California Environmental Protection Agency

AIR RESOURCES BOARD

DRAFT
TECHNOLOGY ASSESSMENT:
MEDIUM- AND HEAVY-DUTY FUEL CELL ELECTRIC VEHICLES

November 2015

State of California
AIR RESOURCES BOARD

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Acronyms and Abbreviations

AB	Assembly Bill
AC	Alternating Current
APU	Auxiliary Power Unit
AQIP	Air Quality Improvement Program
ARB	California Air Resources Board
BAAQMD	Bay Area Air Quality Management District
BOP	Balance of Plant
CalCAP	California Capital Access Program
CEC	California Energy Commission
CHAT	California Hydrogen Accounting Tool
CHIT	California Hydrogen Infrastructure Tool
CNG	Compressed Natural Gas
CPCFA	California Pollution Control Financing Authority
DC	Direct Current
DERA	Diesel Emissions Reduction Act
dge	Diesel Gallon Equivalent
DOE	Department of Energy
DOT	Department of Transportation
EO	Executive Order
FCEB	Fuel Cell Electric Bus
FCEV	Fuel Cell Electric Vehicle
FY	Fiscal Year
FTA	Federal Transit Administration
ft	feet
GGRF	Greenhouse Gas Reduction Fund
GHG	Greenhouse Gas
GMERP	Goods Movement Emission Reduction Program
GMP	Goods Movement Program
GSA	General Services Administration
GVWR	Gross Vehicle Weight Rating
HVIP	Hybrid and Zero-emission Truck and Bus Voucher Program
ITS	Institute of Transportation Studies
kg	kilograms
kW	Kilowatt
kWh	Kilowatt-Hour
L	Liter
lbs.	Pounds
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
MEA	Membrane-Electrode Assembly
mpdge	Miles per diesel gallon equivalent
MPa	MegaPascal
NFCBP	National Fuel Cell Bus Program
NO_x	Oxides of Nitrogen

NREL	National Renewable Energy Laboratory
NY	New York
NYT-VIP	New York Truck Voucher Incentive Program
O&M	Operation and Maintenance
PEM	Proton Exchange Membrane
PGM	Platinum Group Metal
SAE	SAE International
SCAQMD	South Coast Air Quality Management District
SJVAPCD	San Joaquin Valley Air Pollution Control District
SMAQMD	Sacramento Metropolitan Air Quality Management District
STEP	Sustainable Transportation Energy Pathway Program
TFCA	Transportation Fund for Clean Air
TIGGER	Transit Investments for Greenhouse Gas and Energy Reduction
TIR	Technical Information Report
U.S.	United States
U.S. EPA	United States Environmental Protection Agency
VIF	Voucher Incentive Fund
VIP	Voucher Incentive Program
W	Watts
Wt	Weight
W/kg	Watts per kilogram
W/L	Watts per liter
ZEBA	Zero Emission Bay Area
ZEV	Zero-Emission Vehicle

Executive Summary

The Air Resources Board's (ARB) long-term objective is to transform the on- and off-road mobile source fleet into one utilizing zero- and near-zero-emission technologies to meet established air quality and climate change goals. The purpose of the Fuel Cell Electric Vehicle (FCEV) technology assessment is to take a comprehensive look at the current status of and the five to ten year outlook for FCEV technology in the medium-duty (8,501 to 14,000 pounds (lbs.) Gross Vehicle Weight Rating (GVWR)) and heavy-duty (14,001 lbs. and above GVWR) truck and bus market.

FCEVs have the capability to completely eliminate tailpipe emissions of criteria and toxic pollutants and reduce overall greenhouse gas (GHG) emissions compared to a conventional fossil-fueled truck or bus. In this assessment, ARB staff examines current fuel cell vehicle status, as well as the status of hydrogen fueling infrastructure. Overall, the assessment finds that medium- and heavy-duty FCEVs are primarily in demonstration stages, although early commercial models are available for transit buses from two manufacturers. FCEVs can be fuel cell-dominant or battery-dominant, where the fuel cell acts as a range extender. Fuel cells are also used as auxiliary power units. FCEVs use proton exchange membrane (PEM) fuel cells.

Recent and on-going demonstrations for FCEVs include transit buses, shuttle buses, delivery vehicles, refuse trucks and drayage trucks. Fuel cells have also successfully penetrated the forklift category, and the lessons learned there should be transferrable to the on-road market. Overall, fuel cells are a promising approach to enable zero and near-zero emissions from the heaviest vehicle classes, including line haul trucks. Based on this assessment, ARB believes that fuel cell technology will assist California in reaching its climate change, air quality, and petroleum dependence reduction goals.

Presented below is an overview of the FCEV Technology Assessment that describes the potential for emission reductions, the status of FCEVs in medium-duty and heavy-duty trucks and buses, and what the next steps are for FCEVs in the on-road vehicle market. For simplicity, the discussion below is in a question-and-answer format.

1. What is a FCEV?

A FCEV is a vehicle with a fuel cell system that generates electricity to propel the vehicle and to power auxiliary equipment. Hydrogen fuel is consumed in the fuel cell stack to produce electricity, heat, and water vapor—no harmful pollutants are emitted from the vehicle. FCEVs are typically configured in a series hybrid design where the fuel cell is paired with a battery storage system. Together, the fuel cell and battery systems work to meet performance, range, efficiency, and other vehicle manufacturer goals. FCEVs have higher efficiencies, quieter operation, comparable range between fill-up, and similar performance to conventional vehicles (CAFCP, 2013).

2. For what medium- and heavy-duty on-road applications are FCEVs currently used?

Fuel cell electric transit buses (FCEB) were among the first fuel cell demonstrations in the heavy-duty on-road sector and hundreds have been demonstrated globally since 1991. More recent demonstration programs are showing that FCEBs have similar bus availability, performance, and durability to conventional transit buses. FCEBs are now in early commercialization; two manufacturers are offering FCEB models for sale in North America.

Demonstrations for other medium- and heavy-duty vehicles such as step vans, walk-in delivery vans, shuttle buses, and semi-tractors used in drayage service are in early stages. Demonstrations and early deployments are summarized in Table ES-1.

Table ES- 1: Summary of FCEV Deployments and Technology Readiness

Type of Vehicle	Technical Readiness	Numbers Deployed
Transit Bus	Early commercial	>20 active (>300 deployed worldwide)
Shuttle Bus		< 5
Delivery Vehicles	Demonstration	>35
Refuse Truck	Demonstration	<5
Drayage truck	Demonstration	~ 10

3. What upcoming applications are promising for medium- and heavy-duty FCEVs?

The early market for heavy-duty FCEVs is expected to be in applications where the vehicles can be centrally fueled, operated, and maintained. The transit bus experience can be applied to last mile delivery vehicles and other vocational uses where the trucks return to a central base or facility at the end of the day for fueling. As mentioned above, fuel cells are being demonstrated in delivery vans, shuttle buses, and drayage trucks. Recent drayage truck demonstrations have similar fuel cell-dominant series hybrid designs as those used in transit buses, but medium-duty demonstrations are typically using the fuel cell system to extend the range of battery electric vehicles. Fuel cells are the most promising advanced technology to enable long haul trucks, a major contributor to California's criteria and greenhouse gas emissions, to reach zero- or near-zero-emission goals.

4. What are the expected benefits of FCEVs, and what role can they play in meeting California's air quality and petroleum use reduction goals?

FCEVs have zero tailpipe emissions, leading to direct health benefits at the local and regional level. Even in the future, when diesel or natural gas vehicles may be much cleaner than today's vehicles (certified to a 0.02 gram per brake horsepower hour (g/bhp-hr) oxides of nitrogen (NOx) standard, for example), FCEVs still will provide additional tailpipe emission benefits, which may be crucial for attaining ambient air quality standards.

FCEVs can help meet climate change goals as well. Because emissions associated with the production of the hydrogen fuel are significantly lower than those associated with the production and combustion of petroleum fuels, FCEVs are also expected to have substantially lower overall well-to-wheel carbon dioxide equivalent emissions than vehicles powered by diesel- or natural gas-fueled engines. (Well-to-wheel emissions account for extraction, production, delivery, and dispensing of the fuel used in a vehicle, as well as vehicle efficiency in using the fuel.) ARB is developing a separate fuels technology assessment that will include a comparison of well-to-wheel emissions from various transportation fuels.

Use of FCEVs will provide significant reductions in petroleum consumption. Electric powertrains are much more efficient than internal combustion powertrains. This means that less energy is required to move people or goods using electricity than using other fuels. Even conventionally-sourced hydrogen is made from non-petroleum feedstocks. Further, in California, once FCEVs are widespread, hydrogen will be required to have 33 percent renewable energy content by Senate Bill 1505, which will further reduce the petroleum use and well-to-wheel emissions associated with FCEV use. FCEVs can also help balance the grid and reduce dependence on fossil fuels by utilizing hydrogen produced by renewable energy during off-peak hours.

Overall, deployment of FCEVs can help further California's efforts in meeting air quality, climate change, and petroleum use reduction goals.

5. What existing constraints limit the applicability of FCEVs for medium- and heavy-duty on-road applications?

The main constraints for FCEV use are vehicle cost, cost of and access to hydrogen fuel, and potentially, the need for more frequent vehicle fueling. Currently, the costs for FCEVs are significantly higher than for conventional vehicles, but costs are coming down as fuel cell technology continues to advance, and more experience is gained in operating FCEVs, as discussed further below. FCEVs are expected to have similar performance and fueling times as conventional trucks. However, hydrogen tanks currently take more space and weigh more than conventional diesel fuel tanks; this must be considered for the vehicle application. While FCEVs such as transit buses have sufficient space for hydrogen tanks such that comparable range between fueling can be achieved, the mass of stored hydrogen for some vehicles may be limited by weight or space, which may result in somewhat reduced vehicle range between fueling. Hydrogen is currently more expensive than diesel fuel, but these costs will come down with increasing production volume. Additional hydrogen fueling stations accessible to medium- and heavy-duty FCEVs must be constructed. In addition, hydrogen fueling standards for medium- and heavy-duty FCEVs still need to be established.

6. How does the cost for FCEVs differ from conventional vehicles?

Currently, 40-foot FCEBs cost around $1.3 million. The capital costs are high because there is only low volume production of custom built and third-party integrated vehicles. In comparison, diesel and natural gas powered 40-foot transit buses cost about $500,000 each, while diesel hybrid buses cost about $750,000 each (ARB, 2015a).

In California, about half of the new diesel bus purchases are hybrid electric buses. FCEBs are also hybrid electric vehicles, and share the same basic electric drive system components as diesel hybrid buses. As volumes increase and manufacturers move along the learning curve, costs are expected to decline significantly. For example, New Flyer has confirmed that with a multi-year order totaling 40 or more buses, a $900,000 price per bus would be feasible (New Flyer, 2014). With higher volumes, manufacturers can bring costs down by spreading engineering costs across more vehicles, because they have increased bargaining position for components, and because they can move towards assembly line production.

Costs are more difficult to project for fuel cell electric trucks because of the potential effect on payload capacity. Current demonstrations are focused on proving the technology and optimizing system designs to balance efficiency, weight, performance and costs.

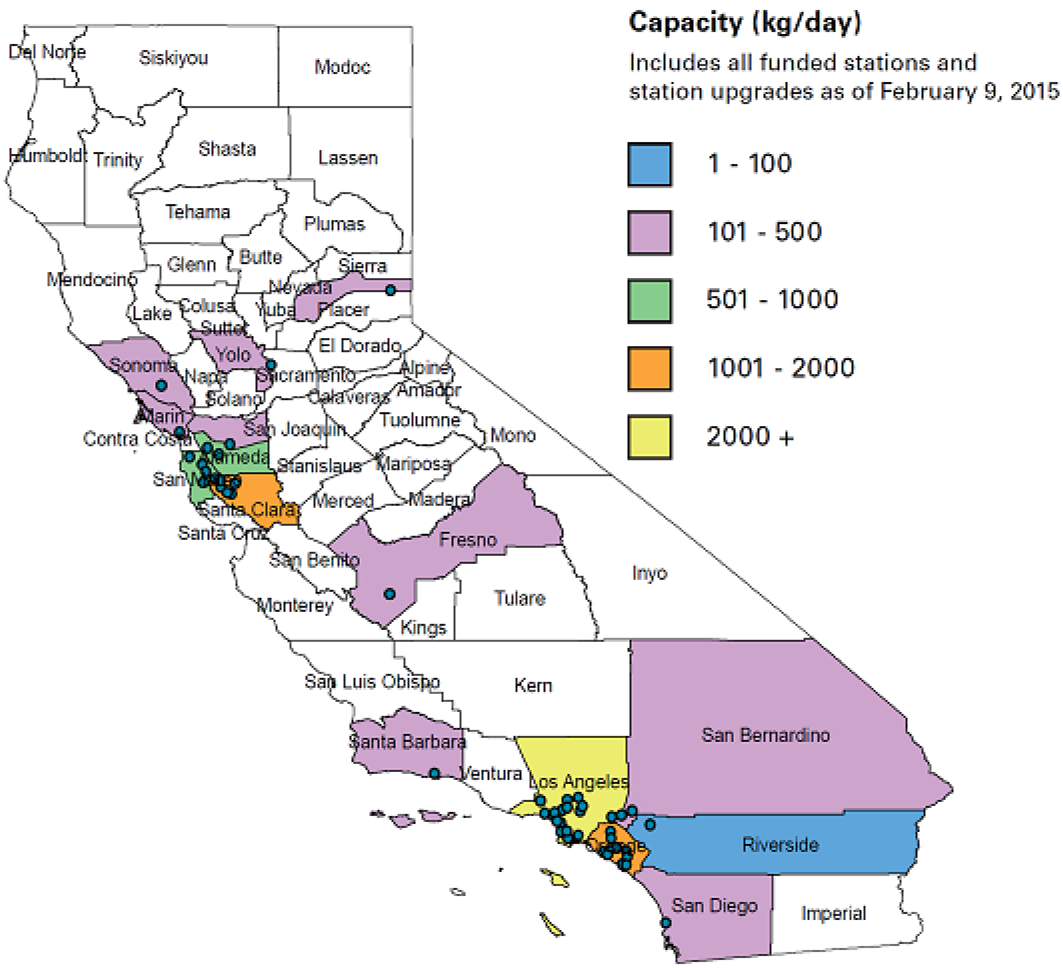
In addition to the costs of the technology itself, FCEV use will also require the development of a fueling infrastructure. In small volumes, hydrogen can be delivered by truck. However, as vehicle volumes grow, hydrogen can be effectively produced on-site, potentially at an equivalent or lower cost than the cost of diesel fuel.

7. What progress has been made to develop a hydrogen fueling infrastructure for fueling light-duty FCEVs in California, and what needs to be done to ensure that infrastructure is available for medium and heavy-duty FCEVs as well?

