Hydrogen Applications for Energy Transition in Port and Airport Operations at the Port Authority of New York and New Jersey

Veronika Semchukova, Kevin Topolski, and Zainul Abdin

National Renewable Energy Laboratory

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Preface

The Port Authority of New York and New Jersey (PANYNJ) aims to reduce emissions as part of its environmental sustainability efforts. To achieve its 2030 target of reducing Scope 1 and Scope 2 carbon dioxide equivalent (CO_2e) emissions by 50% and its goal of net-zero emissions by 2050, PANYNJ is exploring a range of energy solutions, including hydrogen technologies. This report evaluates the potential role of hydrogen in emissions reduction across key operational areas, including vehicles, equipment, stationary power, aviation propulsion, and marine propulsion. It assesses hydrogen's technical feasibility, infrastructure requirements, and economic considerations within PANYNJ's operational framework. The findings aim to inform decision-making as PANYNJ transitions to cleaner energy sources and mitigates environmental impacts. Based on existing literature and stakeholder feedback, the report outlines opportunities and challenges associated with hydrogen integration, providing insights to guide PANYNJ's future sustainability initiatives.

Acknowledgments

The authors acknowledge receiving financial support from the Port Authority of New York and New Jersey and express gratitude to the National Renewable Energy Laboratory for providing essential resources and support for this work. The authors thank the reviewers, Michael Penev, Andrew Kotz, Keith Wipke, Mark Ruth, Scott Cary, Zia Abdullah, and Robert Baldwin, for their constructive feedback that substantially improved the report. The authors also extend special thanks to Scott Kessler, Lauren Filler, Andrew Lo, Calder Orr, Tanja Grzeskowitz, Rimma Krakhmalnikov, Michelle Cohen, Laura Malo Yague, and Jonathan Dinces from PANYNJ for their continued support and contributions to the report.

List of Acronyms

AAAE	American Association of Airport Executives
ABS	American Bureau of Shipping
ANL	Argonne National Laboratory
ATJ	alcohol-to-jet
CAMPD	Clean Air Markets Program Data
CARB	California Air Resources Board
CHE	cargo-handling equipment
CHP	combined heat and power
CO	carbon monoxide
CO_2e	carbon dioxide equivalent
DGE	diesel gallon equivalent
DOE	U.S. Department of Energy
eGRID	Emissions & Generation Resource Integrated Database
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
EWR	Newark Liberty International Airport
FCE	fuel cell electric
HD-FCEV	heavy-duty fuel cell electric vehicle
FT	Fischer-Tropsch
GHI	Ground Handling International
GPU	ground power unit
GSE	ground support equipment
HDV	heavy-duty vehicle (gross vehicle weight rating >33,000 lbs.)
HEFA	hydroprocessed esters and fatty acids
HTDC	Hawaii Technology Development Corporation
ICAO	International Civil Aviation Organization
IMO	International Maritime Organization
IRENA	International Renewable Energy Agency
IRS	Internal Revenue Service
JFK	John F. Kennedy International Airport
KIAC	Kennedy International Airport Cogeneration
LGA	LaGuardia Airport
MPDGE	miles per diesel gallon equivalent
MPG	miles per gallon
MSW	municipal solid waste
NETL	National Energy Technology Laboratory
NOx	nitrogen oxides
NREL	National Renewable Energy Laboratory
OGV	oceangoing vessel
PAFC	phosphoric acid fuel cell
PAMT	Port Authority Marine Terminal
PANYNJ	Port Authority of New York and New Jersey
PEMFC	proton exchange membrane fuel cell
RoRo	roll-on, roll-off
RTG	rubber-tired gantry

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

Executive Summary

The Port Authority of New York and New Jersey (PANYNJ) has been aiming to reduce Scope 1 and Scope 2 carbon dioxide equivalent (CO_2e) emissions by 50% by 2030 and to achieve net-zero emissions by 2050 across Scopes 1, 2, and 3, though implementation challenges remain. In alignment with these goals, this report evaluates hydrogen technology as a potential complementary component within a broader energy transition strategy for port and airport operations. PANYNJ operates multiple airports and marine terminals, facilitating high volumes of cargo and passenger transport, which contribute to its overall energy demand. The analysis focuses on key operational sectors, including cargo-handling equipment (CHE), port drayage trucks, oceangoing vessels (OGVs), stationary power systems, and aviation propulsion. It assesses hydrogen's technological readiness, infrastructure requirements, economic viability, and pathways for potential adoption within PANYNJ's operational framework.

Potential Benefits of Hydrogen Applications

This report assumes that procured hydrogen is 'green', that is, electrolytic hydrogen produced using renewable energy sources, primarily solar and wind. The production process does not directly emit CO_2e, and its use as a fuel presents opportunities for emission reductions in sectors where alternative energy solutions face technical limitations. Although electrification is generally effective for some applications, such as drayage trucks, hydrogen offers distinct advantages for operations requiring extended range, high energy demand, rapid fueling, and grid independence. In aviation propulsion and maritime shipping, where battery-electric systems face energy density and storage challenges, hydrogen and its derivatives may provide a viable alternative for long-term fuel diversification and operational resilience.

- **Emissions Reductions:** Hydrogen fuel cells in vehicles, equipment, and potentially aircraft can eliminate CO_2e and nitrogen oxides (NOx) emissions at points of use, improving local air quality. Hydrogen combustion applications, such as power generation and aviation propulsion, eliminate CO_2 and volatile organic compounds (VOCs) but may increase NOx emissions, which is a particular concern in ozone non-attainment areas such as New York and New Jersey. However, commercial viability will depend on ensuring NOx levels remain comparable to or lower than those of conventional technologies. The potential to reduce lifecycle emissions is contingent upon the adoption of low-carbon hydrogen production technologies, minimizing upstream emissions from hydrogen generation.
- **Operational Efficiency:** Hydrogen fuel cell vehicles and equipment offer rapid fueling and extended operational ranges, making them suitable for multi-shift operations. This is particularly relevant for highest utilization cargo-handling equipment and Class 8 drayage trucks, where battery-electric alternatives may present trade-offs between range and charging time. Additionally, fuel cell vehicles and equipment reduce dependency on the power grid, benefiting facilities with electrical capacity constraints.
- **Energy Resilience:** Hydrogen offers increased energy resilience from its energy storage capabilities by providing backup power during grid outages or periods of peak demand. Ports and airports are experiencing growing electricity demand, leading to increased baseload, peak demand, and load volatility. Stationary fuel cells, either as standalone units or within renewable energy-integrated microgrids, can provide reliable power for critical infrastructure, particularly in grid-constrained environments.

Challenges to Hydrogen Adoption

- **Infrastructure Development:** A key challenge for hydrogen adoption is the diverse infrastructure requirements for each application. Off-road equipment will necessitate on-site hydrogen storage and fueling, while on-road heavy-duty vehicles will require a regional fueling network near key PANYNJ facilities. Liquid hydrogen truck delivery is expected to be the primary mode of supply for vehicles and equipment in the near term, whereas large-scale and long-term applications will likely depend on pipeline delivery. Stationary power applications require minimal new infrastructure if pipeline hydrogen is available, while aviation propulsion will require dedicated liquid hydrogen storage and distribution infrastructure at airports.
- **Economic Viability:** The adoption of hydrogen technologies is constrained by high capital costs, particularly for equipment, storage, and fueling infrastructure, making early-stage deployment financially challenging. Operating expenses remain a concern, with pre-competitive hydrogen prices currently ranging from $12 to $18 per diesel gallon equivalent (DGE) (NREL 2024)[1]. Federal initiatives, such as the U.S. Department of Energy's Regional Clean Hydrogen Hubs program aim to expand supply networks, foster competition, and improve economic feasibility. Additionally, cost structures observed in non-light-duty applications, such as material handling in logistics operations, offer insight into more competitive hydrogen pricing models, particularly in vertically integrated supply chains where hydrogen production, distribution, and fueling infrastructure are managed by a single entity.
- **Technological Readiness Level (TRL):** Hydrogen technologies for CHE and HDVs are advancing toward commercial deployment, while aviation propulsion and certain maritime applications remain in early development phases. Hydrogen co-firing in large-scale stationary power systems is still in the pilot phase, requiring further demonstrations and integration with existing infrastructure. Expanding hydrogen's role in aviation and maritime sectors will depend on scaling production, achieving cost reductions through economies of scale, securing regulatory certification, and driving industry adoption, alongside the necessary infrastructure investments to support widespread deployment.

Table ES-1. Hydrogen Applications, Challenges, and Opportunities by Sector

Application	Hydrogen Technology Status[a]	Challenges	Opportunities
Cargo-Handling Equipment	FCE[b] equipment at TRL 5–7, with ongoing demonstrations for terminal tractors, container handlers, and reach stackers	Higher equipment costs compared to internal combustion engine (ICE) units, due to the complexity of FCE powertrain and limited commercial scale. Lack of commercially available mobile fueling solutions	Suitable for nonstationary equipment types with high power requirements and multi-shift operations requiring rapid turnaround, due to operating ranges and fueling times

[1] The fuel price comprises hydrogen production via low-temperature electrolysis, liquefaction, liquid H_2 truck terminal, liquid trucking, and dispensing at a fueling station for heavy-duty vehicles.

Application	Hydrogen Technology Status[a]	Challenges	Opportunities
		Hydrogen storage footprint at the terminals	
Class 8 Drayage Trucks	HD-FCEVs[c] at TRL 7–8, with multiple trials at maritime ports; a hydrogen pilot proposed by PSE&G and NJEDA at Port Newark is under review	Nonexistent hydrogen fueling infrastructure in the New York/New Jersey region Higher vehicle costs compared to ICE units Regulatory constraints HD-FCEVs are more suitable for long-haul applications than short-haul drayage	Comparable performance to diesel trucks (driving range, fueling time, payload) If incorporated into fleets serving the port, should target units traveling longer distances
Shore Power	Fuel cells at TRL 5	Low technology readiness High initial investment Capacity expansion limited by footprint for hydrogen storage	More suitable for areas where grid capacity cannot accommodate shore power or as a small-scale backup
Stationary Power	Natural gas fuel cells are commercialized, H2 fuel cells at TRL 8-9; hydrogen co-firing in gas turbines at lower TRL, but pilots have been conducted with GE LM6000	Fuel cells: Currently, natural gas is primarily used as feedstock Co-firing: Limited capability of existing equipment to co-fire hydrogen, increased NOx emissions Infrastructure: Fuel delivery by pipeline is preferred; the ability to blend hydrogen in the existing natural gas grid is limited.	Fuel cells: Combined heat and power capability depending on the type, resilience in case of an outage, potential reduction of peak demand charges, integration with renewable energy Co-firing: Decarbonizing existing assets, resilience in case of an outage
Aviation Propulsion	FCE aircraft at TRL 6 for commuter /regional flights; hydrogen combustion remains at early TRL stages	FCE: Design challenges due to the energy density of hydrogen, no FAA certification Combustion: low TRL, NOx emissions, contrails, design challenges Capital expenses for new liquid hydrogen storage and distribution infrastructure at the airport; availability of pure hydrogen delivery via pipeline	In the near term, green hydrogen can lower the carbon intensity of sustainable aviation fuel. In the medium to long term, FCE or hydrogen combustion aircraft could be suitable for commuter to medium haul segments
Ground Support Equipment	Select FCE equipment at TRL 7, several demonstrations completed	Higher equipment costs compared to ICE units Limited fueling infrastructure, footprint of hydrogen storage	FCE could play supplemental role for high-utilization equipment in the medium to long term.

[a] TRL from literature or assigned using the Technology Readiness Assessment Guide (DOE 2015)
[b] FCE: fuel cell electric
[c] HD-FCEV: heavy-duty fuel cell electric vehicle

Strategies for Hydrogen Implementation at PANYNJ

- **Medium-term Applications (Post-2030):** Hydrogen applications could play a role in reducing Scope 3 emissions beyond 2030. Select CHE units could be early adopters of fuel cell technology, given their relatively lower infrastructure requirements, followed by Class 8 drayage trucks. Decision-making should be guided by comparative cost-benefit analyses of hydrogen versus other energy transition options, considering operational requirements, upfront costs, infrastructure deployment timelines, potential grid upgrades, and green hydrogen availability. As fuel cell aircraft move toward Federal Aviation Administration (FAA) certification, their feasibility should be evaluated alongside battery-electric solutions.
- **Long-term Applications (Post-2050):** Potential long-term applications include large-scale stationary power generation and hydrogen combustion aircraft. Both applications will require substantial hydrogen supply, and their feasibility will be highly fuel price-dependent. Stationary power applications will likely require pipeline hydrogen delivery, contingent on utility companies' plans for blending or providing pure hydrogen. Hydrogen combustion aircraft will require new liquid hydrogen storage and distribution infrastructure at airports. The hydrogen value proposition in these applications will likely evolve over time, necessitating ongoing assessment.
- **Indirect Applications:** Hydrogen derivatives (e.g., ammonia, methanol) could serve as alternative fuels for oceangoing vessels in the medium term. PANYNJ should monitor developments in safety, commercial readiness, and infrastructure for potential future adoption. Additionally, natural-gas-powered stationary fuel cells could be a near-term solution, especially if they incorporate combined heat and power (CHP) capabilities. Sustainable aviation fuel (SAF), which requires hydrogen as an input, represents another indirect application that could reduce the carbon intensity of the fuel.

  Safety Considerations: Safe hydrogen deployment requires comprehensive risk management, regulatory compliance, and workforce training. First responders and operational personnel must be trained in hydrogen-specific safety protocols to enhance incident response capabilities. Adherence to established safety codes, such as NFPA 2 (Hydrogen Technologies Code) and ISO 19880 (Hydrogen Refueling Stations), is essential for mitigating risks associated with storage, transport, fueling, and end use. Any hydrogen pilot project must undergo extensive safety review to address both technical risks and community concerns related to perceived hazards. Collaboration with regulatory agencies, emergency responders, and industry stakeholders is critical to ensure alignment with evolving safety standards and best practices, thereby minimizing risks to personnel, infrastructure, and surrounding communities.

  The community's unfamiliarity with hydrogen technology may amplify perceived safety risks, particularly regarding flammability or potential explosions (EFI 2024). To foster social trust, transparency, and community engagement are essential. These can be achieved by disseminating clear information about hydrogen safety, organizing citizen panels, and hosting public forums. Prior to launching pilot projects, ports should not only inform and solicit feedback from the community but also actively integrate community perspectives into the decision-making process to guide project design and implementation (Romero-Lankao et al. 2023).

This report objectively assesses hydrogen's potential role in reducing emissions at PANYNJ while addressing associated technological, economic, and infrastructure challenges. The findings offer a basis for informed decision-making as PANYNJ evaluates pathways toward achieving net-zero emissions.

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1 Introduction

The Port Authority of New York and New Jersey (PANYNJ) has set targets to reduce Scope 1 and Scope 2 carbon dioxide equivalent (CO_2e) emissions by 50% by 2030 and to achieve net-zero emissions by 2050 (AECOM, KO2 Consulting, and Lion Advisors for Community and Environment 2023). Meeting these goals requires addressing emissions across multiple operational sectors, including cargo-handling equipment (CHE), port drayage trucks, oceangoing vessels (OGVs), and airport ground support equipment (GSE). Emissions from CHE, drayage trucks, GSE, OGVs, and aircraft are classified as Scope 3, meaning they are not directly controlled by PANYNJ but can be influenced through infrastructure investments, policy incentives, and partnerships. As part of its broader energy transition strategy, PANYNJ is evaluating multiple energy pathways, including battery-electric systems, hydrogen-based fuel cell systems, and alternative low-carbon fuels such as renewable diesel, sustainable aviation fuel, and ammonia and methanol for maritime applications. Hydrogen is being assessed for its potential role in port operations, particularly in applications where battery-electric solutions or direct grid-based electrification may be challenging due to operational or infrastructure constraints. This report examines the feasibility of hydrogen infrastructure at PANYNJ, its cost implications, and regulatory considerations, alongside alternative energy solutions that contribute to the port's long-term sustainability, energy diversification, and operational resilience objectives.

This report assesses hydrogen's potential to support PANYNJ's energy transition strategy, focusing on its role in reducing emissions across key operational sectors. Clean hydrogen is defined as hydrogen with lifecycle production emissions of less than 4 kg of CO_2e per kg of hydrogen, which aligns with the threshold required for the Clean Hydrogen Production Tax Credit (45V) (IRS 2025). Clean hydrogen can be produced through multiple pathways, including low- and high-temperature electrolysis powered by renewable or nuclear energy, reforming of renewable natural gas with over 90% carbon capture and storage, and pyrolysis (DOE 2025). While the 45V tax credit provides financial incentives for clean hydrogen, alignment with DOE's Hydrogen Production Standard and global best practices in hydrogen certification is essential for ensuring long-term viability.

Low-temperature electrolysis powered by renewable energy sources, such as solar, wind, and hydroelectric power, produces hydrogen with no direct CO_2 emissions. High-temperature electrolysis powered by nuclear energy generates approximately 0.1 kg of CO_2 per kg of hydrogen, primarily due to the carbon intensity of the nuclear fuel cycle. However, steam methane reforming (SMR) without carbon capture remains the dominant production method today, emitting approximately 9–11 kg of CO_2 per kg of hydrogen (DOE 2025). Additionally, hydrogen produced via grid-powered electrolysis is unlikely to qualify as clean hydrogen under current regulatory thresholds, as emissions vary based on regional grid carbon intensity. Biomass gasification with more than 90% carbon capture presents an alternative with the potential for negative emissions, as it can offset CO_2 that would otherwise enter the atmosphere (Elgowainy et al. 2024).

Beyond production, hydrogen's downstream processes, including liquefaction, compression, transportation, and dispensing, also contribute to overall emissions. Gaseous and liquid hydrogen supply chains involve energy-intensive processes, particularly compression and liquefaction, which can significantly increase emissions if powered by fossil-based grid electricity. For

instance, hydrogen liquefaction requires approximately 10–13 kWh of energy per kilogram, making renewable energy integration essential for minimizing lifecycle emissions (Gardiner 2009). Additionally, hydrogen delivery via tube trailers increases emissions due to reliance on diesel-powered transportation, further impacting sustainability (Frank et al. 2021). Transitioning to alternative transport methods, such as fuel cell electric vehicles (FCEVs) for hydrogen delivery, could reduce emissions, particularly when fueling infrastructure is available at both ends of the distribution route. Minimizing emissions across the hydrogen supply chain will require the adoption of low-emission electricity sources and alternative transportation solutions to improve overall energy efficiency and align with broader energy transition goals.

The availability and cost of green hydrogen are critical factors determining its feasibility for large-scale applications. Currently, 95% of hydrogen in the United States is produced via SMR at a levelized cost of approximately $1/kg, with distribution primarily to industrial end-users through 1,600 miles of dedicated hydrogen pipelines (DOE 2025). In contrast, electrolytic hydrogen production cost estimates range from $5–$7/kg without incentives or infrastructure, making cost reductions essential for competitiveness (DOE 2025). Different transportation sectors exhibit varying willingness to pay for delivered hydrogen, with medium- and heavy-duty transport at $3.6–$4.8/kg, aviation fuels at $0.8–$3.3/kg, and maritime fuels at $0.8–$1.6/kg. However, delivered hydrogen costs fluctuate based on geography, supply chain logistics, and infrastructure availability, with limited midstream infrastructure posing a significant challenge where production and consumption sites are not co-located (DOE 2025). Understanding hydrogen's cost impact on end-use sectors is also important. For example, in aviation and maritime transport, fuel costs represent a fraction of total operating expenses, including capital expenditures, labor, maintenance, and regulatory compliance. Further analysis is required to assess the extent to which these sectors can absorb higher hydrogen costs without significantly affecting overall economics.

Regions such as New York and New Jersey face unique challenges in accessing green hydrogen, primarily due to limited renewable energy capacity, high land-use costs, and logistical constraints. The cost of electrolytic hydrogen production depends largely on renewable energy availability and capacity factors, with lower capacity factors for solar and wind contributing to higher production costs. However, existing nuclear facilities offer a potential pathway for lower-cost, high-capacity hydrogen production in the Northeast, given their consistent power output and the ability to support high-temperature electrolysis (DOE 2025). In New York State, an announced electrolyzer project plans to utilize hydroelectric power, while a high-temperature electrolysis demonstration using nuclear energy was already operational in 2023 (Constellation 2023; New York State 2022a).

The report is structured as follows: Section 2 provides an overview of PANYNJ's emissions and operational profile, identifying key sectors for energy transition and emissions reduction. Section 3 analyzes hydrogen applications within port operations, focusing on cargo handling and maritime transport. Section 4 evaluates hydrogen's potential in airport operations, particularly in ground support and stationary power systems. Section 5 summarizes the findings and outlines possible options for further hydrogen deployment to support PANYNJ's long-term energy strategy and sustainability objectives.

