport
FCE	Fuel cell electric (aircraft)
FT	Fischer–Tropsch
GSE	Ground support equipment
HEFA	Hydroprocessed esters and fatty acids
ICAO	International Civil Aviation Organization
IFC	International Fire Code
ISO	International Organization for Standardization
JFK	John F. Kennedy International Airport
KIAC	Kennedy International Airport Cogeneration
LGA	LaGuardia Airport
LH_2	Liquid hydrogen
LTO	Landing and takeoff (cycle)
MCFC	Molten carbonate fuel cell
NFPA	National Fire Protection Association
NO_x	Nitrogen oxides
OEM	Original equipment manufacturer
OSHA	Occupational Safety and Health Administration
PAFC	Phosphoric acid fuel cell
PANYNJ	Port Authority of New York and New Jersey
PEMFC	Proton exchange membrane fuel cell
RNG	Renewable natural gas
SAF	Sustainable aviation fuel
SOFC	Solid oxide fuel cell
SWF	New York Stewart International Airport
TCO	Total cost of ownership
TEB	Teterboro Airport
TRL	Technology readiness level

Data availability

This review reports derived estimates of hydrogen demand and carbon dioxide equivalent (CO_2e) emissions using publicly available sources. All inputs, assumptions, and calculation steps are documented in the article and Appendices A–C, with citations provided for figures, tables, and equations. No proprietary datasets were used.

Appendices

Appendix A: Estimation of hydrogen demand for GSE

This appendix describes the screening-level method used to estimate hydrogen demand for representative GSE and to compare it with diesel demand on both an absolute and diesel gallon equivalent basis. The analysis is based on representative equipment models because detailed, equipment-specific utilization data for PANYNJ airport fleets were not available. Table 6 summarizes the assumed operational characteristics for four GSE categories.

Table 7 lists the assumed powertrain efficiencies and fuel properties used in the calculation. The fuel cell efficiency and hydrogen lower heating value are treated as model assumptions for this screening analysis. Because the calculations use representative nominal conversion efficiencies rather than duty-cycle-averaged field efficiencies, the resulting fuel-demand estimates are likely to understate real-world consumption.

The required average mechanical power for each diesel-powered GSE category is calculated as:[154]

$$P_r = 0.746 \times \text{HP} \times \text{LF} \tag{A.1}$$

Table 6 Operational characteristics of representative GSE

Particulars	Aircraft tractor	Cargo tractor	Forklift	Ground power unit	Reference
Load factor	0.38	0.36	0.20	0.38	149
Operating hours (h per day)	12	12	6	12	—
Horsepower (hp)	288	138	162	130	103–106
Representative model	JBT B1200 push back tractor (DBP, 72 000 lb)	TUG MT (MDP, 12 000 lb)	Toyota, high-capacity IC pneumatic (45 000–72,000 lb)	TLD 28 VDC	103–106

Table 7 Assumed powertrain efficiencies and fuel properties used in the GSE screening analysis

Particulars	Value	Comments	Reference
Fuel cell efficiency (η_{FC})	60%	Electrical efficiency of proton exchange membrane fuel cell on a lower heating value basis	150
H_2 lower heating value, LHV_{H_2}	33.33, kWh kg^{-1}	Energy content of hydrogen on a lower heating value basis	151
Diesel brake engine thermal efficiency (η_{bth})	42%	Representative brake thermal efficiency of modern diesel engines used in heavy-duty applications	152
Ultra-low-sulfur diesel lower heating value, LHV_D	128 488, Btu per gal	Energy content of diesel fuel	153

where P_r is the required mechanical power in kilowatts (kW), HP is the engine power (hp), LF is the engine load factor, and 0.746 is the conversion factor from horsepower to kilowatts. This is equivalent to dividing horsepower by 1.34, since 1 kW ≈ 1.34 hp.