As directed by the legislature in Assembly Bill 8 (AB 8; Perea, Chapter 401, Statutes of 2013, Alternative Fuel and Vehicle Technologies: Funding Programs), the state has made significant efforts to develop a network of hydrogen fueling stations for light-duty FCEVs. Those efforts are bearing fruit in a network of fueling stations, primarily targeted at fueling light-duty FCEVs. California Energy Commission (CEC) has been providing $20 million per year in funding for hydrogen stations (both for station commissioning and operation), and is directed by AB 8 to continue to do so until there is a network of 100 stations statewide.

As of November 2015, California had 13 open hydrogen stations, mostly located at existing gasoline stations (Office of Governor, 2015). By the end of 2016, 51 stations are expected to be operational. These 51 stations will have a capacity of 9,400 kilograms hydrogen per day, equivalent to an expected demand for approximately 13,500 light-duty FCEVs (ARB, 2015h). Figure ES-1 below shows hydrogen station locations and existing and planned hydrogen dispensing capacity by county.

Figure ES- 1: Existing and Planned Hydrogen Dispensing Capacity by County (Predominantly Light-Duty Fueling)



(ARB, 2015h)

ARB staff has been tracking the network of fueling stations and has developed several sophisticated tools, tailored to California's geography and expected rollout of light-duty fuel cell vehicles by zip code, to identify gaps in coverage. The CEC in turn is using that information on projected gaps to aid in deciding where to fund additional stations.

All but a handful of the hydrogen stations described above are in place or planned for light-duty FCEV use, and because of the high pressure at which they dispense hydrogen, as well as different fueling protocols and nozzles, are not compatible for use with current fueling protocols for medium- or heavy-duty vehicles.

Unlike light-duty vehicles, currently, all hydrogen fueling stations specifically for medium- and heavy-duty vehicles are located in private facilities, dedicated to a particular fleet. For example, Sunline Transit operates a hydrogen fueling station in Thousand Palms, California for its FCEB fleet, and allows passenger cars public access for 35MPa fuel. AC Transit dispenses hydrogen to its FCEB fleet in Emeryville with passenger car access to 35MPa and 70 MPa fuel outside the bus yard. In Oakland, AC Transit has located hydrogen dispensers in the same fuel island as diesel, enabling operators to service FCEBs in line with conventional buses and increase operational efficiency.

Because transit buses are currently the only commercially available medium- or heavy-duty FCEV, and because requirements for zero-tailpipe emission buses are being considered as part of ARB's Advanced Clean Transit rulemaking, staff expects the nearest term need for medium- and heavy-duty hydrogen fueling to be for fuel cell transit buses. Staff anticipates such fueling infrastructure would be planned and constructed along with acquisition of fuel cell buses, and that transit agencies affected by the Advanced Clean Transit rulemaking may coordinate on such infrastructure (ARB, 2015a).

Although a full analysis of needed infrastructure for medium- and heavy-duty hydrogen fueling was beyond the scope of this assessment, the issue of future hydrogen infrastructure needs for medium- and heavy-duty vehicles will be explored more fully as part of ARB's upcoming fuels assessment and other efforts. This document lays out steps below for addressing needed hydrogen infrastructure for medium- and heavy-duty FCEVs:

a) Estimate the future populations, deployment timing, vocations, fuel volumes and geographic locations for medium- and heavy-duty FCEVs.
b) Modify or add to light-duty analysis tools to allow analysis of medium- and heavy-duty fueling infrastructure needs.
c) Determine where the greatest anticipated unmet needs for medium- and heavy-duty hydrogen fueling structure are likely to be.
d) Work with CEC and other stakeholders to meet those unmet needs, potentially through co-locating medium- and heavy-duty fueling at light-duty stations, where appropriate, or adding new medium-/heavy-duty stations.

8. What next steps are necessary to foster the expanded use of medium- and heavy-duty on-road FCEVs?

There are a number of steps that should be taken to foster the expanded use of these vehicles, as indicated in Table ES-2. First, continued support of early commercialization and pre-commercial demonstration of fuel cell technology in new applications is critical. The experience and data collected from operating larger numbers of FCEBs are expected to provide more information about the business case for operating FCEVs generally. Using the bus experience, the next focus should be on fuel cell electric trucks that are centrally fueled and have the potential to become commercial in the near future such as delivery vehicles, refuse trucks, and drayage trucks.

Table ES- 2: Heavy-Duty FCEV Action Items and Likely Lead Parties

	Action Item	Lead Party		
		Gov't	Research Institutions	Industry
1	Continue/Expand demonstrations of FCEVs	✓	✓	✓
2	Adopt SAE International fueling standard			✓
3	Hydrogen station validation test equipment/procedures	✓	✓	✓
4	Site publicly available hydrogen stations	✓		✓
5	Improve/continue incentives	✓		
6	Regulatory activity, such as Advanced Transit and Last Mile Delivery regulations, and the development and adoption of other regulations	✓		

Gov't = Government, and includes public entities such as ARB, California Energy Commission, DOE, air districts, and ports
Research Institutions = Academia and National Laboratories, Researchers
Industry = vehicle manufacturers, battery manufacturers, component manufacturers

As these demonstrations take place, development of hydrogen fueling infrastructure will begin in order to fuel the new vehicles. The current Technical Information Report J2601/2 that the SAE International has released for medium- and heavy-duty FCEV fueling should be developed into a standard. Test equipment and procedures should also be developed in parallel to validate that hydrogen stations meet the heavy-duty fueling standard, similar to what has been developed for light-duty FCEVs. Increased use of hydrogen as a fuel for all vehicles, including the light-duty fleet, will contribute to reductions in the cost of hydrogen fuel.

Finally, both financial incentives and regulatory approaches should be used to transition medium- and heavy-duty on-road vehicles to zero-emission technologies, including fuel cell technology. ARB has allocated ~$25 million toward zero-emission drayage trucks and has another $20 million for the zero-emission truck and bus pilot project sourced from Greenhouse Gas Cap and

Trade Auction proceeds to reduce carbon emissions from transportation sectors (AQIP, 2014). On October 1, 2015, ARB released a solicitation to fund larger-scale deployments of zero-emission trucks, buses, and school buses (including hybrid vehicles capable of operating in zero-emission mode within disadvantaged communities) and associated charging/fueling stations. An additional $60 million from fiscal year 2015-16 will be available for these projects pending approval by the California Legislature. For technologies that are commercially available, the California Hybrid and Zero-emission Truck and Bus Voucher Incentive Project (HVIP) assists the introduction of zero- and near-zero-emission trucks and buses by providing vouchers to cover partial purchase cost of these advanced vehicle technologies with the aim to help accelerate market penetration of zero-emission vehicles (e.g., FCEVs). For zero-emission vehicles, voucher amount can be up to $110,000 per vehicle (HVIP, 2015). U.S. Department of Energy continues to fund additional demonstrations to broaden the known applicability for FCEVs as well. Using a combination of incentives and regulations to expand the use of FCEVs provides market signals for manufacturers and reduces risk for fleet owners that operate the vehicles.

I. Introduction and Purpose of Assessment

The Air Resources Board's (ARB) long-term objective is to transform the on- and off-road mobile source fleet into one utilizing zero- and near-zero-emission technologies to meet established air quality and climate change goals. Fuel cells are a technology that supports this objective. The purpose of this Fuel Cell Electric Vehicle (FCEV) technology assessment is to take a comprehensive look at the current status of FCEV technology in the medium-duty and heavy-duty truck and bus market and the 5 to 10 year outlook of technologies that are being employed in FCEVs. This technology assessment will support ARB planning and regulatory efforts, including:

- California's Sustainable Freight Strategy planning;
- State Implementation Plan development;
- Funding Plans;
- Governor's Zero Emission Vehicle Action Plan; and
- California's coordinated goals for greenhouse gas (GHG) and petroleum use reduction.

A FCEV is a zero-emission vehicle with a fuel cell system that generates electricity to propel the vehicle and operate auxiliary equipment. The FCEV also includes a battery pack to assist with additional power demands, such as for rapid acceleration, hill climbing, and auxiliary power needs. Since fuel cells emit only water, and batteries have no associated emissions, there is no on-board source of criteria pollutant or GHG emissions from the vehicle. The prime source of emissions associated with FCEV operations is from the generation of the hydrogen fuel. Even using conventionally-sourced hydrogen from steam reformed natural gas, FCEVs have significantly lower GHG emissions on a well-to-wheel basis compared to combustion vehicles (ARB, 2009). If hydrogen is produced from renewable energy sources, FCEVs have the potential for near-zero total well-to-wheel emissions (as do battery electric vehicles recharged using renewable energy), which will be key to achieving significant GHG reductions in the long term.

The elimination of criteria pollutants from a vehicle's tailpipe can have a significant positive effect in communities that are burdened by the emission of pollutants associated with conventionally fueled vehicle operations. In the medium- and heavy-duty arena, diesel fueled engines are commonly used; utilizing FCEVs in traditional diesel fueled truck and bus applications can yield significant reductions in people's exposure to pollutant emissions. In addition, electric motors are generally more efficient overall than conventional vehicles because their motors and transmissions more effectively convert the potential energy in the fuel source into kinetic energy, or motion, and maintenance requirements for electric motors are substantially less than their combustion-powered counterparts. The estimated emission reduction from FCEVs is explored in Chapter VII Emission Benefits of FCEVs.

Various initiatives have supported demonstration of fuel cell technology in medium- and heavy-duty vehicle applications. Since 1991, over 300 fuel cell electric buses (FCEB) have been deployed worldwide (ARB, undated). Today, in the United States (U.S.), over twenty FCEBs are being demonstrated (NREL, 2014). Their operation and performance is comparable to conventional buses while fuel efficiency (in miles per diesel gallon equivalent, or mpdge) is twice as high (NREL, 2013b). These demonstration programs have supported the advancement of fuel cell technology and vehicle design, provided valuable on-road performance data, and provided a path to commercialization. FCEBs are in the early commercialization stage with two manufacturers offering three transit bus models for sale. The early investments in advanced technologies for transit buses are leading to continued technology improvements and cost reductions that may help enable a transition to zero-emission technologies for trucks and other medium- and heavy-duty applications.

This technology assessment focusses on the current status of the technology, demonstrations completed or in progress, and next steps to be taken. It includes the following elements:

- Chapter II describes fuel cell system components and how FCEVs work;
- Chapter III discusses hydrogen fueling and infrastructure;
- Chapter IV summarizes FCEV demonstration programs in the United States;
- Chapter V examines FCEV, fuel, and fueling station costs and available incentive funds;
- Chapter VI discusses the emission benefits of FCEVs;
- Chapter VII discusses synergies with other technologies; and
- Chapter VIII summarizes the conclusions and proposed next steps.

II. Overview of Fuel Cell Electric Vehicles

A FCEV is a zero-emission vehicle with a fuel cell system that generates electricity to propel the vehicle and operate auxiliary equipment. Hydrogen fuel is consumed in the fuel cell stack to produce electricity, heat, and water vapor—no harmful pollutants are emitted from the vehicle. Fuel cells are attractive as a propulsion technology option for on-road vehicles due to the following environmental and operational benefits:

- Zero tailpipe criteria pollutant and GHG emissions;
- Quiet operation;
- Quick and smooth acceleration;
- High fuel efficiency;
- Lower well-to-wheel GHG emissions compared to conventional technologies
- Range and performance comparable to conventional vehicles; and
- Refueling time similar to conventional liquid fueling.

Section A below discusses how FCEVs are configured, in either a fuel cell-dominant or battery-dominant configuration. Section B discusses each main component of a fuel cell system.

A. Fuel Cell Configuration – Fuel Cell-Dominant vs. Battery-Dominant

Fuel cells are both clean and efficient. However, high transient peak power demands such as are seen with acceleration events cannot be met as quickly by a fuel cell as they can by batteries or capacitors. For this reason, current FCEVs are generally configured in a hybrid design wherein the fuel cell system is used in combination with batteries or capacitors to power the vehicle (i.e., a series hybrid design) (NREL, 2003).

The fuel cell in such a series hybrid FCEV can be used in three configurations:

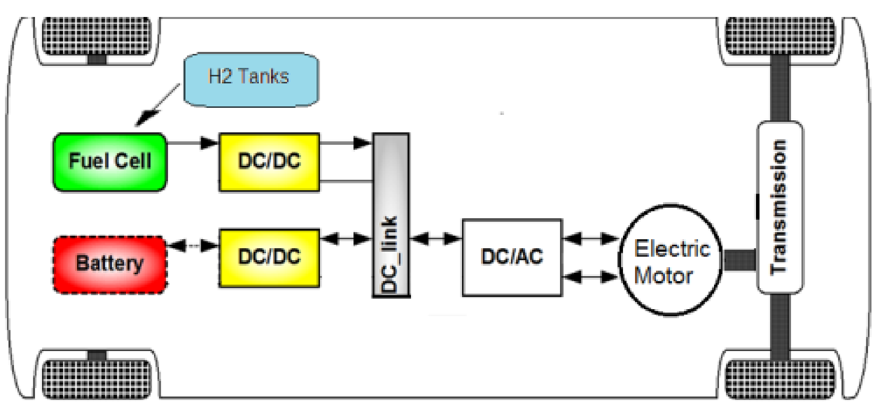
- Fuel Cell-Dominant - When used as the primary source of electricity, the fuel cell, usually over 80 kilowatt (kW) in size, acts as the primary source of power for the electric motor, with a smaller energy storage system, such as batteries or capacitors, to capture regenerative braking energy, to assist with load following, and to assist launch. This configuration is called a fuel cell-dominant FCEV or a prime power FCEV. The battery or capacitor system can assist the fuel cell during start up, while the fuel cell reaches its operating temperature, by providing power to auxiliary components and other start-up loads. Once the fuel cell system is at normal operating temperature, the energy storage system can continue to provide additional power as needed for hill climbing, powering auxiliaries, and other short-term energy demands while the fuel cell either directly provides the balance of power needs to the electric motor or keeps the energy storage system charged. This allows the fuel cell to operate more efficiently, improves vehicle performance and allows for energy from braking to be recaptured, which improves the overall fuel efficiency of the vehicle.

- Battery-Dominant - Fuel cells can also be used in a battery-dominant configuration as range extenders. In this case, the vehicle is primarily propelled by electricity stored in a battery pack. The role of the fuel cell in a battery-dominant system is to provide additional power to extend the range of the vehicle when needed. In this incarnation, the fuel cell is typically rated at 30-80 kW. A battery-dominant FCEV (also called fuel cell range extender) utilizes battery power until the battery state-of-charge falls to a specified level, at which point the fuel cell will begin to produce power to recharge the batteries or to directly power the vehicle, depending on the hybrid configuration. The additional range provided by the fuel cell is determined by the amount of hydrogen stored on-board the vehicle. Battery-dominant systems have cost advantages because batteries currently cost less than fuel cells. Performance is similar between the two configurations, but the battery-dominant fuel cell vehicle may be advantageous to the battery electric vehicle operator because the fuel cell system increases range, limits battery cycling depth (increasing battery life), reduces grid demand charges and charge congestion for large fleets, and reduces downtime for charging.
- Auxiliary Power Unit (APU) - A small 5-10 kW fuel cell can be used as an APU. The role of fuel cells in this application is discussed in *Draft Technology Assessment: Commercial Harbor Craft* and *Technology Assessment: Transport Refrigerators*.

