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Hydrogen Transportation and Distributed Energy Systems Risk Assessment for Airport Facilities (CRADA 555) Final Report

Project 79122

September 2025

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Prepared for the U.S. Department of Energy
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Pacific Northwest National Laboratory
Richland, Washington 99354

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Joint Work Statement Funding Table showing DOE funding commitment:

		Funding Amounts		
CRADA Parties	**DOE Funding**	**Funds-In**	**In-Kind**	**Total**
PDX		$75,000	$150,000	$225,000
PNNL	$212,500	N/A	N/A	$212,500
Sandia	$212,500	N/A	N/A	$212,500
Total of all Contributions	$425,000	$75,000	$150,000	$650,000

Provide a list of publications, conference papers, or other public releases of results, developed under this CRADA:

No publications, conference papers, or other public releases of results were developed under this CRADA.

Provide a detailed list of all subject inventions, to include patent applications, copyrights, and trademarks:

No subject inventions were generated under this CRADA.

Executive Summary of CRADA Work

Portland International Airport (PDX), Oregon, operated by the Port of Portland (Port) is exploring the possibility of operating a fleet of 28 fuel cell electric buses and developing a distributed energy system to support airport operations during various operating modes including large-scale power outages. This study investigates the compatibility of these two missions, which will be key to resilience management at PDX. This study also investigated the risks associated with deploying a hydrogen system that could support bus operations and be utilized during an emergency to ensure continued operation of the airport. This will be a key innovation for the deployment of hydrogen systems at airports. Utilizing the unique benefits of hydrogen infrastructure for multiple roles will aid adopters in justifying new projects and serve to demonstrate the versatility of hydrogen as an energy-carrier to a wider market.

Partnership Acknowledgements

The Port, which owns and operates Portland International Airport (PDX), is honored to have the opportunity to partner with PNNL and Sandia on this innovative study. Building on previous work evaluating new technologies for the airport’s parking shuttle bus fleet, this CRADA provides valuable insight for operational resilience improvements, and may inform and expedite other airports’ evaluation of hydrogen as an emerging fuel.

Airports are complex and changing environments that pose unique operational and safety needs and constraints. PDX’s location next to the Columbia River and within the Cascadia Subduction Zone increases risk of a large earthquake and must be part of the operational resilience considerations. For this reason, including seismic resilience consideration as part of the risk assessment of a hydrogen infrastructure is especially valuable.

This study and its evaluation of emerging hydrogen fuel and technologies in an aviation environment is critical for improved resilience, delivering operational and safety requirements, and meeting evolving needs for airports.

Preface

This 1-year, Hydrogen Transportation and Distributed Energy Systems Risk Assessment for Airport Facilities project was funded under the direction of Laura Hill, Safety Codes and Standards subprogram of the Hydrogen and Fuel Cell Technologies Office (HFTO), under the Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) to enable affordable hydrogen production, storage, distribution, and utilization across multiple sectors in the economy as part of the HFTO H2@Scale initiative. The project is supported by expertise and use cases from Portland International Airport (PDX), Oregon and presents the risk assessment study by Pacific Northwest National Laboratory (PNNL) and Sandia National Laboratories (Sandia) to support the consideration of deploying fuel-cell electric buses (FCEBs) for transportation and as distributed energy systems. The project is comprised of four tasks: (1) transportation risk assessment for a bus fleet, (2) hydrogen equipment risk assessment, (3) hydrogen deployment seismic risk assessment, and (4) FCEB risk for providing emergency generation capacity.

Summary of Research Results

This report evaluates the adoption of hydrogen fuel cell electric buses (FCEBs) within airport settings, focusing on Portland International Airport as its case study. FCEBs offer distinct advantages in operational efficiency and resilience, complementing existing diesel and compressed natural gas (CNG) technologies. Hydrogen FCEBs are capable of operating with extended ranges, quick refueling times, and reliable performance under demanding transit schedules. They ensure streamlined airport operations and the capability for emergency response. Their ability to couple transportation with portable energy generation makes them uniquely suited for critical airport applications.

Risk assessments associated with fuel cell vehicles were performed in four possible configurations (1) leaks on the FCEB (2) leaks from the supporting equipment under operational conditions (3) leaks from the supporting equipment under seismic conditions, and (4) mobilization of FCEBs into emergency service. These assessments provide insights into hazards such as leaks and system failures to inform facility design and operational safety protocols.

- Configuration (1) FCEB Risk: In this case the risk of fatality from overpressure is non-detectable (Figure ES-1). However, the total risk of fatality due to thermal consequence, was observable. The mean annual thermal risk of fatality at the location of the leak origin is 1 in 763 for an individual and reduced to 1 in 8,600, at a distance of 2 m away from the leak source per unit length of piping. The societal risk was anticipated to be limited to the count of passengers and crew onboard, assuming that the bus was situated away from other flammable material outside the bus. The societal risk assessment for FCEBs evaluates potential public risk by scaling individual risk estimates to account for population exposure. The risk associated with FCEB transportation under certain assumptions, calculated at 4×10^{-3} fatalities per mile-year per 100 million passengers, is comparable to transit-related fatalities in 2023, which were 7×10^{-3} fatalities per mile-year per 100 million passengers. While this comparison highlights risk associated with FCEB transportation, it is important to note that these figures represent a larger population, and millions of miles traveled rather than airport specific public transportation risks. It does highlight that FCEB transportation aligns with modern safety standards when proper controls are in place. The risk analysis drew from theoretical data based on generic fuel cell vehicles and provided valuable insights into fatality risk. The analysis identified which components should be improved; however, since it is not based on actual buses, variability in the real-world results is anticipated.

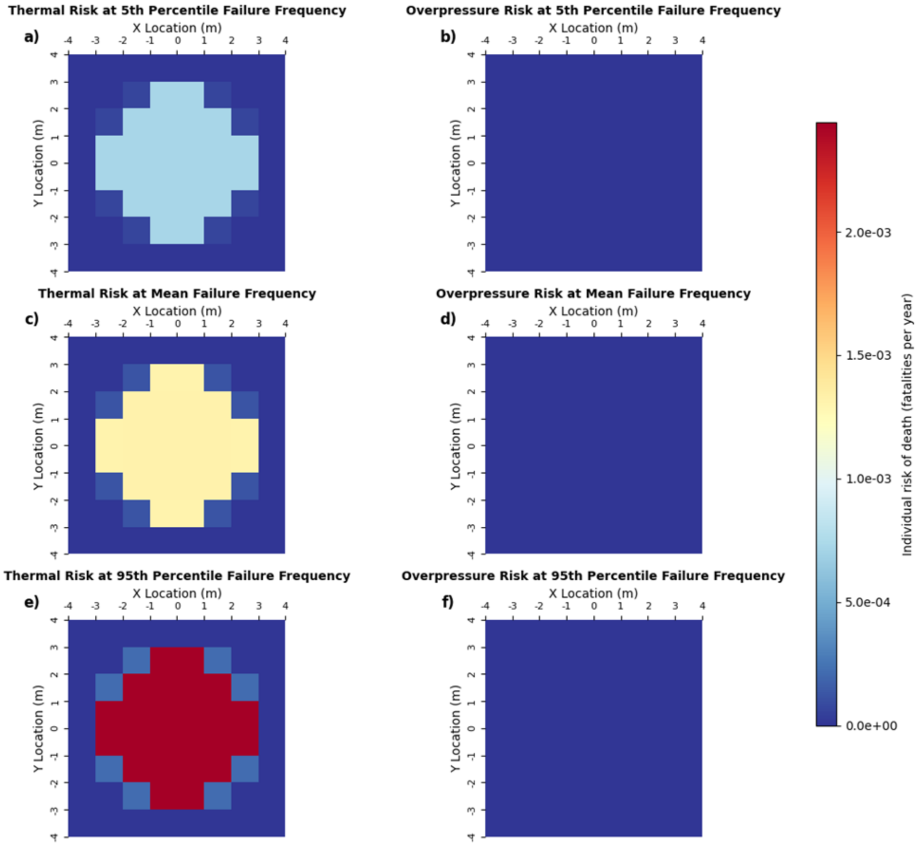

Figure ES-1 Configuration (1) fuel cell electric bus (FCEB) risk. Thermal and overpressure individual risk and uncertainty as a function of distance (X and Y) from the leak location on the bus.

- Configurations (2) and (3) Equipment Risk Under Operational and Seismic Conditions: The analysis by Sandia shows that soil conditions may cause seismic risk to increase, though this risk remains low overall compared to normal non-seismic-specific operational risk (Louie et al. 2025; Veeramany et al. 2025). Fatality risk decreases significantly with distance from the leak point across all scenarios, with a dramatic decrease occurring further than 25 meters (m) from the leak. Under normal, non-seismic-specific conditions, the median risk is around 10^{-8} to 10^{-7} fatalities/year near the source and decreases with distance. Under only seismic conditions, the risk is at least one order of magnitude lower, with approximately 10^{-10} to 10^{-9} fatalities/year for high shear wave velocity soil conditions (stiffer soils). This risk analysis suggests that while seismic risk should not be ignored, it is not as significant as the risk under normal non-seismic conditions for full-bore leaks. This may be likely due to an ensemble of conditions: normal, non-seismic specific risk values inherently encompassing some seismic risk components, in addition to other leak-inducing factors that may include component wear or corrosion, other natural disasters, and damage from misuse of the system. Some epistemic uncertainties such as self-exciting shocks, aftershocks, and the time variant nature of the ground motion were not considered.
- Configuration (4) Mobilization During Emergencies: FCEBs can act as portable generators, which is critical during seismic events that may compromise stationary power infrastructure

(Figure ES-2). While there would be logistical hurdles to clear such as original equipment manufacturer support for tapping power from the FCEB fuel cell stack, a series of backup power needs could be assisted from landing lights to the airport's terminal and rental car center. A potential workflow is presented in this report or the restoration of electric service to critical loads following a seismic event.

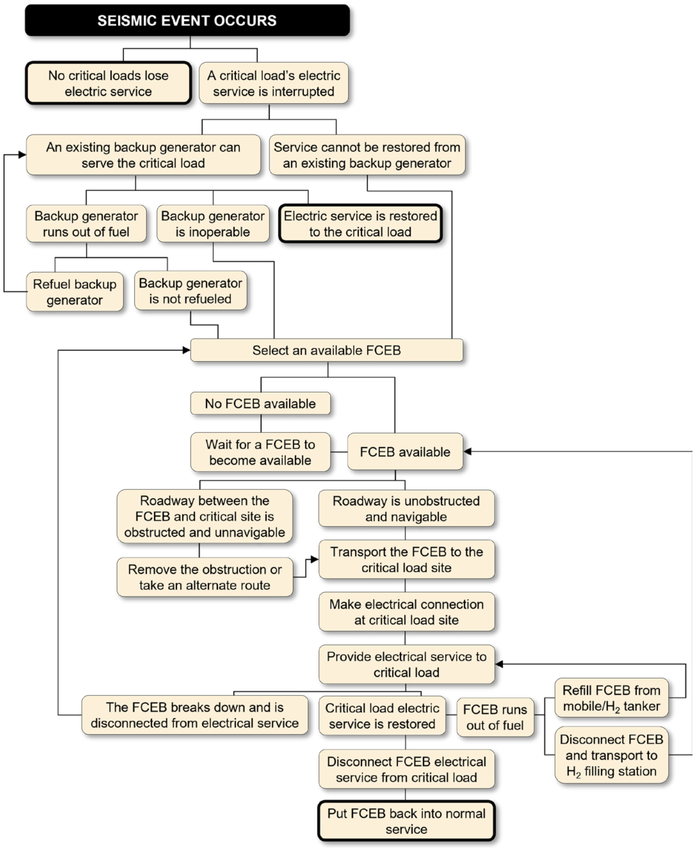

Figure ES-2 Configuration (4) Mobilization During Emergencies: A potential workflow for the restoration of electric service to critical loads following a seismic event.

The integration of hydrogen FCEBs into airport fleets delivers operational flexibility, enhances resilience, and supports safe deployment even under seismic stress conditions. Quantitative risk insights provided herein validate the feasibility of hydrogen systems while informing proactive safety measures. This report recommends hydrogen FCEBs as a complementary addition to diesel and CNG buses, catering to the dynamic and critical demands of airport environments.

Recommendations for PDX include an evaluation of various alternatives to reduce the risk from power outages and supply chain disruptions in procuring hydrogen. PDX should ensure facilities are built to code and that all first responder requirements are met. A risk management plan should be in place to counter the risk of leaks with appropriate prevention and mitigation plans from internal, external, safety critical, indirect, and degradation events. Appropriate pipe material selection, placement, thickness, anchoring, and orientation may lower the risk of leaks during seismic events. Also, seismic-resistant design of piping networks and trenching may reduce the likelihood of failure. In all, the FCEB is an emerging technology in the United States. While some FCEB manufacturers have demonstrated stand-alone emergency power solutions, integrated vehicle-to-grid (V2G) capability remains unavailable across current bus offerings.

Acronyms and Abbreviations

ALARP	as low as reasonably practicable
CAIDI	Customer Average Interruption Duration Index
CCS	combined charging system
CNG	compressed natural gas
DOE	Department of Energy
EDS	emergency detection system
EERE	Energy Efficiency and Renewable Energy
EPS	emergency power supply
EPSS	emergency power supply system
EV	electric vehicle
EVSE	electric vehicle supply equipment
FCEB	fuel cell electric bus
FMEA	failure modes and effects analysis
HFTO	Hydrogen and Fuel Cell Technologies Office
HFCBC	Hydrogen Fuel Cell Bus Council
HyRAM+	Hydrogen Risk Assessment Models Plus
ISO	International Organization for Standardization
JPEC	Japan Petroleum Exploration Company
KHK	The High-Pressure Gas Safety Institute of Japan
MLD	master logic diagram
NFPA	National Fire Protection Association
PDX	Portland International Airport
PEM	proton exchange membrane
PKI	public key infrastructure
PNNL	Pacific Northwest National Laboratory
POC	point of contact
PRA	probabilistic risk assessment
QRA	quantitative risk assessment
Sandia	Sandia National Laboratories
SCC	stress corrosion cracking
TPRD	thermal pressure relief device
V2G	vehicle-to-grid

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1.0 Transportation Risk Assessment for the Bus Fleet

We conducted a high-level risk assessment for a potential fuel cell electric bus (FCEB) fleet at Portland International Airport (PDX), Oregon. Working with PDX, we examined important operational parameters outlined in their internal bus study. Necessary support equipment was identified including generation, storage, and refueling. As a part of this effort, Pacific Northwest National Laboratory (PNNL) and Sandia National Laboratories (Sandia) investigated the wide range of FCEB options available to PDX including bus resilience during normal and seismic conditions. This work provides much needed information concerning risk assessment of hydrogen transportation deployment at airport locations. A safety risk assessment incorporates high-level hazard assessments of FCEBs at airport facilities and includes assessing the potential risk of a hydrogen leak from a bus.

1.1 PDX Internal Report Review

This section is a summary of the PDX FCEB internal feasibility study[1] for expanding its bus fleet to increase its resilience goals and needs. PDX currently has (a) 8 diesel buses transporting international passengers from one area to another on the airfield, and (b) 24 compressed natural gas (CNG) buses which shuttle passengers from the parking lot to the terminal. This study considered the potential replacement of the 35 foot (ft) CNG shuttle buses due to further non-availability of these buses from the manufacturer coupled with challenges pertaining to CNG fueling stations. The parking lot shuttle buses operate daily services for 16-hour long days with 159.2 to 180.8 daily miles (mi) of service and off-service distance of 8 mi. The peak times are typically during 4 a.m., Sunday evenings, and noon–2 p.m. every day with a gross layover time of about 140 minutes (min). A 25,000-gallon (gal) liquid hydrogen tank was recommended to support 2 fueling lanes with estimated fueling time of 10–15 min per bus. The estimated amount of boil-off equated to roughly 1% of the total storage tank per day, while some agencies are known to currently be experiencing higher boil-off rates. The study anticipates better market resolution over time. An FCEB-only option was recommended to avoid the need to install two different types of fueling infrastructure (i.e., electric vehicle [EV] charger and hydrogen refueling station) and to offer the benefit of scalability. The need for smaller batteries in FCEB was stated as a benefit because they are continuously charged by power generated by a hydrogen fuel cell. FCEBs were suggested for having sufficient range to service all of PDX's shuttle service in place of the current technology. The FCEB refueling would be adequate at the end of daily service, thus eliminating mid-service fueling. A primary concern with FCEB was the non-availability of 35 ft buses as a replacement for the existing CNG fleet. This would require reconfiguration of parking lots to accommodate a 40 ft FCEB currently available in the market. Additionally, maintenance bays at each depot will require hydrogen detection and exhaust equipment to ensure safety. Also, the latest FCEB models with federal funding do not include vehicle to grid (V2G) capability. The core emergency issues identified associated with FCEB were power outage, hydrogen shortage, and fueling equipment failure due to operational failures, and natural and human-made disasters. PDX was recommended to evaluate various alternatives to reduce the risk from power outages and fuel disruptions. Another recommendation was to ensure that PDX meets all first responder requirements.

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[1] Center for Transportation and the Environment's presentation to PDX on Zero-Emission Bus Fleet Transition Study in October 2024.

