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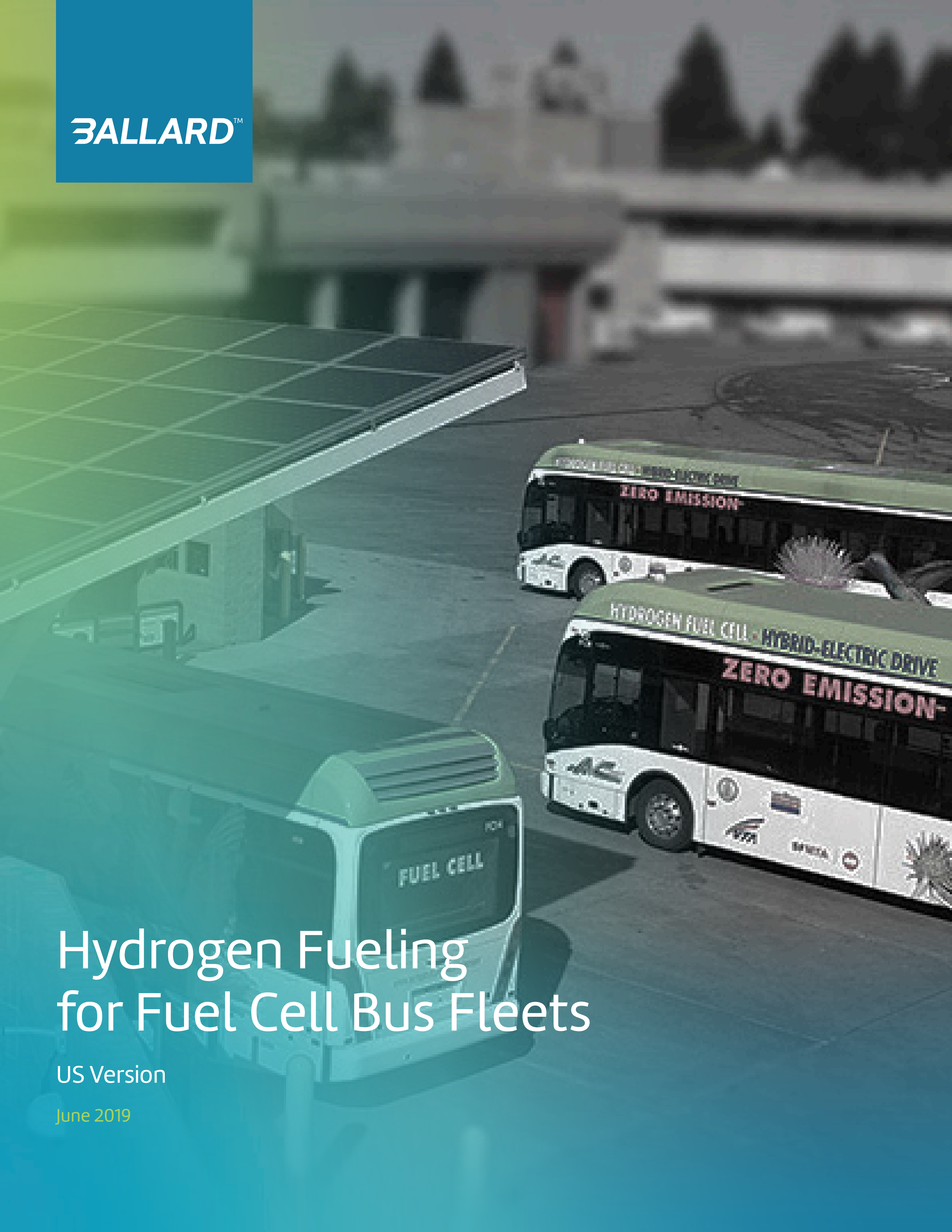

Hydrogen Fueling for Fuel Cell Bus Fleets

US Version

June 2019

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1. Introduction

Figure 1: Fuel Cell Bus Being Refueled With Hydrogen

Hydrogen fuel cell powered vehicles have the potential to significantly reduce the environmental impact of transportation in comparison to vehicles powered by internal combustion engines. Major automakers have intentions for the majority of cars sold by 2030 to be electrified in some way—including hydrogen fuel cell vehicles. To date, a roadblock in major deployments has been the lack of widespread hydrogen fueling infrastructure to serve passenger vehicle customers.

In the nearer term, mass transit applications have the potential to break down the deployment barrier. Significant numbers of fuel cell buses are expected to be deployed around the world in the coming years. With centralized filling and increasing fleet sizes, the deployment of fuel cell buses is providing an ideal opportunity to reduce the cost of hydrogen infrastructure and fuel. However, the success of these deployments will depend on a safe, convenient and clean hydrogen generation and delivery infrastructure.

This paper will provide an overview of the hydrogen supply options available to transit agencies and guide readers in sourcing the appropriate fueling infrastructure and hydrogen supply for their fuel cell bus fleet.