B. Fuel Cell System Components

Like hybrid electric and battery electric trucks and buses, FCEVs also use traction batteries or capacitors, inverters, and electric motors. Similarly, FCEVs also require the use of electrified accessories, which are beginning to be developed for conventional trucks as well to improve overall efficiency and reduce emissions. Figure II-1 shows a basic representation of the major system components in a FCEV.

Figure II- 1: FCEV Major System Components

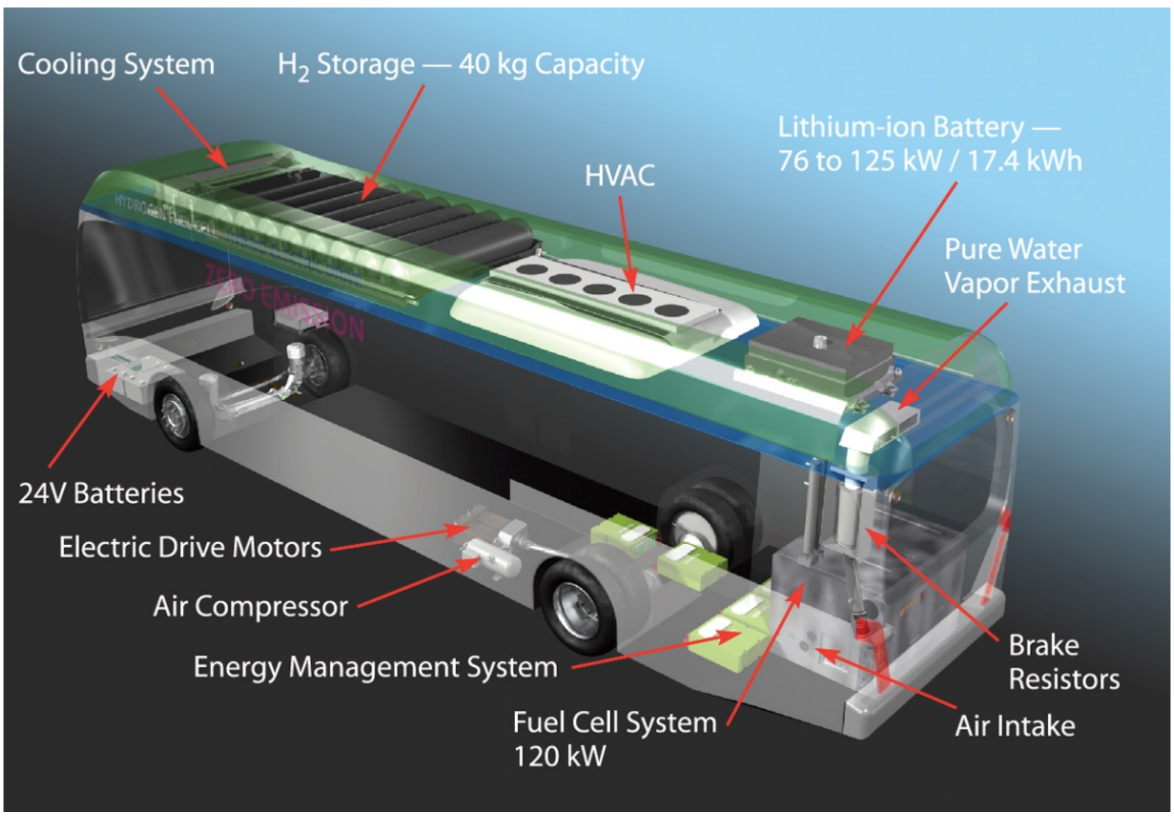


(Intechopen.com, undated)

The energy storage system (batteries or capacitor) is connected via the converters to the electric motor that moves the vehicle. The fuel cell supplies energy to the electric motor and/or delivers power to the energy storage system. This is a series hybrid architecture because the electric motor provides all of the propulsion. For information on other hybrid vehicle configurations, see *Draft Technology Assessment: Medium- and Heavy-Duty Hybrid Vehicles*. For information on the status of batteries used in electric vehicles, see *Draft Technology Assessment: Medium- and Heavy-Duty Battery Electric Trucks and Buses.*

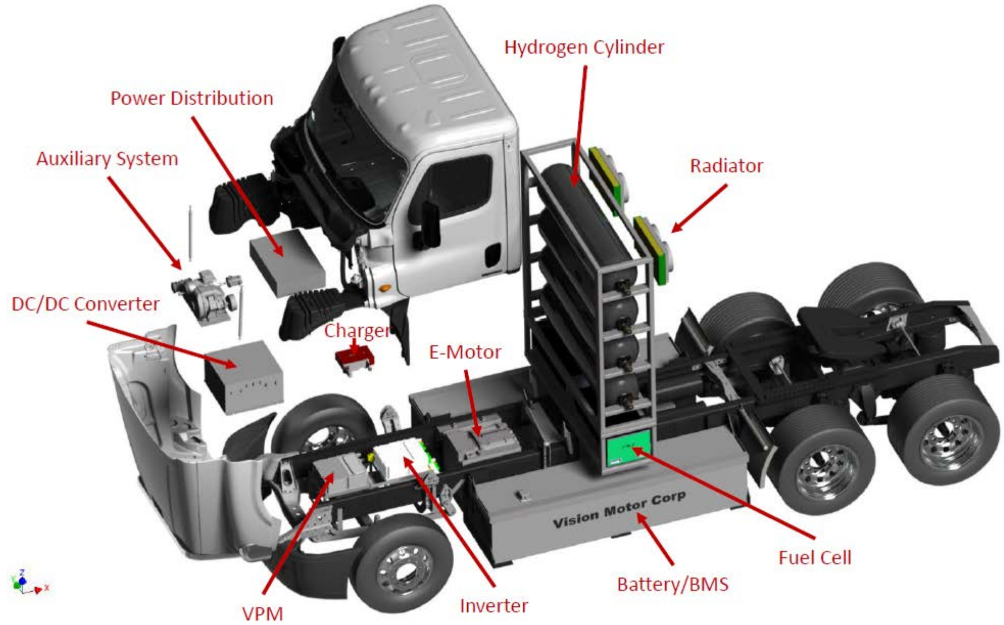
Major subsystems of a FCEV are discussed below and include the fuel cell stack, balance of plant, energy storage system, drivetrain, and hydrogen storage system. These components must all be fit into the existing or modified vehicle architecture. The fuel cell system has been seamlessly incorporated into light duty vehicles, which are now commercially available from major vehicle manufacturers (Hyundai and Toyota). These vehicles are indistinguishable externally from their conventionally fueled counterparts. However, heavy-duty vehicles typically require additional storage, and the placement of sufficient hydrogen tanks is one issue still being resolved. The hydrogen storage system for buses is usually placed on the roof, while trucks, lacking a suitable rooftop footprint, may place the hydrogen cylinders behind the cab. Figure II-2 and II-3 depict examples of typical integration of major subsystems in FCEBs and trucks.

Figure II- 2: Fuel Cell Electric Bus Design



(Golden Gate, 2013)

Figure II- 3: Fuel Cell Electric Truck Schematic

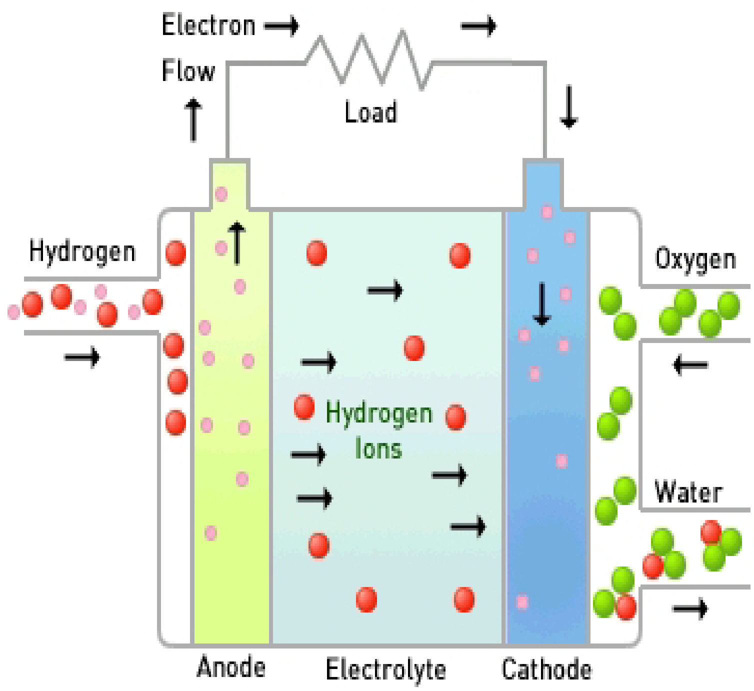


(Vision Industries Corporation, 2014)

1. Fuel Cell System: Fuel Cell Stack

Unlike a battery that stores electricity generated elsewhere, a fuel cell creates electricity from two reactants, hydrogen and oxygen. Like a battery, a fuel cell contains two electrodes, an anode and a cathode. These electrodes are separated by a catalyst-coated membrane. Hydrogen, stored on-board the vehicle, enters one side of the fuel cell while air, containing needed oxygen, enters the other side, as shown in Figure II-4. While the hydrogen molecules move through the electrolyte in the stack towards the oxygen, they are separated into electrons and protons. The protons pass through the membrane while the electrons move to the anode, generating electricity for the vehicle to use for tractive power and auxiliaries. When the electrons reach the cathode, they recombine with the protons, react with the oxygen, and form water, the direct "emissions" from a fuel cell. Unlike a battery for which the amount of electricity is limited by battery size and state of charge, fuel cells can continue to provide electricity as long as hydrogen and oxygen are supplied.

Figure II- 4: Illustration of Generic Individual Cell

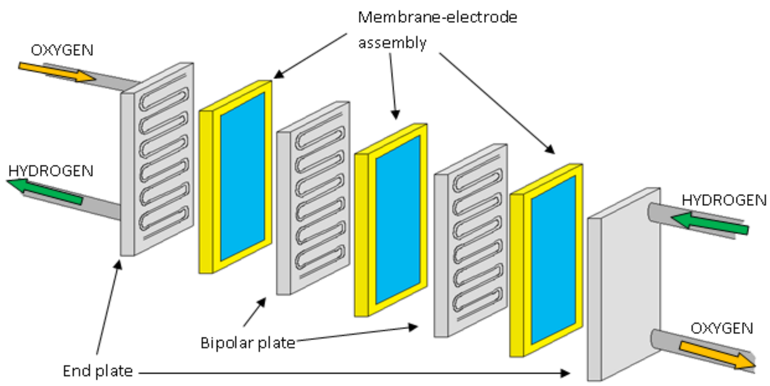


(modified from scopewe.com, 2013)

Various fuel cell types exist today, including alkaline, proton exchange membrane (PEM), direct methanol, molten carbonate, phosphoric acid, and solid oxide fuel cells. However PEM fuel cells are most compatible with motive applications because they have a low operating temperature, high power density, good stop-start and dynamic load following characteristics, and are efficient. The focus on this single electrochemistry for fuel cells in transportation has allowed for substantial technological advancements. Intensive research and development by industry, national laboratories, and academia have led to improvements in almost every facet of PEM fuel cells, including increased durability and cost reduction (FuelCellToday, 2013).

PEM fuel cells are constructed from a proton-conducting membrane, usually a perfluorinated sulfonic acid polymer. The membranes are coated with a thin layer of platinum-based catalyst and porous carbon electrode support material. The membrane is then sandwiched between the anode and cathode to form the membrane-electrode assembly (MEAs), which is the individual fuel cell. The MEAs are connected in series to provide the desired voltage and power output required for the application, forming the fuel cell stack. Figure II-5 illustrates the modular design of a fuel cell stack. Bipolar plates, typically made of graphite or stamped metal, connect the individual cells together. They conduct electrical current from the anode of one cell to the cathode of the next. The anode and cathode electrodes are typically composed of carbon paper or cloth. Each bipolar plate is designed with grooved channels to uniformly distribute the fuel and oxidant separately to the anode and cathode. The bipolar plates also serve to support the thin MEAs. End plates further support the stack, as well as prevent the gases from escaping from between the plates. Typical materials used in PEM fuel cells are summarized in Table II-1. PEM fuel cells are produced by a variety of manufacturers in sizes suitable for smaller applications such as APUs up to megawatt power systems.

Figure II- 5: Schematic of Fuel Cell Stack Assembly



(FuelCellStore, 2015)

Table II- 1: Typical PEM Fuel Cell Materials

Component	Material
Electrolyte	Perfluorinated Sulfonic Acid Polymer
Electrodes	Carbon Paper or Cloth
Catalyst	Platinum Group Metal (PGM) and PGM-alloys
Bipolar Plates	Graphite or Metal

Current performance characteristics of PEM fuel cells used in buses are shown in Table II-2. The power ratings for the fuel cell systems evaluated range from 30 to 150 kW. The system efficiency for the PEM fuel cells included in this aggregate analysis ranges from 48 to 59 percent. This is considerably better than the thermal efficiency of a conventional diesel engine, typically around 40 percent. Further, since the FCEV essentially uses no fuel while idle, the effective system efficiency for the PEM fuel cell is substantially higher than that of the conventional diesel engine, and the fuel economy of medium- and heavy-duty FCEVs on a mpdge basis is 1.5 to 2 times better than conventional vehicles in stop-and-go driving.[1] For example, FCEBs can achieve a fuel efficiency of up to 7.84 mpdge (CAFCP, 2013). Performance characteristics for medium- and heavy-duty PEM fuel cells are expected to continue improving with technology and manufacturing advancements.

[1] An mpdge comparison is made to compare the mpg for diesel vehicles with the mile per kg hydrogen metric for a FCEV. The conversions compare the lower heating value (LHV) of diesel, 128,450 Btu/gal, to the LHV of hydrogen, 51,682 Btu/lbs. The LHV (or net calorific value) of a fuel is the amount of heat released by combusting a specified quantity of the fuel, initially at 25°C, and returning the temperature of the combustion products to 150°C. The assessment assumes the latent heat of vaporization of water in the reaction products is not recovered. Using this approach, 1kg hydrogen is 0.89 dge.

The volume of the fuel cell system is roughly equivalent to a conventional engine of the same power rating. Thus, the fuel cell stack and its associated components can fit in most existing engine bays. The system specific power for medium- and heavy-duty PEM fuel cells is similar to conventional engines. For instance, a Cummins ISB 6.7 diesel engine that is used in hybrid transit buses is rated at 209 kW and, with a system weight of 616 kilograms (kg), has a system specific power of 339 watts per kg (Cummins, 2013), falling in the range of these medium- and heavy-duty fuel cell systems.