1.2 Feedback from Stakeholders

A presentation was delivered to the Hydrogen Fuel Cell Bus Council (HFCBC) on October 17, 2024, with the intent of sharing the work in progress and to solicit feedback from the council members. This paragraph is an excerpt of their opinions based on industry experience. The members have not heard of any facility not being adequately sized for new FCEB bus lengths, but mostly regarding retrofits involving mechanical ventilation, architectural, and electrical upgrades due to the code categorization of maintenance bays. The agencies adopting FCEB typically phase in upgrades (for example start with two hydrogen bays vs. upgrading all bus bays)—this approach works well because fleets typically grow gradually as well. In case of major repairs, FCEBs must be defueled and have certain benchmarks met in terms of ventilation as per the safety. Some transit agencies are of the opinion that the 40-ft bus length would be problematic as their maintenance garage is configured for 35 ft buses and does not have capacity for 40 ft buses. The council members also expressed that they have not seen an evolution in the market wherein buses are being used for backup power, as buses are needed to move people and are not a power source in emergencies. FCEB batteries are not designed to be used as emergency generators. The higher voltage throughput would void the FCEB warranty and replacing them is very expensive. The estimate of hydrogen quantity in gaseous form needed for emergency backup seems like a lot for a site given the footprint needs. Liquid storage would be preferable.

1.3 Fleet Capacity Assessment

FCEBs are suited for airport shuttle services. The travel range is more than 300 mi on a single refueling which ensures long operational hours without frequent stops. Refueling takes about 6–20 minutes depending on the model and operating conditions. Additionally, some of these buses feature a high energy recovery system, capturing up to 90% of the energy with their lightweight electric traction propulsion. These operate across a wide temperature range from −30°C to +50°C and incorporate a waterproof battery enclosure to ensure protection against water intrusion and damage. Hydrogen fuel cell modules on these FCEBs are typically engineered to provide 100 kilowatts (kW) of power making them ideal for medium- to heavy-duty vehicles, such as airport shuttles.

As of this writing, the FCEB options available in the market are limited to less than half a dozen manufacturers. The hydrogen storage cylinder capacity of each FCEB chosen by PDX's internal feasibility study is 37.5 kilograms (kg) operating at 350 bars. This is spread across 5 storage tanks (weighing 7.5 kg each). The cylinders are of Type 4[1] with an inner liner made of non-metallic material and an outer shell made of composite material to withstand high pressures while being lightweight. The standards for these cylinders are addressed by (a) *CSA/ANSI HGV 2-2023: Compressed Hydrogen Gas Vehicle Fuel Containers* relating to material and integrity of storage containers, (b) *SAE J2579: Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles* relating to design, construction, operational, and maintenance requirements, and (c) *SAE J2578: Recommended Practice for General Fuel Cell Vehicle Safety* for crashworthiness and integration of fuel cells with storage systems. The estimated quantity required for a fleet of 24

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[1] https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/04_warner_quantum.pdf.

buses (i.e., the current CNG fleet size at PDX) would be 900 kg (i.e., 27.5 kg hydrogen storage in each of the 24 buses). When taking into account a 1-week contingency, this estimate increases to 6300 kg. However, this stored hydrogen estimate does not consider the actual usage based on number of miles driven per day and any potential variations in that mileage.

1.4 Risk Assessment of FCEB

This section investigates primary factors leading to hydrogen leakage, system locations most vulnerable to hydrogen leakage, and historical incidents of hydrogen incidents that could help deduce methods of improving safety regarding hydrogen leakage.

1.4.1 Vulnerabilities, Incidents, and Mitigation Strategies

Leaks could happen around vulnerable locations due to a range of causes. According to a recent study's sensitivity analysis, factors leading to hydrogen leakage, listed from greatest influence to least influence, include the following: age of the sealing ring, hydrogen embrittlement, material corrosion, interface and connector issues, equipment negligence, over pressure, external shock, temperature variation, improper design, and production defects (Hu et al. 2024). The locations that are the most vulnerable for leakage, listed from greatest influence to least, include: ceiling sealing ring, upper cavity, corner and blind spots, around fixed structures, near obstacles, pipeline and channel, below the device, above windows and doors, within protective walls or fences, and within the ventilation system (Hu et al. 2024).

Reviewing historical hydrogen leakage incidents can provide insight on how safety regulations should be developed so future similar incidents can be avoided. The incidents discussed herein are not exclusively related to FCEBs, nevertheless are applicable in general. One recent hydrogen leakage incident occurred due to an operational error on May 23, 2019, at Daejeon-dong Science and Technology Park in Gangneung, Gangwon Province, South Korea (Guo et al. 2024). During the water electrolysis process, a simultaneous release of oxygen and hydrogen occurred, causing a pressure explosion within one of the three 400 m^3 hydrogen storage cylinders. No fire occurred due to rapid spread of the hydrogen to the ambient environment, but the explosion killed 2 people, injured 6 people, and caused significant infrastructure damage. Ultimately, the explosion stemmed from an improper hydrogen injection operational error, a failure of safety equipment, and poor welding on the cylinder. Another hydrogen incident occurred due to incorrect assembly of plugs in the high-pressure hydrogen storage device on June 10, 2019, at KJøRBO Uno-X hydrogenation station located in Sandvika, Norway (Guo et al. 2024). Two bolts were under-torqued leading to gradual leakage of hydrogen which caused hydrogen build up in the internal sealing area ultimately leading to a sealing failure that caused both fire and an explosion. This incident injured two people and caused significant material damaged (Guo et al. 2024).

Sealing rings, (i.e., O-rings) are responsible for sealing the hydrogen valve and are a known cause of leaks due to their potential for shrinkage, cracks, ruptures, and hardening under temperature and pressure fluctuations (Gao et al. 2024). These O-rings are a component of the high-pressure hydrogen valve onboard the vehicle's hydrogen storage system. A range of organizations and institutions have regulations, codes, and standards relevant to hydrogen storage in composite tanks on-board hydrogen fuel cell vehicles.

Common leakage reduction strategies differ for confined and open-air spaces. In confined spaces, the strategies used for leakage reduction, listed from most influence to least, include: enhanced ventilation, reasonably arranged hydrogen detectors, automatic shutdown systems, isolation and closure technologies, regular inspections and maintenance efforts, use of obstacles, backup energy switching, use of adsorption materials, emergency stop procedures, and design improvements (Hu et al. 2024). In open air spaces, the strategies used for leakage reduction, listed from greatest influence to least, include: reasonable arrangement of hydrogen detectors, automatic shutdown systems, installation of a remote control systems, reasonable arrangement of hydrogen storage locations, regular inspections and maintenance, setting up of a safe area, utilization of high-quality materials, reduction of device connection points, utilization of leak blocking technology, and prevention of static electricity accumulation (Hu et al. 2024). In both confined and open-air spaces, use of hydrogen detectors will be critical in hydrogen leakage mitigation and, ultimately, the safety of hydrogen fuel cells vehicle use.

1.4.2 Review of Codes and Standards

Of the seven codes and standards pertaining to hydrogen storage summarized in recent publications (Table 1), GB/T 42612 is one of the standards to provide recommendations for the rubber material to be used for O-rings (Li et al. 2024). The others assess O-ring sealing performance through testing of gas cylinders (Li et al. 2024). The O-ring performance tests outlined in Annex D of GB/T 42612 include: (1) a temperature retraction test, (2) a compression set test, (3) a hardness change test, and (4) a hydrogen damage test (Li et al. 2024). These tests first assess the mass and volume of the O-ring, then exposure of the O-ring to hydrogen followed by compression and temperature extremes (−50°C to 15°C) (Li et al. 2024). After subjecting the O-ring to the test conditions, it must not: (1) have abnormal breakage, (2) expand in volume by more than 25%, (3) shrink in volume by more than 1%, and (4) have an overall change in mass fraction by ±10% (Li et al. 2024).

1. *National Fire Protection Association a Hydrogen Technologies Code (NFPA 2)* (NFPA 2023)

This code applies to the production, storage, transfer, and use of hydrogen both in its compressed gas and cryogenic liquid form. It is intended for application in stationary, portable, and vehicular infrastructure systems. Section 7.1.15.1 of the code states that gaseous hydrogen valves must be accessible and designed to withstand anticipated pressure. Section 10.3.5 mentions that all hydrogen gas fittings must be designed in accordance with ASME B31, *Code for Pressure Piping* (ASME 2022a).

2. *ASME B31.12—Hydrogen Piping and Pipelines* (ASME 2023)

This second reviewed standard does not entirely address which materials are resistant to deterioration and, when selecting O-rings, their compatibility with hydrogen should be considered. Additionally, Chapter GR-5.2 modifies the language provided by ASME B31.8S (ASME 2022b) on Integrity Management of Piping Systems to consider O-ring equipment failure as a failure mode factor.

3. *ASTM D2000 for Rubber Products in Automotive Applications* (ASTM 2024)

The third available standard was ASTM D2000 for Rubber Products in Automotive Applications (ASTM 2024), which is not specific to hydrogen applications and instead provides guidance on how rubber materials are classified based on type (i.e., heat resistance) and class (i.e., oil resistance).

4. *ASTM D1414 for Standard Test Methods for Rubber O-rings* (ASTM 2022)

The final available standard outlines the following procedures and tests: dimensional measurements, relative density, tension, compression, low temperature, immersion, heat aging, hardness, shrinkage, and corrosion (ASTM 2022).

5. *Additional Standards*

While only in draft form and unavailable for full review, the ISO 19880-7:2018 standard document specifies the requirements for using O-rings to seal high-pressure gaseous hydrogen containers and provides details on the required design, testing, housing, and material of rubber O-rings (ISO 2025b). The standard includes testing requirements to evaluate the impact of temperature and pressure conditions anticipated for high flow heavy duty applications on the rubber O-rings (H2Tools 2024).

Areas of future work in terms of O-ring standards in the hydrogen storage context include: (1) assessing the potential O-ring damage incurred by rapid hydrogen charging and discharging (Chen et al. 2023), and (2) development of an accelerated test method for understanding the service life of O-rings (Li et al. 2024). In general, pertinent data to better inform the developing regulations, codes, and standards, and studies is needed to understand the initial burst pressure, material hydrogen compatibility, and periodic inspection methods (Wang et al. 2019). Additionally, technologies capable of limiting leakage through the O-rings, such as a wedge-ring are being investigated (Zhou et al. 2017).

Table 1. Existing codes and standards associated with hydrogen storage composite tanks (Wang et al. 2019; Li et al. 2024).

Organization/Institution	Regulations, Codes, or Standards	Description	Year
United Nations	UN GTR13-Ph1 UN GTR13-Ph2	Hydrogen and fuel cell vehicles	2013 (Revised 2023) (UN 2023)
The European Union	EC Regulation 406	Type-approval of hydrogen-powered motor vehicles	2010 (EC No. 406/2010)
The American Society of Automotive Engineers	SAE J2579	Standard for fuel systems in fuel cells and other hydrogen vehicles	2008 (Revised 2013, 2018, and 2023) (SAE 2023)

Organization/Institution	Regulations, Codes, or Standards	Description	Year
The International Organization for Standardization	ISO 19881	Gaseous Hydrogen - Land vehicle fuel containers	2018 (Currently under revision) (ISO 2018a, 2025a)
The Canadian Standards Association & the American National Standards Institute	CSA/ANSI HGV 2	Compressed hydrogen gas vehicle fuel containers	2014 (Revised 2021)
State Administration for Market Regulation & Standardization Administration of China	GB/T 35544	Fully wrapped carbon fiber reinforced cylinders with an aluminum liner for the on-board storage of compressed hydrogen as a fuel for land vehicles	2017 (Currently under revision)(NSPRC 2017)
	GB/T 42612	Fully-wrapped carbon fiber reinforced cylinders with a plastic liner for the on-board storage of compressed hydrogen as a fuel for land vehicles	(NSPRC 2023)

1.4.3 Release Scenarios

This section discusses release scenarios categorized by the type of hazardous event—internal, external, safety critical, indirect, or degradation.

1. **Internal events**: These are failure events that are associated with random failures in the FCEB components due to operational use resulting in release of hydrogen. These are captured as initiating events in the master logic diagram (MLD) based on a prior study on generic fuel cell vehicles by Stephens et al. (2009). Broadly, the leaks could happen from the fuel storage system, fuel delivery system, or the fuel cell stack. Rupture causes in system components are summarized in Table 2. For example, valves could spuriously open with no particular failure cause and are difficult to predict or control (Burgess et al. 2016). The failure rate estimates are either available from manufacturers' reliability specifications based on their accelerated life testing or from operational history. The components from the MLD subject to such failure include pumps, valves, regulators, and other instrumentation equipment, accident progression, and end states such as fire and explosion.
2. **External events**: Hydrogen storage containers are susceptible to events such as external fires, penetration by objects, and crash-induced fires (Stephens et al. 2009). When Type IV tanks that are at one-third the nominal work pressure are exposed to fire, experimental evidence show that melting of composite overwrap causes microleaks without rupture (Kashkarov et al. 2021). The thermally activated pressure relief device (TPRD) on the storage container must be functional in such an event to prevent an explosion due to internal gaseous expansion and overpressure. The activation of TPRD is recommended to be accompanied by a remote defueling effort preceding an attempt by first responders to approach the damaged vehicle (Stephenson 2006). The storage cylinders and vehicle itself are recommended to be designed such that the hydrogen release rate and concentration in enclosed areas of the vehicle do not exceed preset thresholds in the event of a crash (Post et al. 2012). Valves, lines, ports, and regulators are also vulnerable to crash-induced ruptures (Stephens et al. 2009).

3. **Safety critical events**: FCEB are equipped with crash sensors so that hydrogen supply to the fuel cell stack can be cut off in the event of a crash. The loss of these sensors has the potential for hydrogen release during a crash as well as the potential for increased hydrogen concentration levels in excess of 4% average by volume in the enclosed spaces of the passenger vehicle. The North American Safety Codes and Standards adopt monitoring requirements set forth in the Global Technical Regulation on Hydrogen and Fuel Cell Vehicles (Buttner et al. 2017). TPRD get activated when a preset temperature is exceeded to allow for a controlled release. The important TPRD parameters to ensure safety are the diameter of the TPRD, direction of hydrogen release post-activation, safety distances, height from vehicle roof to the garage ceiling (if parked in enclosed area), and ventilation. These parameters were discussed for fuel cell cars when parked underground (Shentsov et al. 2023). The failure of the TPRD to activate in an overheating situation could lead to overpressure-induced explosion of the storage cylinders. Emergency shutdown systems ensure hydrogen supply to the fuel cell stack is immediately cut off during an undesirable event. Nevertheless, there is risk of residual hydrogen that could be released and ignited. An FCEB should have a mechanism to either purge the residual hydrogen or consume it through an auxiliary load or form a bypass current path (Coddet et al. 2007). Hydrogen release and fire detection sensors are safety critical devices and also serve in the mitigation of consequences through the activation of emergency shutdown and fire suppression systems (Ramaiyan et al. 2023).
4. **Indirect events**: There are possibilities where failure of a component itself does not lead to a hydrogen release, but the effect of such failure might lead to overheating of the fuel cell membranes, leading to fire. A valve getting stuck closed, failure of a filter, regulator, meter, pressure sensor, radiator, coolant pump, or blower might restrict the flow of hydrogen and/or overheat the membrane (Stephens et al. 2009).
5. **Degradation mechanisms**: Accumulation of contaminants in valves could either lead to the valve getting stuck open or stuck closed (Stephens et al. 2009). The former might not restrict the flow of hydrogen when the flow needs to be stopped either during a crash or maintenance. While pressure cycling and material microstructure effects influence piping embrittlement (Somerday and San Marchi 2014), the inclusion of nonmetallic content can induce stress corrosion cracking (SCC) (Li et al. 2021). Proton exchange membrane (PEM) electrolyzer membranes and electrodes can degrade over time, leading to stack failures (Wallnöfer-Ogris et al. 2024; Patil et al. 2023; Virkar and Zhou 2007). Repeated pressurization and thermal cycling when left unchecked could exacerbate existing fault conditions (De Miguel et al. 2015; San Marchi and Ronevich 2022). Regular calibration, inspection, repair, and replacement are emphasized to prevent degradation of sensors, seals, and gaskets. These degradation-induced failure mechanisms along with mitigation actions are presented in Table 3.