2. Hydrogen Infrastructure at the Bus Depot

Transit agencies refuel their buses at the end of the day within a specific time window to be ready for service the next morning. Deployments around the world have proven fuel cell buses can be fueled safely and efficiently. Transit operators can rely on local industrial gas suppliers to be at the forefront of the development of hydrogen stations for bus fueling. Options include permanent stations to fuel a fleet of transit buses or temporary installations for technology demonstration programs. Regardless of scale, a fully integrated fueling solution installed at a bus depot will include two primary systems:

1. Hydrogen generation – or more typically where the production of fuel takes place off-site and is trucked in – bulk hydrogen storage in the form of compressed cylinders or a liquid hydrogen storage tank. Refer to Appendix II for further details regarding these hydrogen supply alternatives.

Figure 2: Hydrogen Dispenser by Air Liquide

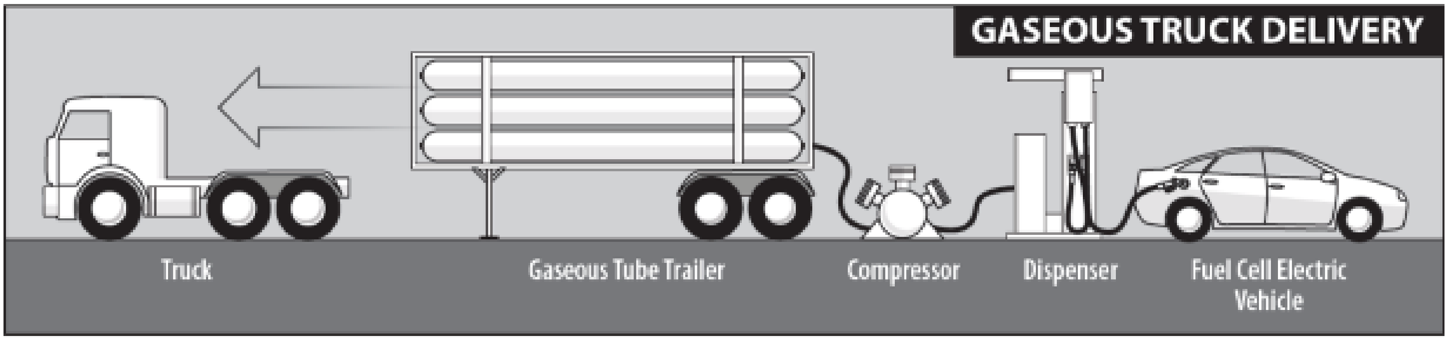

Figure 3: Demonstration Fleet Fueling Pathway With Delivered Gaseous Hydrogen (image courtesy of NREL)

2. A compression, storage and dispensing (CSD) module to deliver fuel to the vehicle, including the hydrogen compression, high-pressure storage, and dispensing systems. Hydrogen is dispensed to the vehicles at a pressure of 350-bar or 700-bar. Typically, the dispenser is located on a fueling island in line with normal bus fueling operations (see Figure 6) but may sometimes be packaged with the compression and storage systems in a "containerized" CSD module.

When considering the implementation of a hydrogen station, every transit property will be unique with regards to their specific requirements. It is not a one-size-fits-all situation related to budget and schedule for each specific property. The following sections describe three phases that a typical transit agency will work through as the fuel cell electric bus fleet grows from a demonstration to a full-scale deployment. These stages are designed to flexibly expand the hydrogen infrastructure to match the growing fuel cell bus fleet in a measured and economical way.

3. Phase I – Demonstration Fleet (~5 buses)

Transit agencies will typically demonstrate one to five fuel cell electric buses before making the strategic decision to expand the fleet. Transit agencies at this stage in deployment are conducting an initial evaluation of the technology to gain a better understanding of the specific benefits to the operator and the riders. The fueling infrastructure for this type of demonstration must be temporary or scalable, and not entail substantial changes to the operating environment at bus fueling facility.

Fuel cell electric buses will typically carry up to 40 kilograms of hydrogen and consume approximately 25 kilograms of hydrogen per day; therefore this station will require a capacity of 125 kilograms per day to fuel up to five buses. This volume is too small to justify the investment required for liquid hydrogen storage or steam methane reforming (converting natural gas into hydrogen).

3.1. Fueling Solution

3.1.1. Supply and Infrastructure

The two most viable options for a demonstration fleet of this size would be on-site electrolysis (producing hydrogen from water and electricity) or compressed gas delivered and stored in tube trailers. Either requires a CSD module to deliver fuel to the vehicle. The block diagram below illustrates the compressed gas delivery fueling pathway.

Figure 4: Hydrogen Refueling Station at UCI by Air Products

3.1.2. Cost

Rental of the tube trailer for delivery and storage of gas is estimated at approximately $3,000 USD per month. The CSD system capable of delivering 125 kg per day is approximately $1.0 million USD. The fuel cost for delivered compressed gas is strongly influenced by the distance between the hydrogen production facility and the bus depot. In California, the typical fuel cost range is $10 -12 USD per kilogram, while in more remote regions it may be higher. With a fuel cell electric bus fuel economy of 8 miles per kilogram, this translates into a fuel cost of $1.25 -1.50 USD per mile.