Table II- 2: Performance Characteristics: PEM Fuel Cell Electric Buses

Characteristic	Units	2014 Status
Operating Temperature	°C	-20 to 90
System Efficiency	percent	48-59
Stack Durability	Hours	19,000
Stack Power Density	W/L	1,500-1,800
System Power Density	W/L	200-300
Stack Specific Power	W/kg	1,000-1,500
System Specific Power	W/kg	250-550
System Volume	--	Equivalent to Diesel

2. Fuel Cell System: Balance-of-Plant

The fuel cell system consists of the fuel cell stack, described above, and the balance-of-plant (BOP). The BOP contains several sub-systems that manage the fuel (hydrogen), oxidant (oxygen), water, power, heat, and other factors that affect the performance of the fuel cell stack. Each subsystem supports the vital functions of the fuel cell stack. A summary of the functions and types of components common to each of these subsystems is below:

- Fuel Delivery: For PEM fuel cells, hydrogen is delivered to the fuel cell stack by pumps or blowers or compressors, in addition to electric motors.
- Air Supply: Air is most commonly used as the source of the oxygen needed for the fuel cells. The air supply subsystem consists of air compressors or blowers and air filters.
- Water Management: Water is produced in the fuel cell stack when hydrogen and oxygen react. Some of the water becomes steam and leaves the system through a vent. Some liquid water can accumulate in the stack, usually during idling or at full speed. This water slows down the conversion process and must be purged periodically, while sufficient water is retained to adequately hydrate the electrolyte to maintain conductivity. The water management subsystem can include a humidifier, water recovery loop, demister, and pump.
- Thermal Management: All fuel cell systems require careful management of the temperature of the fuel, oxidant, water, and fuel cell stack. The thermal

management subsystem can include fans, blowers, pumps, intercoolers, humidifiers, radiators, pre-coolers, preheaters, and other heat exchangers.

- Power Conditioning: The power conditioning requires power regulation and inversion. Fuel cells and batteries both produce direct current (DC) electricity, while the electric drivetrain may require alternating current (AC) or DC. A DC/DC converter regulates the fuel cell power. For AC electric drivetrains, the DC power must be inverted to power the electric motors, typically by using a DC/AC inverter.

3. Drivetrain, Including the Energy Storage Systems

The fuel cell converts the stored hydrogen energy into electricity. The electric propulsion system converts this electricity to traction power to propel the vehicle and to power auxiliary equipment. Excess electricity generated can be used to recharge the energy storage system, which generally consists of battery packs and/or ultra-capacitors. During times when the fuel cell is not producing sufficient electricity, the additional electricity needed is drawn from the energy storage system. The energy storage system also reclaims energy through regenerative braking. Depending on the vehicle design, the fuel cell may power the drivetrain directly, it may keep the energy storage system recharged and then use that stored energy to power the drivetrain, or a combination of the two approaches may be utilized. The FCEV drivetrain is similar to an internal combustion hybrid drivetrain, where the fuel cell system and electric motor takes the place of the engine and the hydrogen tank replaces the conventional fuel tank. The electric motor can be either a single main motor or one or more hub-mounted motors.

Maximum power output and storage capacity of the energy storage system vary depending on hybrid architecture. A discussion of battery storage systems for medium- and heavy-duty vehicles is included in *Draft Technology Assessment: Medium- and Heavy-Duty Battery Electric Trucks and Buses*.

4. Onboard Hydrogen Storage

Although there are several methods to store hydrogen, today's FCEVs generally operate on gaseous hydrogen that is stored in cylinders. Most medium and heavy duty FCEVs carry one or more tanks on-board of high-purity high-pressure hydrogen gas stored at 350 bar (35 megapascal (MPa)). Although not common, higher pressure gas (70MPa) or liquefied hydrogen could be utilized if range considerations necessitate its use.

(a) Compressed Hydrogen

Gaseous hydrogen for mobile sources can be stored in Type III or Type IV tanks. In Type III tank design, an aluminum tank is wrapped in a composite material, usually carbon fiber. In a Type IV tank, the tank is made of composite materials with a thermoplastic polymer liner such as high density polyethylene. This polymer liner helps to reduce hydrogen permeation. For fast fill, Type III tanks are preferable because aluminum can more quickly dissipate the heat that results from hydrogen fueling. Type IV tanks are more suited for applications where slow fill is used so that heat buildup does not stress the polymer materials.

As with compressed natural gas-fueled vehicles, the mass and volume for the stored hydrogen is greater than that required for diesel or gasoline to provide a similar range. The American Fuel Cell Bus uses eight Type III cylinders for hydrogen storage (NREL, 2012). FCEBs typically store 25 to 35 kg of hydrogen on-board. The amount of stored hydrogen is a tradeoff between increased weight/volume and range. Table II-3 summarizes the type, number, diesel gallon equivalent (dge), total tank (with fuel) weight, and total volume for these buses. Note that diesel transit buses usually store 100 to 125 gallons of diesel on-board. As can be seen from the table, hydrogen fuel tanks can store up to 45 dge of hydrogen for a FCEB, or about half the gallons of diesel stored on a diesel bus; however, since heavy-duty FCEBs are 1.9 time more efficient than heavy-duty diesel buses, this amount of fuel is sufficient to give approximately the same range as for diesel transit buses (ARB, 2009). In addition, even though the amount of hydrogen dge stored (45 dge) is about a third of the natural gas dge stored (144 dge), the total weight and volume of hydrogen fuel tanks are about the same as for natural gas fuel tanks and still provide similar range.

Table II- 3: Weight and Volume of Tanks in Bus Applications

Fuel Type	Description	DGE[1]	Total Weight[2] (lbs)	Total Volume (cubic foot)
Diesel	1 Aluminum tank[3]	100	792[4]	14.7
CNG (250 bar)	6 Type III tanks[5]	144	2,210	84.8
CNG (250 bar)	6 Type IV tanks[6]	143	2,355[7]	83.8
H_2 (350 bar)	8 Type III tanks[8 9]	45	2,166	99.6

[1] Although FCEB hydrogen fuel tanks store only about half/ a third the dge as diesel/CNG buses, because heavy-duty FCEBs are nearly twice/more than twice as efficient as heavy-duty diesel /natural gas buses (ARB, 2009), the FCEBs still provide similar range as diesel or natural gas buses.
[2] "Total weight" includes both the tank and fuel weight.
[3] Aluminum cylindrical tank (24 in x 56 in) http://www.clevelandtank.com/aluminum-fuel-tanks.html
[4] Weight of diesel fuel was estimated from its density value of 7.1 lbs./gallon.
[5] Luxfer G-Stor® Pro cylinders (15.9 in x 123.1 in) http://www.luxfercylinders.com/products/alternative-fuel-cylinders/443-type-3-alternative-fuel-cylinder-specifications?tags=undefined&format=pdf&tmpl=component
[6] Hexagon Lincoln TUFFSHELL™ Brochure (16 in x 120 in) http://www.hexagonlincoln.com/downloads
[7] Weight of CNG fuel was estimated from its dge weight value (6.38 lbs./dge) by U.S. Department of Energy (http://www.afdc.energy.gov/fuels/fuel_comparison_chart.pdf).
[8] 8 tanks total: 4 tanks are 16.3 in x 83.1 in and other 4 tanks are 16.3 in x 123.1 in.
[9] Luxfer Dynecell® http://www.luxfercylinders.com/index.php?option=com_k2&view=item&id=504percent3Aluxferdynecell&Itemid=31&tmpl=component&print=1

(b) Liquefied Hydrogen

Liquefied hydrogen has high energy density and is best suited for applications with high fuel consumption where long ranges between fill-ups are needed. Cryogenic tanks are insulated by perlite-packed or multilayer vacuum and may hold liquid hydrogen at up to 35 MPa. If full tanks are left unused, pressure increases as the hydrogen in the tank warms. The extra pressure is vented before it exceeds the design specifications of the tank. This boil-off is not a problem if the filled tanks are returned to service because by the time the hydrogen has warmed enough to require venting, some has already been used, creating more space in the tank. High pressure liquid storage allows for significant range. Although current medium- and heavy-duty FCEVs do not use liquefied hydrogen, it remains an option for long haul or high use applications.

III. Hydrogen Fueling Infrastructure

For medium- and heavy-duty FCEVs to be viable, infrastructure must be developed for fueling the vehicles. Hydrogen stations designed specifically to fuel medium- and heavy-duty FCEVs must be available, and adequate supplies of hydrogen must be produced at or delivered to the stations, compressed, and dispensed. Section A below discusses hydrogen fueling infrastructure, including progress that has been made to develop an infrastructure for fueling light-duty FCEVs and what needs to be done to ensure that infrastructure is available for medium and heavy-duty FCEVs as well. Section B discusses hydrogen fueling protocols; Section C discussed hydrogen production; and Section D discusses hydrogen compression.

A. Hydrogen Fueling Infrastructure in California

For vehicles using alternative fuels, fueling infrastructure availability is an important consideration because it determines where the vehicles can be used.

1. Light-duty Hydrogen Fueling Infrastructure

As directed by the legislature in Assembly Bill 8 (AB 8; Perea, Chapter 401, Statutes of 2013, Alternative Fuel and Vehicle Technologies: Funding Programs), the state has made significant efforts to develop a network of hydrogen fueling stations for light-duty FCEVs. Those efforts are bearing fruit in a network of fueling stations, primarily targeted at fueling light-duty FCEVs. California Energy Commission (CEC) has been providing $20 million per year in funding for hydrogen stations (both for station commissioning and operation), and is directed by AB 8 to continue to do so until there is a network of 100 stations statewide.

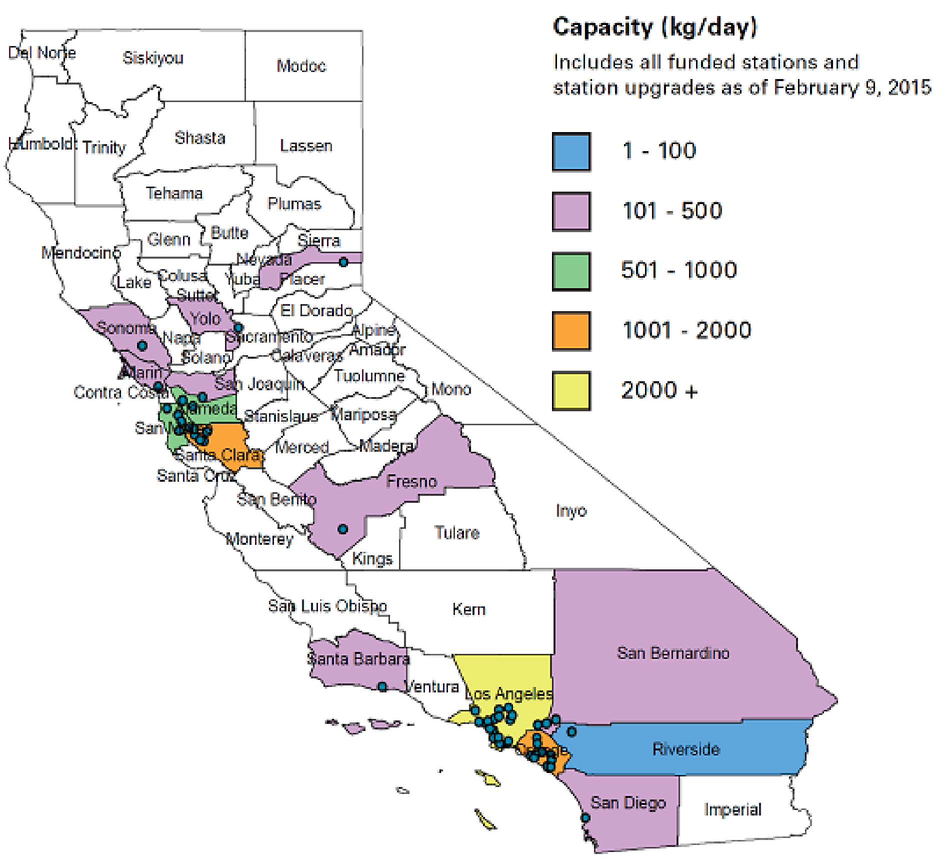
As of November 2015, California had 13 open hydrogen stations (Office of Governor, 2015), mostly located at existing gasoline stations. By the end of 2016, 51 stations are expected to be operational. These 51 stations will have a capacity of 9,400 kilograms hydrogen per day, equivalent to an expected demand for approximately 13,500 light-duty FCEVs (ARB, 2015h).

The two key metrics for hydrogen fueling station infrastructure planning are capacity and coverage. Planning for capacity ensures there will be enough hydrogen available for the vehicles projected to be on the road; planning for coverage ensures that hydrogen fueling stations will be located where they are needed. To predict needed capacity and coverage, one must estimate how many and what type of vehicles there will be, how much hydrogen they will need, and where they will need it. To accomplish this planning for light-duty FCEV purposes, ARB has been conducting an annual survey of auto makers since 2014 regarding their light-duty FCEV plans, as well as gathering data from the Department of Motor Vehicles on how many light-duty FCEVs are in use in California and where their owners reside. There are currently over 150 light-duty

FCEVs registered in California; populations are projected to reach 10,500 by the end of 2018 and 34,300 by the end of 2021.

ARB has been tracking the network of fueling stations and is working to identify gaps in coverage. ARB has developed two analytical tools - the California Hydrogen Infrastructure Tool (CHIT) and the California Hydrogen Accounting Tool (CHAT) – for this purpose. Together, CHIT and CHAT process auto maker survey data, FCEV vehicle owner data and station data, project the needed network of stations, and identify gaps in coverage, down to the zip code level. For light-duty FCEVs, CHIT and CHAT determine needs for stations largely based on anticipated locations of light-duty FCEV owners' homes, under the assumptions that vehicle owners will need to fuel up near home. In turn, ARB has been communicating these projections to CEC, to help inform CEC's station funding activities. In addition to providing funding for stations directly, the state is also working to bring in private investors. Figure III-1 below shows hydrogen station locations and existing and planned hydrogen dispensing capacity by county.

Figure III- 1: Existing and Planned Hydrogen Dispensing Capacity by County (Predominantly Light-Duty Fueling)



(ARB, 2015h)

Hydrogen fueling stations for light-duty vehicles are operational or planned in Southern California and the San Francisco Bay Area, with connector and destination stations in locations such as Coalinga, South Lake Tahoe, Napa and Santa Barbara.

2. Medium and Heavy-duty Hydrogen Fueling Infrastructure

All but a handful of the hydrogen stations described above are in place or planned for light-duty FCEV use. Light-duty stations are typically located at retail gasoline stations which cannot easily accommodate large vehicles. Also, larger vehicles use different fueling protocols, and the longer fueling times and higher fuel volumes required can compromise the fueling experience for passenger car drivers by increasing wait times and reducing fuel availability. In addition, light-duty FCEVs are typically designed to be fueled at 70 MPa, whereas heavy-duty FCEVs require 35 MPa fueling. 35 MPa fueling capability may provide a fallback option to achieve at least a partial fill for light-duty FCEVs; however, 70 MPa fueling currently cannot generally be used for heavy-duty vehicles.

