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PREFACE

Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007) created the Clean Transportation Program. The statute authorizes the California Energy Commission (CEC) to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. Assembly Bill 8 (Perea, Chapter 401, Statutes of 2013) reauthorizes the Clean Transportation Program through January 1, 2024, and specifies that the CEC allocate up to $20 million per year (or up to 20 percent of each fiscal year's funds) in funding for hydrogen station development until at least 100 stations are operational.

The Clean Transportation Program has an annual budget of about $100 million and provides financial support for projects that:

- Reduce California's use and dependence on petroleum transportation fuels and increase the use of alternative and renewable fuels and advanced vehicle technologies.
- Produce sustainable alternative and renewable low-carbon fuels in California.
- Expand alternative fueling infrastructure and fueling stations.
- Improve the efficiency, performance and market viability of alternative light-, medium-, and heavy-duty vehicle technologies.
- Retrofit medium- and heavy-duty on-road and nonroad vehicle fleets to alternative technologies or fuel use.
- Expand the alternative fueling infrastructure available to existing fleets, public transit, and transportation corridors.
- Establish workforce-training programs and conduct public outreach on the benefits of alternative transportation fuels and vehicle technologies.

To be eligible for funding under the Clean Transportation Program, a project must be consistent with the CEC's annual Clean Transportation Program Investment Plan Update. The CEC issued contract 600-11-002, on September 13, 2012, to provide program support on specific Clean transportation Program topics, including a technical and market assessment of advanced vehicle technologies.

ABSTRACT

The *Alternative Refueling Infrastructure Report* is intended for internal use by CEC staff as a review of the technology and market status of the following alternative transportation fuels: ethanol, biodiesel, renewable diesel, natural gas, electricity, and hydrogen. The report conveys the status of key technologies associated with infrastructure supply systems, as well as the current market status and in some cases the potential future market status of each fuel. Each alternative fuel faces unique market adoption challenges, and many are in different stages of technological and market maturity. The scope of this report is intended to provide an overview of issues related to the market acceleration activities being conducted through the Clean Transportation Program.

All alternative fuels discussed in this report offer some near- or long-term advantage over conventional gasoline and diesel fuels, including (in most cases) being less expensive to consumers, having reduced greenhouse gases (GHG) and/or criteria emissions, and displacing petroleum fuels. Disadvantages include being more expensive during market introduction, significant infrastructure capital costs, limited range of vehicles, lack of available infrastructure, and business model challenges associated with early market adoption dynamics.

Significant near-term market intervention will likely be required in order for alternative fuels and associated infrastructure to become established and, ultimately, economically competitive with conventional petroleum fuels. Based upon this and other reviews, there are no clear winners among alternative fuel options, warranting a portfolio policy approach to supporting the deployment of multiple fuel types. It is likely that multiple alternative fuels will compete for different market segments and growth opportunities during the transition to a low-carbon transportation future.

For future work, refined analytical models capable of determining optimal types and locations of future alternative fueling stations can help to ensure that the Clean Transportation Program investments are cost-effective, and that the CEC's transportation sector objectives are met with an efficient use of public funds. This report contributes to a more complete understanding of those investment options by reviewing key technology and market status issues.

Keywords: Alternative fuels, retail infrastructure, alternative fuel vehicles, transportation fuels, compressed natural gas (CNG), liquified natural gas (LNG)

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EXECUTIVE SUMMARY

Two forward-looking alternative fuel infrastructure scenarios will be briefly compared. These studies envision a gradual transition from petroleum fuels to renewable fuels in the transportation sector in California by the year 2050. In order to accomplish this transition, alternative fuel infrastructure investment would need to be on the order of $55 million to $80 million annually from 2010 to 2020, with significant increases in investment after 2020. One study estimates fuel cost savings after 2050 of about $17 per dollar of infrastructure investment. Current investments in California alternative fuel infrastructure are on the order of half that required in the two scenarios in the near term. More detailed analyses are required to better understand the role of the Clean Transportation Program and other state agencies in facilitating this transition.

There were not quite 100 stations offering ethanol blends, or fuel containing 85 percent ethanol, in California as of October 2014, and most were located in urban areas. E85 consumption in California is estimated at about 10-15 million gallons per year but could theoretically approach 240 million gallons per year if all of the approximately 750,000 flex-fuel vehicles in California used fuel containing 85 percent ethanol exclusively. With less than 100 fuel containing 85 percent ethanol stations statewide, there is a market opportunity for increased E85 sales – especially in areas with federal fleets that are required to use E85 if available. There are no significant issues associated with fuel containing 85 percent ethanol storage and dispensing, and Underwriters Laboratory listed fuel containing 85 percent ethanol equipment is commercially available. One challenge associated with fuel containing 85 percent ethanol is cost – while fuel containing 85 percent ethanol may be less expensive per gallon than gasoline, it has less energy content per unit than gasoline does (on the order of 27 percent or so depending on the amount of ethanol in the fuel). As a result, a vehicle typically cannot travel as far on a gallon of fuel containing 85 percent ethanol as on a gallon of gasoline, and in general it costs more to travel a mile using fuel containing 85 percent ethanol than using gasoline.