2 Emissions Within the Context of PANYNJ

This section examines the emissions profile and operational landscape of the marine terminals and airports under the jurisdiction of PANYNJ. This information will guide the subsequent exploration of potential hydrogen applications to address PANYNJ's environmental goals.

2.1 Maritime Emissions and Background

PANYNJ operates as a landlord port, wherein the Port Authority retains ownership of the land and infrastructure while leasing terminals to private operators who manage its daily operations. The Port Authority directly controls only a fraction of total emissions, categorized as Scope 1 and Scope 2, while most emissions, categorized as Scope 3, originate from tenant and customer activities linked to Port Authority facilities. The port complex includes five key marine terminals, as shown in Figure 1: Port Newark, Elizabeth Port Authority Marine Terminal (PAMT), Port Jersey PAMT, and Howland Hook Marine Terminal, New York. To accommodate the diverse cargo handled at the port, six container terminals are equipped to handle general cargo, break-bulk cargo, roll-on/roll-off (RoRo) cargo, and bulk cargo. Additionally, the port features three auto terminals, two cruise terminals, and public berths (PANYNJ n.d.-a; PANYNJ n.d.-b; AECOM, KO2 Consulting, and Lion Advisors for Community and Environment 2023).

Figure 1. Map of PANYNJ's marine terminals[2]

Data sources: NYC Planning 2022, NJGIN Open Data 2022.

The port serves a population exceeding 27 million, contributing to approximately 563,000 direct and indirect jobs (PANYNJ 2019; Strauss-Wieder 2023). In terms of overall tonnage and 20-foot equivalent unit throughput, the port ranks within the top five U.S. ports (Chambers et al. 2023). Over the last 15 years, the port has experienced consistent growth in cargo volume and anticipates continued expansion (PANYNJ 2019). To accommodate this growth, all terminals are

[2] The map shows industrial land zones (purple) that could house hydrogen infrastructure. The designated land includes: New York City - manufacturing zones, New Jersey – industrial, industrial and commercial complexes zones in New Jersey.

planning to undergo strategic enhancements to improve cargo-handling capabilities, from network upgrades at Elizabeth PAMT and Port Newark, to land expansion at Howland Hook and Port Jersey PAMT (PANYNJ 2019).

Figure 2 illustrates the distribution of CO_2e emissions from a selection of mobile combustion sources at the port in 2021 (Starcrest Consulting Group 2022). This visualization indicates that CHE, HDVs, and OGVs collectively account for 92% of total emissions, with HDVs (primarily drayage trucks) contributing nearly half.

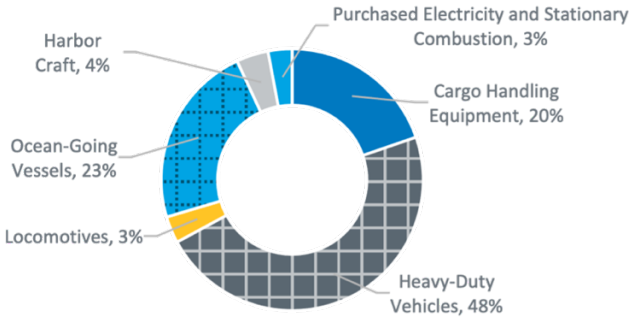

Figure 2. Distribution of CO_2e emissions by source at the PANYNJ in 2021

Data adapted from references: Starcrest Consulting Group 2022, SC&A Inc. 2023

CHE encompasses a range of equipment types that are fundamental to the port's operations and responsible for transferring cargo between vessels and land-based transportation modes, such as heavy-duty trucks and rail. Approximately 86% of the CHE at PANYNJ is powered by diesel engines (Starcrest Consulting Group 2022). This reliance on diesel engines, particularly in short-cycle, repetitive tasks inherent to CHE operations, results in suboptimal combustion efficiencies, leading to a substantial generation of CO_2e emissions. Among the equipment, straddle carriers contribute 42% of the overall CHE emissions profile, followed by terminal tractors (19%), rubber-tired gantry (RTG) cranes (13%), and loaded container handlers (12%) (Starcrest Consulting Group 2022).

Drayage trucks at the port are primarily involved in short-haul drayage operations, transporting cargo between terminals and nearby locations, such as warehouses or distribution centers. Although other types of HDVs (e.g., car carriers and tankers) also visit the port, PANYNJ's emissions reports identifies drayage trucks with a range of up to 200 miles as representative of the fleet servicing the port (Starcrest Consulting Group 2022). Over 99% of the trucks visiting the port are diesel-powered, significantly contributing to the port's emissions profile (PANYNJ 2023c.). Furthermore, CO_2e emissions from HDVs increased by 80% between 2006 and 2021, a trend that correlates with increased truck activity to meet the growing cargo throughput at the port (Starcrest Consulting Group 2022). Nearly 89% of HDV emissions

originate from on-road driving,[3] with intra-terminal driving and idling contributing 5% and 6%, respectively (Starcrest Consulting Group 2022).

OGV activity at PANYNJ is characterized by container ships, auto carriers, tankers, bulk carriers, and cruise ships. The operations of these vessels are predominantly categorized into two modes: transit and dwelling.[4] In the port's territorial waters, the dwelling state of the vessels is prevalent, with most of emissions originating from auxiliary engines, which are essential for maintaining vessel operations, such as lighting; heating, ventilating, and air conditioning; and emergency systems (Ballard Power 2019). Overall, auxiliary engines contribute 54% of OGVs at the port, followed by boilers and main engines, which contribute approximately 30.5% and 15.5%, respectively.

Other notable emissions sources include locomotives, harbor craft, and building energy use. Locomotive operations are divided into two categories: line-haul and switching; the former connects the freight originating at the port with broader regions via long-distance transport, and the latter operate within railyards at or in proximity to marine terminals. Despite a rapid expansion of operations, including a 109% increase in on-dock lifts since 2006, the rise in CO_2e emissions was limited to 88% (Starcrest Consulting Group 2022). Harbor craft, primarily consisting of towboats and assist tugs, serve a vital function in the operations of PANYNJ, facilitating the docking and maneuvering of OGVs and the transportation of cargo-laden barges. The data suggest that due to fleet upgrades, this source saw a moderate 5% increase in CO_2e emissions since 2006 (Starcrest Consulting Group 2022).

Although the contribution of locomotives and harbor craft is limited and not the focus of the report, these transport modes could complement drayage trucks in cargo transit, suggesting the potential to expand their operations. Additionally, the primary focus of this report is on mobile emission sources at ports. However, purchased electricity emissions could become more prominent in the future as ports increasingly rely on electricity. Currently, purchased electricity and stationary combustion (e.g., natural gas combustion for space and water heating, emergency generators) collectively contribute emissions comparable to those from locomotives (SC&A Inc. 2023).

2.2 Aviation Emissions and Background

As illustrated in Figure 3, PANYNJ oversees five airports, including four commercial service airports and one of the busiest general aviation airports in the nation. John F. Kennedy International Airport (JFK), Newark Liberty International Airport (EWR), and LaGuardia Airport (LGA) are designated as large hubs. Collectively, these airports served 144 million passengers and handled 2.29 million tons of cargo in 2022. They employ 79,300 people and contributed more than $88 billion to the economic activity of the New York-New Jersey metropolitan region (PANYNJ 2023a.). All three airports are part of redevelopment programs

[3] On-road driving emissions are estimated based on trips between terminals and the truck's initial point of rest (e.g., warehouse, distribution center) within the boundaries of the New York/New Jersey/Long Island nonattainment area. Should the origin/destination of the trip extend into neighboring counties, emissions are calculated solely within the nonattainment area boundaries (Starcrest Consulting Group 2022).
[4] Transit mode also includes maneuvering; dwelling includes hoteling at berth and at anchorage.

intended to accommodate growth and future travel demand. Additionally, PANYNJ oversees a non-hub primary commercial service airport, New York Stewart International Airport (SWF), and one general aviation reliever airport, Teterboro Airport (TEB).

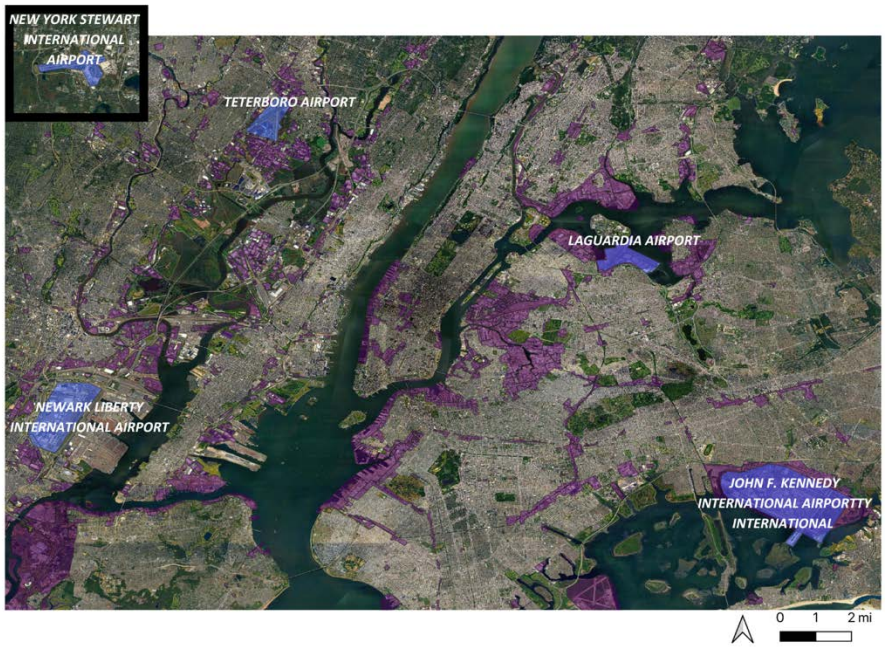

Figure 3. Map of PANYNJ's airports.[5]

Data sources: NYC Planning 2022, NJGIN Open Data 2022.

As shown in Figure 4, aircraft operations heavily influenced CO_2e emissions at PANYNJ airports in 2021, accounting for 56% of total emissions. Passenger-attracted travel contributed 12%, purchased electricity 11%, air cargo 8%, and GSE 6% of CO_2e (SC&A Inc. 2023). Auxiliary power units, energy production, shadow fleets[6], purchased thermal energy, and stationary combustion made up the remaining emissions.

[5] The map shows industrial land zones (purple) that could house hydrogen infrastructure. The designated land includes: New York City - manufacturing zones, New Jersey – industrial, industrial and commercial complexes zones in New Jersey.

[6] "Shadow Fleet" corresponds to mobile emissions from vehicles owned by, but not operated by, the Port Authority. The majority of these vehicles are the airport shuttle buses.

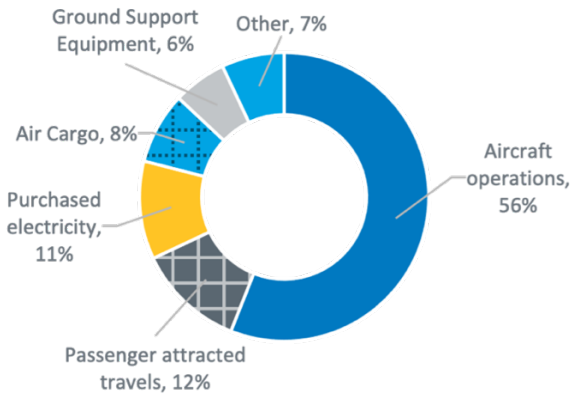

Figure 4. Distribution of CO_2e emissions by source at airports under PANYNJ in 2021

Data adapted from reference: SC&A Inc. 2023

In 2021, despite a reduction in air traffic due to the COVID-19 pandemic, aircraft operations remained the dominant contributor to emissions. JFK alone accounted for nearly half of the total emissions, followed by EWR at 33%, LGA at 14%, TEB at 5%, and SWF at 2% (SC&A Inc. 2023). This distribution is influenced by type, size and volume of aircraft serving each airport. For example, JFK handles a higher proportion of large international commercial operations whereas TEB primarily serves a lower volume of smaller business aircraft.

Among vehicles and equipment, passenger-attracted ground transportation constitutes the most significant emissions source within the aviation department, encompassing the various modes of travel used by airline passengers to access airports, primarily light-duty vehicles such as personal cars and ride-sharing services like Uber and Lyft. Another major category, air cargo transport, includes freight vehicles moving cargo to and from the airport, with emissions largely influenced by cargo throughput at JFK and EWR. Due to the diverse nature of air cargo logistics, including truck feeder services and overnight express deliveries, emissions vary significantly based on vehicle class, fuel type, and trip length. Short-haul feeder services typically range from 10 to 80 miles, primarily supporting regional distribution hubs, while long-haul cargo transfers average between 100 and 200 miles, depending on cargo type and service model (FHWA 2023). Emissions also differ by vehicle type, with light-duty cargo vans emitting approximately 200-300 g CO_2 per mile, while medium- and heavy-duty trucks produce between 1,200 and 1,800 g CO_2 per mile, with diesel-powered models producing the highest emissions impact (EPA 2023a; ANL 2023). Finally, GSE includes airside vehicles and aircraft servicing equipment, with PANYNJ airports operating a diverse fleet of GSE powered by diesel, battery-electric, natural gas, and gasoline, each with varying emissions impacts.

Significant emissions at airports stem from purchased electricity and natural gas combustion for space and water heating that support millions of passengers. At John F. Kennedy International Airport (JFK), a major portion of electricity and thermal energy is supplied by the 121-MW Kennedy International Airport Cogeneration (KIAC) plant, which operates on natural gas fuel. In 2022, the KIAC plant emitted approximately 1,454 metric tons of CO_2 from heating operations and 680 metric tons from cooling operations, contributing to JFK's total energy-related emissions footprint (SC&A 2024). Additionally, the CO_2 emissions factor for the KIAC plant is 1.5 times higher than the regional Emissions & Generation Resource Integrated Database (eGRID) average due to its reliance on natural gas combustion (SC&A Inc. 2023). The KIAC

plant is owned by PANYNJ but operated by a third party under a power purchase agreement (PPA), which governs energy procurement, operations, and resale. Excess electricity generated by the KIAC plant is sold to the regional grid, while surplus thermal energy is distributed to JFK tenants (SC&A 2023).

3 Hydrogen Applications in Port Operations

In global maritime logistics, major ports such as PANYNJ face the dual challenges of maintaining operational efficiency while reducing environmental impacts. This section reviews the potential hydrogen applications at ports focusing on CHE, drayage trucks, marine propulsion, and stationary power. Additionally, it provides the estimated hydrogen requirement for select applications that could aid in infrastructure planning efforts.

3.1 Cargo-Handling Equipment

CHE is essential to port operations, where diesel has long been the dominant fuel due to its high energy density, reliability, and well-established fueling infrastructure. However, increasing regulatory pressure, environmental concerns, and the need to reduce emissions are driving the transition toward low-emission alternatives (Iris and Lam 2019). Various energy transition pathways are being explored, including battery-electric, renewable LNG, and hydrogen-powered fuel cell electric (FCE) technologies. Among these, hydrogen-powered FCE CHE presents a zero-emission solution, offering fast fueling, high energy density, and the ability to support demanding duty cycles without the potential extended charging times required by battery-electric alternatives. However, the adoption of hydrogen in CHE faces challenges related to infrastructure, economic feasibility, public acceptance, and integration into existing port operations. This section reviews the current status of FCE CHE technology, compares hydrogen with other emerging alternative energy solutions, and examines key operational, economic, and infrastructure considerations influencing its potential role in CHE applications.

3.1.1 Current Technologies

Hydrogen, if produced from renewable pathways, can reduce CHE's carbon footprint, promoting sustainable operations at the port. With most hydrogen-powered equipment being developed with FCE powertrains and moving away from internal combustion engines, these solutions are considered zero emissions, eliminating combustion CO_2e and air pollutants.

Table 1 shows the current technological status of hydrogen-powered CHE, covering the technology readiness and operational characteristics of equipment models. Technology readiness levels (TRLs) are based on the California Air Resources Board (CARB) report for yard tractors and empty container handlers (CARB 2022a), and the U.S. Environmental Protection Agency (EPA) report for forklifts (Eastern Research Group Inc. 2022). TRLs for the straddle carrier, loaded container handler, RTG crane, and reach stacker were estimated from ongoing demonstrations at ports.

Additionally, the table compares the estimated current demand for diesel and hydrogen, should these units be substituted with FCE alternatives. To estimate hydrogen demand, the average required mechanical power per type of equipment was calculated based on the rated engine power (hp) and default load factors per the EPA's Port Emissions Inventory Guidance (EPA 2022). Power requirements (kW) were converted to hydrogen demand (kg) by considering

heavy-duty fuel cell efficiency (60%) and the lower heating value of hydrogen (33.33 kWh/kg) (Hydrogen and Fuel Cell Technology Office 2015). Calculations assume an 8-hour shift. To convert kilograms to diesel gallon equivalent, the values were multiplied by the ratio of the energy densities of hydrogen (120 MJ/kg) and ultra-low-sulfur diesel (134.47 MJ/gal) at lower heating values (CARB 2024). More detailed assumptions and fuel demand calculations are provided in Appendices A and B.

Table 1. Status of Hydrogen-Powered FCE CHE

CHE Type	H_2 CHE TRL	H_2 Demand (DGE[a]/unit/ shift)	Diesel Demand (gal/unit/ shift)	H_2 CHE Status
Straddle carrier	5	56	79	In testing phase. Launched at the Port of Antwerp's Noordzee Terminal as part of the Green Straddle Carrier Program following a 2-year design and development stage. This first hydrogen dual-fuel straddle carrier aims to replace up to 70% of diesel use (CMB.TECH 2023; PSA 2023).
Terminal tractor	7	24	34	Pre-commercial demonstrations. Includes a 4x4 RoRo FCE tractor for the Port of Valencia and a yard truck for the Port of Los Angeles with a 16-hour operational range and 15-minute fueling (GTI Energy 2023; California Hydrogen Business Council 2018).
Loaded container handler	7	54	77	Pre-commercial demonstrations. A 52-ton FCE handler tested at the Port of Los Angeles achieved a 10-hour operational range and 15-minute fueling (Hyster-Yale Materials Handling 2023).
Empty container handler	6	30	43	In testing. Deployment planned at the HHLA Container Terminal Tollerortl in Hamburg in 2024, with an expected operational range up to 9 hours (Hyster 2022)
Reach stacker	6	52	74	Pre-commercial FCE demonstration project in Port Valencia, with an 8-hour operation range before fueling (California Hydrogen Business Council 2018)
RTG crane	6	87	123	Pre-commercial demonstration by PACECO at the Port of Los Angeles in 2024. The unit includes a 60-kW fuel cell and 64 kg of storage, enabling up to 16 hours of operation (Mitsui E&S 2022; PACECO n.d.).
Forklift	7	19	37	Commercially available for classes I–III. Pre-commercial demonstrations are underway for classes IV, V, and higher (Eastern Research Group Inc. 2022)

[a]DGE: The amount of fuel it takes to equal the energy content of one liquid gallon of diesel.

To eliminate combustion-related emissions from CHE, ports could transition to battery-electric or FCE equipment. Each option has unique benefits and challenges related to equipment performance, cost, and accessibility. FCE equipment offers the advantage of rapid fueling and maintaining the operational range necessary for multiple shift operations, which can be the case in large container terminals, such as those within PANYNJ. Conversely, battery-electric equipment frequently presents trade-offs between range and charging time, potentially requiring operational planning to prevent additional equipment downtime. If downtime interferes with shifts at a given port, terminal operators might need to purchase additional units to maintain equipment availability (Hyster 2022). Overall, equipment with higher power requirements, such as straddle carriers, might be more effectively powered by hydrogen, especially when required to operate multiple shifts. However, although some equipment types, such as RTG cranes, have high power requirements, their stationary nature allows them to be connected directly to the grid, avoiding downtime and making them more suitable for electrification (Idso et al. 2024).

Transitioning from diesel-powered CHE to FCE technology presents a complex economic dynamic characterized by significant initial investments. The higher purchase price of both FCE and battery-electric equipment presents a significant challenge in transitioning from diesel-powered equipment, with FCE equipment projected to be more costly than battery-electric equipment due to the greater complexity of the powertrain (APM Terminals 2023). A study conducted on conventional diesel and fuel cell yard tractors using duty cycles from PANYNJ indicated that the retail price of fuel cell tractors was projected to be 64% higher in 2020, diminishing to 13% higher by the year 2050, compared to their diesel counterparts. This price difference is primarily due to the costs of fuel cells and fuel storage systems, which are expected to decrease over time. On a total cost of ownership (TCO) basis, fuel cell tractors can achieve a lower TCO due to improved fuel cell efficiency and reduced costs for both the fuel cell system and hydrogen fuel, eventually offering a cost advantage of more than $30,000 compared to diesel units (Gilleon, Penev, and Hunter 2022).