Currently, all hydrogen fueling stations specifically for medium- and heavy-duty vehicles are located in private facilities, dedicated to a particular fleet. For example, Sunline Transit operates a hydrogen fueling station in Thousand Palms, California for its FCEB fleet, and allows passenger cars public access for 35MPa fuel. AC Transit dispenses hydrogen to its FCEB fleet in Emeryville with passenger car access to 35MPa and 70 MPa fuel outside the bus yard. In Oakland, AC Transit has located hydrogen dispensers in the same fuel island as diesel, enabling operators to service FCEBs in line with conventional buses and increase operational efficiency. Although funded with public grant money, these stations may not be accessible for medium- or heavy-duty FCEVs that are not part of the fleet demonstration project.

Figure III-2 shows a hydrogen dispenser that is serving a fuel cell electric transit bus. The dispenser looks similar to a conventional gasoline or diesel dispenser, but the nozzle design allows a gas tight connection to the fuel tank.

Figure III- 2: Fueling a Fuel Cell Electric Bus

(NASA, 2012)

Because transit buses are currently the only commercially available medium- or heavy-duty FCEV, and because requirements for zero-tailpipe emission buses are being considered as part of ARB's Advanced Clean Transit rulemaking, staff expects the nearest term need for medium- and heavy-duty hydrogen fueling to be for fuel cell transit buses. Staff anticipates such fueling infrastructure would be planned and constructed along with acquisition of fuel cell buses, and that transit agencies affected by the Advanced Clean Transit rulemaking may coordinate on such infrastructure (ARB, 2015a).

Although a full assessment of needed infrastructure for medium- and heavy-duty hydrogen fueling was beyond the scope of this document, the issue of hydrogen infrastructure for medium- and heavy-duty vehicles will be explored more fully as part of ARB's upcoming fuels assessment. This document lays out steps below for addressing needed hydrogen infrastructure for medium- and heavy-duty FCEVs:

i. <u>Estimate the future populations, deployment timing, vocations, fuel volumes and geographic locations for medium- and heavy-duty FCEVs.</u>

- Staff will likely want to model various scenarios, including less and more optimistic ones.
- Population estimates may be informed by recent ARB planning exercises, such as those used for the Cleaner Technologies and Fuels Scenario within the Mobile Source Strategy Discussion Document (ARB, 2015i), as well as external projections of medium- and heavy-duty fuel cell deployment such as those prepared by the Sustainable Transportation Energy Pathway Program (STEP) of the Institute of Transportation Studies (ITS) at University of California, Davis (STEP, 2015).
- Staff will also need to work closely with public transit agencies considering the use of fuel cell buses to be aware of their plans for FCEV vehicle acquisition and heavy-duty station development.
- In addition, staff will need to coordinate closely with medium- and heavy-duty FCEV manufacturers to be aware of their production plans; a survey effort parallel to the annual survey for light-duty FCEV manufacturers will likely need to be implemented.

ii. <u>Modify or add to light-duty analysis tools discussed above (CHIT/CHAT) to allow analysis of medium- and heavy-duty fueling infrastructure needs.</u>

- CHIT/CHAT currently uses vehicle owner residence location as an indicator for where light-duty hydrogen fueling is needed; for medium-and heavy-duty station planning, other indicators such as fleet maintenance yard locations will likely be more appropriate.

- For longer term planning for FCEVs used in long haul trucks, location of trucking routes will need to be considered, e.g. along the major trade corridors.
- Opportunities to add to existing and planned light-duty fueling stations should be considered wherever possible, as such additions may be more cost-effective than creating separate medium-/heavy-duty fueling stations.

iii. Determine where the greatest anticipated unmet needs for medium- and heavy-duty hydrogen fueling structure are likely to be.

- Using the population scenarios from step 1 and the modified tools mentioned in step 2, estimate where projected gaps in fueling infrastructure exist and where the highest priority for additional medium- and heavy-duty stations should be.

iv. Work with CEC and other stakeholders to meet those unmet needs.

- Consider opportunities to provide medium- and heavy-duty vehicle fueling co-located with light-duty vehicle fueling stations, where appropriate.
- New funding may need to be identified as well.

In addition to the steps above, which are aimed at planning for needed fueling stations, ARB should continue to work with SAE International (SAE) and other stakeholders to develop fueling protocols for medium- and heavy-duty FCEVs, as discussed further in Section B below.

B. Hydrogen Fueling Protocol

In 2010, SAE adopted J2601, the standard fueling protocol for light-duty passenger cars, and adopted an updated version as J2601 2014 just last year. As medium- and heavy-duty FCEV demonstrations began, the need for a fueling protocol for these vehicles was identified as well. In 2014, SAE published the J2601/2 Surface Vehicle Technical Information Report (TIR) “Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles” (SAE, 2014), which applies to all FCEVs that store over 10 kg of hydrogen on board the vehicle. This likely includes all FCEVs, whether fuel cell-dominant or battery-dominant. This TIR establishes safety limits and performance requirements for medium- and heavy-duty vehicle fueling and sets the following requirements:

- 35 MPa gaseous hydrogen;

- Reach full tank or 100 percent high state of charge within a reasonable amount of time (Fueling rate: 1.8-7.2 kg per minute depending on on-board tank configuration); and
- Avoid exceeding temperature, pressure, and density limits for the storage system.

SAE J2601/2 must be further developed and vetted by stakeholders before being adopted as a standard. Until the standard is adopted, fueling protocols are customized for each vehicle design, which may present challenges at shared public fueling stations. Once the TIR is adopted as a standard, government and other entities will be able to develop test equipment and procedures to validate that hydrogen stations meet the new heavy-duty fueling standard, as was done for light-duty FCEVs.

C. Hydrogen Production

As with light-duty vehicle hydrogen fueling stations, hydrogen stations for heavy-duty FCEVs are most cost-effective when the station is fully utilized. Hydrogen stations with a throughput less than 400 kg per day are typically supplied by truck with either liquid or compressed hydrogen. At greater than 400 kg per day, on-site reformation of natural gas or biogas can become a more cost-effective option. Electrolysis of water on-site can also be used to produce hydrogen; the energy required can come from on-site renewable power or from the grid.

Currently, most hydrogen in California is produced through the reformation of natural gas at a central facility. California Senate Bill 1505, adopted in 2006, requires a third of dispensed hydrogen at state funded stations to be made from renewable sources of energy. Once the annual mass of hydrogen fuel dispensed in California for transportation purposes exceeds 3,500 metric tons, all hydrogen fuel must be sourced from 33 percent renewables whether funded by public or private investment.[1] This requirement will ensure that the production and use of hydrogen fuel contributes to reduced dependence on fossil fuels and reduced GHG, criteria air pollutant, and toxic air contaminant emissions. Renewable sources of hydrogen include but are not limited to biogas, water (via electrolysis), and biomass. More information about production processes can be found at ARB's hydrogen production website, http://www.arb.ca.gov/msprog/zevprog/hydrogen/h2resource/production.htm. High hydrogen fuel quality is required for FCEVs, as specified in SAE standard J2719.

D. Hydrogen Compression

Regardless of the production method, hydrogen must be compressed for storage in high pressure tanks prior to dispensing. Compressing the hydrogen is the largest contributor to hydrogen station costs in terms of capital, energy consumption, and operations and

[1] Current annual mass of hydrogen fuel dispensed in California is still well below this 3,500 metric ton threshold but is increasing. Estimates can be made based on "Status of Existing Hydrogen Refueling Stations" Report by California Energy Commission, available at http://www.energy.ca.gov/2015publications/CEC-600-2015-004/CEC-600-2015-004.pdf.

maintenance. The hydrogen will typically be dispensed at 35 MPa for medium- and heavy-duty FCEVs; pressures greater than this can be achieved and maintained but at a greater cost. To compress hydrogen to 35 MPa requires 4 to 8 percent of its energy content, or 2 to 4 kilowatt hours per kg (kWh/kg), given the efficiency of today's compressors, which is between 50 and 80 percent. Investigation of methods to reduce the energy needed to compress the hydrogen continues.

IV. Medium- and Heavy-Duty Fuel Cell Electric Vehicles

Critical to full market acceptance of medium- and heavy-duty FCEVs is establishment of the premise that these vehicles can meet the same performance and reliability standards set by conventional vehicles. Demonstrations of new technologies are essential in moving toward market acceptance by proving the viability of technology in the real world. In this section, demonstration programs for FCEVs for a variety of vocations are summarized. Section A discusses transit bus demonstrations, Section B discusses shuttle bus demonstrations, and Section C discusses demonstrations of other medium- and heavy-duty FCEVs.

A. Transit Buses

Transit buses, which are classified as buses with a Gross Vehicle Weight Rating (GVWR) of 33,000 pounds (lbs.) or more, operate in municipalities throughout the country and serve a critical role in transporting individuals and providing mobility for transit-dependent individuals. Public transit systems are essential to meeting the State's climate action goals of reducing GHG emissions through coordinated transportation and land use planning for more sustainable communities (Senate Bill 375 - Sustainable Communities and Climate Protection Act of 2008). Transit buses make an ideal platform for advanced technologies because they are professionally fueled, operated and maintained from central hubs and operate on fixed routes. Because of these factors, FCEBs were the first heavy-duty fuel cell vehicle demonstration projects, beginning in the early 1990s. Over 300 FCEBs have been demonstrated worldwide. In general, FCEBs are capable of providing similar operational characteristics as conventional buses such as route flexibility, fast refueling, comparable travelling range, hill climbing ability, and sustained highway speeds. As a result, FCEBs are potentially an ideal replacement for conventional buses.

1. Goals for Demonstration Projects and Current Performance of Fuel Cell Electric Transit Buses

The U.S. DOE established benchmarks for FCEBs to ensure that these vehicles can compete with conventionally-fueled vehicles. Meeting these benchmarks will mark the transition of current and future demonstration projects into the commercial market and indicate that FCEBs can compete with conventional buses on performance and cost. The U.S. DOE has established five main performance targets for evaluating fuel cell electric transit buses: Bus Lifetime, Power Plant Lifetime, Bus Availability, Range and Fuel Economy and analyzed the National Renewable Energy Laboratory's (NREL's) evaluation of 34 FCEBs operated at three different locations in North America to determine the status of these targets as of 2014 (NREL, 2014). Table IV-1 details these performance benchmarks and status towards them as of 2014.

The bus lifetime requirement set by U.S. DOE is 12 years/500,000 miles, which is a requirement directly tied to federal funding guidelines for bus lifetime for transit agencies using federal monies to purchase new buses. FCEB manufacturers are currently in the testing phases to determine their ability to meet this standard. Early evaluation of this lifetime requirement indicates that a rebuild or replacement of the fuel cell stack will be required to meet the lifetime requirement as is similar to the average 6 year engine rebuild needed for conventionally-fueled buses.

Table IV- 1: U.S. DOE Technical Targets and Current Status of FCEBs

Criterion	Units	2012 Status	2014 Status	2016 Target	Ultimate Target
Bus Lifetime[1]	years/miles	5/100,000	5/100,000	12/500,000	12/500,000
Power Plant Lifetime[2]	hours	12,000	19,000	18,000	25,000
Bus Availability	percent	60	70	85	90
Range	miles	270	220-310	300	300
Fuel Economy	mpdge	7	7.26	8	8

(NREL, 2014)

The power plant lifetime target established by U.S. DOE refers to the lifetime of the fuel cell stack and has been set at 25,000 hours. Currently, most FCEBs have not been demonstrated in service for enough time to determine whether this requirement is being met. At the time of this report, one FCEB, which is currently still in service, had already achieved 20,000 hours of service (AC Transit, 2015).

Bus availability refers to the bus's ability to enter service during required service hours and relates to maintenance and duty cycles. U.S. DOE has set the target for bus availability at 90 percent, which exceeds the current 85 percent availability achieved by diesel buses. The current average availability of FCEBs is around 70 percent, but a demonstration FCEB model built by El Dorado National and operated by SunLine Transit has exceeded the 90 percent availability in its demonstration use. NREL reports that FCEBs' downtime is mostly associated with issues of non-fuel cell and non-electric drive train components. In addition, FCEB downtime from fuel cell and electric drive train components is often exacerbated because low-volume, non-OEM built vehicles contain specialized equipment not typically kept on hand at transit agencies (NREL, 2015a; NREL, 2014). This lack of inventory would be expected to be rectified with increased FCEB availability and populations.

The final two performance metrics focus on range and fuel economy. In terms of range, U.S. DOE has set out a goal of 300 miles on a full tank. The 2014 average range varied between 220-310 miles and newer FCEBs are expected to be better designed and

[1] Status represents data from NREL fuel cell bus evaluations. New buses are currently projected to have 8 year/300,000 mile lifetime.
[2] The power plant is defined as the fuel cell and battery systems, excluding power electronics, electric drive, and hydrogen storage tanks; the lifetime represents an average duty cycle.

should achieve the U.S. DOE target. Fuel economy is highly variable depending on the duty cycle and road conditions but U.S. DOE has established a goal of 8 mpdge for FCEB. Two demonstration projects conducted by Alameda-Contra Costa Transit District and SunLine Transit from 2011 to 2014 achieved a fuel economy of 7.26 mpdge. The U.S. DOE target is within reach and likely achievable in the next round of FCEB demonstration projects. This fuel economy goal is substantially higher than the fuel economy of diesel transit buses.

2. Current Demonstration Projects

Demonstration projects are both underway and planned for the future, with the goal of achieving the various performance metrics to ensure these vehicles are market viable. Currently, there are over 20 FCEBs being actively demonstrated in the US. Table IV-2 illustrates some of the current demonstration projects and their operators.

Table IV- 2: Active FCEB Demonstrations in the US, by Operator

Bus Operator	Location	Total Buses
Zero Emission Bay Area (ZEBA)	San Francisco Bay Area, CA	12*
SunLine Transit	Thousand Palms, CA	5
Greater New Haven Transit District	New Haven, CT	1**
Birmingham-Jefferson County Transit Authority	Birmingham, AL	1
Flint Mass Transportation	Flint, MI	1***
Anteater Express (UC Irvine)	Irvine, CA	1
Capital Metro	Austin, TX; Washington, DC	1
U.S. Hybrid	Flint, MI	1
	Total	**23**

*One Connecticut Transit bus was transferred to ZEBA (demonstration status is still unknown), which now brings the total number of buses in ZEBA fleet to 13. ; ** 22-foot bus; ***Flint Mass Transportation now has an additional new American Fuel Cell Electric Bus and will operate that bus in the near future; (NREL, 2015b)

In addition to the active FCEB demonstrations described in Table IV-2, an additional 20 buses are planned to be deployed in future demonstration projects across the country. These projects are a part of the Federal Transit Administration (FTA) National Fuel Cell Bus Program (NFCBP) (NREL, 2015b). Table IV-3 details the planned projects and their proposed locations.