3.2. Case Study: Anteater Express, University of California, Irvine

The National Fuel Cell Research Center was awarded a contract by the California Energy Commission to build and demonstrate a fuel cell bus for operation at the University of California's Irvine (UCI) campus. The addition of the hydrogen fuel cell bus to the UC Irvine Anteater Express fleet is the first of its kind to operate on a University of California campus.

UCI's hydrogen fueling station was constructed in 2015 and is designed to fuel both the bus and fuel cell passenger vehicles operating in the region. The station features the Air Products "S700" compressor, with fuel supplied via a 250 kg gaseous hydrogen tube trailer delivered to the site, then swapped out once depleted.[1] Designed to dispense 100 kg/day (equivalent to 100 gallons per day of gasoline), up to fifteen fuel cell vehicles and two fuel cell buses can be refueled per day. The station has been designed with the capability of accepting 500 kg tube trailers to easily double the capacity as demand grows.

1 National Fuel Cell Research Center. "UC Irvine Hydrogen Station." University of California, Irvine. http://www.nfcrc.uci.edu/3/research/keyInitiatives/hydrogen/IrvineHydrogenFuelingStation.aspx (accessed June 20, 2016).

4. Phase II – Pilot Deployment (5 to 20 buses)

At the next stage, a pilot deployment of fuel cell buses is typically in the range of five to twenty buses. Transit agencies at this stage of deployment have conducted an initial evaluation of fuel cell technology. Operators recognize the business and performance benefits of fuel cell buses and are integrating the zeroemission buses into their normal operations. For example, in the Bay Area of California, Alameda-Contra Costa Transit District (AC Transit) is currently deploying thirteen fuel cell electric buses and Aberdeen, UK has 10 fuel cell electric buses in operation.

At this level of consumption (125 -500 kilograms per day), the installation is not temporary and the dispenser will usually be set up in line with the compressed natural gas (CNG) or diesel buses in order to maintain fueling operations continuity.

4.1. Fueling Solution

4.1.1. Supply and Infrastructure

In terms of hydrogen production, delivered liquid hydrogen storage is often the most economical model for this size of fleet. This hydrogen is produced at a large-scale industrial facility, and delivered via cryogenic transport trailer for storage on-site. It is often produced through large-scale steam methane reforming. Liquid hydrogen is sometimes used in combination with electrolysis, where some agencies have integrated solar panels with an electrolyser to produce some portion of the required fuel through a renewable source. The block diagram below illustrates the delivered liquid hydrogen fueling pathway.

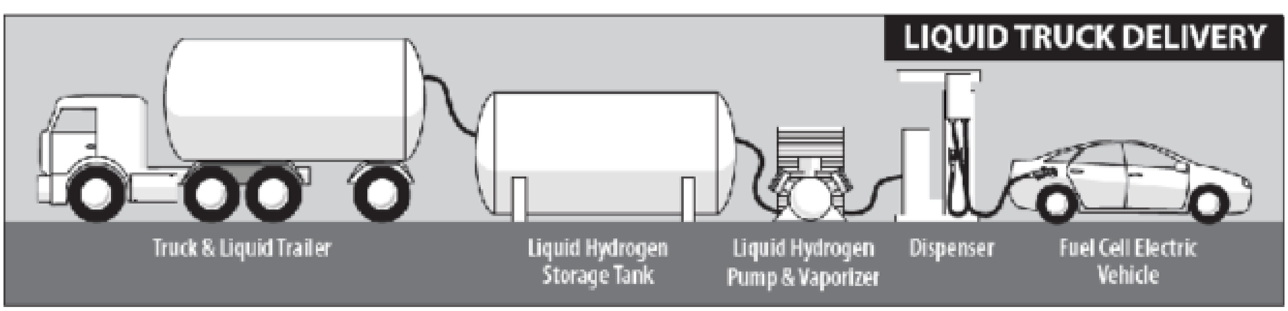

Figure 5: Pilot Deployment Fleet Fueling Pathway With Delivered Liquid Hydrogen (image courtesy of NREL)

4.1.2. Cost

For a liquid hydrogen fueling solution, while the transit agency can purchase the equipment outright, the industrial gas provider typically installs, maintains, and operate and retains ownership of the fuel storage tank and CSD, providing this service for a defined monthly fee over the life of the installation. By extending this fee structure over the typical 12 year lifecycle of a fuel cell bus it is predictably manageable. As compared with delivered gaseous hydrogen, fuel costs are much less dependent on proximity to hydrogen production sources, however it is necessary to carefully align the supply and demand for hydrogen to minimize routine nominal “boil off”. This boil off of fuel is only ~0.1% of tank volume per day and can sometimes be further minimized via economizer capture. Infrastructure equipment costs are approximately $3-5 million USD, including the vaporizer, cryo pump, high-pressure storage systems and a dispenser. The fuel cost for delivered liquid hydrogen is typically $6-9 USD per kilogram. With a fuel cell electric bus fuel economy of 8 miles per kilogram, this translates into a fuel cost of $0.75 -1.13 USD per mile.