The hourly hydrogen demand is then calculated as:

$$H_{2,h} = \frac{P_r}{\eta_{FC} \times LHV_{H_2}} \quad (A.2)$$

where $H_{2,h}$ is the hourly hydrogen demand (kg h^{-1}), P_r is the required mechanical power (kW), η_{FC} is the fuel cell efficiency, and LHV_{H_2} is the hydrogen lower heating value (kWh kg).

The hourly diesel demand is calculated as:

$$D_h = \frac{P_r \times 3412.142}{\eta_{bth} \times LHV_D} \quad (A.3)$$

where D_h is the hourly diesel demand (gal per h), P_r is the required mechanical power (kW), η_{bth} is the diesel brake engine thermal efficiency, and LHV_D is the diesel low-sulfur lower heating value (Btu per gal), and 3412.142 is the conversion factor from kilowatt-hours to British thermal units.

Daily hydrogen demand and daily diesel demand are then obtained by multiplying the hourly values by the daily operating hours in Table 6:

$$H_{2,d} = H_{2,h} \times t_{op} \quad (A.4)$$

$$D_d = D_h \times t_{op} \quad (A.5)$$

where $H_{2,d}$ is the daily hydrogen demand (kg per day), D_d is the daily diesel demand (gal per day), and t_{op} is the operating time (h per day).

For comparison with diesel use, daily hydrogen demand is converted to diesel gallon equivalent (DGE) using lower-heating-value energy densities:

$$DGE_d = H_{2,d} \times (120/134.47) \quad (A.6)$$

where DGE_d is the daily hydrogen demand expressed as diesel gallon equivalent (gal per day), 120 MJ kg^{-1} is the hydrogen lower heating value, and 134.47 MJ per gal is the ultra-low-sulfur diesel lower heating value.[102] This conversion is used only for energy-equivalent comparison and does not imply equivalence in storage volume, refueling rate, or infrastructure requirement.

The resulting daily hydrogen demand in diesel gallon equivalent and the daily diesel demand per unit are reported in Table 2 in Section 3.2.2. These values provide a screening-level comparison across representative GSE categories and are intended to support relative infrastructure planning rather than detailed fleet procurement or dispatch optimization.

Appendix B: Estimation of hydrogen demand for hydrogen co-firing in a gas turbine

This appendix describes the screening-level method used to estimate hydrogen demand for natural gas-hydrogen co-firing in the KIAC gas turbines. Annual hydrogen demand was calculated from historical hourly unit-level heat-input data obtained from the U.S. Environmental Protection Agency's Clean Air Markets Program Data. For each hourly record, the analysis assumes a specified hydrogen blend fraction on a volumetric basis while maintaining the same total turbine heat input. Because hydrogen and natural gas have different volumetric

Table 8 Lower heating values of fuels used in the co-firing analysis

Particulars	Value	Comments	Reference
Lower heating value of H_2, Btu per scf	290	Energy content of hydrogen on a volumetric basis	113
Lower heating value of natural gas, Btu per scf	983	Energy content of natural gas on a volumetric basis	113
Lower heating value of H_2, Btu per lb	52 217	Energy content of hydrogen on a mass basis	155

lower heating values, the hydrogen share of total heat input is lower than the corresponding volumetric blend fraction.

Table 8 lists the fuel properties used in the calculation. Volumetric lower heating values are used to determine the hydrogen contribution to total heat input at a given blend fraction, while the mass-based lower heating value of hydrogen is used to convert hydrogen heat input to hydrogen mass demand.