Table IV- 3: New FCEBs Planned for the FTA NFCBP

Bus Operator	Location	Total Buses
Massachusetts Bay Transportation Authority	Boston, MA	1
San Francisco Municipal Transportation Agency	San Francisco, CA	1
Stark Area Regional Transit Authority	Canton, OH	7
SunLine	Thousand Palms, CA	7
Tompkins Consolidated Transit Authority	Ithaca, NY	1
Hawaii County Mass Transit Agency	Hilo, HI	2
Advanced Fuel Cell Electric Bus (60-ft articulated) - New Flyer/Siemens (NFCBP-CALSTART)	Bus operator to be determined	1
University of Delaware	Newark, DE	2
	Total	**22**

(NREL, 2015b)

Past and current demonstrations have proved the technology and show the suitability and functionality of FCEBs to a variety of transit operators. Future demonstrations will highlight improvements made in FCEBs as well as increase transit operator's familiarity with the equipment. The demonstrations also help fund the needed infrastructure for that transit company to transition to future commercial FCEBs.

Transit buses are in early commercialization with two manufacturers offering three transit bus models. The New Flyer 40-foot bus and 60-foot articulated bus are in advanced demonstration stages, while El Dorado's American Fuel Cell Bus is offered for sale. All three models will be going through Altoona testing soon. Altoona testing provides comprehensive testing results on safety, structural integrity and durability, reliability, performance, maintainability, noise, fuel economy, braking, and emissions. Completion of Altoona testing will enable the buses to be eligible for FTA funds.

B. Shuttle Buses

Shuttle buses have many of the same characteristics as transit buses but are often smaller, usually in the Class 4 to 6 (14,001-26,000 lbs.) range. Shuttle buses have a similar vehicle platform and duty cycle as transit buses. For this reason, they are another vocation that could readily utilize fuel cell technology. Demonstration projects, currently active and planned, are beginning to define the ability and requirements needed for fuel cell technology to be market viable in this vocation.

Table IV-4 lists some of the demonstration projects currently underway. Table IV-5 presents some of the demonstration projects currently planned.

Table IV- 4: Fuel Cell Shuttle Buses in Active Demonstration

Bus Operator	Location	Total Buses
University of Delaware	Newark, DE	1
U.S. Air Force	Pearl Harbor-Hickam, Hawaii	1
	Total	**2**

(NREL, 2015b; Green Car Congress, 2014)

Table IV- 5: Fuel Cell Shuttle Bus Planned Demonstration

Bus Operator	Location	Total Buses
Hawaii County Mass Transit Agency	Hawaii	3
Fresno County Rural Transit	Fresno, CA	1
SunLine Transit/Cal State University, LA	LA and Coachella Valley, CA	4
	Total	**8**

(West Hawaii Today, 2014; San Joaquin Valley, 2015; CEC, 2015)

C. Other Medium/Heavy-duty Vehicles

In addition to bus vocations, fuel cell technology has potential applications in a variety of other vocations performed by medium- and heavy-duty vehicles. More than 50 fuel cell electric trucks have been or are planned to be demonstrated in a variety of vocations including refuse, package delivery, and drayage. These demonstration projects are essential to ensure that fuel cell technology can provide a zero-emission vehicle alternative for various vocations. Several initiatives have supported demonstration of fuel cell technology in medium- and heavy-duty vehicle applications. These programs have funded various demonstrations and additional information about these incentives is provided in Chapter V and Appendix A.

1. Medium-Duty (8,500-14,000 lbs. GVWR) Fuel Cell Electric Delivery Truck Demonstration Projects

Currently, there are fuel cell electric delivery truck demonstration projects, planned and/or active, in California and Tennessee. These projects are being undertaken by both FedEx and UPS with an investment of public funds of over $7.1 million. The trucks are being used in delivery operations and will provide significant information needed to further develop the technology for market acceptance. Table IV-6 details the number and locations of various fuel cell delivery truck demonstrations.

Table IV- 6: Medium-Duty Fuel Cell Electric Delivery Truck Demonstrations

Truck Operator	Vehicle Type	Location	Total Trucks
FedEx	Delivery Van	California/Tennessee	20
UPS	Delivery Van	California	17
Center for Transportation and the Environment	Delivery Van	California	1
		Total	**38**

(DOE, 2013; CTE, 2015)

2. Heavy-Duty (14,000+ lbs. GVWR) Drayage and Refuse Fuel Cell Electric Truck Demonstration Projects

Heavy-duty trucks performing drayage and refuse operations have prescribed routes of definable distance and are centrally fueled. As is the case for transit buses, these factors make these vocations ideal candidates for demonstration of new technologies. Several demonstration projects are currently underway and will evaluate the use of fuel cell trucks in both drayage and refuse vocations. Table IV-7 details some of the planned and/or active heavy-duty fuel cell electric demonstration projects and their locations.

Table IV- 7: Heavy-Duty Fuel Cell Electric Truck Demonstrations

Company	Vehicle Type	Location	Total Trucks
Center for Transportation and the Environment	Drayage Truck	California	1
Port of Houston	Drayage Truck	Texas	3
U.S. Hybrid	Drayage Truck	California	2
TransPower	Drayage Truck	California	3
Hydrogenics USA, Inc.	Drayage Truck	California	1
U.S. Hybrid	Refuse Truck	TBD	1
Vision Industries Corporation	Refuse Truck	California	1
		Total	**12**

(SCAQMD, 2014; EDF, 2015; San Joaquin Valley, 2015; CEC, 2015; DOE, 2014a)

V. Vehicle, Fuel, and Infrastructure Costs

The capital costs of acquiring FCEVs and fueling and maintenance infrastructure remain the greatest barriers for widespread use of FCEVs. Once purchased, however, increased efficiency and other operating and maintenance (O&M) savings can compensate for much of this additional cost. This chapter discusses costs of the vehicle, hydrogen, and hydrogen fueling station. The current infrastructure available in California was discussed in Chapter III. Additional discussion about costs and infrastructure needs will be included in the upcoming Fuels Technology Assessment. Section A below discusses FCEV costs. Section B discusses and hydrogen fuel and hydrogen fueling station costs. Section C discusses available incentives for FCEVs.

A. Fuel Cell Electric Vehicle Costs

1. Transit Bus Cost

The vast majority of current on-road medium- and heavy-duty FCEVs, and the only ones that are commercially available, are FCEBs. The cost of a FCEB is dependent on many factors, but the cost of major vehicle subsystems is a significant determinant of total capital cost. FCEVs that are battery-dominant cost less than fuel cell-dominant architectures because the cost of a battery system is currently less than the cost of a fuel cell system, and battery-dominant FCEVs have smaller fuel cells than fuel cell-dominant systems. The O&M costs for FCEVs are expected to be lower than for conventionally-fueled vehicles. For example, as with other electric buses regenerative braking means lower brake maintenance cost. As fleet owners and maintenance staff develop greater understanding of the vehicles and maintenance procedures, further savings may be realized.

Table V-1 below shows 2012 and 2014 costs for FCEBs, including total bus and power plant cost and hydrogen storage cost (cost for tank, etc.), as well as 2016 and future U.S. DOE targets for these costs.

Table V- 1: U.S. DOE Cost Targets and Current Status of FCEBs

Criterion	2012 Cost	2014 Cost	2016 Target	Ultimate Target
Total Bus Cost	$2,000,000	$1,300,000	$1,000,000	$600,000
Power Plant Cost	$700,000	$450,000	$450,000	$200,000
Hydrogen Storage Cost[1]	$100,000	$100,000	$75,000	$50,000

(DOE, 2012)

[1] The on-board storage system cost includes cost for the hydrogen tanks, frame, and mounting system.

Progress toward DOE's FCEB cost targets is discussed below:

- Total FCEB Cost - FCEB costs have decreased substantially over the past several years. Between 2012 and 2014, FCEB costs declined by 35 percent, from $2 million per bus to $1.3 million per bus. Further, New Flyer, the largest bus manufacturer in the United States, has indicated that $900,000 per bus would be feasible with an order of 40 or more buses over a 3 year delivery period (New Flyer, 2014). A cost of $900,000 per bus is approaching the cost of a conventional diesel hybrid transit bus, currently around $750,000, and, when O&M savings are considered, may well be below that cost. The $900,000 cost would meet DOE's 2016 target.

- Fuel Cell Power Plant Cost Target - The long-term target of $200,000 for the fuel cell power plant is considered aggressive by DOE, but acts as a milestone marking the economic competitiveness of fuel cells in the transit bus application (DOE, 2012). Currently, fuel cell systems range from $2,000/kW - $3,000/kW. At $3,000/kW for a 150 kW fuel cell system, the power plant cost is $450,000, meeting the interim 2106 power plant cost target.

- On-Board Hydrogen Storage Cost Target - The ultimate goal of $50,000 for a capacity of 40-50 kg of hydrogen was set by stakeholder input. The on-board storage system includes the hydrogen tanks, frame, and mounting system. The hydrogen storage cost in 2012 and 2014 was $100,000 for 50 kg capacity. Note that many FCEVs use a smaller storage volume, with 25-30 kg typical for hybrid (fuel cell/battery) FCEB configurations. On-going research and development is expected to reduce the costs of these tanks through reduced materials and manufacturing costs.

2. Non-Bus FCEV Costs

Because non-bus FCEVs are still in the prototype demonstration phase, their market prices are not yet known. However, transferring fuel cell system integration know-how from FCEBs and modifying existing FCEB components to meet the operational needs of similarly sized fuel cell electric trucks should reduce engineering costs for developing and commercializing other FCEVs. The experiences gleaned from operating FCEBs should transfer to other FCEVs as well. As more FCEVs are demonstrated, understanding of the costs associated with the vehicles will improve.

B. Hydrogen Fuel and Hydrogen Fueling Station Costs

1. Hydrogen Fuel Costs

The economics of operating a FCEV fleet will also be dependent on the cost of fuel. A hydrogen cost of around $4.00 per kg for production, delivery and dispensing is likely needed for hydrogen to become a competitive fuel (DOE, 2010; DOE, 2014b). Current costs for production at large facilities are about $2.00 per kg, with significant additional costs incurred to deliver and dispense the fuel.

The FCEB fleet experience reveals the cost of hydrogen at current production volumes. SunLine Transit's hydrogen station in Thousand Palms has been in operation for 15 years. The station produces up to 212 kg of hydrogen on-site each day. The four FCEBs currently in revenue service are filled each day with around 30 kg of 35 MPa hydrogen. Fueling takes about 25 minutes per bus at a net cost of around $12.50 per kg, excluding the station capital cost amortization. This hydrogen cost is still three times higher than needed to be competitive with the cost of diesel fuel.

AC Transit's station in Emeryville began operation in 2011. It is the largest heavy-duty vehicle fueling station in the United States. The station has a baseline capacity of 360 kg hydrogen at 35 MPa per day, enough to fuel 12 FCEBs, and 240 kg per day for cars (approximately 50 cars), which can refuel at a pump just outside the bus yard. The more modern station and increased volumes dispensed result in a net cost of about $9.10/kg dispensed, excluding station capital costs, which is 27 percent lower than SunLine's Thousand Palms station, but still more than twice the cost to be competitive with diesel. Multiple buses can fuel consecutively at 6-8 minutes per fill, which is similar to the diesel bus fueling rate. AC transit operates a second station of similar design in Oakland, where the fuel dispensers are located in line with diesel pumps. Liquid hydrogen is delivered to both stations and is supplemented by hydrogen produced on-site via electrolysis using renewable electricity. At sufficient station volumes, on-site hydrogen production has the potential to reduce hydrogen costs compared to delivered hydrogen.

2. Hydrogen Fueling Station Costs

Thus far, most FCEV demonstration projects have involved FCEBs, which require 35 MPa hydrogen fueling stations. It is anticipated that costs for a 1200 kg/day, 35 MPa hydrogen fueling station capable of completing multiple consecutive 5-8 minute fills will be $5 M or less, including $1 M for site improvements and local requirements. Once the infrastructure is in place, O&M costs are expected to be about $200,000 per year (CAFCP, 2013).

Station cost may be somewhat mitigated as more demonstrations are performed, and further reduced as the number of hydrogen stations grows due to improved supply chain and economies of scale.

C. Available Incentives for FCEVs

There are a variety of incentives available at the federal, state, and local levels to support FCEVs. Nationally, the NFCBP and Transit Investments for Greenhouse Gas and Energy Reduction (TIGGER) program are available. In California, many programs are available that can provide incentive funds for FCEV purchases or demonstrations. These include the Alternative and Renewable Fuel and Vehicle Technology Program, the Air Quality Improvement Program, the Enhanced Fleet Modernization Program, the Greenhouse Gas Reduction Fund, Low Carbon Transportation Investments, Hybrid and Zero-emission Truck and Bus Voucher Incentive Project (HVIP) funds, Carl Moyer program funds, ARB's Truck Loan Assistance Program, and Proposition 1B Goods Movement Emission Reduction Program. On the local level, funding opportunities are available through the local air districts such as the Bay Area Air Quality Management District, the Sacramento Metropolitan Air Quality Management District, the San Joaquin Valley Air Pollution Control District and the South Coast Air Quality Management District. For an explanation of these programs, see Appendix A.

VI. Emission Benefits

Other than pure water, FCEVs have no tailpipe emissions and therefore completely eliminate the emission of criteria pollutants at the source. In other words, FCEV tailpipe emissions are 100 percent lower than tailpipe emissions from today's conventionally fueled vehicles. Even in the future, when diesel or natural gas vehicles may be much cleaner than today's vehicles (certified to a 0.02 gram per brake horsepower hour (g/bhp-hr) oxides of nitrogen (NOx) standard, for example), FCEVs still will provide additional tailpipe emission benefits, which may be crucial for attaining ambient air quality standards. Like battery electric vehicles and in contrast to diesel or natural gas vehicles, FCEVs will always be zero-emission vehicles in real world use regardless of deterioration of the engine or emission control systems over the course of vehicle life.

There are emissions associated with the production and transportation of hydrogen. In addition, if the FCEV uses a plug-in hybrid system, there are emissions associated with the production of electricity when the electrical grid is used to recharge batteries.[1] A well-to-wheel analysis of FCEV operations attributes emissions associated with hydrogen production and transportation and electricity generation to the FCEV. With a well-to-wheel analysis, the magnitude of criteria and GHG emissions associated with FCEV operations will depend on the emissions characteristics of the process that is used to produce and distribute hydrogen, the emissions associated with that process, and the emissions associated with transporting the hydrogen from the point of production to the point of use. As noted in Chapter III, Senate Bill 1505 requires that hydrogen produced in California have 33 percent renewable energy content, and hydrogen can also be produced entirely from renewable resources. Producing hydrogen from renewable resources or using renewable energy in the process will further reduce petroleum use and GHG emissions. For example, hydrogen produced by solar-powered electrolysis or steam-reformed biogas will have few associated emissions.

ARB is developing a separate fuels technology assessment that will evaluate overall well-to-wheel emissions from various transportation fuels. Preliminary results from that assessment indicate that FCEVs have substantially lower well-to-wheel emissions than diesel- or natural gas-fueled engines.

[1] For a discussion of emissions associated with charging medium- and heavy-duty battery electric vehicles, see *Draft Technology Assessment: Medium- and Heavy-Duty Battery Electric Vehicles*. The ARB continues to estimate emissions associated with power generation in California.