4.2. Case Studies

AC Transit, California

AC Transit is one of the largest transit agencies in California, serving over 60 million passengers a year throughout a 364-square mile region. AC Transit currently operates a fleet of thirteen fuel cell buses, with an additional ten buses planned for delivery in the coming years. AC Transit fuels the fleet with a combination of liquid hydrogen and on-site electrolysis.

At AC Transit’s hydrogen station in Emeryville, California, solarpowered electrolysis produces hydrogen from water. With no emissions generated during the production or consumption of the hydrogen, this truly is a zero-emission solution on a well to wheels basis. The hydrogen fueling station was engineered by Linde North America, Jacobs, and EPC, and built by W.L. Butler Construction, and demonstrates the use of “renewable” hydrogen – hydrogen produced using Proton OnSite’s solarpowered electrolyzer. The Emeryville Station has the capacity to rapidly fuel 12 buses consecutively with more than 30 kilograms of hydrogen each.2 Using ‘fast-fill technology’, buses can be refueled at rates up to 5 kilograms per minute, a time comparable with refueling diesel buses. Routine commercial fleet scheduling and service requirements make it necessary to fuel the buses between 11 p.m. and 5 a.m., and the fast fueling afforeded by hydrogen CSDs enables the buses to stay in continuous service from 5 a.m. to 11 p.m.[3] Excluding the implementation and capital costs for the hydrogen station equipment, the combined cost of operation, maintenance and hydrogen to fuel buses at this station is approximately $10.50/kg dispensed.[3]

2 Alameda-Contra Costa Transit District. “Taking the HyRoad… With Zero-Emission Technology.” AC Transit. http://www.actransit.org/wp-content/uploads/010912B_HyRoad_web2.pdf (accessed June 20, 2016).

3 California Fuel Cell Partnership. “A Road Map for Fuel Cell Electric Buses in California.” CAFCP.org http://cafcp.org/sites/default/files/A%20Roadmap%20for%20Fuel%20Cell%20Electric%20Buses%20in%20California.pdf (accessed June 20, 2016).

Figure 6: AC Transit / Linde Emeryville, CA Hydrogen Refueling Station

5. Phase III – Commercial Deployment (>20 buses)

Commercial deployment is typically greater than twenty fuel cell buses. Transit agencies at this stage in deployment have fully embraced zero-emission fuel cell bus technology and are ready to invest in the fueling infrastructure to support a significant fleet of buses. One of the advantages of fuel cell electric buses over other zero-emission technologies is the ability to scale up the fueling infrastructure without requiring substantial changes to vehicle operations or substantial modifications to the electrical grid.

5.1. Fueling Solution

5.1.1. Supply and Infrastructure

There are two viable fueling pathways at this scale of hydrogen production: 1) delivered liquid hydrogen, or 2) on-site hydrogen production through steam methane reforming (SMR); including various combinations of the two.

The equipment used for a commercial liquid hydrogen fueling station would be similar to that illustrated in Figure 7, with additional dispensers to allow streamlined fueling operations. Depending on the size of the storage tank, liquid hydrogen delivery would be 1 -2 times per week, during off-peak hours.

The other viable option at this scale is on-site hydrogen production using natural gas through a process known as steam methane reforming. This production process is based on the "cracking" of compressed natural gas (methane) to produce hydrogen fuel. For agencies with compressed natural gas bus fleets, this is often an attractive option as the fuel feedstock (methane) is common for both bus technologies.

Both fueling pathways are suitable at this level of consumption, with the most economical dictated by geography, where the distance to the hydrogen production facility will impact the cost per kilogram of fuel. The block diagram below illustrates the on-site SMR fueling pathway.