The accessibility of zero-emission CHE at PANYNJ depends on both powertrain technology maturity and energy availability. While battery-electric CHE has a higher TRL and is commercially available for select applications (RMI 2023), large-scale deployment at PANYNJ is constrained by grid capacity limitations. The port's existing electrical infrastructure presents challenges to support the extensive charging demands of a fully battery-electric CHE fleet without substantial utility upgrades, which are both time- and cost-intensive (PANYNJ 2023d).

In contrast, FCE CHE, though still in the demonstration phase, presents an alternative, particularly for high-utilization applications where minimizing downtime and maintaining operational flexibility are critical. Unlike battery-electric systems, hydrogen-powered CHE does not impose significant additional demand on the port's electrical grid, offering a pathway to energy transition without requiring immediate large-scale grid upgrades. However, the feasibility of FCE CHE depends on the development of a reliable green hydrogen supply chain and the establishment of adequate fueling infrastructure within port terminals. Recognizing these challenges, PANYNJ has included hydrogen infrastructure planning in its Net Zero Roadmap, which outlines strategies for reducing greenhouse gas emissions while ensuring operational efficiency. The successful implementation of FCE CHE at PANYNJ will require coordinated efforts between industry stakeholders, policymakers, and infrastructure developers to address both hydrogen production and distribution challenges (PANYNJ 2023d).

To summarize, both battery-electric and FCE CHE can play pivotal roles in achieving net-zero emissions by 2050. Initial efforts might focus on electrifying equipment, such as RTG cranes, which can enable grid power supply via a cable due to limited movement within the yard. Additionally, terminal operators could partially convert the fleet of equipment types that are commercially available in battery-electric versions and can accommodate potential downtime due to charging. As fuel cell technology advances, its deployment can target equipment with the most intensive usage, in line with multi-shift operational needs and environmental impact minimization.

3.1.2 Port Integration Opportunities and Challenges

Specific to PANYNJ, hydrogen can offer operational advantages at busy container terminals, where equipment can continuously operate up to 23 hours. Within the port complex, straddle carriers and empty container handlers have the highest average utilization, with 2,676 and 2,455 hours per year, respectively (Starcrest Consulting Group 2022); however, individual units can operate for more than 5,000 hours annually, indicating that there is limited downtime available for charging equipment between shifts. On the one hand, hydrogen has a high energy density by weight, theoretically allowing for high operational ranges. In practical terms, these are constrained by the capacity of fuel storage on board due to the lower volumetric energy density of the fuel and weight of the tanks. Nevertheless, hydrogen offers quick fueling times, which can benefit high-utilization equipment. The characteristics of FCE units currently in demonstration, including fueling durations and operational ranges for hydrogen-powered equipment, are detailed in Table 1.

But implementing hydrogen-powered equipment entails overcoming infrastructure challenges, particularly regarding storage and supply. One key factor is hydrogen's volumetric energy density, which varies depending on storage form and pressure. When stored as compressed gas at 700 bar, hydrogen has an energy density of 42 kg/m³, significantly lower than conventional liquid fuels such as gasoline and diesel, which range between 720–860 kg/m³(Eastern Research Group Inc. 2022). However, hydrogen's liquid form provides a higher volumetric energy density of approximately 70.8 kg/m³ at -252.8°C, but it remains lower than conventional fuels. Although hydrogen's volumetric energy density remains lower than that of conventional fuels, many port applications can accommodate the additional storage volume required to meet operational needs, thereby reducing the constraints associated with fuel supply capacity. A strategic approach would enable an efficient transition to hydrogen-powered operations, with temporary hydrogen infrastructure supporting early deployment until demand reaches a threshold that justifies permanent infrastructure. Moreover, as hydrogen demand approaches 5,000 kg per day, providers indicate that they are prepared to implement a more robust supply chain to support large-scale operations (Razeghi et al. 2023).

Fueling logistics and the construction of fueling stations for hydrogen-powered CHE are complex, involving permitting, safety regulations, protection measures, and fuel delivery challenges. The Port of Los Angeles's Zero Emissions for California Ports (ZECAP) project demonstrated hydrogen fuel cell yard trucks, highlighting key issues such as fueling efficiency and infrastructure readiness (GTI Energy 2023). Similarly, the Port of Valencia launched the H2Ports project, deploying hydrogen-powered CHE supported by a mobile hydrogen fueling station (Pivetta et al. 2024). This station, located within the port complex, stores gaseous hydrogen delivered by trucks; however, the form of hydrogen, gaseous hydrogen (GH_2) or liquid

hydrogen (LH_2), significantly impacts its scalability and efficiency in port operations. GH_2 delivery via trucks is feasible but limited by low volumetric energy density and storage constraints, making it less practical for large-scale operations unless a pipeline infrastructure is available (Green Hysland n.d.). In contrast, LH_2 delivery offers a higher energy density and may be more suitable for extensive port activities, though it requires cryogenic storage and handling to prevent boil-off losses and maintain operational efficiency. Implementing mobile fueling stations can replicate existing wet-hose fueling practices at ports, facilitating the transition to hydrogen while permanent infrastructure is developed.

Another challenge common to hydrogen deployment at ports, even for temporary projects, is community acceptance. Hydrogen technologies can face public skepticism due to perceived safety risks (Romero-Lankao et al., 2023). Proactive involvement of local communities during the decision-making process is critical to shaping project outcomes. Beyond soliciting feedback and addressing concerns through structured forums, targeted education initiatives and on-site demonstrations of hydrogen systems can help raise awareness about hydrogen technologies and build public trust.

The decision to transition to hydrogen must account for the equipment count by type, as a larger fleet can justify the capital-intensive investment in hydrogen infrastructure by distributing costs across more units. Hydrogen storage and fueling infrastructure benefit from economies of scale, where higher adoption lowers per-unit costs (Ramsden 2013; Metzger and Li 2022). The emissions tier of CHE is another key factor[7]; older diesel engines certified under Tier 0 through Tier 3, which emit higher levels of PM and NOx, may be prioritized for replacement with battery-electric alternatives in applications where hydrogen-powered equipment is not yet commercially viable. Meanwhile, Tier 4 diesel equipment, which meets current emissions standards, may remain in operation, particularly where hydrogen fuel cell alternatives are not yet commercially available or supported by adequate fueling infrastructure. Additionally, annual operational hours must be considered, as fuel cell-powered equipment offers rapid fueling and sustained power output, making it well suited for high-utilization machinery. Battery-electric alternatives, while increasingly viable, may require longer charging windows and careful power management to support continuous-use applications.

To summarize, transitioning to fuel cells for various CHE types, such as straddle carriers, terminal tractors, and container handlers, would maximize CO_2e reduction at PANYNJ. Although straddle carriers are at TRL 5, terminal tractors and container handlers, at approximately TRL 7, have witnessed multiple demonstrations, including those by Hyster. Equipment choice will vary by terminal, aligning with specific operational needs and hydrogen infrastructure usage patterns. The use of mobile fueling trucks or stations, which are emerging as preferred solutions, could replicate existing diesel fueling operations, as recently demonstrated at the ports.

3.2 Drayage Trucks

Drayage trucks, a subset of HDVs, are essential for short-haul freight transport in port operations, moving cargo between terminals, rail yards, and distribution centers. Traditionally powered by diesel engines, they contribute significantly to air pollution, emitting PM and NO_x,

[7] Engine tiers refer to the classification of diesel non-road equipment based on the rate of pollutants, such as particulate matter, and NOx, emitted by the combustion process.

leading to stricter emissions regulations. Compliance requires costly after-treatment systems such as diesel particulate filters (DPFs) and selective catalytic reduction (SCR). To mitigate these challenges, zero-emission alternatives like heavy-duty fuel cell electric vehicles (HD-FCEVs) are being explored. This section assesses the feasibility of HD-FCEVs in drayage applications, comparing their performance and operational characteristics to diesel trucks while examining infrastructure, regulatory, and economic considerations.

3.2.1 Current Technologies

HD-FCEVs offer a competitive driving range comparable to conventional diesel trucks. Initial demonstration projects at the Port of Los Angeles showed that HD-FCEVs achieved a driving range of approximately 300 miles, with advancements, such as Hyundai's latest models, extending this range to up to 450 miles (CARB n.d.-c). Table 2 presents a detailed comparative analysis of HD-FCEVs, battery-electric and diesel trucks, highlighting advantages in driving range, fueling time, and emissions reduction. A conventional diesel truck in this context refers to a Class 8 tractor day cab, which is representative of HDVs operating at the port, typically hooking onto trailers used for port operations (e.g., flatbeds, dry vans, or chassis for container transport). Battery-electric trucks in the table refer to the Class 8 Volvo truck model, which currently participates in the drayage pilot project at the Ports of Los Angeles and Long Beach (CARB n.d.-d). Fueling time in the table is categorized as current and target. The current fueling time reflects recent HD-FCEV demonstrations that utilized light-duty fueling infrastructure, codes, and standards. For reference, the average fueling rate for HD-FCEVs in 2022 demonstration projects was 1.5 kg/min, which often resulted in incomplete fueling due to infrastructure limitations (CARB n.d.-c). The target fueling time refers to medium- and heavy-duty fueling protocols currently in development, which aim to achieve fueling times of under 10 minutes (Onorato et al. 2024).

In terms of gross vehicle weight rating, which defines the maximum weight a vehicle is designed to carry, including the vehicle's net weight, vehicles with alternative powertrains have a 2,000-lb weight expansion. HD-FCEVs, due to their high-energy-density fuel cell powertrains, offer payload capacities comparable to diesel trucks, ensuring minimal compromise on cargo capacity. Battery-electric trucks require additional batteries to achieve necessary driving ranges, potentially leading to payload capacity loss (Hunter et al. 2021). However, this payload reduction is more pronounced in long-haul applications than in short-haul drayage operations, where shorter ranges result in minimal payload loss. Finally, maintenance cost per mile includes labor costs and expenses related to routine vehicle maintenance and repairs. The maintenance costs of HD-FCEVs and diesel trucks are nearly equal. However, as illustrated by analysis of in-service Class 6 fuel cell buses, unscheduled and labor costs contribute most to the costs and are expected to decrease as the deployments scale (Hunter et al. 2021; Eudy and Post 2021). Thus, an optimistic scenario would assume that the maintenance costs of battery-electric and fuel cell trucks would be equal, even though the fuel cell powertrain is mechanically more complex.

Table 2. Comparative Analysis of HD-FCEVs and Diesel Trucks in Port Operations

Application	HD-FCEV	Battery-Electric Truck	Conventional Diesel Truck
Driving range (miles) (Papson and Ippoliti 2013; Hyundai 2023; Volvo n.d.)	Up to 450	Up to 275[a]	400
Fueling time (minutes) (CARB n.d.-c; Onorato et al. 2024; Lee et al. 2023; Volvo n.d.)	Current: 15–20 Target: >10	90[b]	10
Gross vehicle weight rating/maximum payload capacity (lbs) (Basma and Rodríguez 2022; Tetra Tech/Gladstein and Neandross and Associates 2023)	82,000/~60,000	82,000/~60,000	80,000/~62,000
Tailpipe emissions (Reşitoğlu, Altinişik, and Keskin 2015)	Zero emissions	Zero emissions	CO_2e, NOx, hydrocarbons, particulate matter, CO
Maintenance cost per mile (Hunter et al. 2021)	$0.153	$0.098	$0.152

[a] The typical range is 220 miles
[b] Charging time to 80% with a 250 kW charger

Prominent examples of HD-FCEVs at ports include Toyota and Kenworth's development of 10 prototype T680 Class 8 trucks used in the Shore-to-Store project at the Port of Los Angeles, demonstrating a 300-mile range and 15-minute fueling (CARB n.d.-c). These advancements signal a growing trend of implementing HD-FCEV units in demonstration projects near port facilities, such as the deployment of a fleet of 30 HD-FCEVs by Hyundai at the Port of Oakland (CARB n.d.-b).

Fuel economy assessments for HD-FCEVs are primarily derived from vehicle modeling and dynamic simulations due to limited real-world operational data. For instance, a study conducted by (Lee et al. 2018) estimated the fuel economy of a Class 8 drayage HD-FCEV at 10.8 miles per diesel gallon equivalent (MPDGE) by adapting methodologies from the Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) to account for electric vehicle characteristics. Similarly, (Hunter et al. 2021) analyzed fuel economies for diesel, battery-electric, and hydrogen fuel cell trucks using representative drive cycles. In a 300-mile range scenario, where increased idling and limited highway driving were accounted for, the modeled HD-FCEV achieved 12.1 MPDGE. In contrast, real-world data from the Port of Los Angeles demonstration project, involving Kenworth and Toyota's HD-FCEVs equipped with first-generation Toyota Mirai fuel cell stacks, reported an average fuel economy of 6.7 MPDGE over 21,650 miles of operation. The lower fuel economy in this case is largely attributed to short daily trips (approximately 50 miles) and a high idling percentage (~43%), which significantly impacts overall efficiency metrics. Since fuel is consumed during idling without contributing to mileage, reporting fuel economy exclusively during travel, excluding idling periods, would provide a more accurate representation of actual driving efficiency. Future advancements are anticipated with Kenworth's latest HD-FCEV models, which now integrate Toyota's second-generation fuel cell modules, expected to enhance performance, extend vehicle

range, and improve efficiency relative to both first-generation HD-FCEVs and conventional diesel trucks (CARB n.d.-c; Kenworth n.d.).

To estimate the fuel demand for drayage operations at port, the average daily mileage should be considered. Origin-destination studies for PANYNJ indicate that most drayage truck trips from container terminals are less than 30 miles, whereas other trucks, such as car carriers transporting cargo from auto and non-container terminals generally exceed 100 miles (Hatch 2018). A recent drayage analysis found an average of 140 miles for diesel drayage trucks with a fuel economy of 5.1 miles per gallon (MPG) at PANYNJ, whereas the Port of Los Angeles estimated 120 miles per day for diesel drayage trucks (Papson and Ippoliti 2013; Kotz et al. 2022). For this study, a daily mileage of 70 was assumed for comparative analysis. Table 3 estimates daily diesel and hydrogen demand based on the described operational characteristics. Similarly to fueling times, the current fuel economy of HD-FCEVs could be outdated by the time they start deploying at ports in volume. Table 3 presents two cases: one based on previous demonstrations of HD-FCEVs at ports and another forward-looking case based on modeled data. We use 6.7 MPDGE and 10.8 MPDGE for those two cases and 5.1 MPG fuel economy for diesel vehicles. For additional details and fuel demand calculations, refer to Appendix B.

Table 3. Estimated Fuel Demand Comparison for Drayage Trucks at PANYNJ

Application	**H_2 HD-FCEV TRL** (CARB n.d.-a)	**H_2 demand (DGE/unit/day) - current**	**H_2 demand (DGE/unit/day) - modeled**	**Diesel demand (gal/unit/day)**
Drayage operations (Class 8 tractor day cab)	7-8	10.4	6.5	13.7

Multiple demonstrations of HD-FCEVs at ports in recent years, with increasing scale, indicate moderate to high technology readiness for this application. Comparative analysis shows that HD-FCEVs are comparable to diesel trucks in terms of range, payload, and fueling time. Initial demonstrations have shown that HD-FCEV fuel economy can exceed that of diesel trucks, with further improvements expected as new generations of fuel cells are deployed in these products.

3.2.2 Port Integration Opportunities and Challenges

At PANYNJ, the introduction of hydrogen-powered drayage trucks offers both challenges and opportunities. Hydrogen's high energy density by mass and zero-emissions operations make it a viable alternative to conventional diesel-powered HDVs, particularly in contexts where reducing downtime and maintaining payload capacity are critical. Accounting for powertrain and hydrogen storage tank weight, these HDVs approach performance parity with diesel trucks. However, volumetrically, compressed gaseous hydrogen storage tanks occupy significant space and require precise packaging to avoid compromising the overall vehicle configuration (Onorato, Ruple, and Gilleon 2021). To increase capacity and meet range targets, available models position the hydrogen storage tanks behind the cab and maintain onboard hydrogen at 700 bar (Kenworth n.d.; CARB n.d.-b).

Transitioning to HD-FCEVs at PANYNJ presents significant challenges, primarily due to limited fleet ownership among port tenants, who control only 3.4% of all trucks visiting the port—a key barrier, as most vehicles operate across multiple ports, complicating direct investment in zero-

emission replacements (Starcrest Consulting Group 2022). Additionally, hydrogen's classification as a flammable gas imposes regulatory restrictions that further limit HD-FCEV access to key infrastructure, including select tunnels and bridges such as the Holland Tunnel, Lincoln Tunnel, and the lower level of the George Washington Bridge (PANYNJ 2016). While these restrictions add a layer of complexity, they partially overlap with existing NYC DOT regulations on Class 8 drayage trucks, including height limits (10' at the Lincoln Tunnel) and prohibitions on tractor-trailers in the Holland Tunnel (NYC DOT, 2022). Overcoming these regulatory and operational hurdles will require coordinated policy adjustments and infrastructure planning to facilitate the widespread adoption of HD-FCEVs at PANYNJ.

Empirical studies at PANYNJ reveal varied trucking operation profiles, emphasizing the need for tailored solutions in transitioning to zero-emission vehicles. Data from 46 diesel drayage trucks indicate that, as of 2022, approximately 20% of the sample fleet could feasibly transition to battery-electric configurations, given the technological capabilities at that time (Kotz et al. 2022). However, the fleet's operational diversity, including daily mileage, average speed, run time, and dwell time, underscores the impracticality of a one-size-fits-all approach. While both battery-electric and HD-FCEV trucks are viable for port operations, their deployment must align with specific duty cycles, with HD-FCEVs better suited for high-mileage, high-payload applications requiring minimal downtime. TCO analysis suggests that battery-electric trucks may be cost-effective for lower-mileage, less intensive operations, whereas HD-FCEVs offer advantages in long-haul applications due to shorter fueling times and higher payload capacity (Hunter et al. 2021). However, the economic feasibility of HD-FCEVs is influenced by high initial vehicle costs and hydrogen fuel price uncertainty, which remain barriers despite potential long-term operational advantages. The successful deployment of HD-FCEVs will depend not only on cost reductions and policy incentives but also on the availability of an extensive and reliable fueling network.

Fueling infrastructure is a critical determinant of HD-FCEV viability, influencing both operational feasibility and cost competitiveness. As of 2023, hydrogen fueling infrastructure remains concentrated in California, with stations near major ports such as Los Angeles, Long Beach, and Oakland, alongside a limited number farther inland (Alternative Fuels Data Center 2023; Port of Los Angeles 2023). Strategic station siting must consider truck route variability and visit frequency at ports to optimize accessibility and minimize downtime (Densberger and Bachkar 2022). For instance, 75% of PANYNJ's truck destinations are within neighboring counties, indicating that a localized hydrogen fueling network could support a significant share of port-related drayage operations (PANYNJ 2019; Zhu et al. 2022). Similarly, an origin-destination study from the Ports of Los Angeles and Long Beach found that 74% of total mileage is concentrated in six primary route combinations, highlighting the need for well-positioned, high-throughput fueling stations (Prohaska et al. 2016). Nonetheless, expanding infrastructure must weigh substantial capital costs, with estimates placing the investment for a station dispensing 5,000 kg of hydrogen per day at approximately $7.5 million (Kittelson & Associates Inc. 2022). A key opportunity to mitigate hydrogen cost uncertainty lies in leveraging port-based hydrogen import/export infrastructure. If ports in high-density urban areas such as New York/New Jersey become net hydrogen importers due to limited regional renewable energy resources, large-scale import terminals could provide dual benefits, facilitating hydrogen distribution for both maritime and drayage applications, thereby enhancing cost efficiency and supply stability.

Overall, hydrogen applications in drayage operations, primarily used for short hauls with a 200-mile range, should be prioritized for fleet units operating longer distances, where hydrogen's range and fueling advantages can provide logistical and operational benefits. Identifying these fleet segments will require collaboration with third-party trucking companies, as tenant-owned fleets represent only a minor portion of operations. Developing an effective hydrogen fueling infrastructure and corridor network is essential, taking into account key freight routes, fueling logistics, and existing transport restrictions, including limitations on hydrogen vehicles crossing certain bridges and tunnels. Given the economic significance of port operations, port authorities could engage with policymakers and regulatory bodies to assess whether existing restrictions on hydrogen transport and fueling could be revised to facilitate fleet adoption and integration. Addressing these challenges will be critical to ensuring the feasibility and long-term success of hydrogen-powered drayage solutions.