There were 83 stations in California selling various blends of biodiesel fuel (primarily B20) as of October 2014, and most are located in urban areas and/or along major highways. While biodiesel blends are much more prevalent and available commercially, renewable diesel fuel in the United States is in the early stages of development and is appealing because it is chemically similar to petroleum diesel. This similarity means that it could be used in diesel engines without any modifications required to the engines, and that it could be transported in pipelines via the existing infrastructure system. Overall diesel consumption in California is about 2.6 billion gallons annually, and with biodiesel consumption at about 58 million gallons in 2012, there exists an opportunity for significant increases in biodiesel use. A major challenge to increased biodiesel use (besides station availability) is often the generally higher prices for biodiesel – especially for higher blends of biodiesel. Neat biodiesel is often transported via truck or rail for blending, which adds to the cost of biodiesel. About 100 million gallons of renewable diesel was imported by Neste Oil and sold into the California market in 2013, which illustrates demand for this fuel in the state.

Less than 1 percent of all natural gas demand in the state of California comes from the transportation sector. This sector uses natural gas in two forms: compressed natural gas and liquefied natural gas. Liquified natural gas is used much less frequently than compressed natural gas, but it might have applications as a fuel for larger trucks where driving range and fuel energy density are important. Due to the low temperature required for liquified natural gas, pipeline transportation is not practical, and trucks are often used as the transportation mechanism. Compressed natural gas is typically stored at 3,600 pounds per square inch and is dispensed at different rates. A time-fill station takes a significant amount of time for refueling, while a fast-fill station has refueling times similar to a conventional gasoline station. Because natural gas is a regulated commodity and a domestic fuel, there is often less volatility in price compared to other fuels. Natural gas costs are typically lower compared to gasoline on a gasoline gallon equivalent basis, and natural gas generally produces lower greenhouse gas emissions than gasoline does. Perhaps the biggest barrier to natural gas vehicle growth is the higher incremental cost (often several thousand dollars) of a natural gas vehicle compared to a conventional or flex-fuel vehicle. California has about 330 compressed natural gas and liquified natural gas stations (the vast majority are compressed natural gas stations) and about 33,000 natural gas vehicles registered in the state.

As of October 2014, California had the most public electric charging stations of any state, at more than 1,800 stations. Not all equipment and technologies associated with electric vehicles and electric vehicle support equipment have been standardized, although there have been (and continue to be) efforts to do so. For example, multiple connector types (that fit into a plug-in electric vehicle charging receptacle) are in use. Direct current fast charging electric vehicle support equipment frequently use a fast-charging receptacle, called CHAdeMO, that is common in California and Japan, although U.S. manufacturers are working on a separate direct current charging standardized system called a J1772 combo. California faces the same challenges and policy choices that all states face when attempting to encourage electric vehicle growth, including how best to support charging infrastructure development, where charging stations should be located, and how much to support electric vehicle supply equipment expansion compared to vehicle deployment. The *California Statewide Plug-In Electric Vehicle Infrastructure Assessment* suggests a range of home, work, and public charging stations (by level 1, level 2, and fast charging stations) that would likely be sufficient to support an expanding electric vehicle inventory and market in California.

Hydrogen-fueled fuel cell electric vehicles are appealing because their tailpipe emissions are simply water vapor, and like electricity, hydrogen can be produced from low-carbon energy resources. Full production and marketing of fuel cell electric vehicles is expected to occur around the year 2015 in selected markets, including California in the United States, as well as Germany, England, Japan, and South Korea. Fuel cell electric vehicle refueling times are similar to conventional gasoline refueling times, and hydrogen fuel costs are anticipated to be comparable to gasoline on a per mile basis. Hydrogen challenges include the relatively expensive retail infrastructure costs (typically at or above $2-$3 million per station) and additional production and delivery components associated with the full supply chain, which can also be capital intensive. Long distance distribution of small volumes of hydrogen is typically done with liquid tank truck delivery today, while the least expensive distribution method for large volumes is pipeline delivery. Hydrogen pipelines are in use today for high-volume demands within the petroleum sector. Fuel cell electric vehicles in the near future will likely store hydrogen onboard at about 10,000 pounds per square inch (on the order of three times the pressure of compressed natural gas). Currently, most hydrogen is produced using a steam methane reformation process with natural gas as an energy feedstock, but future hydrogen production may be less carbon intensive (using water electrolysis and renewable energy, for example) if the focus on de-carbonization of transportation fuels continues.