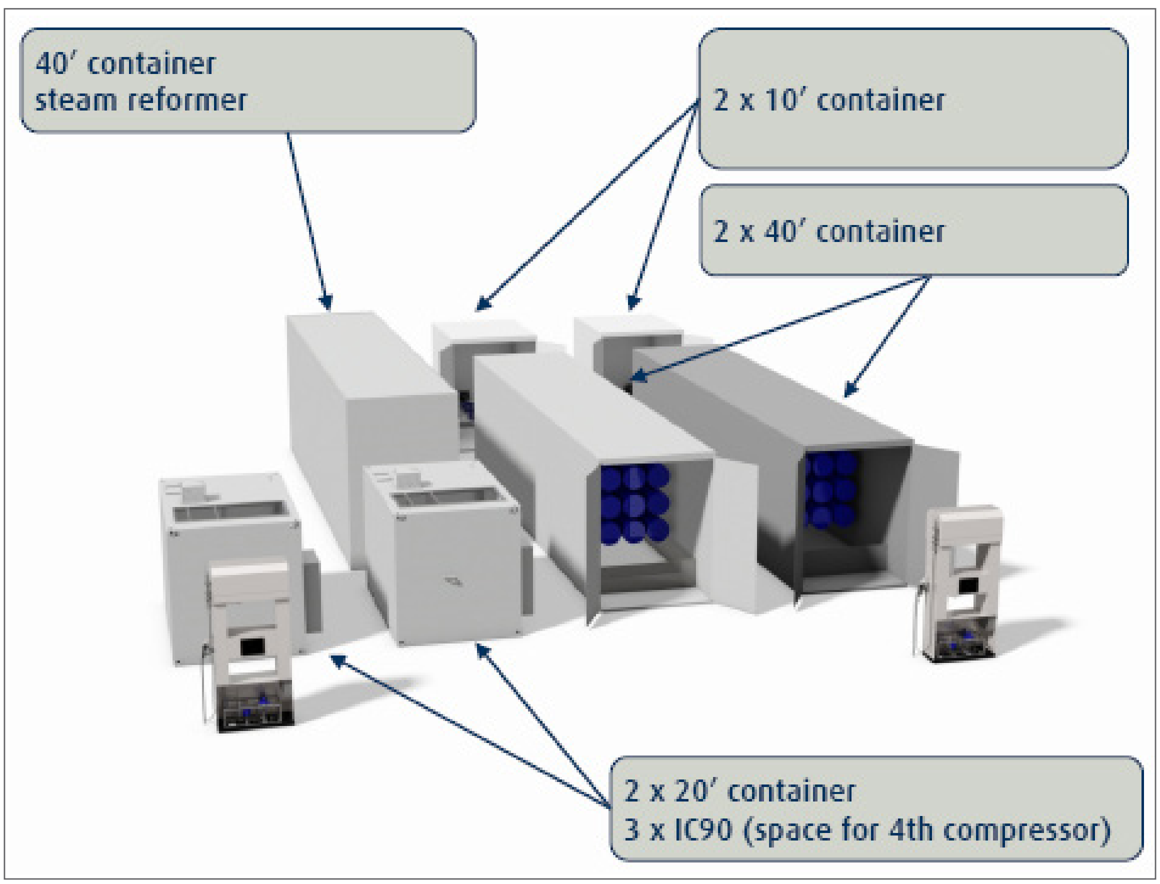

Figure 7: Pilot Deployment Fleet Fueling Pathway with On-site SMR (image courtesy of The Linde Group)

5.1.2. Cost

For an on-site SMR solution capable of delivery up to 700 kilograms of hydrogen per day, the capital costs for infrastructure would include the reformer ($2.5 -$3.5 million USD), and other equipment costs of approximately $3.0 -5.0 million USD, including the vaporizer, compressor, high-pressure storage systems, and multiple dispensers to service a fleet this size. The fuel cost for hydrogen derived from SMR at this scale is typically $3 – 6 USD per kilogram. With a fuel cell electric bus fuel economy of 8 miles per kilogram, this translates into a fuel cost of $0.38 -0.75 USD per mile.

5.2. Case Study: BC Transit, Canada

When BC Transit deployed a fleet of 20 fuel cell buses timed to coincide with the 2010 Winter Olympics, the transit agency contracted with Air Liquide for the fueling infrastructure. The liquid hydrogen storage and gaseous dispensing station was built at a cost of approximately $4.7 million USD.[4] The station was designed to store approximately 10,000 kilograms of hydrogen and achieve a full fill of each bus in ten minutes. During the demonstration program, the station dispensed more than 591,594 kilograms of fuel over 23,671 fills without a safety incident.

4 National Renewable Energy Laboratory. "BC Transit Fuel Cell Bus Project Evaluation Results Report." www.NREL.gov. http://www.nrel.gov/docs/fy14osti/60603.pdf (accessed June 20, 2016)

The planned demonstration period for the fleet of fuel cell buses was five years. Obtaining liquid hydrogen was challenging because of the distance between Whistler and Air Liquide's nearest production facility in Becancour, Quebec. Even with the logistics of trucking this hydrogen across Canada, BC Transit reduced greenhouse gas emissions by 62% compared to what it would have been with a diesel fleet.

SunLine Transit Agency, California

SunLine Transit recently received a grant award under the Air Quality Improvement Program and Low Carbon Transportation Greenhouse Gas Reduction Fund Investments: Zero-Emission Truck and Bus Pilot Commercial Deployment Project to upgrade their fueling station to accommodate their existing fleet and additional fuel cell buses. SunLine is working with Proton OnSite on all aspects of the hydrogen station and electrolyzer construction including siting, permitting, civil and electrical work, installation and commissioning. Proton OnSite will also provide technical expertise and training to SunLine and emergency first responders on hydrogen station operation, servicing and maintenance, expected performance of all equipment, and safety and emergency protocols.