3.3 Oceangoing Vessels

OGVs play a critical role in global trade, transporting approximately 80% of goods by volume and serving as the foundation of international commerce and economic activity. However, the maritime industry is also a significant source of CO_2e emissions, prompting increasing regulatory and industry efforts to transition to alternative energy solutions. This section examines the technological status and feasibility of hydrogen-based fuels, including methanol and ammonia, for deep-sea shipping. It also explores the integration of hydrogen fuel cells for reducing emissions in port operations and onboard auxiliary systems. In addition to supporting cold ironing (shore power) at berth, hydrogen fuel cells are being considered for auxiliary power applications, including refrigerated cargo containers (reefers), to further improve energy efficiency. These developments highlight the expanding role of hydrogen technologies in supporting maritime energy transition efforts across both port and vessel operations.

3.3.1 Hydrogen-Based Fuels

Hydrogen's low volumetric energy density and the requirement for either cryogenic storage or large onboard storage spaces pose challenges for its direct application in deep-sea operations, which are typically dominated by two-stroke engines (Mærsk Mc-Kinney Møller Center 2022; ABS 2022). The maritime industry is exploring the indirect utilization of hydrogen through derivatives such as ammonia and methanol, which offer more practical storage and handling characteristics. Specifically, methanol has gained traction in maritime shipping. Vessels transporting methanol as cargo have been using dual-fuel two-stroke engines for propulsion, demonstrating methanol's feasibility since 2017 (Eirik et al. 2022). An increasing number of ships, including container vessels and tankers, are being outfitted to operate on methanol. For example, Mærsk has ordered container ships capable of operating on methanol (Mærsk 2023).

Ammonia holds promise as fuel but is currently constrained by a lower technology readiness level of engines and the lack of established safety and handling regulations (Mærsk Mc-Kinney Møller Center 2022). Developers, such as MAN Energy Solutions, are actively working on dual-fuel ammonia two-stroke engines, with the first engine delivery to a shipyard anticipated in 2025 (MAN Energy Solutions 2024a). According to projections by the American Bureau of Shipping, the adoption of ammonia and methanol as fuel is expected to increase across all ship types after

2030, with most demand coming from container ships, dry bulk carriers, and chemical carriers (ABS 2022).

The low-carbon benefits of hydrogen-derived fuels depend significantly on their production methods. While ammonia combustion is inherently CO_2-free, methanol combustion still emits CO_2 at levels similar to conventional marine fuels (GREET 2025). However, when methanol is synthesized using captured CO_2 and hydrogen produced via renewable energy sources, it can achieve net-zero emissions, as the CO_2 released during combustion is offset by the CO_2 removed during synthesis (Bureau Veritas Marine & Offshore 2022). Hydrogen production via renewable-powered electrolysis eliminates fossil fuel use and significantly reduces lifecycle emissions compared to steam methane reforming (SMR), which emits approximately 9–11 kg of CO_2 per kg of hydrogen produced (Lee et al. 2022). For instance, ammonia can achieve zero lifecycle CO_2 emissions when synthesized using low-temperature electrolysis powered entirely by renewable energy. In contrast, methanol can be a near-zero-emission fuel when synthesized from captured CO_2 and renewable hydrogen, with lifecycle emissions as low as 2 g CO_2/MJ, as the negative emissions from CO_2 capture offset combustion-related emissions (Zang et al. 2021).

Table 4 expands on the comparison of key alternative marine fuels and their applicability for powering OGVs. It compares the state of technology for alternative-fuel two-stroke engines and existing applications in maritime operations. Additionally, it summarizes fuel properties and density, which introduce considerations regarding safety, onboard storage, and bunkering for each fuel. This table specifically discusses fuel applications for deep-sea shipping, where vessels are designed for long-distance voyages and fuel density is of high importance. Although hydrogen fuel cell container ships have been demonstrated (Ballard Power 2023), they are inland vessels designed for short sea shipping and are outside the scope of this report.

Table 4. Comparative Analysis of Selected Alternative Marine Fuels for Deep-Sea Shipping

Particulars	Methanol	Ammonia	Hydrogen
TRL (MAN Energy Solutions 2024b; Eirik et al. 2022)	9	5–6	4[a]
Existing maritime applications (Shell n.d.)	Tankers carrying methanol as cargo have used dual-fuel engines since 2017.	Tankers carry ammonia as cargo, but ammonia engines are still in development.	A liquefied hydrogen carrier completed its maiden voyage carrying liquid H_2 as cargo.[b]
Projected scalability timeline (ABS 2022)	Uptake in 2020s	Uptake after 2030	Projection not available
Global fleet on order added in 2023 (DNV 2024)	138 vessels, dominated by container ships	11 vessels, indicating the first year with orders	Five vessels with H_2 applications limited to fuel cells serving as auxiliary power on cruise ships or as main power for short sea shipping
Fuel properties under ambient conditions	Liquid	Gas	Gas
Fuel energy density (Bureau Veritas	15.6 MJ/l 19.9 MJ/kg	Liquid: 12.77 MJ/l	Liquid: 8 MJ/l

Particulars	Methanol	Ammonia	Hydrogen
Marine & Offshore 2022)		18.6 MJ/kg	120 MJ/kg
Fuel safety considerations (Eirik et al. 2022)	Toxic, flammable	Toxic, low flammability range	Nontoxic, wide flammability range
Combustion emissions (GREET 2025)	Reduced CO_2, particulate matter, NOx compared to conventional fuels. No SOx.	Reduced NOx, particulate matter. No direct CO_2 and SOx.	NOx if using a combustion engine, zero emissions if using fuel cells
Regulations (ABS 2022)	Covered by the IMO's[c] interim guidelines for low-flash-point fuels and interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel	No prescriptive rules. IMO working item as a fuel, tentative classification rules available	No prescriptive rules. IMO working item, classification rules working item. Current regulations target fuel cells.
On-board storage	Mature solutions for storage, can use established procedures for diesel	Fuel can be compressed or liquified at -33 °C to increase volumetric density.	Fuel can be compressed or liquified at -253 °C to increase volumetric density.
Bunkering (Lee 2023; ABS 2024)	Bunkering is similar to conventional liquid fuels, but additional procedures are required.	Solutions could be developed based on handling ammonia as cargo.	Liquid hydrogen bunkering solutions are in development. Experience with LNG can be applicable because it is also a cryogenic fuel.

[a] The hydrogen engine TRL is estimated based on original equipment manufacturer activity.
[b] The vessel was powered by fossil fuels and does not necessarily represent the development of hydrogen engines for deep-sea shipping. Instead, the research and development is more focused on the integration of fuel cells. Examples include the FCwave, a fuel cell module developed by Ballard specifically for operation in the maritime environment and already being integrated into vessels traditionally powered by four-stroke engines, such as tugs.
[c] IMO: International Maritime Organization

Due to its low volumetric energy density, hydrogen is unlikely to be used directly as a primary fuel for oceangoing vessels. However, the potential for fuel cell-powered vessels is gaining traction, particularly for short-sea shipping, auxiliary power applications, and the utilization of boil-off hydrogen from liquefied hydrogen carriers (PowerCell Group 2024). Methanol engines have already achieved higher technology readiness, with multiple ships in operation and on order utilizing dual-fuel engines. In contrast, ammonia engines are still in development, with MAN Energy Solutions leading efforts to commercialize dual-fuel ammonia two-stroke engines, expected to be available by 2025 (MAN Energy Solutions, 2024a). Additionally, in most ports, including PANYNJ, bunkering facilities are typically managed by private entities, while port authorities focus on regulatory oversight and safety compliance (Wang and Notteboom 2015). This decentralized approach to fuel logistics underscores the evolving infrastructure challenges associated with the adoption of alternative fuels in the maritime industry.

3.3.2 Hydrogen Fuel Cell Applications

Fuel cells could potentially be integrated in place of auxiliary engines in OGVs to reduce emissions while the vessels are docked at berth (Bureau Veritas Marine & Offshore 2022). Specifically, the cruise ship industry, which has auxiliary power requirements on a megawatt

scale while docked, has investigated hydrogen fuel cell utilization. The auxiliary engines' modest power needs compared to the main engines mitigate some storage concerns and make gaseous hydrogen storage viable (McKinlay, Turnock, and Hudson 2021). Bloom Energy's deployment of a 150-kW solid oxide fuel cell (SOFC) system on MSC World Europa cruise ships, initially using liquefied natural gas as a fuel source, demonstrates this approach (Bloom Energy 2023a). The primary challenge of this solution lies in retrofitting the ships and ensuring fuel availability at the ships' destinations.

On the other hand, hydrogen fuel cells can also serve as a shore power solution, known as cold ironing, enabling vessels to shut down auxiliary engines while berthed. The state-of-the-art solution for shore power is grid-based, and ports across the United States, including the Brooklyn Cruise Terminal[8], have been retrofitting berths to enable connection. For instance, California introduced regulatory mandates for the shutdown of diesel engines at berth during specified percentages of fleet visits and has since extended the eligible vessel types from container and cruise ships to include RoRo and tanker vessels by 2023, with auto carriers and liquid bulk vessels to follow by 2025 (CARB 2023). Table 5 provides a general overview of grid-based and hydrogen fuel cell-based shore power solutions excluding regional differences, technology advancements, and other factors. Grid-based systems offer high electrical efficiencies (up to 95%) and moderate initial costs ($8–$10 million per shore power connection with up to 12-MW capacity as a reference) compared to hydrogen (Eastern Research Group Inc. and Energy & Environmental Research Associates LLC 2023). If access to electricity at the port is limited due to aging electric grid infrastructure and the lengthy timelines of required utility upgrades, hydrogen could demonstrate a grid-independent modular shore power solution. Fuel cell-based systems can also supplement grid capacity during peak demands or serve as reliable temporary power sources during infrastructure upgrades or maintenance; however, hydrogen shore power would be contingent on reliable fuel supply and limited by the footprint required to store hydrogen on or near the marine terminal.

Table 5. Comparative Analysis of Grid-Based Shore Power Versus Hydrogen Fuel Cell-Based Solutions

Criteria	Grid-Based	Hydrogen Fuel Cell-Based
System Efficiency		
Electrical efficiency	High (typically 90%–95%)	Moderate (e.g., 53% peak efficiency for PEMFCs[a]) (Ballard Power 2024)
Landside Investment		
Initial installation	Moderate (infrastructure cost) (Moffatt & Nichol 2023)	High (fuel cells, balance of plant, storage systems)
Operations and Maintenance	Low to moderate (depending on electricity price)	Moderate to high (depending on hydrogen price)
Scalability		
Capacity expansion	Moderate (dependent on grid capacity and coordination with utility)	Moderate (limited by hydrogen supply and footprint required for on-site hydrogen storage)

[8] PANYNJ divested of the facility in June 2024.

Criteria	Grid-Based	Hydrogen Fuel Cell-Based
Emissions and Land Use		
Life cycle emissions	Varies (based on carbon intensity of the grid[c]) (Pratt and Harris 2013)	Varies (based on feedstock and production pathway)
Equipment footprint	Moderate	Moderate to high (requires space for hydrogen storage)

[a] PEMFC: proton exchange membrane fuel cell
[b] CHP: combined heat and power
[c] For illustration, NYCW (NYC) and RFCE (NJ) eGRID regions had 0.37kg and 0.3 of CO_2e/kWh emissions factors, respectively (SC&A 2024)

A DOE Maritime Fuel Cell Generator project (Pratt and Chan 2017) demonstrated a containerized fuel cell system designed to initially power refrigerated containers on docks and barges. Despite the higher initial costs, $800,000 to $900,000 for a 100-kW unit quoted in 2017 compared to $300,000 for a conventional 300-kW diesel generator, the project highlighted that fuel cost savings would be possible with hydrogen priced below $5/kg and diesel above $4/gal. Subsequent enhancements to this system aimed to provide electrical power to a research vessel in San Diego, involving upgrades such as a new transformer and junction box for existing cabling. The modifications addressed the shore power demand, estimated at 50 kW during the day and 14 kW at night, necessitating approximately 515 kg of hydrogen delivered monthly. Despite successful power provision to the vessel's mechanical systems, the computer systems did not accept fuel cell power, likely due to grounding issues, highlighting the complexity of system integration (Klebanoff 2023).

Additionally, the fluctuating nature of shore power requirements, as detailed in Table 6, underscores the demand for large-scale hydrogen sourcing at PANYNJ, should hydrogen shore power be adopted (Conte, D'Agostino, and Silvestro 2023). This table offers a comparative hourly analysis of diesel and hydrogen demand for powering vessels at berth, contingent upon vessel type and based on the average load. The daily demand for shore power varies with the number and types of vessels visiting the port each day, exhibiting greater fluctuation. For further information, refer to appendices A and B.

Table 6. Estimated Fuel Demand Comparison for Shore Power at PANYNJ

Application	FC Shore Power TRL	H_2 Demand (DGE/vessel/hour)	Diesel Demand (gal/vessel/hour)[a]
Shore power	5	Ranging from 22 for RoRo to 365 for cruise ships	Ranging from 31 for RoRo to 517 for cruise ships

Overall, stationary hydrogen fuel cells could play a key role in reducing emissions from OGVs by providing auxiliary power and shore power solutions. By enabling the shutdown of auxiliary engines at berth, fuel cell-based shore power can help ports lower emissions and improve air quality. While grid-based shore power systems remain the dominant solution, hydrogen fuel cells offer flexibility in ports with limited grid capacity, ongoing infrastructure upgrades, or intermittent renewable energy availability. However, several challenges remain, including higher initial capital costs, space requirements for hydrogen storage, and ensuring a consistent fuel supply at ports. As ports continue transitioning toward zero-emission solutions, hydrogen fuel

cells present a modular, scalable alternative to conventional grid-based shore power, particularly in regions facing grid constraints, infrastructure limitations, or an increasing need for energy diversification.

3.4 Stationary Power

Although stationary combustion and purchased electricity contribute only a fraction of the port's emissions, integrating hydrogen fuel cells into the port's stationary power infrastructure can play an important role in enhancing the resilience of port operations. This section examines hydrogen's capabilities in the stationary aspects of port operations.

Maritime ports, as demonstrated by PANYNJ, are increasingly adopting electrification and alternative energy strategies to enhance operational efficiency and environmental performance. This shift primarily aims to reduce local air pollution affecting nearby communities while supporting the maritime industry's broader energy transition efforts. For ports, electrification can involve replacing conventional space and water heating systems with heat pumps, transitioning to battery-electric vehicles and cargo-handling equipment, and expanding grid connectivity for essential machinery, such as ship-to-shore cranes. Increased electricity demand may also result from shore power availability for docked ships, as discussed in the previous section, along with advancements in terminal automation (Iris and Lam 2019).

Electrification of these applications is expected to significantly increase the baseload, peak demand, and load volatility at ports. Although ship-to-shore cranes can operate in predictable patterns throughout the day, end uses, such as charging fleets of battery-electric equipment, can cause electricity demand surges. To accommodate peak demand, ports might need to undergo grid infrastructure upgrades, which require substantial time and investment. Stationary fuel cells present a potential solution to support operational needs where grid capacity is insufficient. Fuel cells could offer a range of applications in port operations, from replacing conventional diesel generators to supporting shore power, cranes, buildings, warehouses, and advanced control systems (Eastern Research Group Inc. 2022).

Stationary fuel cells represent one of the earliest applications in the hydrogen market. By 2022, the United States had deployed 852 stationary fuel cell systems, bringing the total installed capacity to 550.6 MW, with New York State contributing notably with installations of 51 MW. SOFCs are the predominant technology, powering 78% of these systems in terms of capacity. They are followed by molten carbonate fuel cells, which account for 15%, and phosphoric acid fuel cells (PAFCs), which contribute 7% of the capacity (H2Tools 2022).

Note that fuel cell installations described above use natural gas almost exclusively as the system-level fuel. Existing SOFCs and PAFCs can generally operate on natural gas, natural gas blended with some percentage of hydrogen, or pure hydrogen. For instance, SOFCs, which reform methane into hydrogen internally, can accommodate up to a 30% vol. hydrogen blend in the natural gas stream or pure hydrogen, depending on the fuel cell system model installed (Bloom Energy n.d.). PAFCs use an external fuel processing system for reforming allowing up to a 30% vol. hydrogen in the natural gas stream. The same fuel cell system can continue to operate with pure hydrogen after the reformer is removed (HyAxiom n.d.-b). In contrast, MCFCs require a carbon source and therefore cannot operate on pure hydrogen alone. Another distinctive feature of the fuel cell types discussed above is their suitability for continuous power generation. Although they can accommodate load following, frequent cycling between on and off states can

negatively impact the lifetime of system components. Thus, connecting to the natural gas grid provides a reliable and continuous fuel supply required for these fuel cell types; however, this approach does not eliminate CO_2 emissions.

Collectively, the fuel cell types described above are high-temperature fuel cells. Original equipment manufacturers report average system efficiencies of 85%–90% when these systems are coupled with heat capture (Bloom Energy 2023b). The heat can be used for space heating or hot water generation; however, due to the nature of cargo-handling operations, ports have a mismatch between electrical and thermal loads, which can limit the utilization of captured heat. Nonetheless, some ports, such as the Port of Palma, have leveraged hydrogen-based small-scale CHP systems to meet specific demands, such as a ferry terminal, where the flow of passengers can increase the thermal energy requirement (Bloom Energy 2023b).

Another fuel cell type, proton exchange membrane fuel cells (PEMFCs), operate at low temperatures. PEMFCs require pure hydrogen as fuel input, and there have been no large-scale stationary installations to date. These fuel cells have a quick start-up time and are tailored for rapid response scenarios in mobility and backup applications (Mac Kinnon, Razeghi, and Samuelsen 2021).

4 Hydrogen Applications in Airport Operations

Airports are significant contributors to global CO_2e emissions, necessitating innovative and effective energy transition strategies. This section explores the integration of hydrogen into airport operations, focusing on three areas: aviation propulsion, ground vehicles and equipment, and stationary power applications. By assessing hydrogen's potential alongside other alternative energy solutions, this section aims to identify operational advantages and complementary strategies for emission reductions and fuel diversification.

4.1 Aviation Propulsion

The transition to lower-emission aviation propulsion presents a multifaceted challenge involving multiple pathways, such as sustainable aviation fuels (SAF), including e-fuels, and alternative propulsion systems, such as battery-electric and hydrogen-powered aircraft. Each of these technologies offers distinct benefits and faces specific challenges, requiring a comprehensive strategy to achieve significant reductions in CO_2e emissions (Oakleaf et al. 2022). This section examines the role of SAF and hydrogen in mitigating CO_2e emissions from existing aircraft, as well as the future potential of hydrogen-powered aviation.

4.1.1.1 Sustainable Aviation Fuel

SAF is a renewable fuel that offers a lower carbon footprint than conventional Jet A fuel. According to the Internal Revenue Service (IRS) guidance, eligible SAF should provide a minimum of 50% reduction in CO_2e emissions on a lifecycle basis, limiting its carbon intensity to 44.5 grams of CO_2e/MJ (IRS 2024). As a drop-in fuel, SAF can be blended with Jet A and used interchangeably in existing aircraft. As of 2023, ASTM International has approved 11 conversion pathways for SAF, allowing blends with Jet A fuel up to 50%, depending on the production pathway (ICAO n.d.). SAF from some pathways may lack aromatic content, which is necessary for ensuring lubrication and sealing, causing blending limitations in existing aircraft; however, pathways in the process of approval, such as synthesized aromatic kerosene, can accommodate 100% SAF. For example, a test flight by Virgin Atlantic from Heathrow to JFK in

late 2023 used a synthesized aromatic kerosene pathway under evaluation to achieve the necessary aromatics content (Virgin Atlantic 2023; Feldhausen et al. 2022). There are also approved coprocessing pathways up to 5%, meaning existing refineries can process SAF with jet fuel with minor modifications, avoiding the need for new stand-alone facilities while producing the finished product without blending. BP, for instance, launched a task force to increase allowed coprocessing to 30% (BP 2022).

4.1.1.2 Hydroprocessed Esters and Fatty Acids

Most SAF today is produced through the hydroprocessed esters and fatty acids (HEFA) pathway, which uses lipids and currently primarily relies on waste fats and oils (primarily soybean oil) as feedstocks. HEFA provides lower costs than other SAF pathways due to feedstock availability and high conversion rates, but long-term feedstock constraints are a concern (O'Malley, Pavlenko, and Kim 2023). The supply of sustainable lipids is crucial for SAF production growth, as 66% of U.S. projects announced as of early 2024 plan to use the HEFA pathway (Cathcart et al. 2024).

4.1.1.3 Fischer-Tropsch Synthesis

Another pathway, gasification followed by Fischer-Tropsch (FT), uses biomass, such as woody biomass or municipal solid waste (MSW) as feedstock for gasification. Although FT was the first pathway approved by ASTM, its initial coal feedstock does not meet CO_2e reduction standards (IRENA 2017). Waste feedstocks such as MSW are inexpensive but require additional preprocessing, such as sorting and decontamination, and have low conversion rates. The FT pathway faces high capital costs and technical challenges (O'Malley, Pavlenko, and Kim 2023). Consequently, SAF produced via the FT pathway can only marginally add to the supply by 2030 (DOE et al. 2022).