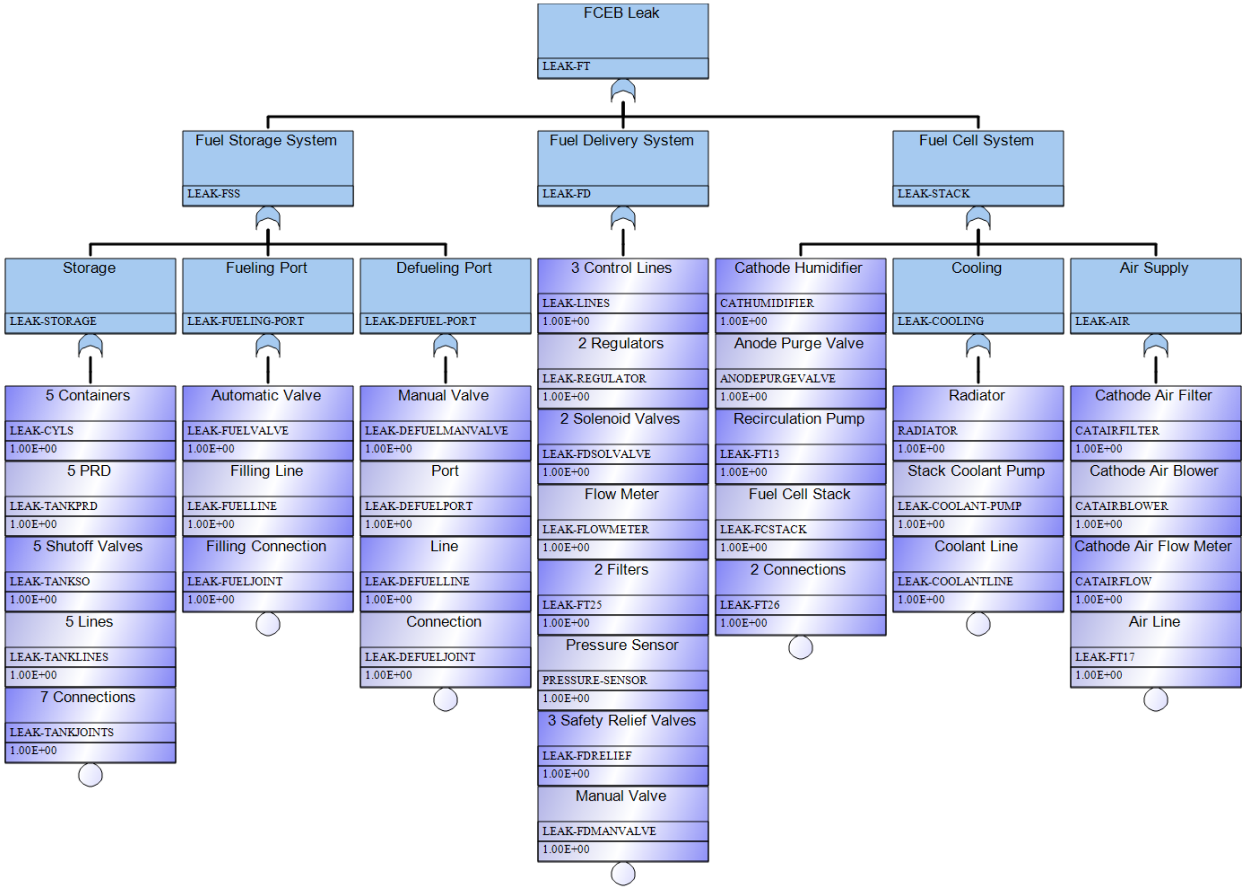

Figure 1. Possible sources of leak from a fuel cell electric bus (FCEB) due to random failures from operational use (fault tree constructed from failure modes and effects analysis (FMEA) study (Stephens et al. 2009)).

Table 2. Underlying causes of ruptures in fuel cell electric bus (FCEB) components leading to potential consequences of fire and explosion (which account for operational failures, natural hazard induced failures, and long-term degradation mechanisms like corrosion and embrittlement)

Component	Component Description	Rupture Cause
Container	Rooftop hydrogen container	Mechanically, chemically, or thermal induced damage
Valve	Release excess pressure automatically after reaching a setpoint	Pressure exceeds maximum allowable pressure
Proton Exchange Membrane (PEM) Fuel Cell Stack	Convert hydrogen to electricity	Overheating
Piping	Hydrogen fuel delivery	Impact damage
Regulator	Control the hydrogen flow pressure	Beyond design overpressure
Pump	Removes excess heat	Fails to circulate coolant
Meter	Measures hydrogen flow rate in the fuel cell system	Overpressure
Filter	Removes impurities from hydrogen before use in fuel cell	Clogging
Sensor	Monitors pressure in hydrogen storage or supply lines	Overheating
Humidifier	Regulates amount of water in the fuel cell	Clogged drain or overheating due to insufficient water
Fueling and De-fueling Ports	Interface to fill or empty the storage cylinders	Bent or damaged port could lead to potential leaks
Connections	Connection point between components and piping	Overpressure and degradation could lead to potential leaks

Table 3. Degradation mechanisms in an fuel cell electric bus (FCEB) components that could potentially lead to ruptures and leaks

Degradation Mechanism	Description	Impact	Mitigation	References
Embrittlement	Hydrogen diffuses into metals causing embrittlement.	Cracks initiate, propagate, and eventually lead to leaks and ruptures.	Ensure hydrogen used for fueling has high level of purity.	Murakami et al. (2008), LaFleur et al. (2023)
Corrosion	Nonmetallic content in stainless steel is susceptible to stress corrosion cracking due to hydrogen dissolved water.	Weakens the structural integrity of the component	Use of corrosion-resistant materials (e.g., graphene) could reduce damage induced by corrosion.	Li et al. (2021)
Pressure Cycling	Repeated pressurization and depressurization causes mechanical fatigue in the material leading to micro-cracks.	Accelerates crack propagation if a crack has already initiated.	Reduce the frequency and magnitude of pressure cycling through adaptive pressure control.	San Marchi and Ronevich (2022)
Proton Exchange Membrane (PEM) Electrolyzer Membrane Degradation	Radicals produced in acidic environment lead to chemical degradation.	Membrane damage could lead to fire.	Moderate the temperature and uniformly distribute the humidity inside the stack.	Wallnöfer-Ogris et al. (2024), Patil et al. (2023)
Contamination	Contaminants in hydrogen or air streams clog filters and valves, damage sensors, or poison fuel cell catalysts.	Clogging could lead to overheating of fuel cell stack and hence rupture of a membrane.	Regular filter maintenance, high-purity hydrogen, clean air supply.	Zhang et al. (2023)
Thermal Cycling and Stress	Fast filling to high pressure causes temperature increase of the polymer liner of the rooftop cylinder.	Exceeding maximum allowed thermal stress could lead to overpressure conditions.	Avoid extreme cycling and ensure hydrogen is precooled prior to dispensation.	De Miguel et al. (2015)
Sensor Drift	Sensors lose accuracy due to aging, contamination, or environmental exposure.	Potential for unsafe decision-making in response to sensor readings.	Opt for regular calibration and use high-quality sensors.	Buttner et al. (2011)
Seal & Gasket Degradation	Seals and gaskets degrade due to hydrogen exposure, high pressures, and temperature fluctuations.	Leaks, pressure loss, and system failure.	Schedule regular replacement and adopt health monitoring.	Lin et al. (2011)
Catalyst Poisoning	Platinum-based electrodes degrade over time.	Loss of fuel cell efficiency, lower power output, stack failure.	Establish policies around regular inspections and preventive maintenance.	Virkar and Zhou (2007)

1.4.4 Risk Analysis

A probabilistic risk assessment (PRA) was conducted to investigate sources of leaks from an FCEB (Figure 1). This analysis aimed to determine the frequency of failure for the top event (i.e., FCEB leak), as well as for the sub-events associated with the fuel storage, fuel delivery, and fuel cell systems. The failure frequencies were calculated using log-normal distributions available in HyRAM+ (Hydrogen Risk Assessment Models), which have been summarized in Appendix A (Table A.1, Table A.2 and Table A.3), and for each of the respective sub-systems. These were available for all components, or logical components to serve as replacements for those listed in Figure 1, except for the fuel cell stack, which was excluded from the assessment because no HyRAM+ data was available for that system. Future analyses should consider the component stack if HyRAM+ failure frequency data becomes available. Moreover, the fuel cell stack operates at about 300× lower pressure than rest of the systems. The failure frequency is higher, but consequences are anticipated to be low. Another limitation of this PRA is the use of a fault tree diagram based on data for hydrogen fuel cell vehicles, as opposed to components specifically onboard FCEB. Future analyses should consider developing fault trees tailored FCEB components and utilizing failure frequencies associated with more specific designs (i.e., actual pipe lengths anticipated on FCEB).

The analysis has been comprehensively visualized through histograms, emphasizing the distribution and significance of each sub-system's failure frequencies compared to the combined system's failure frequency, guiding better risk management strategies for future hydrogen fuel storage, delivery, and fuel cell systems (Figure 2, Figure 3, Figure 4, and Figure 5). The mean frequency of failures per unit pipe length for each system were found to be as follows:

- Fuel Storage System: 3.4×10^{-4} (i.e., once every 2,976 years)
- Fuel Delivery System: 4.6×10^{-4} (i.e., once every 2,188 years)
- Fuel Cell System: 5.2×10^{-4} (i.e., once every 1,908 years)
- Combined System (Top Event): 1.3×10^{-3} (i.e., once every 763 years)

The results indicate that the failure frequency associated with each of the three subsystems is similar. For the fuel storage system, the component with the highest frequency of random leakage is the filling line (i.e., HyRAM+ hose), which has a median failure frequency of 6.2×10^{-5}/m-yr. For the fuel delivery system, the components with the highest failure frequencies include flow meters, 2 filters, and pressure sensors, which have median failure frequencies of 4.8×10^{-5}, 3.7×10^{-5} and 4.8×10^{-5}, per year per unit length of pipe respectively. For the fuel cell system, the components with the highest failure frequencies include the cathode humidifier, recirculation pump, radiator, stack coolant pump, cathode air filter, cathode air blower, and cathode air flow meter (the results indicate that the failure frequency associated with each of the three subsystems is similar. For the fuel storage system, the component with the highest frequency of random leakage is the filling line (i.e., HyRAM+ hose), which has a median failure frequency of 6.2×10^{-5}/m-yr. For the fuel delivery system, the components with the highest failure frequencies include flow meters, filters, and pressure sensors, which have median failure frequencies of 4.8×10^{-5}/m-yr, 3.7×10^{-5}/m-yr, and 4.8×10^{-5}/m-yr respectively. For the fuel cell system, the components with the highest failure frequencies include the cathode humidifier, recirculation pump, radiator, stack coolant pump, cathode air filter, cathode air blower, and cathode air flow meter (see Table A.3 for median failure frequencies for these components). Collectively, the filling line component still has the largest failure frequency of any individual component. These findings are consistent with literature on hydrogen fuel cell vehicle safety and reliability. For example, FMEA and quantitative risk assessment studies highlight that high-pressure components in compressed-hydrogen fuel systems such as hoses and valves are critical points of failure, where a lack of redundancy can lead to hydrogen releases or venting, especially in the event of a single-point failure (Song et al. 2025).

To reduce the frequency of FCEB leaks, future research should prioritize improving the design, maintenance, and monitoring efforts that could reduce the failure frequency of these components with relatively higher failure frequencies. Literature suggests that redundant system design, enhanced component reliability, and real-time diagnostics, such as prognostic health monitoring, are effective for addressing these high-risk failure modes and improving overall system safety and availability (Song et al. 2025).

The analysis has been visualized through histograms, emphasizing the distribution and significance of each sub-system's failure frequencies compared to the combined system's failure frequency, guiding better risk management strategies for future FCEB hydrogen fuel storage, delivery, and fuel cell systems (Figure 2, Figure 3, Figure 4, and Figure 5).

Next, the thermal and overpressure consequence of a failure event was considered to determine the total risk of fatality based on location. a and b illustrate the thermal probability of fatality based on location and the overpressure probability of fatality based on location, respectively and the data was estimated using HyRAM+. The parameters assumed for the modeling are presented in Appendix A. An important note, the x = 0, y = 0 location corresponds to the source of leak and is likely to be located on the roof of the bus where most onboard hydrogen systems are located. However, leaks could happen elsewhere, which could have different implications. The probability of fatality due to overpressure associated with a failure event is not significantly detectable, the thermal consequences from a failure event could be fatal for the 3 m region (in all directions) surrounding the failure origin location, which could span up to 50% of the bus surface area contingent upon leak location.

The probability of fatality estimated using HyRAM+ was multiplied with the failure frequency (i.e., fatality per leak event times failure per year) to determine the individual risk of fatality per year based on location. Based on low consequence due to overpressure, the probability of fatality from overpressure is non-detectable. The total risk of fatality due to thermal consequence, however, is observable. Because the failure frequencies are quantified as a distribution, 3 levels of thermal risk were quantified, 5th percentile, mean, and 95th percentile. This approach provides insights into the range in risk of fatality that originates from the failure frequency distributions. Figure 7 indicates that the location of leak origin (i.e., x = 0, y = 0) experiences a total individual risk of fatality ranging from 7.2×10^{-4}/m-yr per year (5th percentile, corresponds to 1 in 1,393/m-yr) and 2.4×10^{-3}/m-yr (95th percentile, corresponds to chance of 1 in 418 in a year for a unit length of pipe). The mean annual thermal risk of fatality for an individual at the location of leak origin is 1.3×10^{-3} /m-yr (corresponds to 1 in 763 in a year per unit length of pipe). The societal risk is anticipated to be limited to the count of passengers and crew onboard assuming the bus is away from other flammable material outside the bus. While the consequence analysis drew from theoretical data it provides valuable insights on the probability of fatality and which components should be improved, it is not based on actual buses, so variability in real-world results is anticipated.

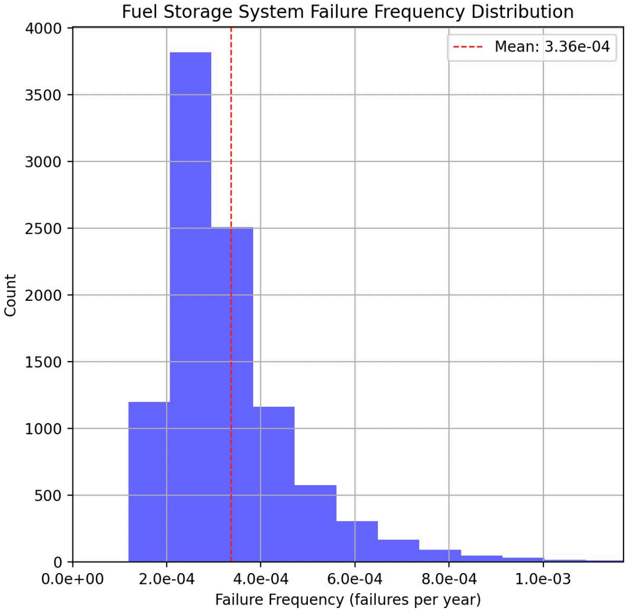

Figure 2. Fuel storage system failure frequency distribution, with calculated mean failure frequency of 3.4 × 10^{-4} failures per year per unit length of pipe.

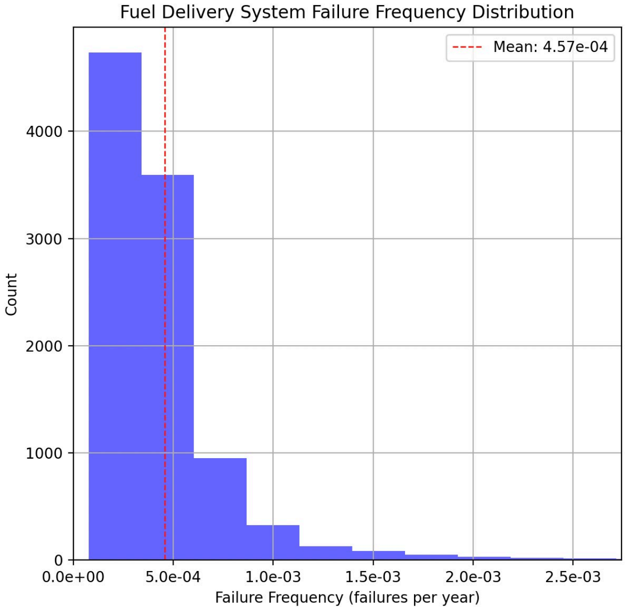

Figure 3. Fuel delivery system failure frequency distribution, with calculated mean failure frequency of 4.6 × 10^{-4} /m-yr.

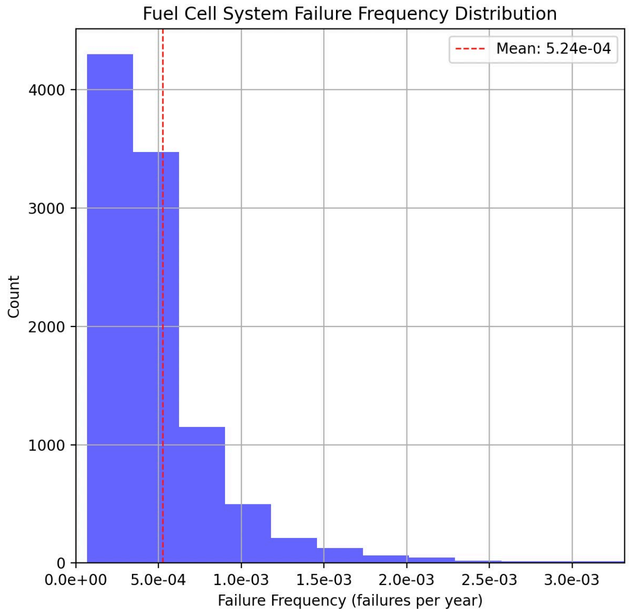

Figure 4. Fuel cell system failure frequency distribution, with calculated mean failure frequency of 5.2 × 10^{-4} /m-yr.

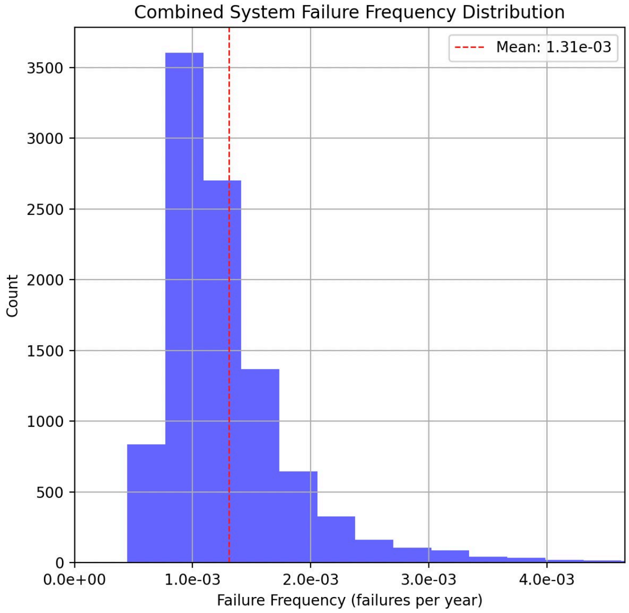

Figure 5. Combined system failure frequency distribution, with calculated mean failure frequency of 1.3 × 10^{-3} /m-yr.