VII. Synergies across Sectors and Technologies

The deployment of hundreds of FCEBs globally over the last two decades has led to technology developments that are directly transferrable to other medium- and heavy-duty vehicles. Market entrance of light-duty FCEVs, light-, medium-, and heavy-duty hybrid and battery electric vehicles, fuel cell forklifts, and the hydrogen infrastructure build-out in California have reduced the hurdles associated with launching a new vehicle technology. These synergies aid in the development of and commercial launch of affordable, well-performing FCEVs. The synergies generally fall into one or more of six areas:

FCEBs

The FCEB platform has been sufficiently optimized to meet many of the transit bus performance targets. The FCEB platform is transferable to other heavy-duty vehicles and can be scaled down for medium-duty vehicles. Technology providers, OEMs, and system integrators that have built FCEBs are using the same or slightly modified platforms to build other medium- and heavy-duty FCEVs.

Light-Duty FCEVs

Fuel cell electric passenger vehicles were commercially launched this year by companies such as Hyundai and Toyota. These light-duty FCEVs will support medium- and heavy-duty FCEVs in terms of technology transferability, market creation, and public acceptance.

Light-, medium-, and heavy-duty vehicles use the same fuel cell technology. The investments and developments made in PEM fuel cells will positively affect all sectors. With greater standardization of PEM fuel cells across these sectors, economies of scale for manufacturing can be more readily realized. For example, the average automotive stack is rated at 80 kW net power. This stack may be suitable, as is, for medium- and heavy-duty applications with lower loads or in a battery dominant fuel cell system design (although fuel cell-dominant buses or trucks with higher power demands such as over-the-road vehicles may require a larger fuel cell system). For instance, FCEBs in Europe and Asia have been using automotive fuel cell stacks.

Developments in on-board hydrogen storage tanks for passenger vehicles may be transferable to the medium- and heavy-duty FCEV fleet as well. Even if the tanks themselves are not suitable, improvements in tank design and manufacturing advances are likely to be transferrable across all sectors.

Finally, the demand for fuel cell systems by the automotive sector creates a broader market for PEM fuel cells, hydrogen tanks, and other related hardware. Where there is overlap in the supply chain, the demand for components may help strengthen confidence in the motive fuel cell market, leverage economies of scale, and lead to cost reductions.

Conventional Hybrid Vehicles

Hybrid vehicle development and deployment have served as a foundation for other fully or partially electric vehicles. The design and optimization of electric components and electric drivetrain are vital steps in the evolution of conventional mechanical drivetrains to fully electric drivetrains. *Draft Technology Assessment: Medium- and Heavy-Duty Hybrid Vehicles* provides additional information about medium- and heavy-duty hybrid electric vehicles. Advancements in medium- and heavy-duty series hybrids are most applicable to the development of medium- and heavy-duty FCEVs, especially for a battery-dominant configuration.

Driver, passenger, and maintenance staff experience with hybrid vehicles increases awareness and familiarity with electric drivetrains and operation. Through work on more common hybrid vehicles, maintenance staff is learning how to diagnose and repair electric components and properly work with high-voltage equipment. The technical knowledge acquired by maintaining a hybrid vehicle is directly transferable to maintaining FCEVs.

Battery Electric Vehicles

Many of the battery chemistries used in battery electric vehicles are also used in FCEVs, whether the vehicle is fuel cell-dominant or battery-dominant with the fuel cell acting as a range extender. The recent *Draft Technology Assessment: Medium- and Heavy-Duty Battery Electric Trucks and Buses* provides additional information about battery chemistry and battery electric vehicles.

Since batteries generally serve as the energy storage systems in FCEVs, innovations in battery technology for motive application are directly transferable to FCEVs. The performance of a FCEV is based on the performance of the FCEV subsystems, including the battery system. Therefore, advancements in battery electric vehicles can be transferrable to FCEVs regardless of the design configuration.

The demand for battery electric vehicles strengthens the supply chain for electric components that FCEVs employ as well. Use of fully electric vehicles familiarizes operators, end-users, and the general public with zero-emission technology and will help make the concept of FCEVs less foreign as well.

Fuel Cell Forklifts

Forklifts are an industrial application where fuel cells have already made substantial inroads due to their economic competitiveness. Over 7,000 fuel cell forklifts have been sold in the United States. The forklifts use the same components as heavier vehicles, and manufacturing PEM fuel cells at higher volumes for fuel cell forklifts lends more certainty to the PEM fuel cell market. Greater volumes support partial or full automation of PEM fuel cell manufacturing, further reducing system costs. For battery-dominant

FCEVs, the fuel cell stacks for forklifts are either the appropriate size or can be scaled up.

Companies that are using fuel cell forklifts are gaining familiarity with this technology and gaining advantages from the improved operational efficiency of their warehouses, which may lead them to try other FCEVs. They may already have the necessary 35 MPa infrastructure in place to allow them to add other fuel cell vehicles to their fleet. Even if some additional equipment is needed for the FCEVs, much of the siting work may have been completed, and the majority of equipment needed to fuel the FCEVs is likely already in place. The familiarity these companies have already gained with fuel cell forklifts may support adoption of fuel cell technology for transportation refrigeration units and other warehouse applications. *Technology Assessment: Transport Refrigerators* discusses fuel cells used for transportation refrigeration units*.*

Fueling Infrastructure for Light-Duty FCEVs

California is investing in the build-out of hydrogen fueling infrastructure across the state to support the wide-scale deployment of commercial fuel cell electric passenger vehicles. The development of hydrogen fueling infrastructure for light-duty vehicles also supports the infrastructure needs of medium- and heavy-duty FCEVs through technology transfer, standardization, supply chain improvements, market creation, and public acceptance.

Although light-duty vehicles refuel at 70 MPa, much of the design for a hydrogen station serving light-duty vehicles is similar to that for medium- and heavy-duty FCEVs. Hydrogen dispensers at retail gasoline locations have fostered public awareness of and familiarity with hydrogen fueling. In conjunction with light-duty FCEV marketing, the stations will increase awareness of fuel cell technology and hydrogen. The presence of public hydrogen fueling stations, and indeed, on-board storage of hydrogen itself on passenger vehicles, will ultimately lead to reductions in “new technology fear” for medium- and heavy duty applications as well.

VIII. Conclusions

FCEVs can help California achieve its climate change, air quality, and petroleum dependence reduction goals. Fuel cells are an attractive option for on-road medium- and heavy-duty vehicles because they offer:

- Zero tailpipe emissions of criteria pollutant, toxic air contaminants, and GHG;
- Low well-to-wheel GHG emissions compared to conventional technologies;
- The ability to use fuels produced from renewable sources, thereby reducing dependence on fossil fuels;
- Grid-balancing opportunities if hydrogen is produced from renewables during off-peak hours;
- Quiet operation with quick, smooth acceleration;
- High fuel efficiency;
- Range and performance comparable to conventional vehicles, including the ability to maintain freeway speeds and climb steep gradients;
- Refueling times similar to conventional liquid fueling.

A. Technology Status

Fuel cell technology has successfully been demonstrated in transit bus applications. Currently, 16 out of 22 active FCEBs in the United States are operated in California (NREL, 2013a). Both Sunline Transit Agency and ZEBA have seen improved vehicle availability and performance during these demonstrations (NREL, 2013a). Collectively, FCEBs operated in California have met DOE's 2016 performance target in range, fueling, and maintenance costs. Compared to conventional buses, availability is similar and fuel efficiency in mpdge is twice as high (NREL, 2013a).

FCEBs are designed in series hybrid configurations and share many of the same components used in conventional diesel electric hybrid buses. For example, New Flyer uses the exact same bus platform and hybrid electric drive components in its FCEB configuration as it does in its diesel hybrid bus configuration. This overlap contributes to transferability of components.

Fuel cell technology development for urban transit buses is expected to accelerate the demonstration and deployment of Class 7 and 8 heavy-duty FCEVs since they can share the same power train design, and basic components. Fuel cell electric trucks are expected to have similar performance, reliability, and fueling times as conventional trucks. However, hydrogen tanks currently take more space and weigh more than conventional diesel fuel tanks. The additional weight or space needed can affect payload or may result in reduced vehicle range between fueling. Nonetheless, fuel cells are a promising zero-emission technology for non-transit vehicles as well. There are on-going and planned demonstrations for both drayage and refuse trucks. Future demonstrations will target class 7 and 8 line haul applications, for which battery electric vehicles currently lack sufficient range, and will for the foreseeable future. The ultimate development and commercialization of fuel cell technology for these most demanding fleet applications may be a necessary and effective approach for meeting emission goals.

Experience and technology improvements from bus deployments and from the expansion of the light-duty passenger car market are also expected to result in synergies that are transferable to fuel cells used in medium-duty vehicles. Planned or on-going demonstrations for medium-duty vehicles include parcel delivery trucks and shuttle buses.

Fuel cells can also be used as range extenders for plug-in battery electric vehicles. There are planned demonstrations of these battery-dominant FCEV in shuttle bus, delivery trucks, and drayage operations. Early commercialization efforts are likely to be with short haul applications where the fleet maintenance and fueling is done at a centralized terminal or yard on a daily basis.

B. Costs

Currently, the costs for FCEVs are significantly higher than for conventional vehicles due to low volume production of custom built and third-party integrated vehicles. Costs are coming down as fuel cell technology advances and OEMs develop fuel cell offerings. Completion of Altoona testing will facilitate the purchase of new FCEBs.

Once acquired, a FCEV also needs access to a hydrogen fueling station. The existing and planned public retail stations are geared towards passenger vehicles and generally not suitable for fueling heavy-duty vehicles. Stations that are accessible and configured for medium- and heavy-duty applications must be built. In addition, hydrogen fueling standards for medium- and heavy-duty FCEVs need to be established. As the infrastructure develops, medium- and heavy-duty FCEV deployments are expected to begin with larger fleets with centralized fueling stations. Hydrogen fueling stations are most cost-effective where the station is fully utilized.

C. Next Steps

ARB's Advanced Clean Transit rule amendments are expected to require the purchase of zero-emission buses (ARB, 2015a). This includes both battery electric and FCEBs. Regulatory requirements coupled with further investments in fuel cell transit buses will ensure there is more than one technology option to transform transit fleets to zero emissions in California. The early transition for buses is a first step, and is expected to lead a broader transition to zero-emission technologies for other medium- and heavy-duty applications.

Additional demonstrations for fuel cell electric trucks and shuttle buses are appropriate and should continue to be supported by public funding programs. When fuel cell electric trucks become commercially available, a similar approach of using regulations and public funding to accelerate the market can be taken. Continued data collection and analysis on FCEVs' performance, related costs, durability, and reliability is also essential to better understand and therefore improve this technology.

Additional support of zero-emission technology on a national level can greatly improve the potential for FCEVs to become widely deployed. U.S. DOE has been playing a pivotal role in funding research and demonstration projects to foster new technology. However, the U.S. Environmental Protection Agency (EPA) should consider the potential role of heavy-duty zero-emission vehicles as part of its planning and regulatory efforts to improve air quality, reduce climate change, improve utilization of clean energy, and reduce dependence on fossil fuels including petroleum. In our comments on the proposed federal Phase 2 heavy-duty truck GHG standards, ARB encouraged U.S. EPA to continue to provide extra credits to incentivize the development of fuel cells and other advanced technologies as a means of reducing GHG emissions (ARB, 2015b).

Developing fueling standards for medium- and heavy-duty FCEVs is also important. The SAE J2601/2 technical report should be developed into a standard. Test equipment and procedures should also be developed in parallel to validate that hydrogen stations meet the heavy-duty fueling standard, similar to what has been developed for light-duty FCEVs.

ARB will continue to work with federal, state, and local government to coordinate policies and planning efforts regarding development and funding of zero-emission vehicles and associated infrastructure. Efforts should seek to leverage the significant progress already made on these issues for fuel cell electric passenger cars. ARB and others will continue to collect data on FCEBs and other medium- and heavy-duty vehicles, including information about maintenance costs, availability, reliability, and durability.

A combination of regulations and financial incentives has the best potential to facilitate development and demonstration of new technology and to send the appropriate market signals to vehicle manufacturers, fuel suppliers, and fleet owners. Both financial incentives and regulatory approaches should be used to transition medium- and heavy-duty on-road vehicles to zero-emission technologies, including fuel cell technology. Using a combination of incentives and regulations to expand the use of FCEVs provides market signals for manufacturers and reduces risk for fleet owners that operate the vehicles.

In sum, fuel cell technology is a very promising approach for significantly reducing emissions from the medium- and heavy-duty vehicle fleet. Together, battery electric vehicles and FCEVs will lead the transition of the medium- and heavy-duty vehicle classes towards zero-emission goals.

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Appendix A: Medium- and Heavy-Duty Zero-Emission Vehicle Initiatives

Local air district, state, federal, and international initiatives have been established to support the commercialization of zero-emission vehicles (ZEV) in medium- and heavy-duty applications. Fuel cells are one type of zero-emission technology that can meet the performance requirements of medium- and heavy-duty vehicles. This appendix presents many available incentive programs.

A. Federal Initiatives

Two pieces of federal legislation provided substantial impetus to the commercial development of fuel cell electric vehicles. The Energy Policy Act of 1992 was the first national legislation that called for large-scale hydrogen research (EPACT, 1992). A five-year program was conducted to research hydrogen production from renewable energy sources and the feasibility of existing natural gas pipelines to carry hydrogen. It also called for the development of fuel cells suitable to power an electric motor vehicle and research into hydrogen storage systems for vehicles. The Energy Policy Act of 2005 called for a wide-reaching research and development program on technologies relating to the production, purification, distribution, storage, and use of hydrogen energy, fuel cells, and related infrastructure with the goal of demonstrating and commercializing the use of hydrogen for transportation, utility, industrial, commercial, and residential applications (EPACT, 2005).

President Obama signed Executive Order (EO) 13693, "Planning for Federal Sustainability in the Next Decade" in March 2015, to maintain policy for federal agencies in sustainability and GHG management. EO 13693 calls for significant reductions in energy consumption and associated emissions. Under this order, agencies are required to reduce fleet-wide per-mile GHG emissions by 4 percent by the end of Fiscal Year (FY) 2017, 15 percent by the end of FY 2021, and 30 percent by the end of FY 2015, as compared to baseline emissions in FY 2014. In addition, the General Services Administration (GSA) has to ensure that agency fleets have access to a variety of alternative fuel vehicles, including E-85 compatible vehicles, zero emission and plug-in hybrid vehicles, and compressed natural gas powered vehicles, through development and implementation of fueling infrastructure and logistical resources for those vehicles (White House, 2015).

Described below are several federal programs that offer funds that can be directed to advanced clean vehicles.

1. U.S. Environmental Protection Agency's (EPA) Diesel Emissions Reduction Act (DERA)

Through the National Clean Diesel Campaign, U.S. EPA has funded approximately 60,000 pieces of clean diesel technology including emissions and idle control devices, aerodynamic equipment, engine and vehicle replacements (e.g., from diesel to hybrid technology), and alternative fuel options. Regions, states, local agencies, and others can be eligible for the DERA funds and may use their allocations to fund emission reductions projects (U.S. EPA, 2007).