4.1.1.4 Alcohol-to-Jet Conversion:

The alcohol-to-jet (ATJ) pathway converts cellulosic (e.g., corn stover), sugar, or starch feedstock into ethanol or isobutanol, which is then processed into jet fuel. This pathway involves three stages: alcohol dehydration, olefin oligomerization, and oligomer hydrogenation (Bhatt et al. 2022). With primary feedstocks being agricultural products, the environmental impact of ATJ includes high energy use and significant land and water requirements for feedstock cultivation. For example, corn ethanol's carbon intensity exceeds the 50% lifecycle GHG threshold and does not qualify as feedstock at present unless additional measures such as carbon capture and storage or renewable power are implemented (Rosales et al. 2024; DOE 2024). Lanza Jet, a SAF producer with the first commercial ATJ facility in the U.S., uses sugarcane ethanol as feedstock, which has lower carbon intensity (EPA 2023b). Additionally, the facility has an electrolyzer for on-site hydrogen production (Nel 2022).

4.1.1.5 E-Fuels

E-fuels, a subset of SAF, can be produced through pathways such as FT and ATJ. E-fuel production includes renewable electricity and/or hydrogen and CO_2 conversion into either SAF intermediates or SAF directly (Grim et al. 2022). The main difference from the pathways described above is that the required feedstocks are renewable electricity and CO_2, allowing for a shift away from finite sources such as lipids, which could face scalability constraints. However, e-SAF faces challenges at present. Firstly, while the electricity requirement may differ based on

the specific production pathway, it is estimated that e-SAF production could require ~ 100-115 kWh/gallon, of which 59% to 93% is attributed to hydrogen production through electrolysis (Li et al. 2023). While renewable electricity is theoretically scalable, e-SAF production is limited by the current high costs and the timeline of adding the dedicated renewable electricity generating capacity (IEA 2023). CO_2 supply as feedstock is also considered nearly limitless, but the availability of dedicated pipelines and transportation infrastructure remains a scalability constraint. Secondly, although technologies such as carbon capture, electrolysis, and fuel synthesis exist and have been demonstrated for e-SAF production on a small scale (Infinium 2024), their large-scale integration remains to be achieved. Thus, while expected to contribute to SAF diversification in the long term, e-SAF's near-term role could be limited due to lower technological maturity and higher expected costs than SAF pathways described above.

In many cases, SAF pathways require hydrogen input, which today is primarily sourced from natural gas reforming. In HEFA processes, hydrogen is needed for reactions such as hydrogenation, hydrodeoxygenation, decarboxylation, decarbonylation, hydroisomerization, and hydrocracking, with consumption varying by feedstock. For example, plant-based oil feedstocks can require 0.08–0.11 kg of hydrogen per gallon of SAF (Han et al. 2013). FT pathways from biomass require some hydrogen input for hydrocracking and catalytic upgrading. An alternative FT process involves green hydrogen and captured CO_2 to produce syngas via the reverse water-gas shift reaction, with hydrogen consumption at 1.38 kg and CO_2 at 8.56 kg per gallon of FT fuel produced (Zang et al. 2022).[9] Finally, ATJ pathways require hydrogen for oligomer hydrogenation, typically consuming around 0.01 kg of hydrogen per kilogram of SAF (ICAO 2023). Because hydrogen is a very light molecule, reporting it on a mass basis underrepresents its contribution relative to its energy content. Figure 5 illustrates the stages at which hydrogen input is required for each pathway. In the long term, using green hydrogen in SAF production could reduce CO_2e emissions and enhance the overall sustainability of the aviation industry.

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

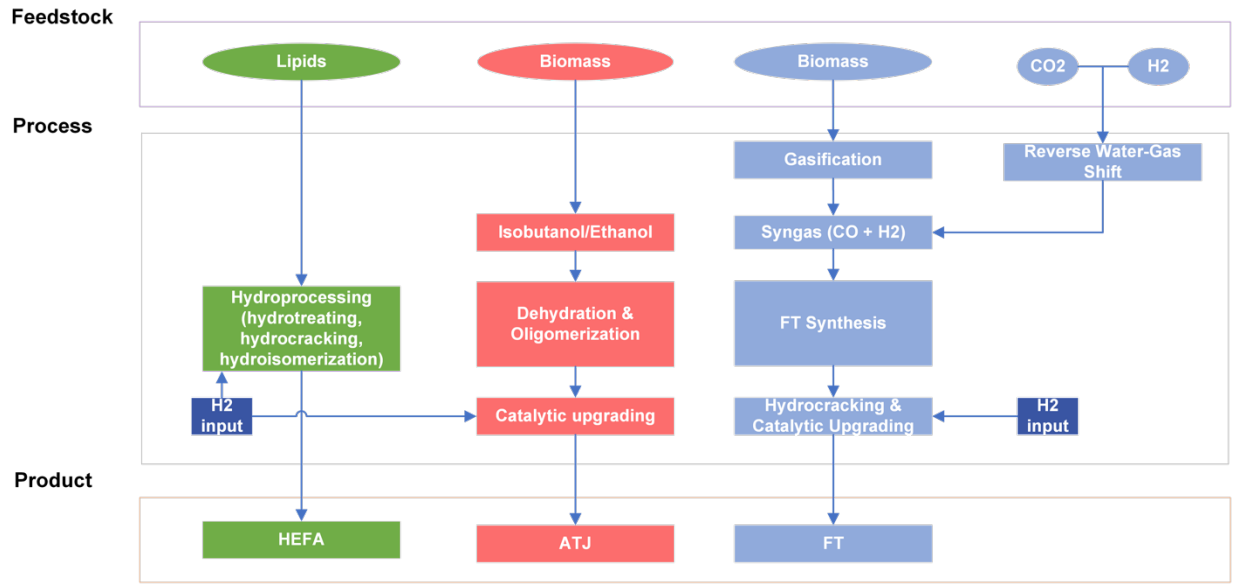

Figure 5. Schematic illustration of key steps for SAF production via HEFA, ATJ, and FT pathways

Adapted from reference: ICAO 2023

Currently, the primary challenges for SAF relate to feedstock availability and technology scale-up. The process of going from demonstration to commercial scale for each pathway is protracted yet essential in properly de-risking the new technologies, and project developers currently struggle to secure financing to build a first-of-a-kind production facility. In 2021, the U.S. Department of Energy, the U.S. Department of Transportation, and the U.S. Department of Agriculture launched the SAF Grand Challenge, a government-wide strategy to expand SAF production, enhance sustainability, and reduce the costs associated with SAF production. Specifically, it sets two production targets, with the long-term goal of meeting 100% of projected aviation jet fuel demand. Achieving near-term production goals of 3 billion gallons per year, as set by the SAF Grand Challenge, necessitates the deployment of pathways ready for commercialization (e.g., HEFA, ATJ) and utilization of refining assets already in place (Grim et al. 2024); however, to meet the ultimate goal of producing 35 billion gallons annually by 2050 (DOE et al. 2022), it will be important to diversify conversion pathways to include technologies that are not bottlenecked by feedstock limitations and that produce carbon-negative fuels.

The development of regional supply chains that connect feedstocks with end users is critical (DOE et al. 2022). Because the SAF industry is still nascent and production remains limited, many current facilities are geographically isolated. The next phase involves understanding regional markets and feedstock availability near end users, such as airports, to determine which conversion pathways can deliver the most benefits in terms of lifecycle CO_2e emissions and production cost reductions (Bhatt et al. 2022).

For example, studies evaluating feedstock availability for regions such as the Rocky Mountains or specific pathways, as in Indiana with cellulosic biomass, indicate that substantial feedstocks can be mobilized (Cathcart et al. 2024; Perkis and Tyner 2018). One study found that feedstocks within a 50- to 200-mile radius of Chicago O'Hare International Airport could displace up to 55% of current jet fuel use, leveraging woody biomass, MSW, and crop residues (Bhatt et al.

2022); however, feedstock supply often competes with demand from other industries, such as renewable diesel and biodiesel production, as reported by a resource assessment study for Seattle-Tacoma International Airport (Washington State University 2020).

A study on the PANYNJ airports (Moriarty, Milbrandt, and Tao 2021) found that among the considered feedstocks, although select organic MSW and woody biomass are abundant local resources and could provide the lowest minimum price at a large production scale, the high capital investment required for FT facilities remains a significant barrier, along with commercial readiness. Further, the minimum selling price of SAF varies significantly with feedstock costs. For example, the study assumed a price of $88 per dry tonne for both MSW and woody biomass without considering the preprocessing steps and transportation costs. As for HEFA pathways, used cooking oil showed availability at all radii and a minimum fuel selling price under $3.44/gal with a feedstock cost of $0.55/kg. Other lipids, however, such as soybean oil feedstock, showed competitiveness with Jet A within a 200-mile radius, whereas fats, oils, and greases feedstock showed a higher minimum fuel selling price even at 200 miles, along with a higher capital investment. In addition to feasibility studies, multiple SAF production plant announcements have been made in the northeastern United States. Examples of producers include Dimensional Energy (New York, CO_2 and hydrogen feedstock), DG Fuels (Maine, cellulosic waste feedstock), and Air Company (New York, CO_2 and hydrogen feedstock).

In summary, the SAF market's progression requires the development of regional supply chains to connect feedstocks with end users, integrating with existing fuel distribution infrastructure, and addressing technology risks and commercialization barriers. The regional availability of a feedstock determines the potential scale of production, which, in turn, determines the minimum jet fuel selling price achievable by a given pathway. For the northeast United States, the FT pathway can achieve a lower price of SAF production than others when the scale of the production is large enough; however, due to the complexity of the feedstock processing and the required high capital investment for a new stand-alone fuel production facility, the FT pathway is still undergoing the lengthy yet crucial process of technology maturation. Additionally, the integration of green hydrogen into the SAF production process presents opportunities to further reduce the carbon intensity over time.

4.1.2 Hydrogen-Powered Aircraft and Infrastructure

There are two primary methods of integrating hydrogen into aircraft: through electrochemical reactions in fuel cells and through direct hydrogen combustion. FCE aircraft offer an electrified powertrain, avoiding CO_2 and NOx emissions at the point of use and reducing contrail formation, although they are not currently commercially available (TRL 6). A key advantage of fuel cells is the separation of hydrogen and oxygen, mitigating flammability concerns. However, fuel cells generate substantial heat, necessitating an onboard cooling system for thermal management. Additionally, despite hydrogen's high energy density by weight, its low volumetric energy density requires larger or external fuel tanks, presenting significant design challenges (Gao et al. 2022).

Tanks contribute significantly to aircraft weight, with the impact depending on the choice of materials, storage pressure, and the physical state of onboard hydrogen storage. While compressed hydrogen may be suitable for short-range flights below approximately 500 kilometers, longer distances exceeding 1,000 kilometers typically require liquid hydrogen to

improve gravimetric efficiency and reduce overall system weight (Gao et al. 2022; Bruce et al. 2020). Research indicates that, for viable onboard use, hydrogen fuel cell powertrains must achieve system-level specific power densities above 1 kW/kg, with demonstrations by ZeroAvia approaching 1.5 kW/kg under optimized configurations (Baroutaji et al. 2019; ZeroAvia 2023). Given aviation's high sensitivity to weight, battery-electric aircraft remain constrained by the relatively low specific energy of current lithium-ion batteries, which range from approximately 90 to 260 Wh/kg at the cell level (Pattanayak and Mavris 2024). This is significantly lower than the projected system-level energy densities of hydrogen fuel cell powertrains, which may reach 800 to 1,000 Wh/kg when accounting for compressed hydrogen storage systems with approximately 6% gravimetric storage efficiency (Mus et al. 2024). Both technologies continue to evolve, and battery-electric and hydrogen-powered aircraft are expected to serve overlapping market segments, particularly in the commuter and regional classes (Air Transport Action Group 2021). For instance, Amprius reports that lithium-ion battery cells based on silicon anode chemistry have achieved energy densities up to 450 Wh/kg, although system-level values will be lower due to the inclusion of battery management and thermal control components (Amprius 2025).

A sensitivity analysis conducted on electric vertical takeoff and landing (eVTOL) aircraft revealed insights into the factors affecting TCO for different powertrain configurations (Ahluwalia et al. 2021). For fuel cell-dominated powertrains, the analysis identified fuel cell specific power as the most critical parameter influencing TCO due to its direct impact on maximum takeoff weight, airframe costs, and fuel consumption. Additional parameters affecting the TCO include fuel cell system costs, annual utilization rates, fuel costs, and the gravimetric capacity of the storage system. In contrast, for an aircraft primarily powered by batteries with a smaller supplementary fuel cell, TCO is significantly influenced by the battery's specific energy, lifetime, and annual utilization. Higher specific energy allows for greater energy storage without a substantial weight increase, enhancing operational efficiency and reducing energy costs. Additionally, a longer battery lifetime decreases the frequency and cost of replacements, thereby lowering the TCO. Increased annual utilization, however, can accelerate battery degradation, leading to higher maintenance and replacement expenses.

Companies such as ZeroAvia are developing propulsion systems for 9- to 19-seat commuter aircraft with a range of up to 300 nautical miles, targeting various airframes including the Dornier 228 and the Cessna 208B Grand Caravan (ZeroAvia n.d). These systems feature gaseous hydrogen storage in lightweight tanks, consuming approximately 25–30 kg of hydrogen per hour, with an overall capacity of 70 kg at 350 bar (ZeroAvia 2023). The company expects certification to be completed by 2025, with entry into service anticipated in 2026 (Moores 2024). For larger regional aircraft with 40–80 seats and a range of up to 1,000 nautical miles, such as the ATR 42/72 and the DHC Dash 8 series, extended range requirements are likely to necessitate cryogenic hydrogen tanks for onboard liquid hydrogen storage (ZeroAvia 2023). As part of its ZEROe initiative, Airbus is also developing a 100-seat regional fuel cell aircraft featuring six fuel cells propulsion systems, each capable of up to 1.2 MW power output, with liquid hydrogen storage. In 2023, the company completed the fuel cell system testing, and according to current timelines, the aircraft could enter service in the 2040s (Airbus 2024). Until its closure in 2024, Universal Hydrogen was another key player in FCE aircraft development, having completed test flights for regional aircraft using hydrogen fuel cells (Universal Hydrogen 2023).

Direct hydrogen combustion in gas turbines is conceptually feasible for aircraft but remains the least advanced propulsion technology in terms of readiness, and it faces substantial technological and infrastructural barriers (FAA 2024). While hydrogen combustion does not produce CO_2 and could potentially decrease NOx emissions depending on combustor system optimization, achieving ultra-low NO_x emissions remains a technical challenge (Fuel Cells and Hydrogen 2 Joint Undertaking 2020). Additionally, hydrogen combustion at high altitudes generates approximately 2.6 times more water vapor than Jet A, which could exacerbate contrail formation. Contrails contribute to radiative forcing by trapping heat in the atmosphere and significantly influencing aviation's overall climate impact (Dray et al. 2022). However, hydrogen combustion is free from particulate matter, which could influence contrail microphysics and potentially reduce their warming effect, warranting further investigation (FAA 2024). Compared to hydrogen fuel cells, direct hydrogen combustion systems typically exhibit lower energy conversion efficiency and face high-temperature operational and emissions-related challenges that must be addressed before they can become a viable alternative to conventional propulsion. In response to these challenges, Airbus is actively developing hydrogen turbine engines as part of its long-term ZEROe initiative and has launched a dedicated project to study hydrogen combustion contrail formation and its environmental implications (Airbus 2023a; Airbus 2023b).

Liquid hydrogen is likely the only feasible storage solution for short and medium haul flights due to its reduced tank weight and higher gravimetric density (Gaubatz et al. 2023). Key design challenges include developing and positioning lightweight, insulated storage tanks with high gravimetric efficiency to minimize boil-off and optimize structural weight while providing the same payload and range compared to existing missions (Xu, Li, and Huang 2015; Afonso et al. 2023). Therefore, the aircraft likely require a novel design as well as new combustors to reduce NOx emissions before the technology can be commercialized (Pratt & Whitney 2022). According to projections, hydrogen combustion technology could be deployed in short haul and potentially medium haul aircraft, although SAF is expected to dominate for the latter during the 2040-2050 timeframe (Air Transport Action Group 2021).

While fuel cell propulsion system developers have demonstrated progress by securing Experimental Certificates and Part 21 Permits (ZeroAvia 2022), as well as G-1 Issue Papers and Supplemental Type Certificates (Airport Technology 2023), there is a long path to establishing certification regulations for hydrogen as an aircraft fuel. According to the FAA's Hydrogen-Fueled Aircraft Safety and Certification Roadmap, the certification procedures for aircraft propulsion systems could reach high readiness levels by 2032 for fuel cell propulsion engines and by 2036 for hydrogen-powered gas turbine aircraft (FAA 2024).

Safety is critical for achieving certification of hydrogen-powered aircraft. Hydrogen exhibits unique properties, including a wide flammability range, extremely low ignition energy, and high diffusivity, which can lead to leakage if not properly managed through material selection and system design. Specifically, the primary safety challenges associated with hydrogen propulsion involve fire and explosion hazards, and current aviation safety standards may not fully account for the unique risks posed by hydrogen fuel systems (FAA 2024).

Hydrogen propulsion systems introduce several safety design considerations, including ensuring proper separation of hydrogen from potential oxidizers in enclosed environments, minimizing hydrogen leaks, integrating effective leak and flame detection systems, and implementing fuel

shutoff mechanisms while maintaining adequate propulsive power (FAA 2024). Additional hazards include material degradation risks, such as hydrogen embrittlement and permeation. Hydrogen embrittlement is a process that results in a decrease in the fracture toughness or ductility of a metal due to the presence of atomic hydrogen (Lee 2016). Crashworthiness remains a concern, as the behavior of hydrogen fuel systems in crash scenarios is not well characterized and is difficult to evaluate. Physiological hazards include risks to personnel from hydrogen leaks, fire, or explosions. Electrical hazards also present a challenge, as absolute elimination of ignition sources may not be feasible, but rigorous mitigation strategies must be employed. Additionally, airplane/engine interface issues, such as hydrogen leakage during fuel transfer from onboard storage tanks to the engine, require careful design considerations (FAA 2024).

A major challenge specific to the cryogenic properties of liquid hydrogen is managing the phase transition from liquid to gas in confined spaces. The volumetric expansion ratio of liquid hydrogen to gaseous hydrogen is approximately 1:848 at standard conditions, which can result in rapid pressure buildup and potential structural failure if not properly controlled. Therefore, hydrogen storage and distribution systems must incorporate robust ventilation and pressure relief mechanisms to mitigate this risk (H2Tools n.d.b). Additional safety considerations related to liquid hydrogen storage tanks will be addressed later in this section.

Fuel availability and fueling infrastructure are also critical for aircraft deployment. FCE aircraft can initially be supported by mobile fueling trucks with 400-bar storage, delivering hydrogen from production sites to airports. This approach might suffice for small airports or during early deployment at low technology penetration levels, avoiding the need for permanent infrastructure (ZeroAvia 2023), however, transitioning to hydrogen combustion aircraft necessitates reliable, large-scale delivery of liquid hydrogen to airports.

Multiple pathways for hydrogen supply are proposed, varying by airport size, location, geography, and hydrogen volume requirements (Postma-Kurlanc, Leadbetter, and Pickard 2022). For small airports, where fuel is traditionally delivered by truck, liquid hydrogen can be similarly delivered and offloaded to on-site storage or directly to aircraft; however, as hydrogen demand increases, the frequency of tanker deliveries may increase, potentially causing delays and road congestion. For larger airports, supplying hydrogen via pipelines with on-site liquefaction could be feasible. This approach demands significant capital investments to install new hydrogen pipelines, liquefaction plants, and on-site storage. Key considerations for this pathway include land use requirements and the substantial electricity demand for liquefaction. Studies also suggest that repurposing existing natural gas pipelines could be a feasible solution for hydrogen delivery, though this pathway presents several challenges (Oakleaf et al. 2022).

On-site hydrogen production through electrolysis and liquefaction is another potential pathway for aviation fuel supply. While some airports, such as Groningen Airport Eelde in the Netherlands, are planning to produce gaseous hydrogen on-site (Eurocontrol 2023), large-scale hydrogen production for aircraft fueling remains highly challenging due to the immense energy and infrastructure requirements. A study on Chicago O'Hare Airport estimated that producing 719 tonnes of liquid hydrogen daily via electrolysis would require 44.5 GWh of electricity, necessitating an installed renewable generation capacity of approximately 1.5 GW (Gaubatz et al. 2023). For context, large international airports typically consume 100–300 MWh of electricity per day, whereas producing the required hydrogen on-site would demand over 150 times this

amount, making such production infeasible without extensive external power generation. Furthermore, the infrastructure required for electrolysis, liquefaction, and hydrogen storage would occupy several hectares, necessitating significant land allocation and stringent safety measures to ensure seamless integration into airport operations.