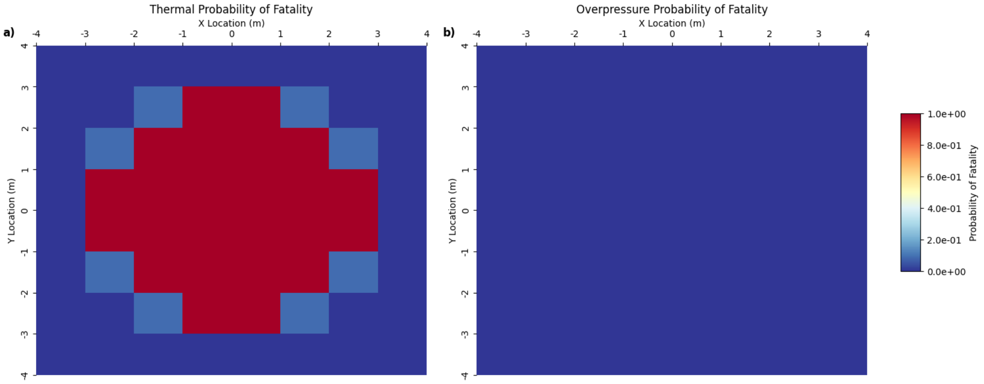

Figure 6. Thermal (panel a) and overpressure (panel b) probability of consequence (i.e., fatality) as a function of the X and Y location (m).

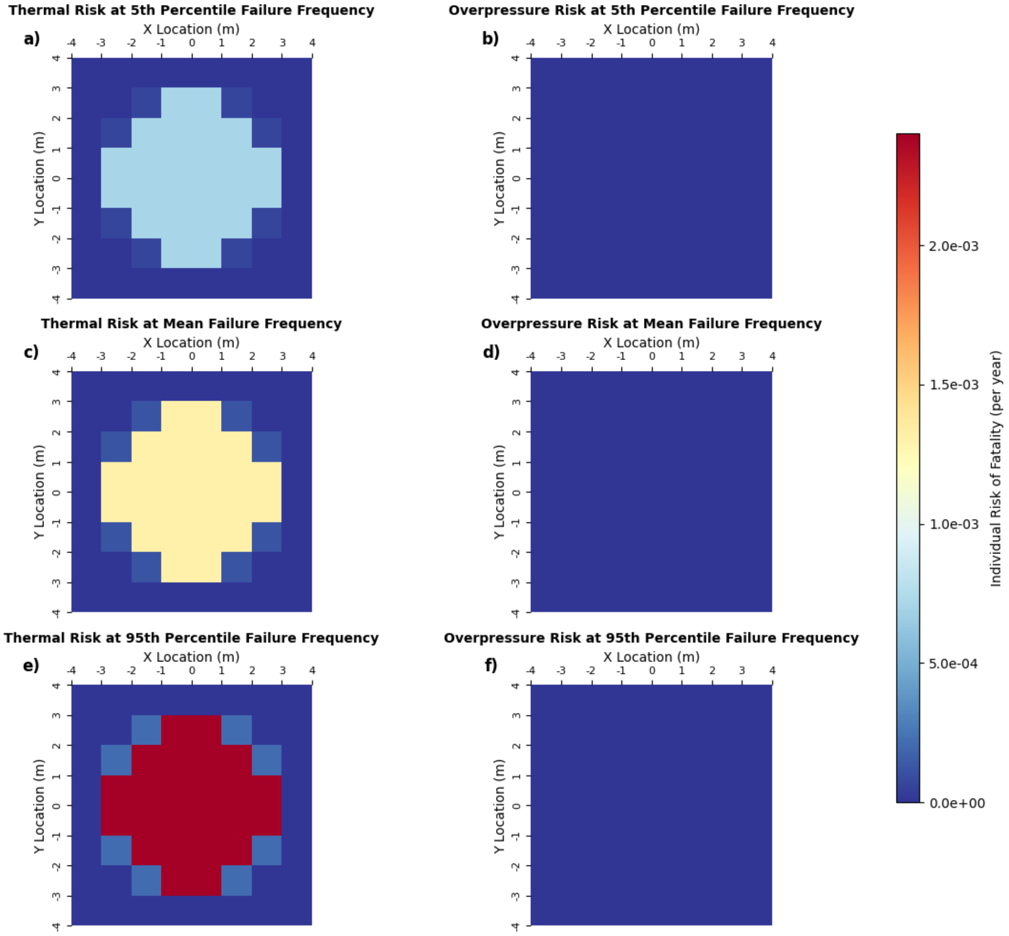

Figure 7. Thermal and overpressure individual risk as a function of the X and Y location. For 5th percentile failure frequency values, panel a) illustrates the thermal risks and panel b) illustrates the overpressure risks. For mean failure frequency values, panel c) illustrates the thermal risks and panel d) illustrates the overpressure risks. For 95th percentile failure frequency values, panel e) illustrates the thermal risks and panel f) illustrates the overpressure risks.

1.4.5 Risk Evaluation

The societal risk assessment for hydrogen FCEBs evaluates potential public risk by scaling individual risk estimates to account for population exposure. This assessment is crucial for understanding the safety implications of deploying hydrogen FCEBs in public transportation.

The methodology considers a real-world assessment in which the mean risk of fatality (Figure 7c) is assumed to apply to 15% of all 20 passengers in the bus and PDX bus ridership is considered to estimate risk per passenger. As a note, this simplified analysis aims to provide an estimate of risk, where the mean risk of fatality experienced at the center of the leak (i.e., largest risk location) was applied. The impact of mitigations such as TPRDs, safe egress, safety distances, and emergency shut-off were not factored in. The rooftop placement of hydrogen storage on FCEBs minimizes the safety risks associated with thermal radiation during a leak or a fire, as thermal radiation primarily propagates upward and outward, which SNL HyRAM+ does not consider significant in the downward direction.

The real-world assessment approximates that 209,000 passengers ride each bus annually over 51,538 mi (value derived from PDX FCEB Internal Feasibility Report, which provides in-service distance driven per each duty cycle). We assume that passengers are exposed to 15% of the pipe length on 1 bus and on average, each bus carries 20 people per trip.

The risk associated with FCEB transportation under these assumptions, calculated at 3.8×10^{-3} fatalities per mile-year per 100 million passengers, is comparable to transit-related fatalities in 2023, which were 7×10^{-3} fatalities per mile-year per 100 million passengers.[1] This estimated risk level is below accepted thresholds for public infrastructure, where risks below 1 in a million are considered “broadly acceptable” and those between 1–100 per million require mitigation under the As Low As Reasonably Practicable (ALARP) principle.

While this comparison highlights risk associated with FCEB transportation, it is important to note that these figures represent a larger population, and millions of miles traveled rather than airport specific public transportation risks. Nonetheless, the comparison underscores that FCEB transportation aligns with modern safety standards when proper controls are in place. This comprehensive assessment demonstrates that FCEBs present a low societal risk, making them a safe option for public transportation.

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[1] https://injuryfacts.nsc.org/home-and-community/safety-topics/deaths-by-transportation-mode/

1.5 Reference Station Design

PDX has multiple options to procure hydrogen for refueling its FCEBs: (1) liquefied hydrogen delivery from off-site suppliers, and (2) on-site gaseous or liquefied hydrogen production. The on-site production could either be self-managed or leased to a third-party. This section assumes PDX chooses to produce gaseous hydrogen onsite and to that effect a reference station design proposed by Wiryadinata and Hecht (2023) is presented in Figure 8. In this design, hydrogen production utilizes a PEM electrolyzer during off-peak hours to reduce electricity expenses. As well, PDX could choose to produce hydrogen 24 × 7 given the minimal difference in the electricity tariffs for PDX. The system is engineered to fulfill a daily hydrogen requirement of 4,200 kg, with the electrolyzer functioning during off-peak hours. However, PDX would need to fill their on-site storage vessels on the first day and then only refill as much as hydrogen consumed at the end of the day. Hydrogen is produced at the rate of 50 kg/h and handles peak electrical demand of 12.5 megawatt (MW). Hydrogen is stored in low-pressure vessels at 100 bars, enhancing bulk storage capabilities and facilitating effective operation during off-peak periods. A compression system increases the output pressure of the electrolyzer before dispensing, ensuring a reliable supply for fueling. The total daily energy consumption is around 228 megawatt-hours (MWh). The conceptual design occupies approximately 33,000 feet square (ft^2) (0.76 acres [ac]). This configuration maximizes space efficiency while incorporating all essential components for hydrogen production and dispensing.

A 4200 kg/day production rate would suffice the needs of a single day fleet usage as well as residual capacity of about a1 week's worth of contingency. As PDX considers further expansion of its fleet and looks for larger storage capacity, it would be prudent to consider on-site liquefaction to avail liquefied hydrogen's benefit of increased volumetric energy density. However, it comes with the caveat that energy would be required to maintain cryogenic operating conditions despite an outage during an emergency.

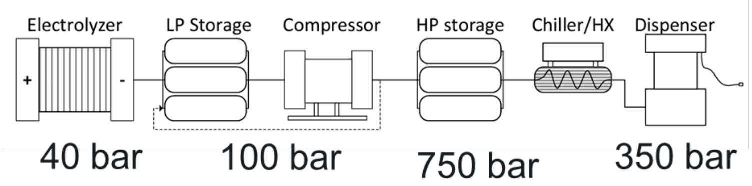

Figure 8. A reference hydrogen refueling station design that operates during off-peak hours. The pressures represent outputs along the process flow (Wiryadinata and Hecht 2023).

2.0 Hydrogen Equipment Risk Assessment

Fueling of buses and a distributed energy system require a substantial investment into hydrogen generation, storage, compression, and distribution equipment. A review of the loads, facilities, and operating modes at PDX has been presented in this section. A semi-QRA is performed on the hydrogen system to estimate the potential release impacts on surrounding facilities, people, and operational equipment. It is anticipated that using hydrogen for such a wide variety of applications may introduce risks that are not accounted for in existing risk assessments.

2.1 Review of Loads and Facilities

The recommendation from PDX in lieu of non-availability of average and peak power demand needs at facilities was to use each generator's rated output since the generator would be sized to exceed peak electricity demand by some factor (e.g., 2×). For average demand, PDX would need historical data from a power monitoring system to know the average usage on the circuits tied to the generators, but their monitoring system is undergoing upgrades. In the meanwhile, Table 4 presents some of the significant loads at PDX and corresponding diesel consumption on an hourly basis when put into service. A 1 week contingency estimate is shown in the last column which when converted to hydrogen using diesel gallon equivalent[1] gives an upper bound estimate of the quantity of hydrogen needed in reserves. The estimated quantity is large enough to warrant hydrogen storage in liquefied form in potentially a spherical aboveground tank to serve emergency purposes. The estimate assumes that a generator would be needed continuously for the 1 week of outage which may have to be corrected based on actual estimates. Additionally, the large volume estimates of hydrogen do not reflect the practical availability in the market. The estimates do not account for differences in the efficiency of respective generator technologies.

Table 4. Diesel required currently by emergency generators at Portland International Airport, Oregon.

Priority	Loads	Diesel Generator Nominal Power Output (kW)	Fuel Cell Electric Bus (FCEB) Count @ 95 kW output per FCEB†	Diesel Fuel Consumption (gal/hr)	1-wk Diesel Contingency (gal)
*	Airfield landing lights	494	6	37	6216
*	Central utility plant 1	986	11	70.1	11,777
*	Central utility plant 2	986	11	70.1	11,777
*	Central utility plant 3	1480	16	103.2	17338
-	De-icing treatment plant	592	7	40.8	6854
*	Rental car center/Emergency Operations Center	592	7	42	7056

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[1] 1 gal diesel ~ 1.12 kg hydrogen.

Priority	Loads	Diesel Generator Nominal Power Output (kW)	Fuel Cell Electric Bus (FCEB) Count @ 95 kW output per FCEB†	Diesel Fuel Consumption (gal/hr)	1-wk Diesel Contingency (gal)
*	Terminal	1480	16	103.2	17,338
*	Maintenance facility	345	4	24.4	4099
*	Fire department	345	4	24.4	4099
-	Parking lot office	123	2	9.5	1596
-	Parking lot	79	1	6.6	1109
-	Parking lot	79	1	6.6	1109
-	Toll plaza	98.5	2	8.2	1378
*	IT Communications	98.5	2	8.2	1378
-	Diesel (gal)	-	-	-	93,124
-	Diesel at 80% capacity (gal)	-	-	-	74,499
-	Gaseous H_2 (kg) [upper bound]	-	-	-	83,439
-	Liquefied H_2 (gal) [upper bound]	-	-	-	311,473

Diesel emergency generator nominal power output was assumed to be a proxy for the electrical demand attached to each facility. The estimated amount of total hydrogen from Table 4 required for contingency was converted to equivalent electricity that could be generated by fuel cells. This resulted in PDX having 1.7 gigawatt hours (GWh)[1] of electricity at disposal if it could store or produce 83,439 kg of hydrogen for an emergency. Logistically, the markets may not be ready as of date to supply this quantity of hydrogen either through off-site procurement or on-site production. The recommended aboveground storage tank would need to be spherical in shape like the ones hosted by the National Aeronautics and Space Administration (NASA)[2] but less than half the capacity at about 1,178 cubic meters (m^3)[3] of liquefied hydrogen. An alternative is geological storage of gaseous hydrogen in underground gas storage facilities if PDX has access to such resources (Lackey et al. 2023).

On the other hand, PDX could have access to 383 MWh[4] of energy based on 24 FCEB with 95 kW AC power output each and 1 week of stored power supply or daily energy production of 6300 kg hydrogen. This would be contingent on the availability of hardware to convert DC power produced by FCEB fuel cell into AC power and having access to the bus bar on the FCEB to directly tap into the generated power. Further information would be needed to decide which

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[1] Energy from stored bulk hydrogen (GWh) = Hydrogen mass (kg) * Energy content (kWh/kg) * Fuel Cell Efficiency) / 10^6 = (83,439 * 33.6 * 0.60) / 10^6 ≈ 1.7 GWh.

[2] https://www.energy.gov/sites/default/files/2021-10/new-lh2-sphere.pdf.

[3] Volume of liquefied hydrogen = mass/density = 83,439 kg/70.85 kg/m^3 ≈ 1,178 cubic meters.

[4] Energy from FCEB (MWh) = 24 FCEB * 95 kW AC power output per FCEB * 168 hr/week ≈ 383 MWh.

loads and for how long they could be served. A more detailed analysis of FCEB logistics during emergencies is discussed in Section 4.0.

2.2 Supporting Equipment Risk Assessment

Louie et al. (2025) performed a QRA for a hypothetical FCEB hydrogen storage and refueling facility, focusing on the potential frequency of leaks and the risks posed by the infrastructure. The analysis assumed a purchase of 24 New Flyer Xcelsior Charge FC 40’ FCEBs for use as passenger transport and potential emergency power generation. Wiryadinata and Hecht (2023) described a gaseous hydrogen station with a capacity of 4186 kg/day, with a 20,000 ft^2 footprint, and capable of dispensing 750 bar −40°C gaseous hydrogen; that station is used in this analysis. A separate QRA was run for both the station and the dispenser.

The QRA by Louie et al. (2025) found that, in the production, compression, and storage area, the compressor has the highest leak frequency, the filter and valves have a moderate leak frequency, and the remaining components have relatively low leak frequencies. A commonly accepted measure of risk at gasoline refueling stations is 2×10^{-5} fatalities per year; the risk fell below this metric at around 3 m from the leak. The risk could be further mitigated by enclosing the production, compression, and storage area with a blast or fire wall. Risk could also be mitigated by targeting the components with the highest leak frequencies (i.e., compressor, filter, and valves) for reduction.

In the dispenser area, the heat exchanger that delivers −40°C hydrogen to the dispenser has the highest component leak frequency, followed by the valves and the other components. Annual fatality risk is greater with the refueling system compared to the production, storage, and compression system, due to the high leak frequency of the heat exchanger/chiller (Louie et al. 2025). Fatality risk dropped below 2×10^{-5} fatalities per year around 26 m from the leak. It may be helpful to prioritize the dispenser and its associated components for risk mitigation efforts, such as developing a strategy for inspection, maintenance, and replacement. See Louie et al. (2025) for more information about this QRA.

2.3 Review of Operating Modes

Hydrogen fueling stations operate under a range of modes. Given the safety concerns associated with hydrogen usage as a fuel, particularly with respect to its propensity for leakage, a deeper analysis of the risks associated with the fueling station operating modes was conducted. Specifically, station standard operation encompasses a production mode, compression and storage mode, dispensing mode and stand-by mode.

2.3.1 Production Mode

2.3.1.1 On-Site Production

A system is in production mode when hydrogen is created using an energy supply. Literature has considered the risks associated with two on-site hydrogen production strategies: (1) production via a natural gas reformer, and (2) production via a water electrolyzer (Genovese et al. 2020). On-site production facilities can be designed with advanced safety features, such as reinforced structures and flexible piping systems, to handle seismic events. This is particularly important for airports in seismic-prone regions like Portland, where earthquakes are a concern. Recent studies (Zhang et al. 2023) emphasize the importance of resilience planning, including running simulations for disaster scenarios to identify weak points and implement solutions like backup systems and flexible pipelines.