Alternative fuel infrastructure policies and funding can assist in removing early market barriers that inhibit development of a mature market for any of the alternative fuels. One such barrier is the "chicken or egg" challenge – potential alternative fuel vehicle owners are often hesitant to purchase an alternative fuel vehicle without adequate refueling infrastructure in place, and potential infrastructure developers are not inclined to invest in alternative fuel infrastructure without adequate numbers of alternative fuel vehicles that might be potential customers. CEC funding support for alternative fuel infrastructure has risen significantly over the last several years – both in real dollars and as a percent of overall investment – and appears poised to do so again for the 2014—2015 timeframe. Benefits of these investments are quantified in the 2014 Benefit Guidance Report developed by National Renewable Energy Laboratory for the CEC. Future challenges include the need for the development of more refined and accurate modeling tools that can assist with the analysis required to determine the optimal size, type, and location of future infrastructure projects, such that CEC goals are maximized.

CHAPTER 1: Alternative Fuel Infrastructure Funding Analysis

Public sector funding for alternative fuel infrastructure comes from a variety of federal, state, regional, and local sources, as illustrated in Table 1. The CEC's Clean Transportation Program has provided significant support for infrastructure projects within the state, as documented within the 2013-2014 Investment Plan[1] and examined within the 2014 Benefits Guidance Report[2]. Outside of the Clean Transportation Program, there are a variety of additional supportive programs at the federal, state, regional and local levels. Direct funding at the federal level is primarily provided through programs administered by the U.S. Department of Energy (U.S. DOE) Office of Energy Efficiency and Renewable Energy. Indirect funding is also available in the form of tax credits and other incentives. Table 1 lists some of the primary federal funding sources and a brief description of programs applicable to alternative fuel vehicle fueling infrastructure in California. A more detailed summary of federal, state, and local incentives is provided in Chapter 7.

In 2009 and 2010, the CEC offered several solicitations to help California companies obtain funding through the American Recovery and Reinvestment Act. The solicitations leveraged $36.5 million of CEC funding with $105.3 in American Recovery and Reinvestment Act funding and $113.3 in private funding for various transportation projects.[3] Table 2 lists alternative fuel infrastructure and related projects funded in California through the American Recovery and Reinvestment Act solicitations. Data for Table 2 are taken from the U.S. DOE American Recovery and Reinvestment Act State Memo for California.[4]

Of the CEC's approximately $100 million annual budget, funding for alternative fueling infrastructure has remained between $20 million and $30 million per fiscal year period. In the proposed 2014—2015 investment plan, however, infrastructure expenditures exceed $36 million (see Chapter 7). The CEC has shifted funding priorities toward support of electric charging infrastructure and hydrogen fueling infrastructure in alignment with the California *Vision for Clean Air: A Framework for Air Quality and Climate Planning* Scenario 2 discussed in more detail later in this report.

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[1] Smith, Charles, Jim McKinney. *2014. 2014-2015 Investment Plan Update for the Alternative and Renewable Fuel and Vehicle Technology Program*. California Energy Commission, Fuels and Transportation Division. Publication Number: CEC-600-2013-CMF.

[2] Melaina, Marc, Ethan Warner, Yongling Sun, Emily Newes, Adam Ragatz. 2014. *Program Benefits Guidance: CEC-600-2013-CMF Analysis of Benefits Associated with Projects and Technologies Supported by the Alternative and Renewable Fuel and Vehicle Technology Program*. California Energy Commission, Fuels and Transportation Division. Publication Number: CEC-600-2014-005-D.

[3] Baroody, Leslie, Charles Smith, Michael A. Smith, Charles Mizutani. 2010. *2010-2011 Investment Plan for the Alternative and Renewable Fuel and Vehicle Technology Program* Commission Report. California Energy Commission, Fuels and Transportation Division. Publication Number: CEC-600-2010-001-CMF.

[4] U.S. DOE 2010, Department of Energy Recovery Act State Memos California.
http://energy.gov/sites/prod/files/edg/recovery/documents/Recovery_Act_Memo_California.pdf.