Although salt caverns are among the most economical large-scale storage solutions for hydrogen due to their low cushion gas requirements, structural integrity, and excellent sealing capacity, their availability is geographically limited, and many airports may not have direct access to such geological formations (Quintos Fuentes and Santos 2023; Walsh et al. 2023). If hydrogen is delivered via a pipeline, it is possible that the pipeline could connect to existing salt cavern storage or other geological hydrogen storage sites, enabling a reliable supply chain for airports. If pipeline delivery is not feasible, or if additional on-site capacity is needed to ensure continuous dispensing and receiving operations, several on-site liquid hydrogen storage tanks would be required, with capacity determined by airport demand. The largest liquid hydrogen storage tank currently in use is located at the NASA Kennedy Space Center, with a capacity of 1.25 million gallons, an outer diameter of 25.3 meters, and an overall height of 28.0 meters. For comparison, John F. Kennedy International Airport (JFK) has 26.2 million gallons of Jet A fuel storage on-site; however, hydrogen has a lower volumetric energy density than Jet A. Liquid hydrogen has an energy density of approximately 8.5 MJ/L (~30,000 BTU/gal), whereas Jet A has approximately 34.7 MJ/L (~120,000 BTU/gal). Thus, to achieve an equivalent energy storage capacity, significantly more hydrogen storage would be required than a direct volumetric comparison suggests. Storage requirements and placement would also be subject to NFPA 2: Hydrogen Technologies Code, which regulates hydrogen storage through measures such as setback distances from exposures and prescribes a maximum system capacity of 75,000 gallons per liquid hydrogen storage unit (NFPA 2022). Large-scale hydrogen storage at airports would likely be considered a non-routine project requiring additional scrutiny for safety compliance (Rivkin, Burgess, and Buttner 2017). However, this illustration assumes a complete transition of all aircraft segments to hydrogen, whereas, in practice, only a portion of aircraft operations could feasibly adopt hydrogen propulsion.

The distribution of liquid hydrogen to aircraft can begin with mobile bowsers, but should transition to hydrant systems for large-scale operations due to efficiency, reduced handling risks, and improved fueling logistics. Unlike Jet A, liquid hydrogen hydrant systems present greater complexity due to cryogenic temperature requirements, slower flow rates, and heightened leakage risks. Hydrogen's small molecular size, high diffusivity, and potential for material embrittlement necessitate stringent leak prevention measures. Additionally, minimizing boil-off losses requires effective thermal management, typically achieved through vacuum-jacketed pipelines and active cooling (Bruce et al. 2020). Preventing oxidant ingress is critical, as hydrogen's combustion properties create explosion hazards if mixed with oxygen. Safety codes, such as NFPA 2 and ISO 19880-1, mandate maintaining positive tank pressure to prevent air contamination, as well as purging oxidizers before filling (FAA 2024; H2Tools n.d.-b.).

For gaseous hydrogen, nitrogen is commonly used as a purge gas (H2Tools n.d.-b.). However, for liquid hydrogen, most gases, such as nitrogen and oxygen condense or solidify at cryogenic temperatures, potentially blocking transfer lines and causing system failure (Brewer 1991). While helium is the preferred purge gas in space applications, its use in commercial aviation presents two challenges: extended turnaround times and high costs, due to helium's non-

renewable nature and limited supply (Mangold 2022). To address these issues, clean break disconnects, which are designed to prevent spillage and air ingress have been proposed as a long-term solution. They could potentially eliminate the need for purging (Gaubatz et al. 2023). Although proven in select industrial settings, their deployment in aviation remains under evaluation, and will require further validation for large-scale hydrogen infrastructure.

For hydrogen-powered aircraft, achieving fueling turnaround times comparable to those of Jet A-fueled aircraft is essential to maintain operational efficiency. NREL demonstrated an average mass flow rate of 14 kg/min (and a peak of 21 kg/min) for gaseous hydrogen, which aligns with the fueling rates of diesel HDVs (Oakleaf et al. 2022); however, since hydrogen has a lower volumetric energy density than Jet A, a significantly larger volume of hydrogen is required to achieve the same energy output. For liquid hydrogen, one point of reference could be the flow rate for space applications. NASA's Space Shuttle External Tank estimated fueling time is 3 hours, yielding a 580 kg/min liquid hydrogen flow rate (Lockheed Martin n.d.; Partridge 2011). However, this is still lower than the requirement for larger aircraft proposed by the literature and it necessitates improvements in fueling times to ensure that the operational turnaround for hydrogen aircraft is not adversely affected (Hoelzen et al. 2022; Mangold et al. 2022). To ensure hydrogen aircraft maintain operational feasibility, further advancements in fueling infrastructure and fueling speeds are required.

The integration of advanced materials and technologies can significantly enhance the performance and safety of hydrogen fueling infrastructure. Composite materials, such as carbon-fiber-reinforced polymers (CFRP), used in storage and transfer systems help mitigate hydrogen embrittlement by reducing hydrogen diffusion and improving fracture resistance, thereby enhancing durability (Okonkwo et al. 2023). Additionally, smart monitoring systems equipped with ultraviolet/infrared (UVIR) flame detectors, ultrasonic sensors for hydrogen leak detection, and flammable gas detectors enable real-time monitoring of temperature, pressure, and potential leaks, significantly improving operational safety and efficiency. Furthermore, the development of standardized protocols and international cooperation are crucial to ensuring interoperability across hydrogen fueling networks, regulatory harmonization, and supply chain resilience, thereby facilitating the widespread, scalable adoption of hydrogen infrastructure at airports.

Fuel cell aircraft are emerging as a technically feasible option for commuter and regional segments and have a moderate TRL with completed test flights. Direct hydrogen combustion in gas turbines could support short-to-medium-haul flights, though widespread adoption is unlikely before 2040 due to developmental and certification challenges. While hydrogen-powered aircraft, particularly fuel cell systems, present emissions reduction potential, their adoption will require addressing significant safety, certification, and infrastructure challenges. A phased approach could accelerate adoption, starting with cargo aircraft due to their predictable routes, controlled operations, and lower public exposure. Initial airport retrofits should focus on select airport pairs to maximize efficiency, while large hubs with higher air quality concerns could be prioritized for early implementation. Hydrogen deployment should complement battery-electric strategies, focusing on longer routes where electrification is impractical. Additionally, first responder training, safety protocols, and regulatory standards must be established to ensure safe integration. A coordinated effort across certification, operations, and infrastructure development will be essential for hydrogen-powered aviation to become commercially viable.

4.2 Vehicles and Equipment

Vehicles and equipment, including GSE, air cargo transport, and attracted travel, such as passenger shuttles and rental car services, represent the second-largest source of emissions at airports after aircraft operations. While attracted travel primarily consists of light-duty vehicles and is not the primary focus of this report, hydrogen-fueled shuttle buses offer an opportunity to broaden hydrogen integration at airports. Air cargo operations, despite their varied nature, share operational characteristics with drayage applications and can draw upon the analysis in Section 3.2.

This section examines the potential applications of hydrogen in GSE, focusing on technical feasibility, economic considerations, and real-world deployment insights. It also explores the complementary roles of FCE and battery-electric alternatives in airport operations. Additionally, leveraging hydrogen infrastructure for GSE could support synergistic use cases, such as powering DC fast chargers for EVs and supporting passenger-facing hydrogen fueling stations. The section further highlights ongoing airport hydrogen deployments worldwide and presents strategies for integrating hydrogen into airport operations.

4.2.1 Technology Status and Integration Challenges

The integration of hydrogen technology into airport GSE presents an opportunity to enhance energy efficiency and fuel diversification, though its adoption is constrained by the diversity of equipment types and their specific operational requirements. Ground power units (GPUs), which supply electrical power to parked aircraft, have been identified as particularly suitable for fuel cell conversion due to their high utilization rates, stationary operation, and consistent power demand. Several feasibility studies have supported this conclusion (Ballard Power, BAE Systems, and SCG 2012), identifying GPUs as promising candidates for hydrogen compatibility based on reliability, ease of use, and cost-effectiveness. Similarly, (Johnson et al. 2012) found GPUs to be strong candidates for hydrogen adoption due to their typical operation of up to 15 hours per day and their reliance on point-of-use fueling, as they often function away from airport gates. (Sezer et al. 2023) corroborated these findings while highlighting the higher total cost of ownership compared to diesel alternatives remains a key barrier. This cost disparity is primarily driven by the capital expense of fuel cell technology, hydrogen infrastructure requirements, and operational complexities, which must be addressed to enable large-scale deployment and commercialization.

There have been several hydrogen-powered GSE demonstrations over the past decade. Plug Power's retrofitted Charlatte baggage tow tractor, for example, met operational targets but faced challenges due to infrastructure constraints, leading to a reduction in planned units from 15 to 2 and relocation to Albany International Airport (Blanchard 2020). The units featured a relatively small-scale 20-kW fuel cell with 3.75 kg of onboard storage and an 80-kWh battery, meeting all operational targets, including a speed of 10 mph, a run time of 3 to 4 shifts, and a maximum cargo capacity of 40,000 lb; however, FedEx decided not to continue deploying the FCE tugs because maintaining hydrogen infrastructure for just two units was not justified, and the airport's operational schedule did not necessitate multiple-shift equipment use (Blanchard 2020). This underscores the importance of scaling the number of units to justify the investment in the fueling infrastructure, as well as the need to match FCE equipment deployment with airports that operate

multi-shift schedules. In 2024, a hydrogen baggage tractor trial was also conducted at a UK airport by Hydrogen in Aviation Alliance (Bristol Airport 2024).

Similarly, a retrofit of a U-30 aircraft tow tractor at a U.S. Air Force base in Hawaii demonstrated feasibility, featuring a 30-kW fuel cell with 10 kg of onboard storage and a 22-kWh battery with plug-in charging capability. This unit demonstrated a 12-hour range and a max drawbar pull of 72,000 lb (HTDC n.d.). A GPU demonstration is also planned in the Netherlands, where the unit is currently undergoing the certification process. Groningen Airport Eelde is hosting a 40-kW fuel cell GPU retrofit with 10 kg of onboard storage at 350 bar and a 70-kWh battery, showcasing the potential to address long charging times and centralized charging issues previously observed with a battery-electric GPU at Amsterdam Airport Schipol (GHI 2024).

As of late 2024, there are no large-scale commercial deployments of FCE GSE at airports. The primary challenges hindering the adoption of hydrogen-powered GSE include market acceptance due to cost sensitivity, limited hydrogen fueling infrastructure, and regulatory uncertainties. In contrast, the adoption of battery-electric GSE is increasing rapidly, driven by public commitments from both airlines and airports to achieve environmental goals. For instance, American Airlines reported electrifying 23% of its fleet by 2022, Delta Air Lines achieved 31% by 2023, Southwest Airlines reached 37% by 2023, and United Airlines reported 35% by 2023 (American Airlines 2022; Delta 2024; Southwest Airlines 2024; United 2024). PANYNJ has mandated the incremental restriction of registrations for new and replacement conventional airside vehicles, including renewal applications. By 2030, only zero-emission models will be approved for registration unless such models are not commercially available or operationally feasible (PANYNJ 2022).

Electrified versions of GSE, especially for narrow-body aircraft, are widely available and can directly replace diesel-powered units (Oshkosh AeroTech 2021). However, for high-utilization equipment with demanding duty cycles, if the battery is depleted before the end of the shift, operators may need to acquire additional units, increase battery capacity, or implement opportunity charging strategies during the day (Timmermans et al. n.d.). In cases like that, FCE GSE could provide faster fueling and longer operating range. A case study conducted by NREL on port authority-owned vehicles at a separate airport indicated that while most light-duty vehicles are relatively straightforward to electrify, vocational vehicles, such as sewer trucks, street sweepers, and snow removal equipment, are unlikely candidates due to high fuel consumption or intensive daily usage, even if annual utilization is low. However, it is worth noting that airlines focus their near-term efforts on electrifying the core fleets, including baggage tractors, belt loaders, and aircraft tow tractors.

As battery-electric fleets expand and simultaneously elevate peak power demand at airports, the potential for hydrogen deployment may depend on the grid's ability to accommodate increased charging loads. Hydrogen can serve as a supplemental solution for battery-electric vehicles and equipment charging in multiple cases, such as delayed utility upgrades, mitigation of peak demand charges, or scenarios in which large-scale charging infrastructure is infeasible at a specific airport (Kopasz and Krause 2021). For example, Universal Hydrogen collaborated with Oshkosh to develop hydrogen-powered chargers as a transitional solution, replacing diesel

generators that were temporarily scaled up due to delays in EV charging infrastructure deployment at the airport (Universal Hydrogen 2024).

In the early stages of GSE deployment, airlines have emphasized that standardization across equipment types is important to facilitate operator cross-utilization and reduce maintenance training requirements. However, as battery-electric equipment becomes more widespread and potentially leads to infrastructure constraints, another scenario suggests that replacing battery-electric powertrains with fuel cells is relatively straightforward. Accordingly, several original equipment manufacturers have developed models capable of supporting multiple power sources, including lead-acid batteries, lithium-ion batteries, and fuel cells, providing airports with greater powertrain flexibility (TLD n.d.).

Overall, hydrogen-powered GSE demonstrates moderate to high technological readiness; however, market acceptance remains a key challenge due to the cost sensitivity associated with this equipment. Battery-electric alternatives are commercially available and are currently favored due to their lower capital costs and less complex infrastructure requirements relative to hydrogen-powered options. In the medium to long term, fuel cell GSE could serve as a complementary technology. This role is particularly relevant for high-utilization equipment or in settings where grid capacity limitations hinder large-scale electrification. Safety considerations remain paramount for airport ground operations, especially given the perceived risks associated with hydrogen deployment. FCE equipment differs from conventional units, and new safety standards and procedures must be developed prior to commercial deployment in the airside environment.

4.2.2 Scaling Hydrogen Use at Airports

Scaling hydrogen use at airports requires the strategic integration of hydrogen technologies across diverse operational domains, including an estimation of hydrogen demand for key GSE types. Estimating demand supports infrastructure planning and helps identify high-impact opportunities for hydrogen integration.

Table 7 presents the estimated hydrogen demand for selected GSE catagories, based on representative models. Given limited data availability, the estimates assume 12-hour daily operations for aircraft and cargo/baggage tractors, and 6-hour daily operations hours for forklifts, to illustrate general utilization trends. In actual airport environments, GSE operating hours vary based on time-in-mode during landing and takeoff cycles, as well as the daily frequency of such operations. Utilization rates also differ depending on aircraft type (narrow-body vs. wide-body), aircraft function (passenger vs. cargo), and the specific carrier. The TRL values shown are derived from available demonstration projects. See Appendices A and B for the full set of assumptions and detailed calculations.

Table 7. Comparative Analysis of Selected GSE

GSE Type	H_2 GSE TRL	H_2 Demand (DGE/unit/day)	Diesel Demand (gal/unit/day)
Aircraft tractor [a]	7	43	61
Cargo/baggage tractor [b]	7	20	28
Forklift [c]	7	6	9
Ground power unit [d]	6	20	28

[a] Representative model JBT B1200 Push Back Tractor (DBP – 72,000 lb.). JBT B1200 aircraft tractor can accommodate aircraft Maximum Take-Off Weight from 75 to 590 metric tonnes. That includes wide-body aircraft such as B747, A380.
[b] Representative model TUG MT (MDP – 12,000 lb.). The MT can be used as a heavy-duty cargo/baggage towing tractor as well as a pushback for narrow-body and regional aircraft.
[c] Representative model Toyota - High-Capacity IC Pneumatic (45,000-72,000 lb.). It is noted that PANYNJ airports typically use forklifts with much lower load capacity (~5,000 lb.) (SC&A 2023); however, for illustrative purposes, we provide calculations for a heavier-duty model.
[d] Representative model is TLD 28 VDC.

While the preceding section addressed limitations of hydrogen-powered GSE, several airports globally have implemented hydrogen fueling stations to serve ground vehicles (Ochoa Robles et al. 2019). These installations primarily aim to familiarize airports with hydrogen infrastructure and operational protocols, facilitating future readiness for potential increase in hydrogen demand from aviation. Initial use cases, such as GSE and ground vehicles, are frequently cited in the literature as foundational steps toward transforming airports into hydrogen hubs (Postma-Kurlanc, Leadbetter, and Pickard 2022; ARUP 2022; Jacobs 2022). Companies such as Airbus are working to prepare airports for the anticipated deployment of hydrogen-powered aircraft. For example, Airbus partnered with Toulouse-Blagnac Airport to establish a 400 kg/day electrolytic hydrogen production system, along with associated storage and distribution infrastructure via two fueling stations, one serving airside equipment such as shuttles, aircraft tractors, and GPUs, and the other serving landside buses and light-duty vehicles (Engie 2023). Notably, in 2009, JFK Airport hosted a temporary on-site fueling station that served Port Authority fleet vehicles for four years, under a partnership between PANYNJ, Toyota, and Shell.

In the long term, if hydrogen-powered aircraft are widely adopted, fuel storage at airports would likely be designed around peak demand and may be shared with ground vehicles and equipment, depending on seasonal fluctuations and operational requirements (Postma-Kurlanc, Leadbetter, and Pickard 2022). While hydrogen offers favorable economies of scale through shared infrastructure (Oakleaf et al. 2022), infrastructure scalability is not straightforward. On-site electrolysis may be sufficient to meet hydrogen needs for ground vehicles but is unlikely to support the substantially higher demand associated with hydrogen-powered aircraft. As discussed previously, if hydrogen demand increases with aircraft deployment, most medium- to large-sized airports would likely need to adopt pipeline-based gaseous hydrogen delivery followed by on-site liquefaction. An additional challenge lies in the uncertainty surrounding the deployment timeline and scale of demand for hydrogen-powered aircraft, with some projections indicating broader adoption in the early 2050s (Postma-Kurlanc, Leadbetter, and Pickard 2022). In the interim, airports have set near-term zero-emission targets for core GSE fleets, making battery-electric equipment a more practical solution due to its greater commercial availability.

Overall, this section offers a complementary perspective on FCE equipment and vehicles. The installation of hydrogen fueling infrastructure and the limited deployment of FCE ground equipment are viewed as preparatory steps to familiarize airports with hydrogen systems and operational protocols. These activities are intended to support anticipated future hydrogen demand, particularly from the eventual introduction of hydrogen-powered aircraft.

4.3 Stationary Power

The growing energy demand at airports, driven by increasing electrification, requires both the deployment of new decentralized energy systems to enhance operational resilience and strategies to decarbonize existing energy infrastructure. This section examines the potential integration of hydrogen into stationary power applications at airports, focusing on two primary use cases: hydrogen co-firing in existing gas turbines and the incorporation of hydrogen into airport microgrids. It specifically evaluates the technical feasibility, challenges, and emissions implications of hydrogen co-firing, drawing from recent demonstration projects. Additionally, the section discusses fuel-sourcing pathways based on projected hydrogen demand associated with these two applications.

4.3.1 Technology Status and Challenges of Hydrogen Co-Firing in Gas Turbines

The integration of hydrogen into airport power systems can follow multiple approaches, with the optimal method varying according to the infrastructure and operational characteristics of each airport. This section evaluates the current technological status and challenges of hydrogen co-firing, using JFK as a case study, and discusses broader implications for the aviation sector.

The KIAC facility at JFK is equipped with two GE aeroderivative LM6000 turbines that currently operate on natural gas. As airports consider hydrogen integration, modifications to both fuel delivery infrastructure and turbine operation are required. Hydrogen and methane exhibit significantly different combustion properties, which influence the feasibility of hydrogen co-firing. Table 8 summarizes the differences between hydrogen and methane and outlines their implications for turbine operation. If hydrogen's combustion characteristics are not appropriately addressed, co-firing can result in challenges such as flame flashback, elevated NO_x emissions due to higher flame temperatures, and potential reductions in turbine power output at elevated hydrogen blend levels. Appropriate retrofits and operational modifications are necessary to mitigate these risks. Several retrofit technologies are available to adapt existing gas turbines for hydrogen co-firing. For example, PSM's Flamesheet technology enables flexible fuel operation, supporting hydrogen blends of up to 50% while mitigating risks such as flashback and NO_x formation (PSM n.d.). These retrofits are critical to maintaining combustion stability, preserving turbine efficiency, and addressing material and thermal management challenges posed by hydrogen's higher flame temperature.