On-site production also reduces transportation risks, as hydrogen does not need to be moved over long distances, which lowers the likelihood of accidents during transit. For instance, steam methane reforming was successfully demonstrated as a first-of-its-kind technology for carbon-negative hydrogen production using renewable natural gas at SunLine Transit Agency. Achieving near-commercial readiness (TRL 7), the PNNL-licensed commercial project established pathways for cost-competitive hydrogen distribution, leveraging existing infrastructure and tax credits to reduce pump prices significantly[1]. Additionally, on-site facilities can be designed with seismic resilience in mind, incorporating reinforced structures and specialized bracing systems to maintain functionality during earthquakes. An analysis of this possibility is discussed in Section 3.0.

2.3.1.2 Off-site Production and Delivery

Another option is for a refueling station to have hydrogen delivered, which would eliminate the need for on-site production but require off-site production and delivery. In Honselaar et al. (2018), the risks associated with two off-site hydrogen production and delivery strategies, delivery via pipeline and delivery via trailer, were considered. For pipeline delivery via either an aboveground pipe or an underground pipe Honselaar et al. (2018) evaluated two failure scenarios: pipe rupture and pipe leak through a hole with an effective diameter that is 10% the pipe's nominal diameter. Transporting hydrogen over long distances requires specialized infrastructure like high-pressure tanks or cryogenic systems. In regions prone to natural disasters, such as earthquakes or hurricanes, transportation infrastructure is vulnerable to damage. For example, an earthquake could disrupt pipelines or delay deliveries leading to fuel shortages.

For the second off-site hydrogen delivery strategy, hydrogen tube or cylinder trailers deliver hydrogen to the refueling station and sometimes serve as temporary storage vessels for the hydrogen on-site. Off-site procurement ties the airport's hydrogen supply to external suppliers, which limits emergency responsiveness. During supply chain disruptions, such as those caused by natural disasters or geopolitical conflicts airports may face critical fuel shortages. This makes off-site procurement less resilient compared to on-site methods. To mitigate these risks, airports must establish strong partnerships with reliable suppliers and develop contingency plans, such as backup supply chains and rapid repair strategies. Regardless of the selected production mode, the failure frequencies we relatively low, ranging from once every 10,000 years (i.e., 10^{-4} yr^{-1}) to once every 10,000,000 years (i.e., 10^{-7} yr^{-1}). Zhang et al. (2023) emphasize the importance of resilience enhancement measures for hydrogen-integrated energy systems, including preventative, emergency, and restoration response stages. These measures are crucial for maintaining operational integrity during and after disruptive events such as earthquakes,

2.3.2 Compression and Storage Mode

Hydrogen compression and storage occur after hydrogen has been produced on-site or delivered (Genovese et al. 2020). A study that evaluated data from 42 hydrogen refueling stations in South Korea found that of the 410 recorded failure events, 48% were associated with

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[1] SoCalGas Breaks Ground on First-of-its-Kind Technology to Produce Clean Hydrogen for SunLine Transit Agency's Hydrogen Fuel Cell Electric Buses | SoCalGas

the compressor and 3.4% were associated with the storage tanks. Given that the compressor is responsible for increasing hydrogen's pressure, the compressor system and its associated pipes and sensors operate under high pressures when filling storage tanks, which make these systems highly susceptible to leakage. The study emphasized that components of the compressor must be able to withstand pressurized conditions and fatigue caused by the reciprocating nature of the compressor system during dispensing. The types of failure storage tanks experience included gas leaks, damage, and other (Kim et al. 2024). To reduce impacts, the study recommended changing the station wall to be greater than 3 m in height and greater than 0.3 m in thickness (Zhou et al. 2024).

2.3.3 Dispensing Mode

A system is in dispensing mode when refueling occurs and hydrogen is transported from a high-pressure storage tank (i.e., main storage system) to the vehicle's tank. Often booster compressors are necessary to elevate the hydrogen's pressure to align with the relatively higher pressure requirements for onboard hydrogen storage systems. As the pressure of hydrogen increases, it must be cooled using a pre-cooling unit (i.e., chiller or a heat exchanger) (Genovese et al. 2024; Zúñiga-Saiz and Sánchez-Díaz 2025). It is also crucial that the pressure increase is well-controlled, which is achieved using a pressure control valve. After traveling through high-pressure piping, the hydrogen, which is now the correct temperature and pressure, can go through the dispenser unit (i.e., hose and nozzle) (Genovese et al. 2024).

Various protocols specify the temperature, maximum fuel flow rate, pressure rise rate, and final pressure required for safe and efficient fueling (SAE J2601, ISO 17268, UNE 17127) (SAE 2020; ISO 2020a, 2025c; AERNOR 2024; Zúñiga-Saiz and Sánchez-Díaz 2025). Dispenser selection can also dictate refuel time (Zúñiga-Saiz and Sánchez-Díaz 2025). Stipulations may be a function of geographical location, with different countries having different setback distances (Zhou et al. 2024) and pressure requirements.

In terms of safety and risk, the dispensing mode is a source of observed failure events. A recent analysis of station maintenance events investigated the root causes of failure for dispenser systems. Of the 4,663 events included in the analysis, 46% were associated with the dispenser subsystem, 21% with the compressor subsystem, and 11% with the chiller subsystem, with the remaining events corresponding to the entire system (19%) or other subsystems (3%). Most of the failure modes were associated with scheduled preventative maintenance or upgrades with the event was associated with the entire system, whereas the cause of events associated with the various subsystems was often undetermined. The analysis concluded that part failures, communication errors, and design flaws were significant sources of unplanned maintenance events associated with the nozzle component of the dispenser subsystem (Kurtz et al. 2020). In the study where 420 hydrogen refueling station failure events were analyzed, it was concluded that 17.9% of failures were associated with the dispenser receptacle and 16.7% of failures were associated with the chiller (Kim et al. 2024). When in dispensing mode, stored compressed gas will be discharged, chilled, and dispensed. The observed cooling system (i.e., chiller) failure events were the result of a breakdown of the system that occurs during operation (Kim et al. 2024). The observed dispenser receptacle failure events were often the result of moisture in the atmosphere mixing with chilled hydrogen, which can lead to the dispenser sticking to the vehicle during the dispensing process and subsequently lead to leakage (Kim et al. 2024).

One study considered a dispenser leak from hole accident scenario for a 700 bar station (Gye et al. 2019). While this pressure is more relevant to light duty vehicles (Genovese et al. 2024), the study found that when additional safety barriers are added to the dispenser systems, the probability of a major accident occurring can be decreased by three orders of magnitude, decreasing to a failure frequency of less than 10^{-9} yr^{-1} (Gye et al. 2019). The safety barrier system assumed in the study included an Emergency Detection System (EDS) to instigate immediate emergency shut down. As such, the societal risks align within the ALARP criteria (Gye et al. 2019). In addition to safety barriers, periodic maintenance of pipes, valves, the compressor, and the dispenser are critical for leak prevention and proper compressor function (Kim et al. 2024). Genovese et al. (2020) thoroughly details key aspects of hydrogen dispensing safety, which include intentional design aspects, calls for regular testing and maintenance, and training.

The same paper that evaluated the “hydrogen storage tank accident scenario” and “compressor accident scenario” also simulated the explosion process at the dispenser (i.e., “dispenser accident scenario”) (Zhou et al. 2024). The dispenser accident could occur if the shutoff and relief valves remain fully open and inactive, which was identified as one of the primary causes of leakage from dispensers. The study also considered how canopy inclination angle and width could reduce the consequences associated with leakage, finding that canopy angles less than 15° and widths less than 12 m led to the lowest retention of leaked hydrogen (Zhou et al. 2024). Of these accident scenarios, more leaked gas accumulates via the hydrogen storage tank and compressor accident scenarios compared to the dispenser accident scenario. The study recommended that public-facing walls near the compressor be replaced with explosion-proof walls (Zhou et al. 2024).

2.3.4 Stand-By Mode

A system is in stand-by mode when there are no working components, compression, production or dispensing. Studies have concluded that the potential for leaks during stand-by mode is minimal (Genovese et al. 2023). In their work, two stand-by scenarios were considered: (1) the main storage tanks are full and nobody is actively fueling their vehicle, and (2) station is closed to the public, so no fueling is occurring. For this first scenario, the study estimates that the mass of hydrogen in the piping between the electrolyzer and the main storage tanks is 0.043 kg, so if all hydrogen in these pipes were leaked daily, the refueling station would lose approximately 1.8 kg of hydrogen monthly (Genovese et al. 2020). This leaked hydrogen would vent until an equilibrium with the atmosphere is achieved. To evaluate the second scenario, the study assessed the stand-by mode of the Cal State LA Hydrogen Fueling Station by considering the change in the storage tank’s hydrogen mass over 8 weekends in which no fueling occurred. No leaks were observed, and after accounting for fluctuations in hydrogen mass measurements attributable to changes in temperature and instrument reading errors, the study identified a flux in hydrogen mass greater than 1% could indicate a leak is present (Genovese et al. 2020). Overall, these findings underscore the importance of rigorous monitoring and maintenance practices to mitigate the minimal yet non-negligible risk of leaks during the standby mode of hydrogen fueling stations.

2.3.5 Summary of Operating Modes Safety Considerations

Overall, recent analyses of station maintenance events highlight that a significant percentage of failures are associated with the compressor and dispenser subsystems, which are relevant when the hydrogen refueling station is in compression and storage mode as well as dispensing mode. Accident scenarios, such as dispenser leaks and compressor failures, have been studied to improve safety measures and recommend structural changes like explosion-proof walls. Other advances that have been made to mitigate these failure risks include the use of emergency detection systems and periodic maintenance.

3.0 Hydrogen Deployment Seismic Risk Assessment

3.1 Seismic Risk Assessment

The tectonically active Cascadia Subduction Zone means that Oregon has a significant risk of experiencing an earthquake of greater than 9.0M within the next 50 years, and emergency planners in both federal and state agencies are interested in using PDX as a response facility. This section considers the risk and resilience of a hydrogen deployment during and after a seismic event—the potential for hydrogen release but also the potential ability for the bus fleet and hydrogen system to operate in the aftermath of a major earthquake.

Veeramany et al. (2025) completed an assessment of the seismic risk associated with the potential hydrogen deployment. The assessment uses site-specific seismic hazard data and nuclear-industry derived pipe fragility models to quantify failure risk across different soil conditions. Softer soils, such as those that occur closer to the Columbia Rivers and in some areas of Portland itself, can amplify ground motions and contribute to greater hazard. PDX is currently invested in a resilient runway project and understanding the potential next stages of a backup power system that is resilient to earthquakes would be an important step in planning the operational functionality after a seismic event.

The results of the assessment found that seismic-induced pipe rupture probabilities are one to two orders of magnitude lower than non-seismic-specific operational risks, which do already account for a range of hazards including seismic events. The risk from potential amplification of ground movements through soft soils can possibly be mitigated through a combination of soil stabilization and seismic flexible piping. Because the greatest risk comes from the combination of seismic hazard with other factors (e.g., component wear/corrosion, other natural disasters, or misuse of the system), robust inspection and maintenance protocols, emergency preparedness, and worker training are important mitigation strategies. See the report by Veeramany et al. (2025) for the complete hazard and risk assessments, and possible approaches to mitigation.

3.2 Deployment's Ability to Support Emergency Response

Section 3.2 examines how deployments can effectively support emergency responses, particularly in the event of a seismic event. The analysis covers several key aspects including: (1) a statement describing the current feasibility of using FCEB for emergency electricity generation, (2) an evaluation on how the approach to acquiring hydrogen may affect readiness for emergencies, and (3) a scenario state model to analyze different possible future FCEB scenarios after a seismic event occurs.

3.2.1 FCEB as Backup Electricity Generators: Technology Status

Use of FCEB to support emergency response by providing an alternate source of electricity generation requires infrastructure that is not yet fully supported by existing technologies. However, it is expected to resemble what is needed for conventional V2G buses, where electric bus power may be injected into an operating AC power grid. For example, BorgWarner advertises its RES-DCVC125-480 EV DC Fast Charging Power Conversion System, which is claimed to invert 125 kW DC to a 3-phase 480 VAC power grid when paired with its RES-D3-CS20-V2G dispenser model.[1] EV charger standards are emerging, including various

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[1] Borgwarner RES-DCVC125-480-V2G.

Combined Charging System topologies, which derive from the EIC 62196 Type 1 connector standard. EV charger communications often follow IEC 15118 and include its plug and charge use case or scenario.

This work presumes that V2G technology evolves to provide access to the FCEB's high-voltage busbar via two 97.5% efficient power electronic conversions. An FCEB is presumed to have a small, high-voltage (e.g., 600 Volts [V]) battery on the dc busbar interface between its fuel cell and drivetrain motors. A DC–DC converter helps control the fuel cell's power generation to the high-voltage DC bus bar. In this configuration, the fuel cell and its DC–DC converter must be sized to supply the FCEB's long-term average drive power that is necessary to maintain its transportation needs—100 kW in this case. The small, high-voltage battery's stored energy helps supply short-term peak power demands, as might be needed for acceleration and hill ascent. The high-voltage battery must be sized to reliably supply those accelerations that might exceed the fuel cell and dc-dc converter power rating.

3.2.2 Implication of Hydrogen Procurement Approach on Emergency Preparedness

On-site production of hydrogen, whether through third-party or ownership, offers significant advantages in emergency preparedness if mitigation strategies are in place to counter the soft soil conditions. By localizing hydrogen production, airports can ensure a steady supply of hydrogen even during supply chain disruptions. This is particularly critical in seismic-prone regions like Portland, where earthquakes or other natural disasters could damage transportation infrastructure and disrupt external supply chains. On-site facilities would have to be designed with seismic resilience in mind, incorporating reinforced structures, flexible piping systems, and advanced safety features to withstand earthquakes. For example, Zhang et al. (2023) highlight the importance of running simulations for disaster scenarios to identify weak points and implement solutions like backup systems and flexible pipelines. This ensures that hydrogen production and storage facilities remain operational during and after seismic events. On-site production eliminates the need to transport hydrogen over long distances, reducing the risks associated with high-pressure tanks, cryogenic systems, and other specialized infrastructure required for hydrogen transportation. This not only enhances safety but also ensures that the airport is not reliant on external suppliers during emergencies. By producing hydrogen on-site, airports can integrate energy sources, further enhancing energy security and reduced dependence on external energy suppliers. This aligns with broader sustainability goals while ensuring a reliable energy supply during emergencies.

Off-site procurement, where hydrogen is produced at a remote facility and transported to the airport, introduces significant vulnerabilities in emergency scenarios. Reliance on external suppliers means that any disruption in the supply chain, such as damage to pipelines or transportation delays caused by natural disasters, could lead to critical fuel shortages. This makes off-site procurement less resilient compared to on-site methods. Transporting hydrogen over long distances requires specialized infrastructure, such as high-pressure tanks or cryogenic systems, which are expensive and come with inherent safety risks. An earthquake could disrupt pipelines or delay deliveries, leaving the airport without a reliable hydrogen supply. During emergencies, airports relying on off-site procurement may face delays in received hydrogen due to supply chain disruptions or transportation issues. To mitigate these risks, airports must establish strong partnerships with reliable suppliers and develop contingency plans, such as backup supply chains and rapid repair strategies.

3.2.3 The FCEB Mobile Emergency Electricity Generation Scenario State Model

The FCEB mobile emergency electricity generation scenario commences after a causal event induces an electrical outage, such as a seismic event, and an FCEB is deemed necessary to supply mobile emergency electricity generation at one of the airport's critical electric load sites. Other project tasks address risks that might occur during routine operation of hydrogen fuel infrastructure at the airport, including routine bus operations. This section details a scenario state model to analyze different possible future scenarios after a seismic event occurs.

Figure 15 illustrates a summarized analysis for the restoration of electric service to critical loads following a seismic event. The FCEB mobile emergency generation scenario begins with an event that might cause an electricity outage at the airport (i.e., a causal event) such as a seismic event. For our purposes, we define potential critical airport outage locations (i.e., critical loads) as those where the airport already has installed emergency generators. The severity of an electric service outage may then be expressed by the number of such critical sites that lose electric service. However, the likelihoods and impacts of truly infrequent and potentially catastrophic outages must be derived from fragility-based models, as is discussed by Zhai et al. (2021). Fragility-based approaches model the interconnected resilience or fragility of power system components and therefore require rich knowledge or inference of transmission or distribution grid systems. Ultimately, the likelihoods of very infrequent events like earthquakes must be modeled as in Section 3.1.

As outlined in Figure 9, either no critical loads lose electric service or a critical load's electric service is interrupted. If the latter occurs, either an existing backup generator can serve the critical load, or service cannot be restored from an existing backup generator. However, use of a backup generator could lead to subsequent disruptions such as running out of fuel, from which either refueling occurs or it does not, or the generator becomes inoperable. These scenarios could lead to the selection of a FCEB for obtaining backup electricity.

When selecting an FCEB, either one will be immediately available or all will be in service, and waiting for a FCEB to become available may be necessary. Regardless, once a FCEB becomes available, it will be transported to the critical load site, an electrical connection will be made at the critical load site, and it can begin providing electric service to the critical load site. At this point, three different scenarios were considered: (1) the FCEB breaks down and is disconnected from electrical service, (2) conventional electric service is restored at the critical load site, or (3) the FCEB runs out of fuel. If the FCEB breaks down, another FCEB must be selected (i.e., either one is available or waiting for an FCEB to become available may be necessary). If electricity is restored, the FCEB can be disconnected and put back into normal service. If the FCEB runs out of fuel, it can either be refilled from a mobile hydrogen tanker or disconnected from the critical load and transported to a H_2 filling station where in the interim available FCEB can be used.