The Proton OnSite fueling equipment will include a PEM electrolyzer utilizing a minimum 33% renewable energy, and compression, storage and dispensing equipment. This 350-bar station will be capable of producing 900 kilograms of hydrogen per day, enough fuel for 30 -35 buses in normal revenue service.

Figure 7: Air Liquide Hydrogen Station at Whistler Transit Centre

6. Paying for the Hydrogen Infrastructure in the United States

Transit agencies in the United States struggle with their internal budgets to meet daily service levels. It would be unreasonable to expect these agencies to make multimillion-dollar investments in hydrogen infrastructure without support from other stakeholders.

In the United States, the Federal Transit Administration (FTA) has developed the Low or No Emission Vehicle Deployment Program (LoNo Program) which provides funding for both zero and low emission transit buses and the cost of leasing or acquiring transit bus-related equipment and facilities. Under the LoNo Program, up to 90 percent of the net project cost of the equipment or facilities attributable to compliance with the Clean Air Act is covered through the FTA.

There are also similar State programs, such as the California Air Resource Board's (CARB) Air Quality Improvement Program (AQIP and HVIP with $100,000 /bus voucher for the hydrogen infrastructure), California Energy Commission that can be used singularly or in combination with FTA funding to pay for hydrogen infrastructure to support deployments.

7. Transitioning from CNG Buses to Hydrogen Fuel Cell Buses

Unlike battery electric buses that require a total replacement of the existing fueling infrastructure, fuel cell electric buses allow transit agencies that are currently operating CNG buses to transition to a low and zeroemission fleet mix using a common fuel feedstock (methane) and leveraging the existing infrastructure.

A combination of low-emission CNG buses with zero-emission fuel cell electric buses would demonstrate an "integrated" solution from a common fueling supply chain under a model that is both economical and scalable to hundreds of buses (perhaps the 'Achilles heel' for battery electric buses).

Hydrogen and compressed natural gas share many of the same characteristics, making implementation easier:

- Similar codes and standards for the safe handling of Class 2 flammable gases
- Common distribution equipment up to the steam methane reformer; similar piping, compression, gas storage and dispensing systems
- Similar refueling procedures
- Similar regulatory process with fire marshall and other authorities having jurisdiction (AHJ)
- Similar leak detection and other safety systems
- Similar training and qualifications for technicians

With the Advanced Clean Transit rule making currently under review in California, it is likely that large fleets will be required to purchase and operate some percentage of their fleet as zero-emission vehicles. For state transit agencies with large CNG bus fleets, on-site hydrogen production presents the opportunity to leverage existing assets to create a complementary zero-emission infrastructure, rather than starting from scratch.

The estimated cost to convert CNG maintenance facities to hydrogen will vary from $500,000 to $1M (including engineering and equipment)

8. Hydrogen Infrastructure Suppliers

Every transit agency will have unique requirements impacting the choice of fueling technology. Suppliers of hydrogen infrastructure with experience supporting deployments of fuel cell buses in the United States include the following companies. Contact these companies to find the right solution for each specific property.

SUPPLIER	FUELING TECHNOLOGY	REFERENCE TRANSIT SITES
AIR PRODUCTS www.airproducts.com	Gaseous hydrogen delivered in tube trailer Bulk delivery of liquid hydrogen On site reforming of natural gas	• University of California, Irvine campus • Stark Area Regional Transit Authority, Ohio
AIR LIQUIDE www.airliquide.com	Gaseous hydrogen delivered in tube trailer Bulk delivery of liquid hydrogen On-site SMR or electroylsis	• BC Transit, British Columbia, Canada • Birmingham Jefferson County Transit Authority • University of Delaware
LINDE GROUP www.linde.com	Bulk delivery of liquid hydrogen On-site electrolysis	• Alameda-Contra Costa Transit District, California
PROTON ONSITE – NEL www.protononsite.com	On-site electrolysis	• Alameda-Contra Costa Transit District, California • Sunline , Palm Spring, California
NUVERA www.nuvera.com	On-site reforming of natural gas	• Boston MBTA
TRILLIUM CNG https://www.loves.com/en/ lovessolutions/ trillium-homepage	Turnkey hydrogen station (equipment, gas supply, operation & maintenance)	• OCTA, Orange County, California

9. Summary

Transit agencies who start to engage with hydrogen buses for the first time generally report lack of information as the first barrier to adoption. This paper aims to provide an introduction to the hydrogen supply alternatives available to transit agencies deploying fuel cell bus fleets. With fleets operating at various locations in the United States (see Appendix I), it is now possible to provide guidelines for consideration when deploying hydrogen infrastructure to support fleets of various sizes and assign some associated costs to these parameters, as summarized in the table below.