Table 8. Hydrogen and Methane Combustion-Related Properties and Impacts on Gas Turbines

Properties	Hydrogen	Methane	Implications for Combustors
Lower heating value (BTU/scf)	~290	~983	Hydrogen has a lower volumetric energy density than methane, but the total volumetric flow rate of the air–fuel mixture remains similar due to differences in oxygen requirements. However, hydrogen's significantly higher flame speed (approximately ten times greater than methane's) necessitates combustor redesign to manage shorter residence times and avoid flashback risks (NETL 2022; Goldmeer 2019; H2Tools n.d.-a.).
Adiabatic flame temperature (°F)	~4,089	~3,565	The higher flame temperature of hydrogen can alter thermal acoustics and increase NO_x formation, requiring advanced combustor cooling, staged combustion, or lean-premixed strategies to maintain emissions within acceptable limits (NETL 2022).
Flame speed at standard temperature and pressure(cm/s)	200–300	30–40	Values are provided at standard temperature and pressure (STP). Under actual gas turbine conditions, higher pressure and temperature reduce absolute flame speeds; however, hydrogen still maintains a flame speed significantly higher than that of methane (approximately tenfold). This necessitates combustor modifications to prevent flashback and ensure stable operation (NETL 2022; Goldmeer 2019; Topolski et al. 2022; GE 2020)

The capability of gas turbines to co-fire hydrogen largely depends on the flexibility of the combustion system to accommodate the differing combustion characteristics of hydrogen and methane. Lean premixed combustion systems, optimized through design and control strategies for low NOx emissions, are less flexible when operating on various fuel blends (Topolski et al. 2022). In contrast, diffusion combustion systems operate at higher temperatures, produce more NOx emissions, and are generally more adaptable to varying fuel compositions (Goldmeer et al. 2024). The ability of gas turbines to operate on hydrogen blends does not eliminate the necessity for modifications to turbine components, ancillary systems, and balance-of-plant infrastructure, with the extent of these changes being dependent on the proportion of hydrogen in the fuel mixture (GE 2020). The magnitude of modifications can range from minor adjustments, such as changes to control systems and fuel nozzles, to more comprehensive upgrades including combustor retrofits, replacement of fuel skids, enclosure reconfiguration, and installation of hydrogen-compatible sensors, particularly at high hydrogen blending levels (Goldmeer 2019). Combustor retrofits for fuel flexibility, including hydrogen, are already available commercially and supported by OEM-led upgrade programs (PSM n.d.).

Hydrogen co-firing can reduce CO_2 emissions, but the reduction is nonlinear with respect to the volumetric hydrogen blend due to hydrogen's lower energy density. Figure 6 illustrates this nonlinear relationship, showing that a 5 vol % hydrogen blend results in a 1.5% CO_2 reduction, whereas a 35 vol % blend achieves a 13.7% reduction. However, increased hydrogen content increases NOx emissions because of hydrogen's elevated adiabatic flame temperature. While

NO_x formation is a concern, emissions can be effectively controlled using well-established strategies such as lean premixed combustion, flame dilution, water injection, and selective catalytic reduction (SCR). Additionally, hydrogen flames lack common catalyst poisons found in fossil fuels, enabling the use of 3-way catalytic converters, similar to those used in automotive applications, to significantly reduce NO_x emissions. If uncontrolled, hydrogen combustion can produce up to eight times more NO_x than natural gas (NETL 2022), but emissions reduction strategies, including pre-mixed combustion and catalytic conversion, have already been successfully deployed in hydrogen-fueled gas turbines, such as Mitsubishi's H-Series and GE's H_2-capable turbine platforms. According to the EPA, natural gas-fired combined cycle power plants with a rated capacity exceeding 50 MW, including KIAC, must limit Nox emissions to 9 ppm at 15% O_2 (EPA n.d.-b). To comply with these regulatory limits, the KIAC plant employs both water injection and SCR, technologies consistent with diffusion combustor systems (New York State 2022b). Given the demonstrated effectiveness of current NO_x control technologies, hydrogen combustion is not expected to be a limiting factor for commercial-scale deployment.

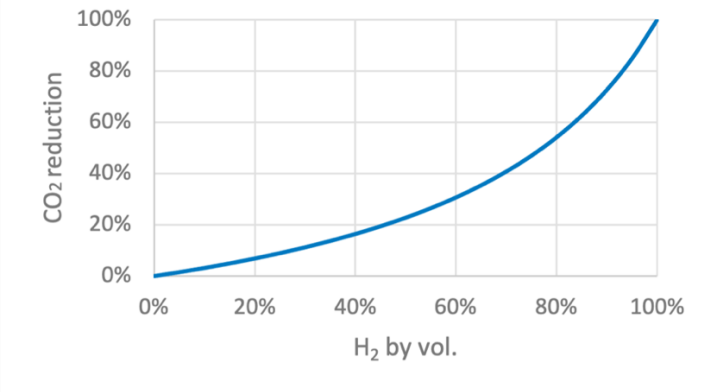

Figure 6. CO_2 emissions reduction potential based on the volumetric percentage of hydrogen co-firing with natural gas.

Hydrogen co-firing with natural gas has been explored in several demonstration projects to assess its feasibility and environmental impact. A notable example is the collaboration between the Electric Power Research Institute (EPRI), General Electric (GE), and the New York Power Authority at the Brentwood Power Station, a 45-MW peaking power plant equipped with a simple-cycle GE LM6000 turbine, where hydrogen co-firing ranged from 5 vol% to 44 vol% (EPRI and GTI Energy 2022). Both the Brentwood and KIAC plants utilize single annular combustion systems and employ water injection along with selective catalytic reduction for emissions control. The pilot demonstrated stable combustion dynamics without requiring modifications to the gas turbine; however, the limited duration of the test highlights the need for long-term studies to assess impacts on turbine durability, materials, and overall system performance. The study found that proportional increases in water injection, aligned with hydrogen blends, kept NOx emissions within regulatory limits. However, this finding is specific to the single annular combustion technology used and does not necessarily apply to other combustor configurations. NOx formation in hydrogen combustion is influenced by multiple factors, including adiabatic flame temperature, residence time, mixing characteristics, and combustor design. While water injection is an effective mitigation strategy by lowering flame temperature, alternative approaches, such as combustor design optimization, lean-premixed combustion, and advanced fuel-air mixing, can also provide effective NOx control. Hydrogen's

higher flame speed compared to methane reduces residence time in the flame front, which, in theory, limits thermal NOx formation by reducing the available reaction time. However, NOx emissions are also affected by turbulence, equivalence ratio, and local temperature gradients, requiring further analysis to fully understand the interplay of these factors. Given the complexity of NOx formation in hydrogen co-firing, additional long-term experimental validation would be beneficial to optimize emissions control strategies while ensuring efficient and stable turbine operation.

Another hydrogen co-firing demonstration at the McDonough-Atkinson power station (2,520 MW capacity) utilized a Mitsubishi Power M501G combined cycle turbine to evaluate hydrogen-natural gas blending. The project achieved a 7% reduction in CO_2 emissions when operating at a maximum hydrogen blend of 20.9 vol %, relative to baseline operation on 100% natural gas. However, this reduction was accompanied by a slight efficiency penalty due to hydrogen's lower volumetric energy density (Harper et al. 2023). The lean-premixed combustion system successfully controlled NO_x formation, maintaining emissions below regulatory thresholds and comparable to natural gas combustion upstream of SCR. Notably, GE Vernova and Siemens Energy have conducted similar tests on H_2 combustion turbines, reporting NO_x emissions ranging from 25 to 50 ppm at 15% oxygen for blends of up to 50% hydrogen, with further reductions achievable through advanced combustor designs and optimized water injection (GE 2023; Siemens Energy 2020). Further research and operational validation at higher hydrogen blend ratios will be necessary to fully characterize the impact on turbine efficiency, materials durability, and long-term emissions performance.

Overall, hydrogen co-firing at the KIAC plant is being explored as a strategy to reduce CO_2e emissions while utilizing existing gas turbine infrastructure. The primary challenges associated with hydrogen co-firing include increased NOx emissions, which require effective mitigation strategies, and combustion instability due to differences in properties between methane and hydrogen. Please refer to Section 4.3.3 for a discussion of other challenges associated with hydrogen co-firing, including the quantities of hydrogen required and implications for fuel costs. The GE LM6000 turbines have demonstrated potential for hydrogen co-firing up to 44 vol % without significant modifications. Achieving higher hydrogen blending ratios in gas turbines is being explored as a strategy to reduce carbon emissions through co-firing with green hydrogen. However, increasing hydrogen content in the fuel mix introduces combustion challenges, including NOx emissions and system stability concerns. Original equipment manufacturers, in collaboration with system operators, must assess turbine compatibility and determine necessary modifications based on hydrogen concentration levels, combustion characteristics, and emissions control strategies.

4.3.2 Distributed Energy Resources

As energy demand at airports continues to grow due to the electrification of ground operations and increased passenger traffic, there is a need for distributed energy systems that enhance airport resilience (AAAE Services and AlphaStruxure 2023). Microgrids are localized grids that can operate independently or in conjunction with the main electric grid, enhancing energy security, providing operational flexibility, and supporting the integration of renewable energy sources. Two key features of microgrids are the co-location of supply and demand and the ability to deliver most day-to-day energy needs (AAAE Services and AlphaStruxure 2023). Integrating hydrogen into microgrids, particularly through fuel cells, offers a pathway to further decarbonize

airport energy systems as they generate electricity with zero or near zero emissions at the point of use, depending on the type of fuel cell and input fuel. As illustrated in Figure 7, a microgrid can use photovoltaic arrays, residential waste, and municipal waste to produce electricity, heating, and cooling via various components, such as energy storage systems, fuel cells, and boilers (Tooryan et al. 2022).

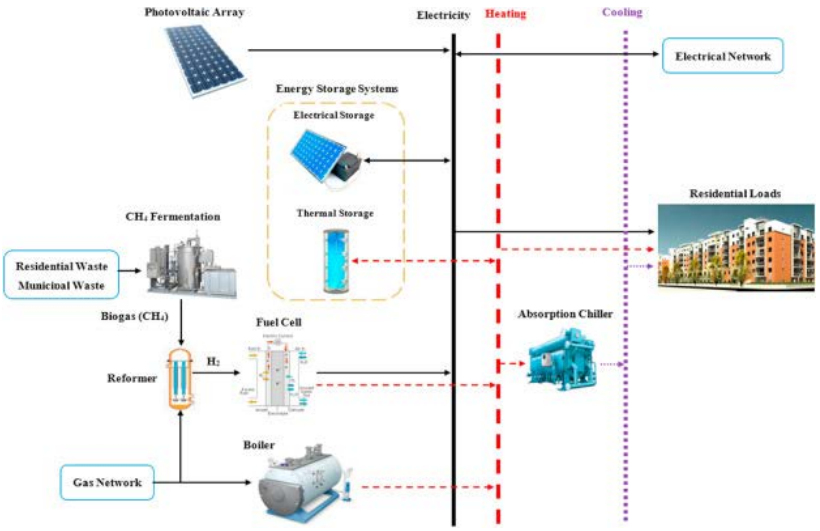

Figure 7. An integrated hydrogen combined heat and power microgrid system

Source: Tooryan et al. 2022

Fuel cells convert chemical energy from hydrogen into electricity through an electrochemical reaction, producing only water and heat as byproducts. Certain fuel cell technologies, particularly those operating at higher temperatures such as phosphoric acid fuel cells (PAFCs) and solid oxide fuel cells (SOFCs), are well suited for combined heat and power (CHP) applications due to their ability to recover and utilize waste heat (Abdin et al. 2020). In contrast, low-temperature fuel cells such as proton exchange membrane fuel cells (PEMFCs) offer rapid response and high power density but are less efficient in CHP configurations because of their lower operating temperatures and limited heat recovery potential. When deployed in microgrids, fuel cells can operate using natural gas, reformed on-site to hydrogen, or pure hydrogen, depending on the system design. PAFCs and some SOFCs can accept hydrogen blends or transition to pure hydrogen with appropriate system modifications. In addition, the load-following capabilities of PAFCs and PEMFCs enable real-time adjustment of power output to meet fluctuating demand, helping to reduce costs during peak electricity pricing periods (HyAxiom n.d.-a). Microgrids also enhance airport resilience by providing a reliable and locally controlled power supply, which is particularly important during grid outages or times of high demand (Shahbazbegian et al. 2023). The New Terminal One microgrid at JFK, which incorporates PAFCs for CHP, illustrates the practical integration of fuel cells into airport energy systems (PANYNJ 2023b.).

The New Terminal One at JFK is planning to implement a microgrid consisting of rooftop solar panels, battery energy storage, and fuel cells for CHP. The system is expected to comprise 6.63 megawatts of rooftop solar, 3.84 megawatts of natural gas-fueled PAFCs, and 1.5 megawatts / 3.34 megawatt-hours of battery energy storage, capable of powering the terminal's critical loads. The microgrid's PAFCs, initially powered by natural gas, offer a pathway for fuel flexibility and

energy transition. As advancements in fuel cell technology and fuel availability progress, these PAFCs may incorporate renewable natural gas (RNG) and hydrogen, supporting long-term energy diversification. The baseline PAFC model is capable of accommodating up to 30% hydrogen blends, with the potential for full hydrogen operation through targeted system upgrades involving the fuel processing unit, heat recovery integration, and control architecture optimization (HyAxiom n.d.-b)

Although integrating hydrogen into microgrids offers numerous benefits, several challenges must be addressed to support its scalable and reliable implementation. The high initial cost of fuel cell technologies and associated hydrogen infrastructure remains a barrier. Long-term economic analyses are necessary to evaluate the cost-effectiveness of hydrogen integration into microgrids, considering factors such as fuel supply costs, operational and maintenance requirements, and potential gains in energy efficiency, reliability, and emissions reduction. Business models that minimize upfront capital investment, such as energy-as-a-service (EaaS), may be particularly viable for airport authorities such as PANYNJ by enabling hydrogen adoption without immediate capital expenditures. Additionally, seamless integration of hydrogen fuel cells with other microgrid components including photovoltaic systems, battery energy storage, and advanced power electronics depends on intelligent energy management systems that enable real-time power distribution, load balancing, and dynamic response. Alongside these technical challenges, factors such as safety protocols, regulatory and permitting frameworks, and stakeholder engagement must also be integrated into the planning and deployment process to ensure safe, compliant, and publicly supported deployment.

To summarize, integrating fuel cells into airport microgrids, as demonstrated by the New Terminal One microgrid at JFK, can enhance energy resilience and sustainability. By leveraging CHP functions and incorporating renewable electricity generation, airports may establish decentralized, lower-emission energy systems with enhanced reliability and operational flexibility. PAFCs and SOFCs provide fuel-flexible platforms capable of operating on natural gas, renewable natural gas, and hydrogen blends, typically accommodating up to 30% hydrogen by volume; however, full conversion to 100% hydrogen may require system modifications to the fuel processor, thermal integration, and control system. In contrast, PEMFCs operate exclusively on pure hydrogen and may be more applicable in the long term when dedicated hydrogen infrastructure becomes commercially viable and widely accessible. The selection of appropriate fuel cell technology should be guided by airport-specific energy transition pathways, infrastructure constraints, and operational requirements to ensure long-term technical feasibility and cost-effectiveness.

4.3.3 Infrastructure Requirement for Large-Scale Hydrogen Sourcing

The transition to hydrogen as a clean fuel for power applications requires a reliable and scalable infrastructure to support large-scale sourcing and delivery. This section evaluates the projected hydrogen demand for the KIAC plant and the New Terminal One microgrid at JFK to assess infrastructure requirements for hydrogen integration in airport power applications. It also identifies key challenges and examines potential pathways for aligning hydrogen sourcing, storage, and distribution with existing energy systems.

Table 9 presents annual hydrogen demand estimates for the KIAC plant, derived from historical hourly unit-level heat input data obtained from the U.S. EPA's Clean Air Markets Program Data

(CAMPD) database (EPA n.d.-a). These estimates assume capacity factors ranging from 46% to 59% for the years 2021 through 2023 and reflect hydrogen blends up to 35 vol%, which is the maximum supported by the original equipment manufacturer (GE 2022). The data reveal year-to-year variability in hydrogen demand, underscoring the importance of flexible and adaptive planning approaches. In particular, future infrastructure planning should consider how increasing renewable energy generation at JFK may alter the operational output and hydrogen demand profile of the KIAC plant. Appendix C provides a detailed summary of underlying assumptions and supporting calculations.

Table 9. Annual Hydrogen Demand for KIAC Plant Calculated Based on the Percentage H_2 Co-Firing Volume, metric tonnes/year

H_2 vol % / Year of Operation	5%	10%	15%	20%	25%	30%	35%
2021	616	1,278	1,993	2,767	3,606	4,521	5,521
2022	717	1,487	2,319	3,219	4,196	5,260	6,424
2023	550	1,142	1,781	2,472	3,222	4,039	4,933

If hydrogen is supplied to the KIAC plant independently of natural gas, an on-site blending system would be required to accommodate co-firing operations (GE 2020). A primary challenge associated with this delivery pathway is ensuring a continuous and scalable hydrogen supply. This was evident during the Brentwood Power Plant demonstration, where hydrogen was delivered by tube trailers, and sustained injection over a 12-hour period required manual adjustment of trailer-mounted hydrogen regulators, an approach unsuitable for routine operations (EPRI and GTI Energy 2022). At KIAC, maintaining a 5 vol% hydrogen blend would require an estimated 1,687 kg/day of hydrogen, translating to five daily gaseous tube trailer deliveries (at 300 kg per trailer) or one liquid hydrogen tanker delivery every two days (at 4,000 kg per tanker), based on typical industry capacities (DOE n.d.; S&P Global 2021).

On-site hydrogen storage may mitigate supply chain disruptions, but it presents notable technical and logistical challenges. For reference, the largest commercially deployed liquid hydrogen tank has a capacity of approximately 335,000 kg (Youngquist et al. 2024). Compliance with safety regulations, such as setback distances and site permitting, further complicates tank siting and integration into constrained airport environments (Goldmeer 2019). Given the hydrogen volumes projected for KIAC and similar facilities, pipeline delivery may offer the most cost-effective solution, particularly if existing natural gas infrastructure can be repurposed to avoid the capital costs of constructing new dedicated pipelines (Frank et al. 2021).

For the New Terminal One microgrid at JFK, hydrogen demand was estimated under two operational scenarios: one assuming a hydrogen blend of up to 30% by volume in the natural gas stream and the other assuming full conversion to 100% hydrogen. As the microgrid remains under construction and lacks an operational load profile, demand estimates in Table 10 are derived from the maximum rated capacity of the fuel cells, as specified by the original equipment

manufacturer (HyAxiom n.d.-b). A full set of assumptions and calculation details is provided in Appendix D[10].

Table 10. Hydrogen Demand for the New Terminal One Microgrid Estimated Based on the Percentage H_2 Co-Firing Volume

H_2 vol % Operating Metrics	5%	20%	30%	100%
H_2 demand (kg/year)	31,755	143,080	233,965	1,834,125
CO_2 reduction (%)	1.5%	6.9%	11.2%	100%

Integrating hydrogen into airport energy systems requires rigorous evaluation of sourcing strategies and infrastructure requirements to support reliable operations and meet sustainability objectives. Because estimated rather than observed operating profiles were used, hydrogen sourcing decisions must retain flexibility to account for variability in actual energy demand. PAFCs and SOFCs are best suited for continuous baseload operation because they require sustained high temperatures and are less effective under cycling conditions. In such applications, pipeline delivery of pure or blended hydrogen could be a feasible supply option, especially under medium- to high-utilization regimes. For intermittent or standby power applications, PEMFCs may be more suitable due to their low-temperature operation and fast startup response. Access to hydrogen blends through existing natural gas infrastructure could reduce the need for dedicated hydrogen infrastructure investment by PANYNJ. However, the feasibility of hydrogen blending introduces complex technical and regulatory challenges, which are further examined in the following paragraphs.

Hydrogen blending provides a transitional approach toward cost-effective pure hydrogen delivery by leveraging existing pipeline infrastructure. However, hydrogen blending into natural gas pipelines typically falls outside the jurisdiction of PANYNJ. Instead, natural gas infrastructure owners and operators, such as National Grid, are responsible for enabling the availability of blended hydrogen fuels. As part of its net-zero strategy, National Grid has outlined opportunities for hydrogen blending in New York State and proposed preliminary targets for integration into the existing gas network (National Grid 2021).