2. National Fuel Cell Bus Program and Transit Investments for Greenhouse Gas and Energy Reduction Assistance

The Federal Transit Administration (FTA) has sponsored programs that support the federal initiatives described above and support use of fuel cell propulsion in transit applications. The National Fuel Cell Bus Program (NFCBP) and Transit Investments for Greenhouse Gas and Energy Reduction (TIGGER) program, described further below, are U.S. Department of Transportation (DOT) programs that support the demonstration of fuel cell electric buses (FCEB).

a. National Fuel Cell Bus Program

The goal of the NFCBP is to assist in the development of commercially viable fuel cell electric bus technologies and related infrastructure with funding awarded through a competitive grant process. Consideration is given to those that have managed advanced transportation projects, including projects related to hydrogen and fuel cell public transportation operations for a period of at least five years. NFCBP has provided over $60 million to date to advance the commercialization of American-made FCEBs for the transit industry (DOT, undated a).

b. Transit Investments for Greenhouse Gas and Energy Reduction Assistance (DOT, 2012)

The TIGGER program works directly with public transit agencies to create strategies for reducing GHG emissions and energy use from transit operations (DOT, undated b). Eligible projects include on-board vehicle energy management systems such as energy storage, regenerative braking, fuel cells, and turbines. The TIGGER program funded two FCEBs to be used in revenue service with SunLine Transit in Thousand Palms, California. The Mass Transportation Authority in Flint, Michigan also used TIGGER funds to acquire a fuel cell electric bus.

B. State Initiatives

California

ZEVs are a key element of California's plan for attaining health-based air quality standards and achieving greenhouse gas reduction goals. California has supported fuel cell electric vehicles and hydrogen infrastructure through legislation, EOs, and regulations. Governor’s EO B-16-2012 directed California to “encourage the development and success of zero-emission vehicles to protect the environment, stimulate economic growth and improve the quality of life in the State” (Office of Governor, 2013). The EO set explicit targets for California, including reaching 1.5 million ZEVs on California’s roadways by 2025. Several California government agencies collaborated to outline the actions necessary to meet the goals of the EO, which was compiled in the *2013 ZEV Action Plan: A Roadmap toward 1.5 Million Zero-Emission Vehicles on California Roadways by 2025*. The *ZEV Action Plan* includes the action items for medium- and heavy-duty zero-emission vehicles listed below:

- Actively consider medium- and heavy-duty ZEVs when planning infrastructure for light-duty vehicles, including hydrogen stations, to ensure that infrastructure can benefit medium- and heavy-duty ZEV models where appropriate;
- Expand use of ZEVs for private light- and medium-duty fleets;
- Incorporate light-, medium-, and heavy-duty ZEVs into the state vehicle fleet;
- Help to expand ZEVs within bus fleets;
- Reduce cost barriers to ZEV adoption for freight vehicles; and
- Integrate ZEVs into freight planning.

The sections below discuss California legislation, regulations, and incentive programs that will help increase use of heavy-duty ZEVs.

1. Assembly Bill 118 and Assembly Bill 8

Assembly Bill (AB) 118 (Nuñez Statutes of 2007), also known as the California Alternative and Renewable Fuel, Vehicle Technology, Clean Air, and Carbon Reduction Act of 2007, provides approximately $150 million annually, depending on reserves, for three programs to fund air quality improvement projects and develop and deploy technology and alternative and renewable fuels. The three programs are described below:

- The Alternative and Renewable Fuel and Vehicle Technology Program provides annual incentive funding to develop and deploy innovative technologies (CEC, undated). The program is administered by the California Energy Commission. The program currently makes available approximately $100 million annually to co-fund alternative fuels projects, a portion of which has been set aside for hydrogen infrastructure.
- The Air Quality Improvement Program (AQIP) has been awarded $23 million in the Governor's proposed State Budget in FY 2015-2016 Funding Plan to fund clean vehicle and equipment projects that reduce criteria pollutants and toxic air contaminants, as well as research on the air quality impacts of alternative fuels and advanced technology vehicles (ARB, 2015c). The program is administered by ARB.
- The Enhanced Fleet Modernization Program provides about $30 million per year for voluntary retirement of high emitting passenger cars and medium- and heavy-duty trucks (ARB, 2015d). The program is administered by the Bureau of Automotive Repair, but statute directs the Air Resources Board (ARB) to adopt guidelines for the program.

In 2013, the Legislature passed and Governor Brown signed AB 8 (Perea, statutes of 2013), which extends the sunset date for AB 118 funding from 2015 to January 1, 2024

(CLI, 2013). The bill includes a commitment of up to $20 million a year from the Alternative and Renewable Fuel and Vehicle Technology Program for hydrogen stations until there are at least 100 publicly available hydrogen-fueling stations in California.

2. California Climate Investments

In 2012, the Legislature established the Greenhouse Gas Reduction Fund (GGRF) to receive Cap-and-Trade auction proceeds and provide a framework for how the auction proceeds will be administered to further the purposes of AB 32. The *Cap-and-Trade Auction Proceeds Investment Plan: Fiscal Years 2013-14 through 2015-16* identified ARB as the lead agency for implementing Low Carbon Transportation investments, and the existing AQIP program for the framework. In FY 2014-15, ARB received $200 million to accelerate the transition to low carbon freight and passenger transportation, with a priority for projects benefitting disadvantaged communities. In May 2015, the Governor's proposed state budget for FY 2015-16 included $350 million for Low Carbon Transportation, which is reflected in the ARB's *FY 2015-16 Funding Plan for Low Carbon Transportation and Air Quality Improvement Program* (ARB, 2015c). ARB has allocated ~$25 million toward zero-emission drayage trucks and has another $20 million for the zero-emission truck and bus pilot project sourced from Greenhouse Gas Cap and Trade Auction proceeds to reduce carbon emissions from transportation sectors (AQIP, 2014). The FY 2015-16 Funding Plan directs $148 million toward the development, demonstration, and deployment of zero- and near zero-emission heavy-duty vehicles and equipment, with close to 75 percent of the funding going to projects that benefit disadvantaged communities. On October 1, 2015, ARB released a solicitation to fund larger-scale deployments of zero-emission trucks, buses, and school buses (including hybrid vehicles capable of operating in zero-emission mode within disadvantaged communities) and associated charging/fueling stations. An additional $60 million from FY 2015-16 will be available for these projects pending approval by the California Legislature.

3. Governor's Executive Order S-07-04

The California Hydrogen Highway Network was initiated in April 2004 by EO S-07-04 under Governor Arnold Schwarzenegger to ensure that hydrogen fueling stations are in place to meet the demand of fuel cell and other hydrogen vehicle technologies being placed on California's roads (ARB, 2013).

In 2008, ARB awarded $7.6 million for three hydrogen station projects including a heavy duty fueling station at AC Transit, which has since played a critical role in supporting their hydrogen fuel cell electric bus demonstration program (CHBC, 2008). Hydrogen policies continue through Governor Brown's Executive Order B-16-2012 and the Zero Emission Vehicle Action Plan (Office of Governor, 2013). These directives further mobilize state government to continue hydrogen funding, and prepare consumers, fleets, communities, the workforce, and the fueling network for commercialization of hydrogen fuel cell electric vehicles.

4. Fleet Rule for Transit Agencies

The commercialization and widespread adoption of zero-emission transit buses is a key step for California in meeting air quality standards and achieving greenhouse gas emissions reduction goals. In February 2000, ARB adopted the Fleet Rule for Transit Agencies. The regulation required reductions in both criteria and toxic air pollutants from urban buses and transit fleet vehicles. The transit fleet rule also established a demonstration and purchase requirement for zero-emission technologies for large transit agencies. As a result of the Fleet Rule for Transit Agencies, some transit agencies are actively operating and demonstrating zero-emission fuel cell electric and battery electric buses in California.

5. California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP)

California HVIP assists the introduction of zero- and near-zero-emission trucks and buses by providing vouchers to cover partial purchase costs of these advanced vehicle technologies with the aim to help accelerate market penetration of ZEVs (e.g., fuel cell electric vehicles). For ZEVs, the voucher amount can be up to $110,000 per vehicle (HVIP, 2015).

6. Carl Moyer Memorial Air Quality Standards Attainment Program

The Carl Moyer Program is a grant program that provides incentive funds to private companies and public agencies to purchase cleaner-than-required engines, equipment, and emission reduction technologies. Projects that reduce emissions from heavy-duty on-road and off-road equipment qualify for Moyer grants. These projects go beyond regulatory requirements by replacing, repowering or retrofitting older, higher-emitting engines (ARB, 2015e).

7. ARB's Truck Loan Assistance Program

The Truck Loan Assistance Program is a partnership between ARB and California Pollution Control Financing Authority (CPCFA). This program utilizes the Independent Contributor provisions of CPCFA's California Capital Access Program (CalCAP), which enable outside sources of funding (e.g., State or federal funds) to be used for loan assistance. ARB funds are used in CalCAP to enable lenders to improve their ability to provide financing to small businesses to assist them in growing or maintaining their business. Loans in the program can be used to finance heavy-duty trucks and buses (over 14,000 pounds (lbs.) Gross Vehicle Weight Rating (GVWR)) equipped with engines certified to specified engine emission standards for 2007 and newer model year engines, and diesel exhaust retrofits (ARB, 2015f).

8. Proposition 1B Goods Movement Emission Reduction Program (GMERP)

Proposition 1B, approved by voters in 2006, authorizes $1 billion in bond funding to ARB to cut freight emissions along California's four priority trade corridors. The Program is a partnership between ARB and local agencies (such as air districts) to quickly reduce air pollution emissions and health risk from freight transport. ARB awards Program funds to local agencies; those agencies then use a competitive process to provide incentives to equipment owners to upgrade to cleaner technology. The funds provide an incentive to equipment owners to upgrade to cleaner equipment and achieve early or extra emission reductions beyond those required by applicable regulations or enforceable agreements. The Program supplements regulatory actions and other incentives to cut diesel emissions by funding projects "not otherwise required by law or regulation" (ARB, 2015g).

New York

In partnership with the New York (NY) State Energy Research and Development Authority, NY State Department of Transportation, NY City Department of Transportation, and CALSTART, the *New York Truck Voucher Incentive Program (NYT-VIP)* is a 'first come – first serve' incentive program to provide incentives for the purchase of alternative fuel vehicles and diesel emission control devices. The program contains three funds: NY State Electric Vehicle Voucher Incentive Fund (VIF), NY City Alternative Fuel Vehicle –VIF, and NY City Diesel Emission Reduction VIF. Vendors that market and sell these technologies are eligible for a voucher incentive to reduce the cost to the purchaser. Once the purchaser receives the new truck or diesel emission control devices, the vendor will be redeemed the full voucher amount. This program aims to promote and accelerate the integration of advanced vehicle technologies in NY (New Work State, undated).

Chicago

One of the programs under Drive Clean Chicago is the *Drive Clean Truck – Voucher Program* that provides incentives to purchase zero and low emission vehicles. This program accepts voucher requests from vendors and dealers on behalf of the purchasers of commercially available Class 2 – 8 All-Electric and Hybrid Trucks and Buses. They can apply for incentives up to $150,000 (Drive Clean Chicago, undated).

C. Local Air Districts

The local air pollution control and air quality management districts are currently offering incentive programs mainly through Air District's Moyer and Proposition 1B GMERP funds.

Bay Area Air Quality Management District (BAAQMD) has provided funding for zero- and near-zero-emission heavy-duty vehicles with a GVWR of greater than 14,000 lbs. through the Voucher Incentive program (VIP), the Transportation Fund for Clean Air (TFCA) Heavy-Duty Electric Vehicle program, and the Goods Movement program

(GMP) (BAAQMD, undated a). The programs offer grants to owners of heavy-duty vehicles to reduce diesel-related emissions from heavy-duty engines. VIP grants (part of Moyer) are currently available for fleets of three or fewer vehicles to help vehicle owners replace their 2006 or older heavy-duty diesel vehicles. VIP funded grant projects must operate within California 75 percent of the time. TFCA Heavy-duty EV grants are currently available for public or private entities located within the boundaries of the Air District's jurisdiction (BAAQMD, undated b). The Air District will accept applications until December 18, 2015. The GMP (part of Proposition 1B GMERP) provides funding for truck replacement used to move commercial freight, bulk or goods for sale or for purchase along California's trade corridors (BAAQMD, undated c).

Sacramento Metropolitan Air Quality Management District (SMAQMD) provides funding to offset the incremental cost of purchasing low or zero-emission technologies and promotes early introduction of low or zero-emission technologies. Current funding programs are: 1) the Lower-Emission School Bus program for school buses equipped with pre-1987 model year engines (SMAQMD, undated a); 2) the Sacramento Emergency Clean Air & Transportation (SECAT) grant program, which is the collaborating work between SMAQMD and Sacramento Area Council of Governments (SACOG) to provide funding for replacement of heavy-duty diesel vehicles equipped with 2006 and older model year engines (SECAT, undated); 3) the Goods Movement Emission Reduction Program (GMERP- part of the Proposition 1B GMERP), which provides funding for owners of heavy-duty vehicles used in freight movement along California's trade corridor, to purchase a new cleaner vehicle (SMAQMD, undated b); and 4) the VIP (part of Moyer) for small fleets of three or less 2006 heavy-duty diesel vehicles (SMAQMD, undated c).

The San Joaquin Valley Air Pollution Control District (SJVAPCD) is providing funding for new alternative fuel vehicle purchase through its Public Benefit Grants Program to local public agencies. Maximum funding is up to $20,000 per vehicles with limit of $100,000 per agency per year (San Joaquin Valley, undated a). In addition, the Proposition 1B - GMERP provides financial incentives for owners of freight movement trucks along California's trade corridors to upgrade to cleaner technologies through truck replacement or engine replacement (San Joaquin Valley, undated b). Another program is the Truck Voucher Program that allows participants to apply through SJVAPCD-certified dealerships to replace old, high-polluting, heavy-duty diesel trucks. Applications are only available at SJVAPCD certified dealerships and are accepted on a continual basis until funding is exhausted (San Joaquin Valley, undated c). There is also a program similar to Truck Voucher Program for Class 5 and 6 trucks, called Class 5 & 6 Truck Program (San Joaquin Valley, undated d).

The South Coast Air Quality Management District (SCAQMD) is currently providing financial incentives for commercializing ZEVs through Moyer, Proposition 1B GMERP, and VIP (part of Moyer). Moyer provides funding for the incremental cost of cleaner-than-required heavy-duty vehicles to encourage the replacement of older heavy-duty diesel vehicles (SCAQMD, undated a). Proposition 1B GMERP provides funding for replacing old heavy-duty diesel vehicles involved in goods movement (SCAQMD, undated b). VIP is a streamlined approach to reduce emissions by replacing old, high-polluting vehicles with newer, lower-emission vehicles, or by installing a retrofit device. This program is limited to owners/operators with fleets of 10 or fewer vehicles that have been operating at least 75 percent (mileage-based) in California during the previous 24 months (SCAQMD, undated c).