Table 1: Primary Federal Funding Sources for Alternative Fuel Vehicles and Infrastructure

Funding Source	Program Description
American Recovery and Reinvestment Act of 2009	The U.S. DOE was awarded $35.2 billion for programs and initiatives under its purview.[5] Eleven advanced fuels and vehicles projects totaling $141.8 million were funded in California. California also received $393.2 million for 21 smart grid projects providing critical electricity load management capability that will facilitate the deployment of electric vehicles.[6] American Recovery and Reinvestment Act funding is no longer available.
Clean Cities[7]	The Clean Cities program is part of the U.S. DOE's Vehicle Technologies Office. Clean Cities helps vehicle fleets and consumers reduce their petroleum use in transportation through supporting partnerships with local and statewide organizations. Clean Cities has funded more than 500 transportation projects and has distributed $377 million in project awards, which leveraged an additional $740 million in contributions from other public and private sector organizations.
State Energy Program	The U.S. DOE Office of Energy Efficiency and Renewable Energy State Energy Program provides funding to states through formula and competitive grants. States provide 20% matching funds used to develop state energy strategies.
Alternative Fuel Infrastructure Tax Credit[8]	This incentive covered fueling equipment for various alternative fuels installed between January 1, 2006, and December 31, 2013. This incentive expired December 31, 2013.
Hydrogen Fuel Infrastructure Tax Credit	A tax credit is available for the cost of hydrogen fueling equipment placed into service after December 31, 2005. The credit amount is up to 30% of the cost, not to exceed $30,000. Consumers who purchase qualified residential fueling equipment may receive a tax credit of up to $1,000. Under current law, this credit expires December 31, 2014.
Airport Zero Emission Vehicle (ZEV) and	The Zero Emissions Airport Vehicle and Infrastructure Pilot Program under the Federal Aviation Administration provides funding to airports to acquire ZEVs. Public use airports are eligible for funding to install or

[5] U.S. DOE 2012, Department of Energy: Successes of the Recovery Act. http://energy.gov/sites/prod/files/RecoveryActSuccess_Jan2012final.pdf

[6] U.S. DOE 2010, Department of Energy Recovery Act State Memos California. http://energy.gov/sites/prod/files/edg/recovery/documents/Recovery_Act_Memo_California.pdf

[7] U.S. DOE Clean Cities Coalition Network About https://cleancities.energy.gov/about/

[8] U.S. DOE Alternative Fuels Data Center Federal and State Laws and Incentives http://www.afdc.energy.gov/laws

Funding Source	Program Description
Infrastructure Incentives	modify fueling infrastructure to support the vehicles involved in the project.

Sources: U.S. DOE

Additional American Recovery and Reinvestment Act funds, U.S. DOE grants, and private sources have also funded a wide range of Clean Cities projects. Total federal (U.S. DOE/ American Recovery and Reinvestment Act) and non-federal average yearly expenditures for alternative fuel infrastructure in California are being developed and will be included in the next draft of this report.

Table 2: American Recovery and Reinvestment Act-Funded Projects in California 2009—2010

Funding Amount ($Million)	Description
60.3	Los Angeles Department of Water and Power; Los Angeles Smart Grid Regional Demonstration Project. The demonstration projects will include gathering data on how consumers use energy in a variety of systems, testing the next generation of cybersecurity technologies, and researching how to integrate a significant number of plug-in hybrid electric vehicles onto the grid.
45.4	South Coast Air Quality Management District Building Corp. in Diamond Bar received $45.4 million for transportation electrification. The overall objective of the Plug-In Hybrid Electric Medium Duty Commercial Fleet Demonstration and Evaluation Program is to develop plug-in hybrid technology for a very broad range of vehicles, create production capability as quickly as possible, and establish a supporting charging infrastructure.
15	Coulomb Technologies, Inc. in Campbell received $15 million to demonstrate the viability and economic and environmental benefits of an electric vehicle charging infrastructure.

Source: U.S. DOE

California has led the nation in construction of many types of alternative fuel infrastructure. Table 3 illustrates that the percentage of various alternative fuel stations and electric vehicle supply equipment (EVSE) in California relative to the national total is high – especially for EVSE and hydrogen[9]. California's long-term emphasis on zero emission vehicles (ZEVs), plug-in electric vehicles, and hydrogen fuel cell vehicles is reflected in the number of stations and EVSE that have been installed in California. While California's early lead in alternative fueling infrastructure has been reduced by recent infrastructure installations nationwide, California has continued to accelerate its infrastructure investment, especially in EVSE (Figure 1 and 2).

[9] U.S. DOE, Alternative Fuels Data Center Station Locator database http://www.afdc.energy.gov/locator/stations/.