Because hydrogen and natural gas contribute different amounts of heat per unit volume, the hydrogen share of total turbine heat input is first calculated as:

$$f_{H_2} = \frac{x_{H_2}\mathrm{LHV}^{\mathrm{vol}}_{H_2}}{x_{H_2}\mathrm{LHV}^{\mathrm{vol}}_{H_2} + (1 - x_{H_2})\mathrm{LHV}^{\mathrm{vol}}_{\mathrm{NG}}} \tag{B.1}$$

where f_{H_2} is the fraction of total turbine heat input supplied by hydrogen, x_{H_2} is the hydrogen fraction in the blended fuel on a volumetric basis, $\mathrm{LHV}^{\mathrm{vol}}_{H_2}$ is the lower heating value of hydrogen on a volumetric basis (Btu per scf), $\mathrm{LHV}^{\mathrm{vol}}_{\mathrm{NG}}$ is the lower heating value of natural gas on a volumetric basis (Btu per scf). In this study, x_{H_2} takes values from 0.05 to 0.35, corresponding to 5 to 35 vol% hydrogen blends.

For each hourly turbine record, the corresponding hydrogen heat input is then calculated as:

$$\mathrm{HI}_{H_{2,h}} = \mathrm{HI}_{\mathrm{TT,h}}\, f_{H_2} \tag{B.2}$$

where $\mathrm{HI}_{H_{2,h}}$ is the hydrogen heat input in hour h(MMBtu per h), $\mathrm{HI}_{\mathrm{TT,h}}$ is the total turbine heat input in hour h(MMBtu per h).

The hourly hydrogen mass demand is calculated from the hydrogen heat input as:

$$\dot{m}_{H_{2,h}} = \frac{\mathrm{HI}_{H_{2,h}} \times 10^6}{\mathrm{LHV}^{\mathrm{mass}}_{H_2}} \times 0.453592 \tag{B.3}$$

where $\dot{m}_{H_{2,h}}$ is hourly hydrogen demand (kg h^{-1}), and $\mathrm{LHV}^{\mathrm{mass}}_{H_2}$ is the lower heating value of hydrogen on a mass basis (Btu per lb), 10^6 converts MMBtu to Btu, and 0.453592 converts pounds to kilograms.

Finally, the annual hydrogen demand is obtained by summing the hourly hydrogen demand across all hourly records in year y:

$$M_{H_{2,y}} = \frac{1}{1000}\sum_{h=1}^{N_y} \dot{m}_{H_{2,h}} \tag{B.4}$$

where $M_{H_{2,y}}$ is the annual hydrogen demand MT per year, $\dot{m}_{H_{2,h}}$ is the hourly hydrogen demand in hour h(kg h^{-1}), and N_y is the total number of hourly records in year y. Division by 1000 converts kilograms to metric tons.

A volumetric hydrogen blend does not translate directly into the same share of thermal input because hydrogen has a much lower volumetric lower heating value than natural gas. Eqn (B.1)–(B.4) therefore first convert the volumetric blend fraction to a heat-input share and then convert that hydrogen heat input to hourly and annual mass demand.

The resulting annual hydrogen demand values for KIAC under co-firing scenarios of 5 to 35 vol% are reported in Table 4 in Section 3.3.3. These estimates are intended to support infrastructure planning and comparative assessment of hydrogen supply requirements under transitional co-firing scenarios.

Appendix C: Estimation of hydrogen demand for the New Terminal One microgrid

This appendix describes the screening-level method used to estimate hydrogen demand for the fuel-cell component of the New Terminal One microgrid under two operating modes: blended operation with hydrogen introduced into the natural gas stream at 5, 20, and 30 vol%, and full conversion to 100% hydrogen. Because the facility is under construction, the estimates are based on the installed fuel-cell capacity and representative operating assumptions rather than measured field performance. The calculation also distinguishes between the lower-bound electrical efficiency used for the blended-fuel cases and the upper-bound electrical efficiency used for the 100%

Table 9 Fuel properties and fuel-cell inputs used in the microgrid hydrogen-demand analysis

Particulars	Value	Comments	Reference
Lower heating value of H_2, Btu per scf	290	Hydrogen lower heating value on a volumetric basis	113
Lower heating value of natural gas, Btu per scf	983	Natural gas lower heating value on a volumetric basis	113
Installed capacity, MW	3.84	Nameplate electric output of the fuel-cell system	122
Capacity factor, %	95	Assumed average operating capacity factor	126
Electrical efficiency, %	44–50	Lower value used for blended-fuel cases; upper value used for pure-hydrogen case	126

hydrogen case. Table 9 lists the fuel properties and fuel-cell inputs used in the analysis.