Hydrogen's physical and chemical properties significantly influence its transport, particularly regarding material compatibility and diffusion, rather than general leakage rates. As with gas turbines, the permissible hydrogen blending ratio in pipelines must be evaluated on a case-by-case basis, considering factors such as equipment type, component condition (e.g., compressors and valves), materials of construction, network layout, and gas transport capacity (Topolski et al. 2022). Natural gas pipeline infrastructure is generally divided into two main segments: transmission pipelines, which move gas in large volumes over long distances, and distribution pipelines, which deliver gas to end users. In transmission pipelines, hydrogen's potential to induce steel embrittlement requires careful evaluation to maintain long-term mechanical integrity and operational safety. In the case of distribution pipelines, hydrogen's diffusion through

[10] These estimates were developed by the NREL team based off publicly available information and may not match New Terminal One project specifics.

polyethylene (PE) piping systems warrants further analysis, since standards such as NFPA 2 currently do not fully endorse PE for hydrogen conveyance. If diffusion losses through PE are found to be substantial, retrofitting distribution networks with hydrogen-compatible materials, such as steel, may become necessary. Moreover, end-use facilities should incorporate dedicated leak detection systems to mitigate the risk of hydrogen accumulation in enclosed or poorly ventilated spaces. Maintaining energy throughput across both transmission and distribution networks may also necessitate compressor station upgrades, given hydrogen's lower volumetric energy density relative to natural gas. Required upgrades may include increased compression capacity or adjustments to pipeline specifications, depending on the target hydrogen blending levels (Topolski et al. 2022). Currently, hydrogen blending pilot projects have primarily focused on distribution pipelines, which typically operate at lower pressures than transmission systems. For context, the KIAC plant receives its natural gas supply via a National Grid-operated transmission pipeline (National Grid 2017).

The cost of delivering blended natural gas and hydrogen fuel is influenced by several variables, including the hydrogen production pathway, prevailing natural gas prices, and the targeted blending ratio, all of which affect the extent and cost of required pipeline modifications. A recent techno-economic study evaluating two natural gas pipelines indicated that even at hydrogen blending levels up to 50% by volume, the transportation segment contributes only marginally to the overall levelized cost of energy. However, the total delivered energy cost increases with greater hydrogen blending ratios, reaching approximately $12 per MMBtu at a 50% hydrogen blend, largely driven by the elevated cost of electrolytic hydrogen production (Chung, Elgowainy and Topolski 2024). Although this cost escalation has implications across user segments, the power sector's willingness to pay for hydrogen varies substantially depending on the specific application. Grid-scale generators, operating under variable cost competition, typically demonstrate a low willingness to pay for hydrogen, often ranging between $0.3 and $0.6 per kilogram. By contrast, distributed generation applications, including on-site power systems at airports, are benchmarked against higher retail electricity prices, which may improve hydrogen's cost competitiveness in those contexts. Moreover, hydrogen-based power generation at airports is likely to be deployed intermittently, especially during periods of elevated grid electricity prices, coinciding with dips in renewable generation output. While the "duck curve" phenomenon, characterized by peak demand as solar generation wanes, is prominent in markets such as California, states like New York and New Jersey currently experience midday peak electricity prices. Nonetheless, with continued growth in renewable energy penetration, pricing patterns may evolve, potentially enhancing the relative competitiveness of hydrogen in power generation. To address high production costs, ongoing hydrogen projects targeting power and blending applications are prioritizing low-carbon reforming over electrolysis, not only to reduce cost but also to capitalize on existing infrastructure and to align with policy mechanisms that support scalable hydrogen deployment (DOE 2025).

In summary, this section evaluates the infrastructure needs associated with integrating hydrogen into the KIAC plant and the New Terminal One microgrid at JFK. It outlines potential strategies, including hydrogen blending into existing natural gas pipelines, while identifying the technical and regulatory challenges associated with these approaches. As with hydrogen co-firing in gas turbines, allowable hydrogen blending ratios in pipeline systems require site-specific evaluation based on equipment compatibility, pipeline condition, and material specifications. Furthermore,

ensuring a reliable supply of blended hydrogen requires coordination with natural gas infrastructure owners and operators, such as National Grid.

Conclusion

This report assesses the potential role of hydrogen technologies in supporting PANYNJ's objective of reaching net-zero emissions by 2050. Hydrogen provides a pathway for reducing dependence on conventional fuels across multiple sectors, including CHE, drayage trucks, OGVs, stationary power, and aviation propulsion. However, successful adoption depends on the development of infrastructure, reduction in fuel and system costs, alignment with supportive policy frameworks, and cross-sectoral coordination.

Strategic Hydrogen Integration at PANYNJ

Maritime Sector:

- **Drayage Operations:** Hydrogen fuel cell electric vehicles (HD-FCEVs) could reduce emissions in drayage operations; however, limited fueling infrastructure in the Northeast, evolving fueling standards, and the need to coordinate with third-party fleet operators present significant challenges.
- **Cargo-Handling Equipment (CHE):** Battery-electric CHE should be prioritized where feasible. As infrastructure matures, fuel cell CHE may be introduced for high-utilization equipment such as container handlers, provided that on-site hydrogen storage and dispensing capacity is available.
- **Oceangoing Vessels (OGVs):** Hydrogen-derived fuels such as ammonia and methanol are emerging as decarbonization options in the maritime sector. While grid-based shore power solutions are being implemented, hydrogen fuel cells may support emissions reduction at berth in the long term. However, challenges related to large-scale hydrogen storage logistics warrant further evaluation.

Aviation Sector

- **Aviation Propulsion:** Sustainable aviation fuel (SAF) remains the most near-term option to reduce aviation emissions. Hydrogen may reduce SAF carbon intensity or serve as a direct propulsion fuel. Fuel cell aircraft for regional markets could enter service in the medium term, subject to certification progress. Hydrogen-fueled combustion turbines are in early development and would require substantial infrastructure for liquid hydrogen storage and distribution.
- **Ground Support Equipment (GSE):** Battery-electric systems remain the preferred solution for GSE; however, hydrogen-powered GSE may be advantageous at grid-constrained airports or for high-duty-cycle applications.
- **Stationary Power:** Short-term actions include deploying commercially available natural gas fuel cells, with the potential to transition to green hydrogen. Co-firing hydrogen at the existing KIAC plant is a long-term option, subject to availability of pipeline-supplied hydrogen and evaluation of the plant’s service life.

Potential Deployment Roadmap

Short-Term: Feasibility

- Conduct grid capacity assessments to enable near-term deployment of battery-electric CHE, and evaluate the suitability of hydrogen fuel cell CHE for long-range or high-duty applications.
- Engage hydrogen producers and explore fuel delivery pathways, pricing structures, and funding sources.
- Initiate pilot programs for HD-FCEVs or FCE CHE, based on feasibility outcomes.
- Assess the need for near-term deployment of natural gas-powered fuel cells to meet projected energy demand.

Medium-Term: Early Adoption

- Collaborate with tenants and third-party operators to enable commercial deployment of CHE and/or drayage trucks, with permanent hydrogen fueling infrastructure.
- Support adoption of hydrogen-derived maritime fuels (e.g., ammonia).
- Evaluate hydrogen applications for GSE and regional aircraft.

Long-Term: Scaling of Large-Scale Applications

- Assess conversion of existing gas-based fuel cells and turbines to hydrogen, contingent on cost and infrastructure readiness.
- Based on aircraft technology maturity, evaluate requirements for permanent liquid hydrogen infrastructure at airports.

Key Policy, Infrastructure, and Economic Considerations

Community engagement:

- Engage local communities through public forums to assess social acceptance.
- Clarifying the hydrogen technology to nearby communities through information sharing and acting upon the community's preference in the technology choice could help build trust.

Public-Private Collaboration:

- Partner with government agencies to secure incentives and de-risk hydrogen infrastructure investments.
- Facilitate stakeholder engagement, including hydrogen producers, logistics providers, and fleet operators.

Regulatory and Market Alignment:

- Participate in hydrogen policy dialogues to ensure compliance and funding access.
- Advocate for clear regulatory standards and safety codes to support deployment.

Economic Feasibility and Risk Management:

- Hydrogen costs remain elevated (~$12–$18 per DGE). Continued scale-up, infrastructure investment, and use of incentives are critical.

- Prioritize deployment of mature (TRL 7–9) technologies and monitor emerging solutions (TRL 5–6) for future consideration.

This report outlines phased pathways to integrate hydrogen into PANYNJ's broader energy transition strategy. A collaborative, data-driven approach will be essential for scaling hydrogen adoption while ensuring operational continuity, fuel diversity, and long-term environmental benefit.

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Appendix A. Estimation of Power Requirements for Maritime End-Use Applications

This appendix details the calculation of the average mechanical power requirement for various diesel-powered use cases based on equipment characteristics, including rated engine power, and activity profiles, such as load factors. Representative equipment characteristics for ground support equipment (GSE) and oceangoing vessels (OGVs) are drawn from the operation of the Port Authority of New York and New Jersey fleet.

A.1 Cargo-Handling Equipment and Ground Support Equipment

The load factor, associated with the duty cycle, accounts for the effects of idling and partial load conditions. Note that load factors for some types of equipment were unavailable; thus, default load factors for general industrial equipment (43%) have been applied (see Table A-1).

Table A-1. Load Factor for Diesel-Powered CHE

Source: EPA 2022

CHE Type	Load Factor
Straddle carrier	43%
Terminal tractor	39%
Loaded container handler	43%
Empty container handler	43%
Reach stacker	43%
Rubber-tired gantry crane	43%
Forklift	59%

Table A-2 shows operational characteristics (load factor, operating hours, and horsepower) and representative models for three types of ground support equipment (GSE). Industry sources provided this data due to the limited availability of GSE-specific information at PANYNJ airports.

Table A-2. Operational Characteristics of GSE

Source: JBT AeroTech n.d.; CARB 2022b; TUG Tech n.d.; Toyota n.d.; TLD 2017.

Particulars	Aircraft Tractor	Cargo Tractor	Forklift	Ground Power Unit
Load factor	0.38	0.36	0.20	0.38
Operating hours	12	12	6	12
Horsepower	288	138	162	130
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

The average required mechanical power for diesel-powered cargo-handling equipment (CHE) and GSE by type is calculated using the following equation, adapted from EPA (2022):

$$P_r = \left(\frac{HP}{1.34}\right) \times LF \quad \text{(A.1)}$$

where P_r is the required mechanical power in kilowatts, HP is the average rated engine power in horsepower, LF is the engine load factor, and 1.34 is the conversion factor from horsepower to kilowatts.

Table A-3. Average Auxiliary Engine Load for Vessels

Source: Starcrest Consulting Group 2022

Vessel Category	Auxiliary Engine Load During Berth Dwelling (kW)
Auto carrier	1,143
Bulk carrier	523
Container—1000	767
Container—2000	679
Container—3000	1,026
Container—4000	944
Container—5000	998
Container—6000	980
Container—7000	844
Container—8000	1,221
Container—9000	1,037
Container—10000	1,165
Container—11000	880
Container—12000	1,050
Container—13000	976
Container—14000	1,148
Container—15000	850
Cruise ship	8,176
General cargo	715
RoRo[a]	490
Tanker	1,302

[a] RoRo: roll-on, roll-off

Appendix B. Estimation of Hydrogen and Diesel Demand

This appendix estimates the potential demand for hydrogen- and diesel-powered applications using the average power requirements outlined in Appendix A. The equations apply the energy balance principle to translate the power requirements into fuel demand, factoring in the lower heating values and the average efficiency of the powertrain. An exception is made for the daily fuel demand of heavy-duty vehicles, which is determined through a modeled fuel economy derived from a literature review due to data limitations.

B.1 Cargo-Handling Equipment, Shore Power for Oceangoing Vessels, and Ground Support Equipment

Table B-1 presents efficiency and fuel economy values for hydrogen fuel cell systems and diesel engines. This information, combined with fuel properties, allows the conversion of mechanical power requirements to fuel demand for both technologies. Note that calculations compare hydrogen and diesel demand by considering peak efficiency for both powertrains, which can underestimate the required fuel quantities. Future studies should consider average efficiency over the duty cycle for more accurate results.

Table B-1. Efficiencies and Fuel Economy of Hydrogen Fuel Cells and Diesel Engines

Particulars	Value	Comments	Source
Fuel cell efficiency	60%	Electrical efficiency of PEMFC[a] at lower heating value	(Hydrogen and Fuel Cell Technologies Office 2015)
Lower heating value of H_2 (kWh/kg)	33.33	Energy content of the fuel	(Hydrogen and Fuel Cell Technologies Office n.d.)
Diesel brake engine thermal efficiency	42%	Brake efficiency of modern internal combustion engines used for heavy-duty transportation	(Edwards et al. 2011)
Low-sulfur-diesel lower heating value (Btu/gal)	128,488	Energy content of the fuel	(Alternative Fuels Data Center n.d.)
Average HD-FCEV[b] fuel economy (MPDGE[c])	10.8	Applicable to a short-haul (200-miles) Class 8 HD-FCEV	(Lee et al. 2018)
Average diesel truck fuel economy (MPDGE)	5.1	Based on the sample fleet (46 trucks) at PANYNJ	(Kotz et al. 2022)

[a] PEMFC: proton exchange membrane fuel cell
[b] HD-FCEV: heavy-duty fuel cell electric vehicle
[c] MPDGE: miles per diesel gallon equivalent

Hourly hydrogen demand for cargo-handling equipment (CHE), shore power for oceangoing vessels (OGVs), and ground support equipment (GSE) is calculated using the following equation:

$$H_{2_H} = \frac{P_r}{\eta_{FC} \times H_{2_{LHV}}} \quad \text{(B.1)}$$

where H_{2_H} is the hourly hydrogen demand in kilograms, P_r is the required mechanical power in kilowatts, η_{FC} is the fuel cell efficiency, and $H_{2_{LHV}}$ is the lower heating value of hydrogen in kilowatt-hours per kilogram.

Hourly diesel demand for CHE, shore power for OGVs, and GSE is calculated using the following equation:

$$D_H = \frac{P_r \times 3.6 \times 10^6}{\eta_{bth} \times 1055.058 \times D_{LHV}} \quad \text{(B.2)}$$

where D_H is the hourly diesel demand in gallons, P_r is the required mechanical power in kilowatts, η_{bth} is the diesel brake engine thermal efficiency, and D_{LHV} is the low-sulfur diesel lower heating value in British thermal units per gallon.

Table B-2 illustrates the projected hourly hydrogen and diesel demand for providing shore power to OGVs by type based on the average load. We provide hourly fuel consumption for shore power because the operational characteristics of vessels, such as the number of visits per day and the dwell time at berth, vary and should be evaluated separately for each port.

Table B-2. Projected Hydrogen and Diesel Demand for OGVs

Vessel Category	Average H_2 Demand (kg/hour/unit)	Average Diesel Demand (gal/hour/unit)
Auto carrier	57.1	72.3
Bulk carrier	26.2	33.1
Container—1000	38.4	48.5
Container—2000	34.0	42.9
Container—3000	51.3	64.9
Container—4000	47.2	59.7
Container—5000	49.9	63.1
Container—6000	49.0	62.0
Container—7000	42.2	53.4
Container—8000	61.1	77.2
Container—9000	51.9	65.6
Container—10000	58.3	73.7
Container—11000	44.0	55.6
Container—12000	52.5	66.4
Container—13000	48.8	61.7
Container—14000	57.4	72.6
Container—15000	41.5	52.5
Cruise ship	408.8	517.0
General cargo	35.8	45.2

Vessel Category	Average H_2 Demand (kg/hour/unit)	Average Diesel Demand (gal/hour/unit)
RoRo[a]	24.5	31.0
Tanker	65.1	82.3

[a] RoRo: roll-on, roll-off

B.2 Heavy-Duty Vehicles

The daily hydrogen demand for heavy-duty trucks is calculated based on the modeled fuel economy and the assumed daily driving distance of 70 miles, as described by the following equation:

$$H_{2_D} = 1.13 \times (M/F) \quad \text{(B.3)}$$

where H_{2_D} is the daily hydrogen demand in kilograms, M is the daily mileage, F is the fuel economy in miles per diesel gallon equivalent, and 1.13 is the conversion factor from diesel gallon equivalent to kilograms of hydrogen.

Appendix C. Estimation of Hydrogen Demand for Co-Firing in a Gas Turbine

This appendix details the calculation of the average hourly demand based on the percentage of hydrogen co-firing. Table C-1 presents the lower heating values of hydrogen and natural gas used for calculating the heat input required when co-firing a percentage of hydrogen by volume in natural gas combustion turbine systems.

Table C-1. Lower Heating Values of Fuels

Source: H2Tools n.d.-a.; NREL 2008

Particulars	Value	Comments
Lower heating value of H_2 (BTU/scf)	290	Energy content of fuel per unit volume
Lower heating value of natural gas (BTU/scf)	983	Energy content of fuel per unit volume
Lower heating value of H_2 (BTU/lb)	52,217	Energy content of fuel per unit mass

Hourly hydrogen heat input in the turbine is calculated using the following equation:

$$HI_{H_2} = HI_{TT} \times \frac{H_{2_{LHV}} \times H_{2_{\%\,vol.}}}{H_{2_{LHV}} \times H_{2_{\%\,vol.}} + NG_{LHV} \times \left(100\% - H_{2_{\%\,vol.}}\right)} \quad \text{(C.1)}$$

where HI_{H_2} is the hydrogen heat input in metric million British thermal units, HI_{TT} is the total turbine heat input in metric million British thermal units, $H_{2_{LHV}}$ is the lower heating value of hydrogen in British thermal units per standard cubic foot, $H_{2_{\%\,vol.}}$ is the hydrogen content in the fuel blend in percentage by volume, and NG_{LHV} is the lower heating value of natural gas in British thermal units per standard cubic foot.

Hourly hydrogen demand for co-firing is calculated using the following equation:

$$H_{2_D} = \frac{HI_{H_2} \times 1{,}000{,}000}{H_{2_{LHV}}} \times 0.45 \quad \text{(C.2)}$$

where H_{2_D} is the hydrogen demand for co-firing in kilograms, HI_{H_2} is the hydrogen heat input in metric million British thermal units, $H_{2_{LHV}}$ is the lower heating value of hydrogen in British thermal units per pound, and 0.45 is the conversion factor from pounds to kilograms.

The annual hydrogen demand for co-firing is calculated using the following equation:

$$H_{2_{TD}} = \frac{\sum_{n=1}^{8760} H_{2_D}}{1{,}000} \quad \text{(C.3)}$$

where $H_{2_{TD}}$ is the total hydrogen demand for co-firing in tonnes, and H_{2_D} is the hydrogen demand for co-firing in kilograms per hour.

Appendix D. Estimation of Hydrogen Demand for Fuel Cells in a Microgrid

This appendix details the calculation of the average hourly demand based on the percentage of hydrogen in the natural gas stream. The calculations are based on the characteristics of the fuel cell system and the energy content of the fuels, as shown in Table D-1. Note that the electrical efficiency of the fuel cells varies from 45% with natural gas as the feedstock to 50% with pure hydrogen as the feedstock; thus, the calculations assume two scenarios: one with the lower bound efficiency with a hydrogen blend up to 30 vol % and one with the upper bound efficiency with a pure hydrogen input.

Table D-1. Lower Heating Values of Fuels and Fuel Cell System Inputs

Source: H2Tools n.d.-a.; AAAE and AlphaStruxure 2023; HyAxiom n.d.-b

Particulars	Value	Comments
Lower heating value of H_2 (BTU/scf)	290	
Lower heating value of natural gas (BTU/scf)	983	
Installed capacity (MW)	3.68	The electric output of the fuel cell system
Capacity factor (%)	95	
Electrical efficiency (%)	44–50	The total combined heat and power efficiency is 90%.

The hydrogen energy content in the fuel blend is calculated using the following equation:

$$H_{2_{\%\,energy}} = \frac{H_{2_{LHV}} \times H_{2_{\%\,vol.}}}{H_{2_{LHV}} \times H_{2_{\%\,vol.}} + NG_{LHV} \times \left(100\% - H_{2_{\%\,vol.}}\right)} \quad \text{(D.1)}$$

where $H_{2_{\%\,energy}}$ is the hydrogen fraction of the blend in percentage by energy content, $H_{2_{LHV}}$ is the lower heating value of hydrogen in British thermal units per standard cubic foot, $H_{2_{\%\,vol.}}$ is the hydrogen content in the fuel blend in percentage by volume, and NG_{LHV} is the lower heating value of natural gas in British thermal units per standard cubic foot.

The daily fuel input for the fuel cell is calculated using the following equation:

$$Fuel_{in} = \frac{P_{FC} \times 24 \times CF \times 3{,}600}{\eta_{electrical}} \quad \text{(D.2)}$$

where $Fuel_{in}$ is the fuel input requirement in megajoules, P_{FC} is the electric output of the fuel cell in megawatts, CF is the capacity factor of the fuel cell system in percentages, and $\eta_{electrical}$ is the electrical efficiency of the fuel cell on the lower heating value basis.

The daily hydrogen demand for the fuel cell is calculated using the following equation:

$$H_{2_D} = Fuel_{in} \times H_{2_{\%\,energy}} / H_{2_{LHV}} \quad \text{(D.3)}$$

where H_{2_D} is the hydrogen demand in kilograms, $Fuel_{in}$ is the fuel input requirement in megajoules, $H_{2_{\%\,energy}}$ is hydrogen's fraction of the blend in percentage of energy, and $H_{2_{LHV}}$ is the lower heating value of hydrogen in megajoules per kilogram.