TYPICAL FUEL SUPPLY	AVERAGE FLEET CONSUMPTION	CAPITAL COSTS (USD)	DELIVERED FUEL COST (USD)	FUEL COST PER MILE (USD)	INSTALLATION FOOTPRINT
PHASE I – Demonstration Fleet (~5 buses)					
Compressed gaseous hydrogen in tube trailers	~125 kg/day	Tube trailer rental: $3,000/ month Compression, storage and dispenser: $1 millon	$10 - $12/kg	$1.25- $1.50/mile	Temporary deployment of 40' trailer (20' x 50')
PHASE II – Pilot Deployment (5–20 buses)					
Liquid hydrogen storage	125 to 500 kg/day	Vaporizer, pump, storage & dispenser: $3-5 million	$6 - $9/kg	$0.75 - $1.13/mile	30' x 60'
PHASE III – Commercial Deployment (>20 buses)					
Liquid hydrogen storage or on-site SMR	500 to 1,000 kg/day	On-site SMR: $2.5 - 3.5 million Vaporizer, cryo-pump, storage & dispensers: $3-5 million	$3 - $6/kg	$0.38 - $0.75/mile	77' x 60'

In addition to the type of hydrogen fuel production (SMR, electrolysis), there are several variables such as on-site vs. centralized production, fuel distribution method, buffer storage, dispensing rate etc. that have a major impact on the fueling infrastructure costs. Industrial hydrogen gas suppliers indicate that these values are an estimate only and must be validated for each individual proposed site.

As hydrogen infrastructure technology continues to mature, improvements will be made in solutions available to transit agencies. Hydrogen produced from renewable sources, such as solar, wind or biomass will become more prevalent and economical. While this study provides a guideline for transit agencies transitioning to hydrogen fuel, agencies are encouraged to contact a regional gas supplier (as outlined in Section 8) to determine the ideal solution for a particular scenario.

Appendix I – Recent Fuel Cell Bus Fleets at US Transit Agencies[5]

TRANSIT AGENCY FUEL CELL	BUS FLEET	FUELING LOCATIONS	STATION TYPE	SUPPLIER
AC Transit	13 buses (+11)	Oakland, CA Emerville, CA	Bulk delivery of liquid hydrogen On-site electrolysis	Linde, Proton OnSite
SunLine Transit Agency (current)	5 buses	Thousand Palms, CA	On-site reforming of natural gas	Hyradix
SunLine Transit Agency (2019)	(18 buses)	Thousand Palms, CA	On-site electrolyis	Proton OnSite
SARTA	5 (+10)	Canton, OH	Bulk delivery of liquid hydrogen	Air Products
Flint Mass Transportation Authority	2 buses	Flint, MI	On-site electrolysis	Air Products, Proton OnSite
UCI Transportation & Orange County Transportation Authority	2 buses	Irvine, CA	Bulk delivery of liquid hydrogen	Air Products
Massachusetts Bay Transportation Authority	1 bus	Boston	On-site reforming of natural gas	Nuvera
Orange County Transportation Authority	(10)	Orange County	Bulk delivery of liquid hydrogen	Trillium CNG

5 National Renewable Energy Laboratory. "U.S. Fuel Cell Bus Projects." NREL.gov http://www.nrel.gov/hydrogen/proj_fc_bus_eval.html (accessed June 20, 2016).

Appendix II – Hydrogen Supply Alternatives

Hydrogen is one of the most abundant elements, but it is rarely found in its purest form. Hydrogen fuel can be obtained from many sources, including natural gas, biogas or other hydrocarbon fuels, as a by-product of chlor-alkali production, or from water through electrolysis. The base substance dictates the production process chosen. Each of these production methods has a varying environmental impact.

Hydrogen can be produced in large "central production" plants and transported to the point of end-use. Liquid hydrogen is the most cost-effective form of hydrogen to transport. Hydrogen may also be produced in smaller "distributed production" facilities, very near or at the point of end-use. Delivery methods for hydrogen fuel are determined by the production volume and delivery distance, as shown in Figure 8.