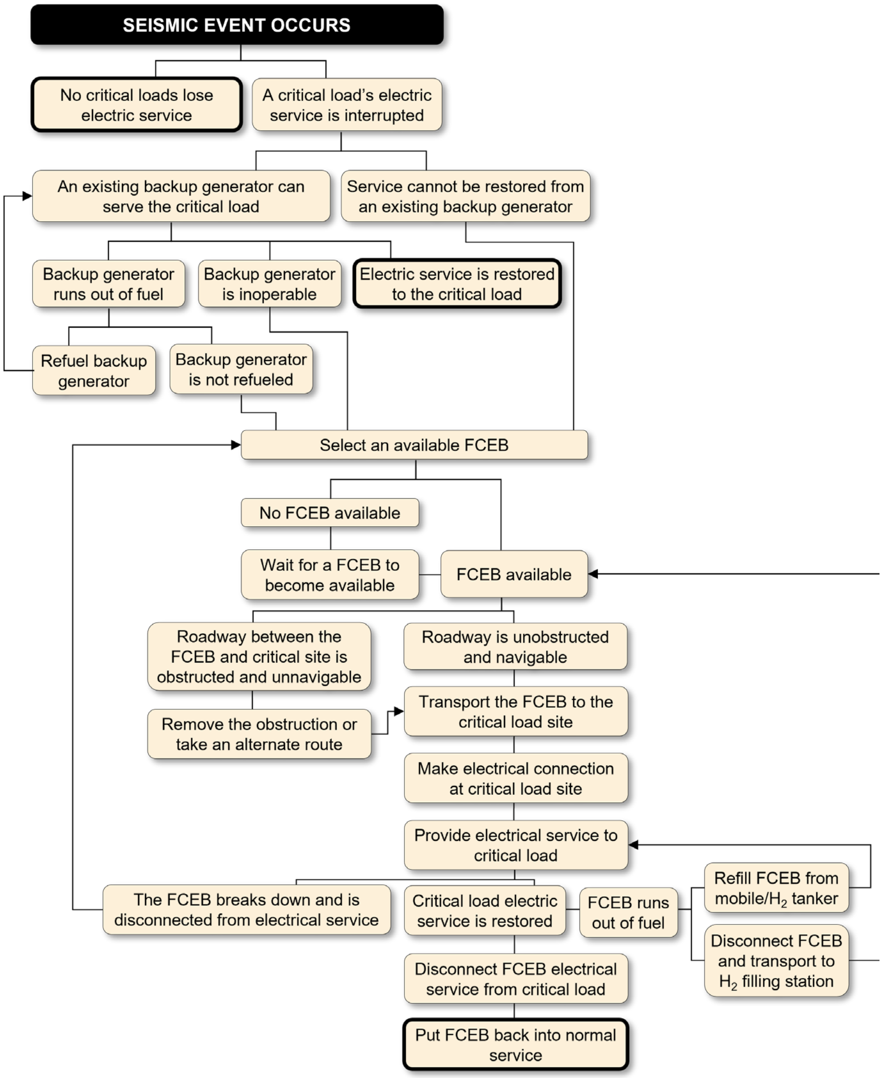

Figure 9. Suggested workflow for the restoration of electric service to critical loads following a seismic event. Bolded nodes indicate the end of an event sequence.

4.0 Use of FCEB for Distributed Energy Management

This section involves investigating the potential of operating FCEBs as mobile generators. FCEBs can be moved to multiple locations and refueled with hydrogen via mobile fuelers, allowing for extended operations. This capability could be highly advantageous to an airport due to the variety of facilities located on airport property. This section examines the technology needed for deploying FCEBs as mobile generators at PDX, aiding in recovery efforts after a natural disaster or prolonged power disruption. Additionally, a review and gap assessment of current regulations, codes, and standards for the use of hydrogen as mobile power sources on airport facilities was performed. The potential for future aviation fueling with mobile hydrogen equipment was also explored.

4.1 Technology Status and Assumptions

The FCEB is an emerging technology in the United States. Few FCEB vendors offer an option yet for their buses to provide mobile emergency electric power generation, a capability referred to as V2G power generation. For example, Toyota Motor Corporation and Honda R&D Co., Ltd. recently announced demonstration of their innovative "Moving e" system that can produce a modest 18 kW of mobile emergency electric power generation.[1] PDX is considering its first FCEBs from a vendor that does not currently offer a V2G capability. Therefore, this task must make assumptions about PDX's future FCEB fleet, based in part on the FCEB that is currently under consideration.

We will presume that V2G technology evolves to provide access to the FCEB's high-voltage bus bar via two 97.5% efficient power electronic conversions. An FCEB is presumed to have a small, high-voltage (e.g., 600 V) battery on the DC bus bar interface between its fuel cell and drivetrain motors. A DC–DC converter helps control the fuel cell's power generation to the high-voltage DC bus bar. In this configuration, the fuel cell and its DC–DC converter must be sized to supply the FCEB's long-term average drive power that is necessary to maintain its transportation needs—100 kW in this case. The small, high-voltage battery's stored energy helps supply short-term peak power demands, as might be needed for acceleration and hill ascent. The high-voltage battery must be sized to reliably supply those accelerations that might exceed the fuel cell and dc-dc converter power rating.

Figure 10 compares two alternative electrical topologies with which an FCEB might provide emergency electric power to critical airport electric loads. The two topologies differ in the assigned location of the grid inverter:

(a) V2G-AC Topology: In this configuration, the grid inverter is integrated within the FCEB system. The vehicle handles the DC-to-AC conversion onboard before dispatching AC power to the critical airport load. This allows the FCEB to directly supply AC electricity to the facility's distribution panel, minimizing the need for external power electronics.

(b) V2G-DC Topology: Here, the grid inverter is located on the facility side. The FCEB provides high-voltage DC power directly to the airport load system, where the conversion to AC occurs via an external inverter. This approach may simplify vehicle design but shifts conversion complexity to the infrastructure.

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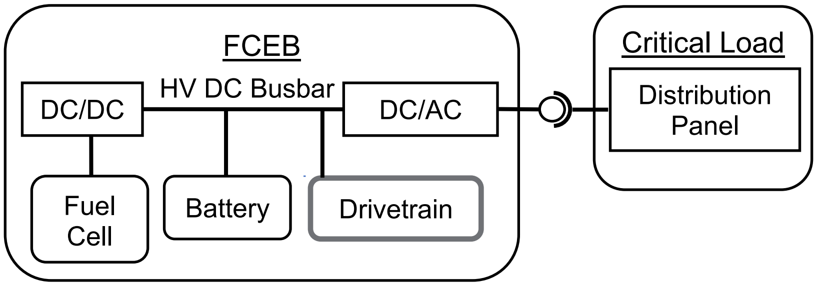
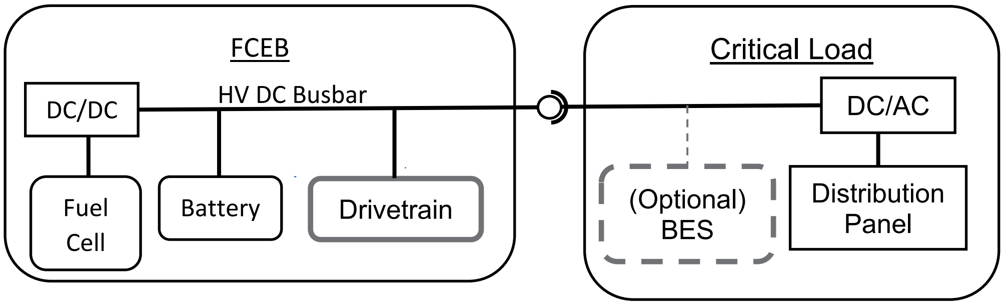
[1] Toyota and Honda to Begin Demonstration Testing of a Mobile Power Generation/Output System to Deliver a Secure Supply of Electricity in Times of Disaster.

The term “V2G-AC” refers to a topology wherein the grid inverter and its requisite controls reside on the FCEB (a). However, we presumed that the “V2G-DC” topology (b) would be adopted instead, wherein the grid inverter and its controls reside with the stationary critical electric load. This topology was preferred because (1) its grid inverter can be tailored to the specific electrical needs of its critical electric load (e.g., its AC voltage, numbers of phases, and power demand) and (2) the V2G-DC topology could be modified to include battery electric energy storage under a future FCEB mobile emergency generation scenario.



(a) V2G-AC Topology



(b) V2G-DC Topology

Figure 10. Comparison of (a) V2G-AC and (b) V2G-DC electrical topologies.

Critical airport electric loads were presumed to exist in scenarios where the airport has already located emergency backup generators, many of such sites have been listed in Table 4.

4.2 Characterization of Electricity Outage Events

The FCEB mobile emergency generation scenario would be triggered by an event that disrupts service to one or more critical airport electricity loads. The overall likelihood of an electricity outage at an airport critical electrical load site should be the product of a causal event’s probability and a contingent probability that that event would induce an electricity outage at one or more of the airport’s critical load sites.

Electricity outages in the United States are infrequent and unpredictable, and highly variable. Historical data about electricity outages in the State of Oregon may be gleaned from Pacific Power’s annual reports to the Oregon Public Utility Commission concerning their system reliability. This section presents findings from Pacific Power’s 2023 report to the Oregon State

Utility Commission (*Re 171--Annual Reliability Report for Calendar Year 2023* 2023). The Portland airport resides among a large, scattered, “Coast Plus” region of PacifiCorp’s service territory. While historical data cannot predict worst case outages, they perhaps reveal expectations about the numbers and severity of annual electricity outages. The airport did not necessarily experience all the outages that are reported for the Coast Plus service region.

Major outage events are often removed from metrics reported by electric utilities because such major outage events are often outliers, and their causes are outside the control of the electric utility. However, the metrics reported here include major events, which may strongly skew the reported system reliability. Figure 11 reports the average annual counts of sustained outages in the Coast Plus region categorized based on their causes over the period from 2019 to 2023. The three most frequent causes of sustained outages were distribution equipment failures, planned distribution outages, and vegetation striking distribution circuits. Figure 12 reports total sustained outages, including major events, in Pacific Power’s Coast Plus region by year.

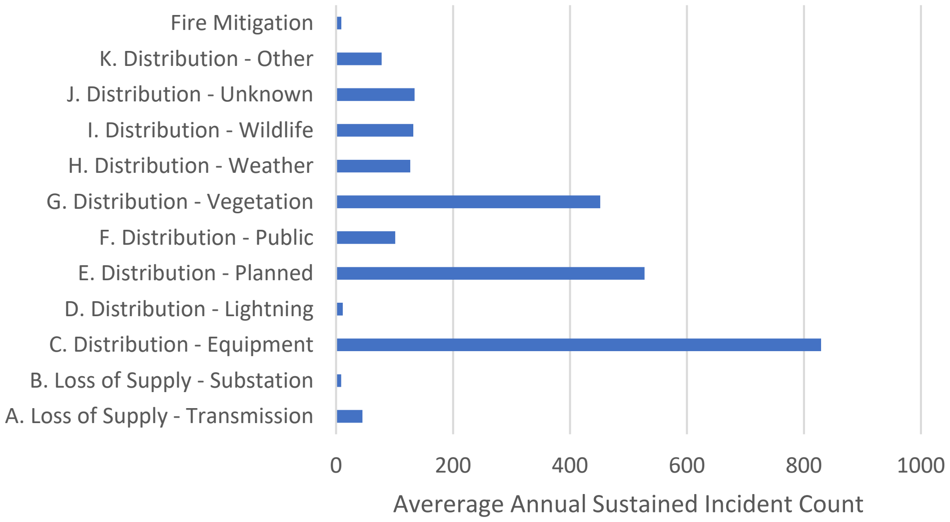


Figure 11. Average annual sustained incident counts categorized by underlying cause in the Pacific Power’s Coast Plus service region, including major events, 2019–2023.

Figure 11 reports total sustained outages, including major events, in Pacific Power’s Coast Plus region by year.

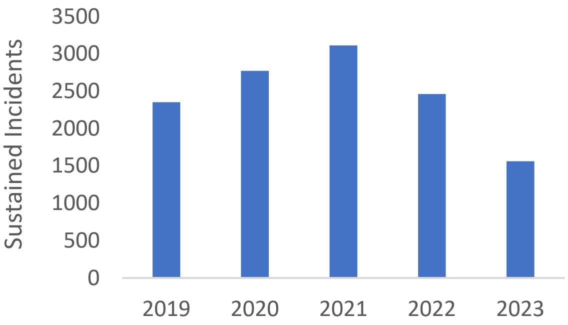


Figure 12. Sustained incident counts including major events for the Pacific Power’s Coast Plus region, 2019–2023.

Customer average interruption duration index (CAIDI) is a measure of the average time that it took an electric utility to restore power after a sustained outage, averaged over all customers and all outage events. Figure 13 confirms that, on average, the greatest average annual CAIDI metrics were caused by “other” uncategorized distribution causes. The longest average sustained outages are caused by changes in weather, planned distribution outages, substation outages, and vegetation.

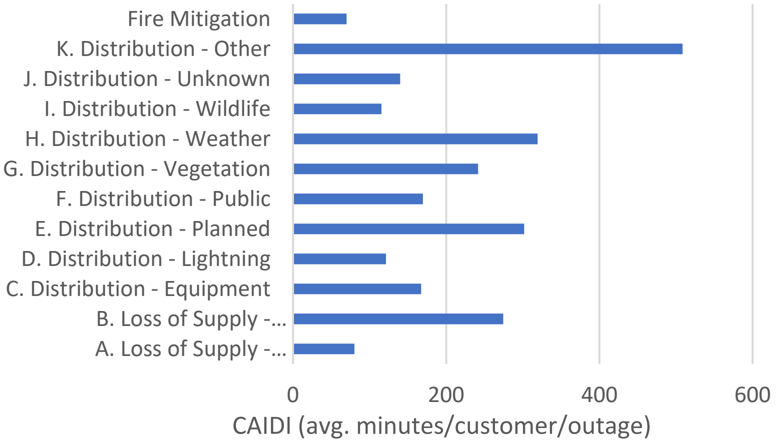


Figure 13. Average annual CAIDI (customer average interruption duration index) for Pacific Power’s Coast Plus service region, categorized based on the cause including major events, 2019–2023.

CAIDI for sustained outages, including major events, are shown by year in Figure 14. There was a steady decline in CAIDI, including major events, from 2020 through 2023, although no claim is being made that this is a statistically relevant trend.

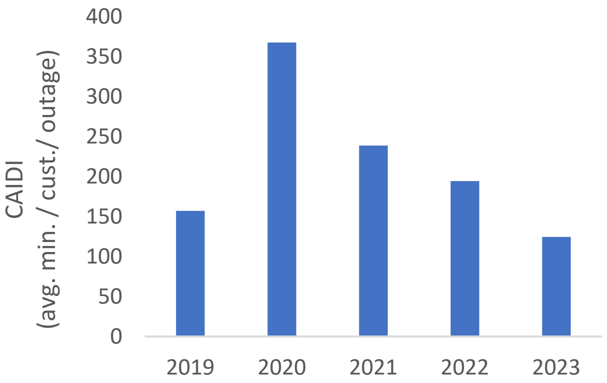


Figure 14. Graph showing changes in CAIDI (customer average interruption duration index) including major events, for Pacific Power's Coast Plus service region, 2019–2023.

We next look at the worst major outage events from 2019 through 2023 to report outage durations that are more representative of worst-case electricity outages. Table 5 reports calculated average outage durations for those customers impacted by reported major outage events, which were gleaned from individual Oregon Public Utility Commission reliability reports issued by Pacific Power for years 2019 through 2023. The longest average major event duration is over 19 hours for a February winter storm in 2021. For each year, there is at least one event exceeding 5 hours of average customer outage duration.

Note that these reported durations reflect neither the total numbers of customers impacted by events, nor the longest durations encountered by the last customers to have had their electricity restored. And as said before, these long outages did not necessarily affect the airport. Major outage events are most likely to affect customers in remote locations, where electricity circuits are relatively weak and vulnerable to weather-caused damages. All but three of the reported major events were attributed to weather-related causes.

Table 5. Average outage durations for customers impacted by major events for which Pacific Power reported filings from 2019 through 2023.

Year	Outage Dates	Reported Cause	Duration (h:mm)
2019	February 24–March 5	Storm	1:56
	August 9–10	Lightening	5:43
2020	January 11, 15–20	Winter storm	14:23
	February 23	Windstorm	7:14
	February 23	Windstorm	6:50
	May 30–June 2	Windstorm	8:10
	September 7–19	Wind and wildfires	4:52
2021	February 8	Loss of supply	5:37
	February 11–20	Winter storm	19:21
	March 28–29	Windstorm	7:38
	December 25–29	Winter storm	6:09
2022	December 26–30	Winter storm (atmospheric river)	8:04

Year	Outage Dates	Reported Cause	Duration (h:mm)
2023	September 9–10	Public safety power shutoff	16:42
	February 22–24	Winter storm	7: 28
	March 2–3	Loss of transmission (equipment failure)	11:55

The analysis of historical electricity outage events did not particularly help us predict risks from infrequent causes like earthquakes because such extraordinary events were not among those historically observed.

4.3 Integration of FCEB Mobile Emergency Generation with Existing Backup Generation Resources

The value of FCEB mobile emergency generation may be greatly affected by the airport's evolving backup power strategy. The airport already has stationary emergency backup generators sited at the most critical electric loads. Therefore, the strategy for engaging FCEBs as mobile emergency electricity generators must be integrated with these pre-existing stationary backup generators.

When an emergency generator is supplying electricity, the system must be disconnected from the electrical distribution system. Given that emergency generators already exist at critical load sites, it was assumed that this infrastructure is in place at the airport. In principle, it would be possible to power multiple critical load sites from one location, but doing so would require coordination of distribution circuit switches that is beyond the scope of this study. Besides, an FCEB's V2G electrical power generation capacity is small compared with many of the airport's critical electricity site demands, lessening any advantage to be had by serving multiple sites with a single FCEB.