Because hydrogen and natural gas have different volumetric lower heating values, the hydrogen share of total fuel energy is first calculated as:

$$f_{H_2} = \frac{x_{H_2}\mathrm{LHV}^{\mathrm{vol}}_{H_2}}{x_{H_2}\mathrm{LHV}^{\mathrm{vol}}_{H_2} + (1 - x_{H_2})\mathrm{LHV}^{\mathrm{vol}}_{\mathrm{NG}}} \tag{C.1}$$

where f_{H_2} is the fraction of total fuel energy supplied by hydrogen, x_{H_2} is the hydrogen fraction in the fuel blend on a volumetric basis, $\mathrm{LHV}^{\mathrm{vol}}_{H_2}$ is the lower heating value of hydrogen on a volumetric basis (Btu per scf), and $\mathrm{LHV}^{\mathrm{vol}}_{\mathrm{NG}}$ is the lower heating value of natural gas on a volumetric basis (Btu per scf). For the blended-fuel scenarios, x_{H_2} takes values of 0.05, 0.20, and 0.30. For the pure-hydrogen case, $f_{H_2} = 1$.

The daily fuel input required to generate the target electrical output is then calculated as:

$$E_{\mathrm{fuel,d}} = \frac{(P_{\mathrm{FC}} \times 24 \times \mathrm{CF}) \times 3,600}{\eta_{\mathrm{e}}} \tag{C.2}$$

where $E_{\mathrm{fuel,d}}$ is the daily fuel input (MJ per day), P_{FC} is the installed fuel-cell electric output (MW), CF is the fuel-cell capacity factor, η_{e} is the electrical efficiency of the fuel-cell system, and 3600 converts MWh to MJ. In this study, $\eta_{\mathrm{e}} = 0.44$ is used for the 5 to 30 vol% blend cases and $\eta_{\mathrm{e}} = 0.50$ is used for the 100% hydrogen case.

The corresponding daily hydrogen demand is calculated as:

$$M_{H_{2,\mathrm{d}}} = \frac{E_{\mathrm{fuel,d}} f_{H_2}}{\mathrm{LHV}^{\mathrm{mass}}_{H_2}} \tag{C.3}$$

where $M_{H_{2,\mathrm{d}}}$ is the daily hydrogen demand (kg per day), $E_{\mathrm{fuel,d}}$ is the daily fuel input (MJ per day), f_{H_2} is the hydrogen fraction of total fuel energy, and $\mathrm{LHV}^{\mathrm{mass}}_{H_2}$ is the lower heating value of hydrogen on a mass basis (MJ kg^{-1}).

Annual hydrogen demand is then obtained by:

$$M_{H_{2,\mathrm{y}}} = 365\, M_{H_{2,\mathrm{d}}} \tag{C.4}$$

where $M_{H_{2,\mathrm{y}}}$ is the annual hydrogen demand (kg per year).

For the blend cases, the fuel-input CO_2 reduction is approximated by the hydrogen share of total fuel energy, assuming that the hydrogen portion of the blend contributes no direct fuel-input CO_2:

$$R_{CO_2} = 100\, f_{H_2} \tag{C.5}$$

where R_{CO_2} is the estimated percentage reduction in fuel-input CO_2 relative to the natural-gas-only case. For the 100% hydrogen case, $R_{CO_2} = 100\%$.

Eqn (C.1)–(C.5) are used to estimate the hydrogen demand and corresponding fuel-input CO_2 reduction reported in Table 5 in Section 3.3.3. The method is intended to provide a screening-level estimate of fuel requirement under staged hydrogen integration scenarios rather than a detailed operational simulation of the microgrid under time-varying dispatch conditions.

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