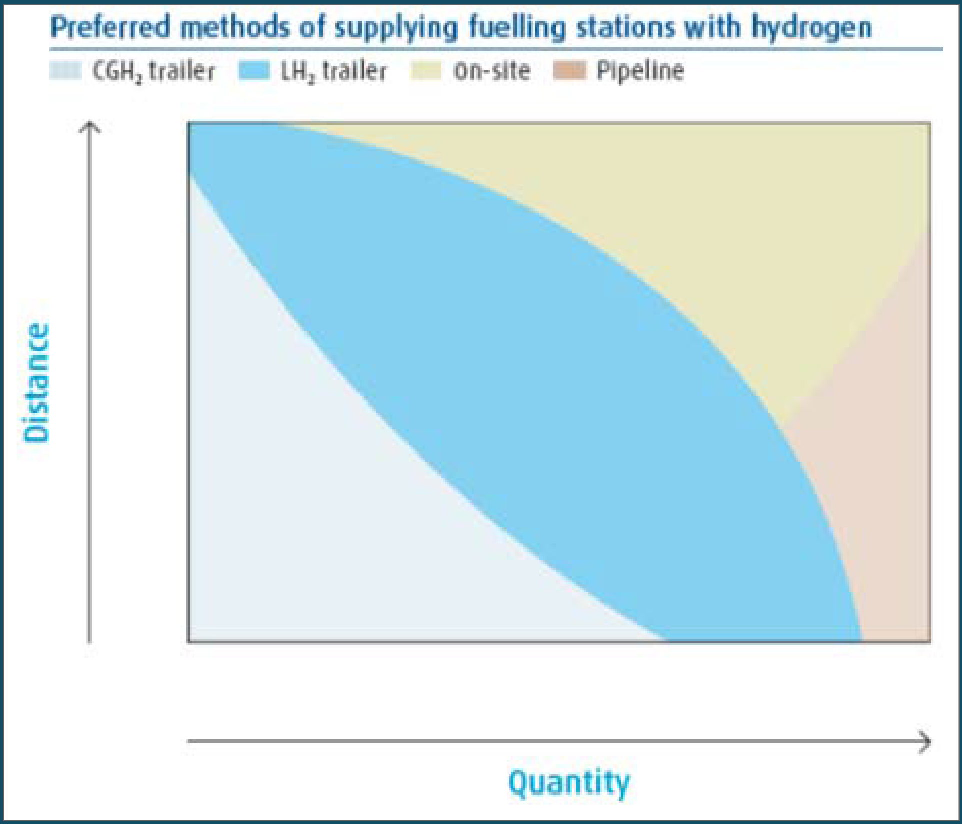

Figure 8: Preferred Hydrogen Supply Methods (image courtesy of The Linde Group)

There are various feasible hydrogen fuel production and delivery methods for transit agencies. The choice is most often based on fleet size and location.

9.1. Compressed gaseous hydrogen in tube trailers

Compressed hydrogen tube trailers are typically used in low-volume commercial applications or temporary demonstration projects. Trucks transport vessels of compressed gaseous hydrogen for short distances to deliver hydrogen from a central facility. These tube trailers provide convenient and portable fueling solutions but are typically less efficient than permanent liquid hydrogen installations. Limitations include the low storage capacity requiring frequent delivery and the low pressure of hydrogen delivered, which requires additional compression at the fueling station site. Nominal emissions are associated with the delivery to the site by internal combustion engine transport trucks.

Figure 9: Hydrogen Delivered Via Tube Trailer by Praxair

9.2. Liquid hydrogen delivery and storage

Figure 10: Liquid Hydrogen Storage by Air Liquide

Liquid hydrogen installations are an ideal solution for high-volume, permanent commercial installations, such as fueling stations for fuel cell transit bus fleets. The energy density of liquid hydrogen is considerably higher than that of compressed hydrogen and is therefore generally a more cost-effective solution for large-scale use, as fewer journeys are necessary to transport the same quantity of energy. The liquid hydrogen is then vaporized to a high-pressure product for use at the bus depot. Again, some nominal emissions are associated with the delivery to the site by internal combustion engine transport trucks.

9.3. On-site steam methane reformation

In North America today, more than 95% of hydrogen is produced by large-scale SMR. This is the most cost-effective method of hydrogen production. Medium-scale reformers are available for producing on-site hydrogen from natural gas for hydrogen bus fleets. Fully skidded, modular designs allow for low cost installation at the bus depot in a compact footprint. Also, renewable natural gas (RNG or biogas) can be a feedstock for the reformer to create renewable hydrogen in the SMR process. Although the SMR technology is popular and can be renewable, there are some emissions as a result of the process.

Figure 11: Air Products PRISM On-Site Hydrogen Generation System

9.4. On-site electrolysis

Figure 12: ITM Power's HFuel Unit Generates Hydrogen Gas From Water By Electrolysis

Electrolysis is a promising option for hydrogen production from renewable resources. Electrolysis is the process of using electricity to split water into hydrogen and oxygen. The resulting hydrogen is stored until it is needed to fuel the bus. Hydrogen produced via electrolysis can result in zero greenhouse gas emissions, depending on the source of the electricity used.

The table below summarizes the key characteristics of each hydrogen supply alternative.

TOPIC	Compressed gaseous hydrogen	Liquid hydrogen	On-site SMR	On-site electrolysis
Overall	Good for volumes <125kg/day	Excellent for large volumes	Good supplement for large volumes	Good supplement for large volumes
Distribution Costs	High; price drastically affected by location	Nominal; range flexibility	None	None
Price Volatility	Cost dependent on fuel prices but can be set with contract	Cost dependent on fuel prices but can be set with contract	Cost dependent on maintenance and fuel costs	Cost dependent on maintenance and electricity costs
Infrastructure Costs	Lower	Higher	Depends on production capacity	Depends on production capacity
Carbon Emission Reductions	Renewable hydrogen available at higher cost	Renewable hydrogen available at higher cost	Renewable biogas available at higher cost	Renewable energy is available at higher cost or renewable energy infrastructure can be installed on-site

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