Today, to improve site resilience, a FCEB mobile electric generator would only be put into service if a site's generator fails to start, becomes damaged, or runs out of fuel and use of the airport's mobile diesel generators is also not possible or undesirable.

An argument might be made that the stationary backup generators—largely fossil-fueled—should be decommissioned for environmental reasons. If the stationary fossil-fueled backup generators were simply replaced by alternatively fueled (e.g., hydrogen-fueled) generators, then the role of FCEB mobile generators would be deployed if a site's generator became inoperable. However, if the new policy is focused on providing emergency backup power to critical airport loads from battery energy storage, then stationary battery energy storage might be sized to provide backup power to critical loads until the FCEB mobile generators arrive, making the future role of FCEB mobile generation critical.

4.4 The Impact of the Chosen FCEB Hydrogen Fueling Strategy

The airport's future hydrogen fuel strategy may affect how or whether its FCEBs can be used as mobile emergency electricity generators.

The airport will likely refuel FCEBs with hydrogen at a dedicated fueling station that might reside at or near a bus barn to which the buses periodically return to be fueled, maintained, and cleaned. If an FCEB must be driven back to a filling station periodically to be refueled, then successive FCEBs must be used to provide continuous emergency backup generation for long-duration electricity outages at critical load sites. The numbers of buses needed in this case is a function of the critical load's electricity demand, the distance between the critical load and hydrogen filling station, and the rate at which a bus can be refueled. These relationships and strategies are discussed by (Schraeder et al. 2023) for conventional electric buses.

Alternatively, mobile hydrogen cylinders might exist to ferry hydrogen fuel to an FCEB. If hydrogen cylinders are used, each FCEB might be able to provide virtually continuous electric power generation at a critical load site. Mobile cylinders might be used, too, if the airport chooses to replace its existing diesel backup generators with hydrogen-fueled backup generators, or if air transportation evolves to use hydrogen.

Other project tasks address the aspects of storing hydrogen as a gas or liquid, which choice may affect the hydrogen fueling paradigm. Other project tasks also address the comparative risks of these alternative fueling paradigms, which will not be repeated here.

4.5 Risks

In most scenarios, emergency backup generator systems are expected to seamlessly restore electric power to essential demand at critical airport sites. Upon restoration of electric service at a critical site, the emergency backup generation system must seamlessly coordinate the transfer of electricity demand from the FCEBs back to the bulk power grid. Typically, this transfer is highly automated and, depending upon the sophistication of the transfer strategy employed, can be virtually seamless from the user's perspective. To facilitate this, critical electric demand components must be automatically isolated from the electric power grid. This prevents the risk of back feeding electricity into damaged or unenergized electric power circuits. Once isolation is achieved, the stationary backup generator injects the required electricity into the isolated circuit. Currently, these stationary backup generators are primarily diesel-powered, with a few utilizing gas-power.

Given the similarities between EV charging and V2G emergency backup scenarios, the connection between a FCEB mobile generator and the critical site could, theoretically, be established at locations that also support the charging of the airport's or even public EVs. The interconnection infrastructure includes a power electronic inverter, which must safely connect the FCEB DC power generation to a circuit that distributes AC power to preselected essential electric loads at the critical load site.

Table 6 provides a summary of the risks, mitigation strategies, and outcomes associated with various events that could occur in the event of adopting FCEBs as emergency backup electric power. The focus is on risks unique to the FCEB emergency mobile backup generation scenario, distinguishing them from regular bus route operations. It is important to note that this list is not exhaustive but is intended to act as a guiding framework to understand and prepare for potential challenges in backup power scenarios.

Table 6. Overview of risks, mitigation strategies, and outcomes for emergency backup power events.

Event	Hazard/Threat(s)	Mitigation Strategy(s)	Outcome(s)
The emergency backup power generation system senses loss of electric grid power.	The sensor does not correctly sense the loss of grid power.	• A qualified person manually starts the backup generator. • Improve and conduct more frequent scheduled maintenance testing.	• The electricity outage is prolonged.
A switch is automatically thrown to isolate predetermined essential electric loads from the larger distribution circuit and electric power grid.	The critical site's distribution circuit does not successfully isolate itself from damaged, unenergized circuits. The isolation switch mechanism fails.	• A qualified person manually actuates the isolation and transfer switches.	• The backup generator should not automatically energize a faulted system. The electricity outage is prolonged.
	The critical site's distribution circuit is or becomes and remains faulted. The critical site's distribution circuit has been damaged by the causal event.	• The critical site's electric distribution system must be fixed and made safe by qualified persons.	• The backup generator should not automatically energize a faulted system. The electricity outage is prolonged.
The backup generator (diesel or gas or power electronic) starts up and delivers needed electric power to the isolated circuit.	The critical site's existing backup generator fails to start.	• A qualified person troubleshoots the problem and starts the backup generator. • Transport an existing mobile fueled airport backup generator to the critical site to supply backup power. • Engage the needed number of available fuel cell electric buses (FCEBs) for mobile backup power generation.	• Failure to avoid electricity outage. Prolongation of an electricity outage.
	The critical site's existing standby generator has been damaged by the causal event.	• The critical site's existing standby generator is fixed and energized by qualified persons. • Transport an existing mobile fueled airport backup generator to the critical site to supply backup power. • Engage the needed number of available FCEBs for mobile backup power generation.	• Failure to avoid electricity outage. Extended period of an electricity outage. • Diesel fuel leakage occurs without fire. • Diesel fuel leakage occurs with fire. • Diesel fuel leakage occurs with explosion. • A person experiences electrical shock. • An electrical blast occurs.
An emergency dispatcher allocates available FCEB mobile generators among critical airport sites	The airport emergency operations center or emergency communications infrastructure have been damaged.	• Construct a secondary backup operations center and emergency communications infrastructure.	• An electricity outage occurs or is prolonged.

Event	Hazard/Threat(s)	Mitigation Strategy(s)	Outcome(s)
A qualified driver drives a FCEB mobile generator to a critical airport site	No, or too few, FCEB emergency generators are available when they are needed. FCEBs have been damaged by the causal event. See Section 4.5 concerning the availability and emergency generation capacity of the airport FCEB fleet.		• An electricity outage occurs or is prolonged.
	One or more FCEB drivers have become incapacitated by the causal event. There are not enough qualified FCEB drivers.	• Plan for extra bus drivers. Have extra bus drivers on standby.	• An electricity outage occurs or is prolonged.
	A FCEB has non-driver occupants at the time they are needed. Perhaps these occupants have been hurt by the causal event.	• An FCEB's occupants must be transported to safe, final destinations before the FCEB can be used for emergency backup power.	• An electricity outage occurs or is prolonged.
	The route between the assigned FCEB mobile generator and critical airport site is obstructed and unnavigable.	• Clear the route obstructions. • Allocate a different FCEB to the airport critical site.	• An electricity outage occurs or is prolonged.
	The assigned FCEB mobile generator is in a traffic accident while enroute.	• Allocate another FCEB to the airport critical site. • Train and plan for traffic accidents during emergency events.	• An electricity outage occurs or is prolonged. • The FCEB is damaged. • Other damage occurs to the airport campus. • The airport incurs financial liability. • Lives are lost.
	The FCEB driver does not know how to navigate to the critical airport site.	• Provide drivers with navigation tools. • Train FCEB drivers concerning emergency driving routes.	• An electricity outage occurs or is prolonged.
The driver parks a mobile FCEB generator at a critical airport site	A FCEB mobile generator parking spot is not available. The parking site is obstructed. If a critical airport site also serves as an EV charging station, then the stalls could be occupied by EVs that have been damaged or are in the process of charging.	• Remove the obstruction. • Provide signage to dissuade persons from occupying designated FCEB parking sites.	• An electricity outage occurs or is prolonged.

Event	Hazard/Threat(s)	Mitigation Strategy(s)	Outcome(s)
	The FCEB driver does not know where designated FCEB generator parking spots are at this critical site.	• Provide driver training. • Provide signage that directs FCEB drivers to designated parking sites.	• An electricity outage occurs or is prolonged.
A qualified person completes electric connections between the mobile FCEB generator and critical airport site distribution system	Upon arrival, the FCEB mobile generator and airport critical site are found to have different standard electric power connectors that do not mate.	• Adopt the V2G-DC, not V2G-AC, topology (see), which requires fewer options and less variability. • Make sure that all FCEBs and critical sites deploy compatible standard dc power connectors. • Dispatch another FCEB that has compatible power connectors. • An electrician modifies or replaces connectors (not advisable).	• An electricity outage occurs or is prolonged.
	Upon arrival, the FCEB and critical site are found to use different basic V2G communication standards.	• Make sure all airport FCEBs and critical sites employ the same V2G communication standards. • Conduct periodic tests of the FCEB V2G capability using different buses and at different airport critical sites. • Dispatch a different FCEB to the critical site.	• An electricity outage occurs or is prolonged.
	The critical site cannot recognize and accept the FCEB's public key infrastructure (PKI) certificates.	• Reconsider whether encryption is necessary in this scenario. • If encryption is determined to be necessary, schedule periodic updates and testing of certificates.	• An electricity outage occurs or is prolonged.
	Electrical connectors are found to be in nonfunctional or damaged condition.	• A qualified electrician replaces the damaged cable or cables. • If the damaged cables are on the FCEB, deploy a different FCEB to the critical site.	• An electricity outage occurs or is prolonged.
	The airport critical site's power electronic inverter is found to have been damaged and is unworkable.	• A qualified electrician repairs or replaces the damaged power electronic converter.	• An electricity outage occurs or is prolonged.
	The output AC voltage or phase configuration of the power electronic inverter does not match the voltage configuration of the airport critical site distribution system.	• Use the V2G-DC, not V2G-AC, topology (see). The power electronic inverter resides at the critical site for the V2G-DC topology and must have	• This risk is completely avoidable. Alternatively, an electricity outage occurs or is prolonged.

Event	Hazard/Threat(s)	Mitigation Strategy(s)	Outcome(s)
		been tailored to the site's ac voltage and phase configuration.	
	The output DC voltage of the FCEB mobile generator does not lie within the power electronic inverter's allowable range of input DC voltages. (This risk assumes that the V2G-DC topology has been adopted.)	• Limit the numbers of FCEB drivetrain variations so that the fleet of airport FCEBs will have few, if not one, nominal DC output voltage. • Design the critical site power electronic inverters to have few, if not one, input voltage range that matches the FCEB fleet output voltages. • Deploy another FCEB that has the appropriate output DC voltage.	• This risk is avoidable. Alternatively, an electricity outage occurs or is prolonged.
	A trained and qualified operator is not present to complete the electrical connections.	• Dispatch a qualified operator to the critical site. • Design and automate the FCEB-to-critical-site interface to diminish the need for skilled operators. Operator skill level should be comparable to that required at electric vehicle (EV) charging sites. • Train FCEB drivers to be qualified operators.	• An electricity outage occurs or is prolonged.
	The electricity generation capacity of the FCEB mobile generator or generators does not match or exceed the airport critical site's electricity demand.	• Improve the emergency FCEB dispatch process. Critical site electrical demand and FCEB generation capacity should be known at the time a dispatch occurs. • Dispatch more FCEB, if available, to the airport critical site.	• Breakers actuate to protect the FCEB or critical site electric loads. • AC power quality is poor at the critical site. AC voltage sags. Critical site electric loads may become damaged. • An electricity outage occurs or is prolonged.
An FCEB mobile generator provides electricity to a critical airport site	The power electronic inverter fails while the FCEB is supplying power to the airport critical site. This risk assumes adoption of the V2G-DC topology (Figure 16).	• A qualified electrician is dispatched to repair or replace the power electronic inverter. • Conduct scheduled maintenance testing to detect and avoid impending hardware failures.	• An electricity outage occurs or is prolonged.
The FCEB mobile generator runs out of hydrogen—the FCEB is driven to a hydrogen refueling station.	Congestion occurs at the hydrogen filling station. FCEBs cannot be filled as quickly as they arrive.	• Build more hydrogen filling stations or lanes.	• An electricity outage occurs or is prolonged.

Event	Hazard/Threat(s)	Mitigation Strategy(s)	Outcome(s)
	Miscoordination of FCEB mobile generator operations with critical site electricity demand. For example, multiple FCEBs at a critical site could run low on hydrogen fuel at the same time. The temporary loss of a FCEB during its refueling could mean that the current critical site electrical load cannot be supplied.	• Dispatch extra FCEBs to critical sites during emergencies. These extra FCEBs can be rotated into the set of active mobile generators as others leave to be refilled. • Improve dispatch process to forecast and manage FCEB fuel levels. Optimize timing of FCEB refill operations.	• An electricity outage occurs or is prolonged. • Financial inefficiency. Provision for spare FCEB mobile generators is not cost effective.
	Repetition of risky electrical connection and disconnection processes. A FCEB must be electrically disconnected from and reconnected to the critical site electricity distribution system every time it leaves to be filled with hydrogen and returns. The listing of those corresponding mitigation and outcomes will not be repeated here.	-	• Risk is increased due to repetitions of the electrical connections and disconnections
The FCEB mobile generator runs out of hydrogen—the FCEB is refueled from a mobile hydrogen supply vehicle as the FCEB provides emergency backup electricity generation at a critical site.	The normal risks of hydrogen storage, transport, and transfer are exacerbated by effects of the causal event or by mobile electricity generation processes. The causal event might have created uneven surfaces and active fires. The mobile generation hardware might exceed hydrogen's autoignition temperature or create sparks.	• Provide good ventilation at critical load sites where FCEBs are to be parked and refilled. • Provide hydrogen monitors at critical load sites where FCEBs are to be parked and refilled. • Reduce combustible fuels at and near critical site emergency backup generation locations. • Design the FCEB and critical site power electronics to avoid exposed temperatures that exceed hydrogen's autoignition temperature and to prevent or arrest sparks.	• Hydrogen leakage, ignition, or explosion.
	The roadway between the mobile hydrogen refilling vehicle and critical site is obstructed and unnavigable.	• Remove the obstruction. • Design critical site backup generation sites to offer ample access for mobile hydrogen refilling vehicles.	• An electricity outage occurs or is prolonged.
Electric grid service becomes reestablished at the critical airport site	The return of electric power service is not properly sensed, or the transfer switch fails to operate.	• The power transfer process must be completed manually by a qualified person. • Backup up power transfer systems should be tested regularly.	• The critical site's reliance on FCEB mobile generation is extended.

Event	Hazard/Threat(s)	Mitigation Strategy(s)	Outcome(s)
A qualified person disconnects the electric connections between the FCEB mobile generator and critical airport site	A trained and qualified operator is not present to disconnect the electrical connections.	• Dispatch a qualified operator to the critical site to disconnect the electric connectors. • Select connectors and technologies that reduce the operator's required skill level. The process should be comparable to that for EV charging. • Train FCEB drivers to perform this task.	• An FCEB's return to normal service is delayed.
	A FCEB drives away without having disconnected the dc electrical connections to the ac inverter at the critical site.	• Install interlocks to prevent FCEB drivetrain operation while the FCEB is connected as a mobile electricity generator. • Design alerts to let a FCEB driver know that the bus is still connected as a mobile electricity generator. • Improve FCEB driver training to include a check for this electrical connection. • The FCEB's power connector automatically should become deenergized whenever the FCEB enters transportation (drivetrain) mode.	• Connectors or power electronic conversion equipment becomes damaged. • Possibility of electric shock to personnel.
The FCEB is reassigned to a normal transportation route or destination	No exceptional risks are identified for this step. The normal bus route schedule might have been perturbed by the diversion of FCEBs to be used as mobile emergency generators.	-	-
A qualified driver drives the FCEB away from the airport critical site	An able, qualified FCEB driver is not available at the airport critical electric load site to transport the bus.	• Wait for a qualified FCEB driver.	• Reentry of the FCEB into normal bus route operations is delayed.
	The FCEB is in a traffic accident enroute.	• Improved FCEB driver training. • Improved airport traffic signage.	• Delay of FCEB's return to normal transportation route service. • Loss of life. • Damage to the FCEB. • Damage to other airport infrastructure. • Airport liability.

4.6 Standards Relevant to the FCEB Mobile Emergency Electricity Generation Scenario

Table 7 outlines a range of standards that may be relevant to the FCEB mobile emergency electricity generation scenario. While most of the standards outlined in Table 7 are related to V2G and charging infrastructure and safety requirements, two of the standards specifically focus on emergency and standby power systems (i.e., National Fire Protection Association [NFPA] 110 and NFPA 111). When the primary power source fails, which could occur during a natural disaster such as an earthquake, an alternate source of electrical power is crucial for the development of resilient operations. Both NFPA 110 and NFPA 111 were reviewed in detail.

NFPA 110 outlines the installation, maintenance, operation, and testing requirements for emergency and standby power systems (i.e., power sources, transfer equipment, controls, supervisory equipment, and all related auxiliary equipment). Chapter 4, “Classification of Emergency Power Supply Systems (EPSSs)”, defines three important terms: Class, Type and Level. Class is the minimum time, in hours, a EPSS can operate without being refueled. For example, a *Class 0.25* EPSS implies that the system must be refueled after 15 min of use at its rated load. Type specifies the maximum allowable amount of time, in seconds, an EPSS can go without power restoration (i.e., time between loss of power and power restoration). For example, a *Type 10* EPSS means power restoration occurs within 10 seconds. If no amount of power loss is acceptable the EPSS is deemed *Type U*, whereas if there is no stipulated time requirement for power restoration the EPSS is deemed *Type M*. Level indicates the severity loss of equipment performance could cause where *Level 1* means that failure of equipment could result in loss of life or serious injury and *Level 2* means that failure of equipment would not result in loss of life or serious injury.

Chapter 5, “Emergency Power Supply (EPS): Energy Sources, Converters, and Accessories” discusses the various fuels that can be used to provide emergency energy and how that energy is converted into electrical energy. Use of hydrogen gas as fuel sources is covered under this standard. Further, conversion of the hydrogen gas to electrical energy using fuel cells is also discussed. In terms of capacity, the standard specifies that the energy converter (i.e., fuel cell) must be able to carry the load in the timeframe specified by the Type and the fuel tank capacity (i.e., amount of hydrogen gas stored) must be 133% of the low-fuel sensor quantity (i.e., minimum fuel required for full load running). The standards also provide guidance on fuel cell system equipment ratings, accessories, starting equipment, control functions and cooling systems.

Chapter 6, “Transfer Switch Equipment” discusses the instigating mechanism that leads to the transfer of electric loads from one power source (i.e., normal power) to the backup power source. Three types of transfer switches were explored: automatic, delayed automatic, and manual. Given the proposed use of mobile FCEB as the EPS at PDX, automatic transfer would be impossible unless connected to the hydrogen refueling station or a hydrogen storage system.

Chapter 7, “Installation and Environmental Considerations” outlines the minimum requirements and considerations for the EPSS installation environment. More specifically, the chapter discusses details pertaining to EPSS location, lighting, mounting, vibration, noise, heating, cooling, venting, ventilating, the fuel system, exhaust system, protection, distribution, and testing. A detail worth noting is that systems that utilize fuel cell systems should be installed and maintained according to NFPA 853 (Standard for the Installation of Stationary Fuel Cell Power systems). As such, the use of mobile fuel cell power systems has not been explicitly outlined in this standard, however, many of the requirements are still applicable for mobile fuel cells. A similar standard explicitly pertaining to portable fuel cell power systems is ANSI/CSA FC3, which should be reviewed and considered.

Chapter 8, “Routine Maintenance and Operational Testing” specifies the required amounts of regular inspections, system testing, and maintenance needed to ensure the EPSS will be able to properly operate when an emergency situation occurs.

Broadly, the structure of NFPA 111 follows that of NFPA 110

Unlike NFPA 110, which covers generator-based backup for longer-term power, NFPA 111 covers battery-based backup power which is more relevant for immediate, short-term power requirements, however, hydrogen gas as a fuel source and fuel cells as a means of converting the hydrogen gas to electrical energy are not discussed in NFPA 111. Overall, this summary is not intended to replace a more detailed review of the exact requirements stipulated in NFPA 110 and NFPA 111.

Table 7. Electric vehicle standards that may be relevant to hydrogen vehicle-to-grid (V2G) infrastructure.

Standard	Title	Description
UL 2202	Standard for Safety: DC Charging Equipment for Electric Vehicles	Covers the safety requirements for electric vehicle (EV) charging equipment, ensuring safe operation and installation (UL 2022).
UL 2231-1	Personnel Protection Systems for Electric Vehicle (EV) Supply Circuits: General Requirements	Provides safety standards for personal protection systems in EV charging to prevent electric shock hazards (UL 2012).
UL 9741	Outline of Investigation for Bidirectional Electrical Vehicle (EV) Charging System Equipment	Specifies safety and performance requirements for electric vehicle supply equipment (EVSE), focusing on the equipment used for charging EVs (UL 2023).
SAE J1772	Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler	Defines the standard for the charging connectors and protocols used in electric vehicles and their charging stations in North America (SAE 2024a).
SAE J2836/3	Use Cases for Communication between Plug-in Vehicles and the Utility Grid	Provides guidelines for communication between electric vehicles and charging stations to enable smart charging and optimized energy management (SAE 2024b).
ISO 15118-1	Road vehicles -- Vehicle to grid communication interface -- Part 1: General Information and Use-Case Definition	Specifies the general requirements for communication between electric vehicles and charging stations for charging, focusing on the high-level framework (ISO 2019).
ISO 15118-2	Road vehicles -- Vehicle to grid communication interface -- Part 2: Network and Application Protocol Requirements	Defines the network and communication protocols used for plug-and-charge functionality between electric vehicles and charging stations (ISO 2019).
ISO 15118-3	Road vehicles -- Vehicle to grid communication interface -- Part 3: Physical and Data Link Layer Requirements	Specifies the security architecture for secure communications between EVs and charging infrastructure (ISO 2015).
ISO 15118-4	Road vehicles -- Vehicle to grid communication interface -- Part 4: Network and Application Protocol Conformance Test	Outlines the communication protocols for smart charging and energy management to support efficient power distribution (ISO 2018b).

Standard	Title	Description
ISO 15118-5	Road vehicles -- Vehicle to grid communication interface -- Part 5: Physical and Data Link Layer Conformance Test	Defines vehicle-to-grid (V2G) communication protocols, enabling two-way communication between EVs and the grid (ISO 2018c).
ISO 15118-6	Road vehicles — Vehicle to grid communication interface — Part 6: General information and use-case definition for wireless communication	Specifies energy management systems for V2G and grid integration to optimize power use and enhance grid stability (ISO 2017a).
ISO 15118-7	Road vehicles — Vehicle to grid communication interface — Part 7: Network and application protocol requirements for wireless communication	Defines requirements for the wireless communication between electric vehicles and charging stations for wireless charging (ISO 2017b).
ISO 15118-8	Road vehicles -- Vehicle to grid communication interface -- Part 8: Physical Layer and Data Link Layer Requirements for Wireless Communication	Provides guidelines for charging and billing for electric vehicles, particularly in international settings (ISO 2020b).
ISO 15118-20	2nd Generation Network and Application Protocol Requirements	Specifies requirements for interoperability between electric vehicles and charging stations to facilitate global compatibility (ISO 2022).
IEC 61850	Communication protocols for intelligent electronic devices at electrical substations. / Communication Networks and Systems for Power Utility Automation	Focuses on communication networks and systems used in electric power substations and their integration with smart grids (IEC 2023).
IEC 62196-2	Plugs, Socket-Outlets, Vehicle Connectors, and Vehicle Inlets - Conductive Charging of Electric Vehicles - Part 2: Dimensional compatibility requirements for AC pin and contact-tube accessories	Specifies the plugs, socket-outlets, and vehicle connectors used for electric vehicle charging in Europe (IEC 2022a).
IEC 63110	Protocol for the management of electric vehicles charging and discharging infrastructures - Part 1: Basic definitions, use cases and architectures	Provides the standards for energy management and the communication systems in electric vehicle charging infrastructure (IEC 2022b).
IEEE 2030.5	Standard for Smart Energy Profile Application Protocol	Establishes the standard for smart grid communications, focusing on the interoperability of energy systems with electric vehicles and grid infrastructure (IEEE 2023).
IEEE 1547	Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces	Sets the standards for interconnection and interoperability of distributed energy resources (like solar, storage, and EVs) with the grid (IEEE 2018).
UL 1741	Standard for Safety- Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources	Covers the safety requirements for inverters, converters, controllers, and interconnection systems for distributed energy resources (UL 2021).
UL 1741 SC	Safety in V2G-AC configuration (adopted by SAE J3072)	Focuses on the safety requirements for smart grid-compatible inverters and their communication capabilities with the grid (UL 2024).
CSA22.2	General requirements — Canadian Electrical Code, Part II	Provides standards for electrical equipment and systems used in electric vehicle charging and related technologies.
NFPA 110	Standard for Emergency and Standby Power Systems	Establishes standards for emergency and standby power systems, ensuring reliable operation during power outages, including fuel cell-based systems (NFPA 2025a).
NFPA 111	Standard on Stored Electrical Energy Emergency and Standby Power Systems	Defines the safety requirements for stored electrical energy systems used in emergency and standby power, including batteries and fuel cells (NFPA 2025b).

4.7 Hydrogen for Aviation

The appeal of hydrogen as a fuel also extends to aircraft and has an aeronautical history dating back to the 18th and 19th centuries with balloons and Zeppelins (Khandelwal et al. 2013), and has been considered as a possible alternative to traditional fuels for over half a century (e.g., Brewer (1976)). Modern applications of hydrogen as aviation fuel include everything from unmanned aerial vehicles (i.e., drones; De Wagter et al. (2021)) to medium- and long-range passenger aircraft (Baroutaji et al. 2019).

Challenges to hydrogen for aviation include necessary reconfigurations of aircraft—the volume of liquid hydrogen is approximately four times that of kerosene, although its weight is almost one third that of kerosene (Khandelwal et al. 2013)—to accommodate larger fuel tanks, and the lack of hydrogen infrastructure for refueling (Tiwari et al. 2024). Mobile hydrogen fueling equipment is a potential solution to this second problem, allowing delivery of hydrogen at airports without permanent hydrogen infrastructure. This is especially valuable in the early stages of hydrogen introduction (Phase 1 in Tiwari et al. (2024)), for early operational testing, technological demonstration, certifications, and initiating gradual scale-up to fixed infrastructure development.

An airport that is considering developing hydrogen infrastructure in any context, such as the FCEB fleet at PDX assessed in this report, could benefit from considering other potential future applications of hydrogen at airports. A pilot program at Brussels Airport in Belgium tested the use of a hydrogen powered ground-handling cargo tractor coupled with a mobile refueling station (Stargate 2014). Expecting and preparing for future uses and applications of hydrogen in the aviation space could position PDX to be a pioneer in an expanding new technology.

Safety concerns remain paramount when considering hydrogen technologies, especially in the aviation space where public opinion is both crucial and fragile. Despite perceptions, current findings report that hydrogen can be as safe as kerosene as long as appropriate fuel storage, ventilation, and fire detection and containment systems are in place (Tiwari et al. 2024; Yusaf et al. 2024). In 2024, the Federal Aviation Administration released a roadmap for developing safety standards and certification for hydrogen-fueled aircraft (Federal Aviation Administration [FAA] 2024). Proactive development and adherence to safety standards can help to build public confidence in hydrogen.

Table 8 details the hazards associated with mobile hydrogen fueling equipment in aviation. Emerging cases and real-world incidents have demonstrated the need for thoughtful system design, procedural discipline, and harmonized safety standards to be established before scaling up mobile hydrogen fueling operations at commercial airports. In particular, protocols should be developed to meet or exceed standards (e.g., SAE International (2024.); FCW. (2024)) that address leak detection, emergency shutdown, and fire protection. Specialized equipment (e.g., hydrogen-compatible materials, reliable valves, and sensors) and extensive operator training that focuses on the unique properties of hydrogen need to be implemented (Federal Aviation Administration [FAA] 2024; Barilo et al. 2019; Hydrogen Safety Panel 2023). Finally, mobile hydrogen fueling logistics will need to be integrated into airport planning processes, including zoning, exclusion areas, and support for rapid emergency intervention (Barilo et al. 2019; Hydrogen Safety Panel 2023; Li et al. 2023; SAE International 2024.).

Table 8. Hazards associated with the use of hydrogen in aviation.

Aspect	Safe Handling
Operational Flexibility	Apron congestion needs to be managed.
Transport and Storage	Enhanced monitoring systems are needed that ensure safe operation.
Equipment	Preventive maintenance schedules, component inspection programs, and predictive monitoring systems are needed. Safety equipment include: Redundant safety systems Automated shut-off valves Pressure relief systems
Cross-Contamination	Comprehensive purity management protocols need to be incorporated.
Regulation and Standards	Evolving hydrogen standards landscape presents opportunities for proactive compliance management and industry leadership.
Personnel Safety	Advanced leak detection networks with automatic shutdown capabilities provide early warning and system isolation are needed.

5.0 Conclusion

This comprehensive risk assessment demonstrates that hydrogen fuel cell electric buses (FCEBs) represent a viable and advantageous transportation solution for airport facilities, as evidenced through the Portland International Airport case study. The evaluation reveals that FCEBs offer significant operational benefits including extended range capabilities, rapid refueling times, and reliable performance under demanding transit schedules, while also providing unique emergency response capabilities through their potential for portable energy generation. Through systematic risk assessments covering four critical scenarios - vehicle leaks, supporting equipment failures under both normal and seismic conditions, and emergency mobilization—this study has identified key hazards and developed appropriate mitigation strategies to inform safe facility design and operational protocols. The findings indicate that with proper safety measures and infrastructure design considerations, FCEBs can effectively complement existing diesel and compressed natural gas technologies while enhancing both operational efficiency and emergency preparedness capabilities at critical airport facilities, positioning hydrogen fuel cell technology as a strategic asset for modern airport transportation systems.

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Appendix A – HyRAM+ Parameters for FCEB Risk Analysis

fuel_species = “H2”

fuel_temperature = 300 # K

fuel_pressure = 5075*6895 # Pa (convert 5075 psi to pa) (350 bar) #[1]

pipe_inner_diameter = 0.00635 # m

orifice_thickness = 0.001 # m (1mm to 3 mm)

fractional_hole_size = 1E-0 # rupture 100% of the pipe

ambient_species = “AIR”

ambient_temperature = 300 # K

ambient_pressure = 101325 # Pa

ambient_humidity = 0.5

release_angle = 0 # 0 degree is horizontal (in radians)

exposure_time = 30 # seconds

mach_flame_speed = 0.35 # important parameter for overpressure

Table A.1. Fuel storage system failure frequency data.

Subsystem	Component	Log-Normal Distribution Probability of 100% Leak Size Event			Rupture Rate Reference
		(μ)	(σ)	Median	
Storage	5 Containers	−15.3	0.6	2.3×10^{-7}	HyRAM+ “Vessel (Tank/Cylinder)”
	5 Pressure Relief Devices	−12.2	1.4	4.8×10^{-6}	HyRAM+ “Valve”
	5 Shutoff Valves	−12.2	1.4	4.8×10^{-6}	HyRAM+ “Valve”
	5 Lines	−15.7	1.8	1.5×10^{-7}	HyRAM+ “Pipe”
	7 Connections	−12.0	0.7	6.4×10^{-6}	HyRAM+ “Joint”
Fueling Port	Automatic Valve	−12.2	1.4	4.8×10^{-6}	HyRAM+ “Valve”
	Filling Line	−9.7	1.0	6.2×10^{-5}	HyRAM+ “Hose”
	Filling Connection	−12.0	0.7	6.4×10^{-6}	HyRAM+ “Joint”
Defueling Port	Manual Valve	−12.2	1.4	4.8×10^{-6}	HyRAM+ “Valve”
	Port	−12.2	1.4	4.8×10^{-6}	HyRAM+ “Valve”

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[1] https://nfi-roofexplorer.netlify.app/xcelsior-charge-fc

		Log-Normal Distribution Probability of 100% Leak Size Event			
Subsystem	**Component**	**(μ)**	**(σ)**	**Median**	**Rupture Rate Reference**
	Line	−15.7	1.8	1.5×10^{-7}	HyRAM+ “Pipe”
	Connection	−12.0	0.7	6.4×10^{-6}	HyRAM+ “Joint”

Table A.2. Fuel delivery system failure frequency data.

		Log-Normal Distribution Probability of 100% Leak Size Event			
Subsystem	**Component**	**(μ)**	**(σ)**	**Median**	**Rupture Rate Reference**
N/A	3 Control Lines	−15.7	1.8	1.5×10^{-7}	HyRAM+ “Pipe”
	2 Regulators	−12.2	1.4	4.8×10^{-6}	HyRAM+ “Valve”
	2 Solenoid Valves	−12.2	1.4	4.8×10^{-6}	HyRAM+ “Valve”
	Flow Meter	−10.2	1.5	3.7×10^{-5}	HyRAM+ “Instrument”
	2 Filters	−5.4	0.8	4.8×10^{-5}	HyRAM+ “Filter”
	Pressure Sensor	−10.2	1.5	3.7×10^{-5}	HyRAM+ “Instrument”
	3 Safety Relief Valves	−12.2	1.4	4.8×10^{-6}	HyRAM+ “Valve”
	Manual Valve	−12.2	1.4	4.8×10^{-6}	HyRAM+ “Valve”

Table A.3. Fuel cell system failure frequency data.

		Log-Normal Distribution Probability of 100% Leak Size Event			
Subsystem	**Component**	**(μ)**	**(σ)**	**Median**	**Rupture Rate Reference**
N/A	Cathode Humidifier	−11.1	1.2	1.5×10^{-5}	HyRAM+ “Compressor”
	Anode Purge Valve	−12.2	1.4	4.8×10^{-6}	HyRAM+ “Valve”
	Recirculation Pump	−11.1	1.2	1.5×10^{-5}	HyRAM+ “Compressor”
	Fuel Cell Stack	No HyRAM data available; assumed to be zero because of relatively low pressure (3 bar) in the fuel cell stack			
	2 Connections	−12.0	0.7	6.4×10^{-6}	HyRAM+ “Joint”
Cooling	Radiator	−10.2	1.5	3.7×10^{-5}	HyRAM+ “Instrument”
	Stack Coolant Pump	−11.1	1.2	1.5×10^{-5}	HyRAM+ “Compressor”
	Coolant Line	−15.7	1.8	1.5×10^{-7}	HyRAM+ “Pipe”
Air Supply	Cathode Air Filter	−5.4	0.8	4.8×10^{-5}	HyRAM+ “Filter”
	Cathode Air Blower	−11.1	1.2	1.5×10^{-5}	HyRAM+ “Compressor”
	Cathode Air Flow Meter	−10.2	1.5	3.7×10^{-7}	HyRAM+ “Instrument”
	Air Line	−15.7	1.8	1.5×10^{-7}	HyRAM+ “Pipe”

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