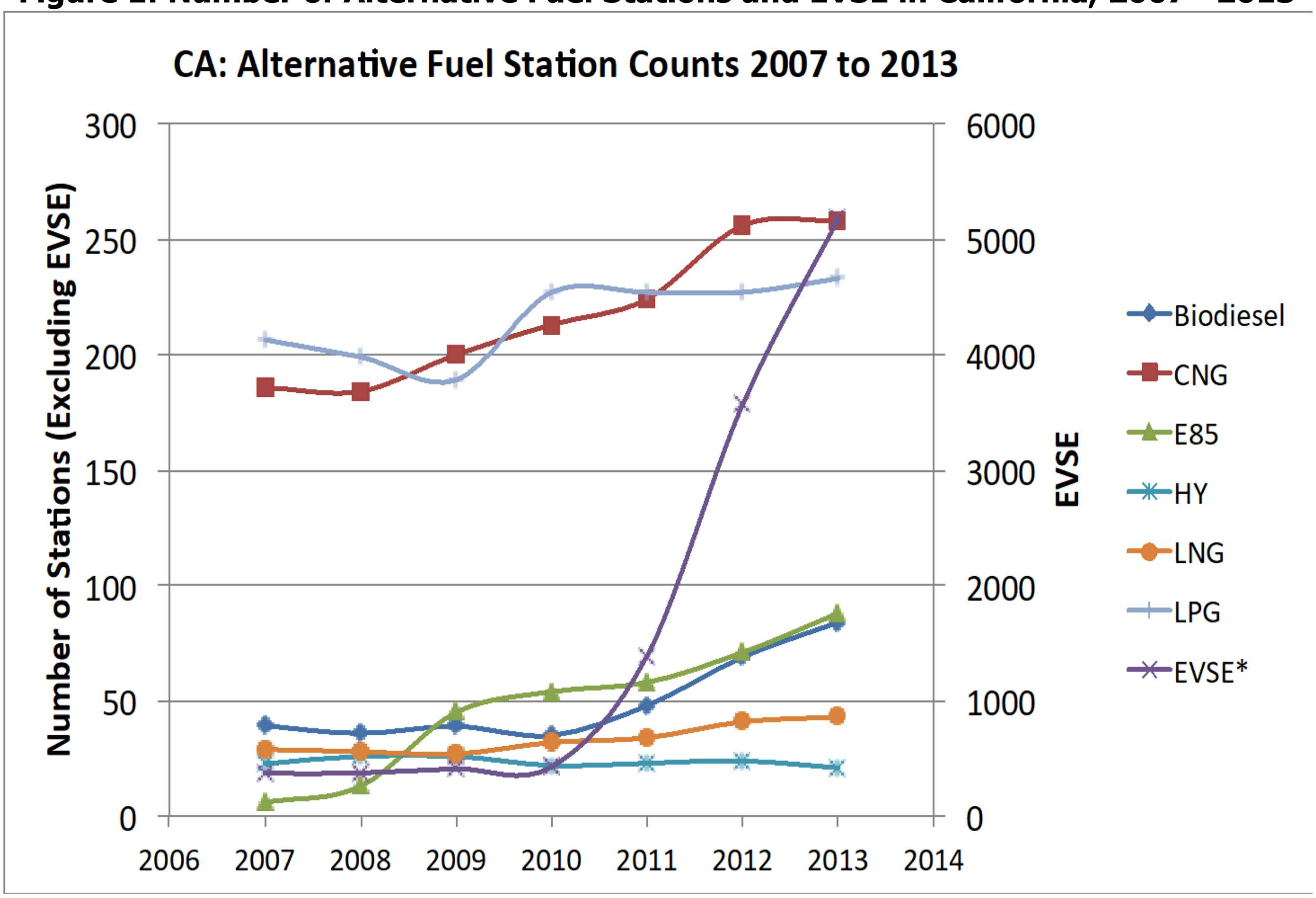
Table 3: Number of Alternative Fuel Stations/EVSE in California as a Percentage of the National Number 2007—2013

Year	EVSE*	Natural Gas (CNG, LNG)	Hydrogen	Biodiesel
2007	85%	28%	70%	5%
2008	85%	26%	51%	6%
2009	85%	27%	41%	6%
2010	68%	27%	38%	6%
2011	27%	26%	41%	8%
2012	24%	24%	41%	10%
2013	27%	22%	40%	10%

***In this table, electric charging units, or EVSE, are counted once for each outlet available. This includes legacy chargers (such as inductive paddles) but does not include residential electric charging infrastructure.**

Source: Alternative Fuel Center Data Station Locator

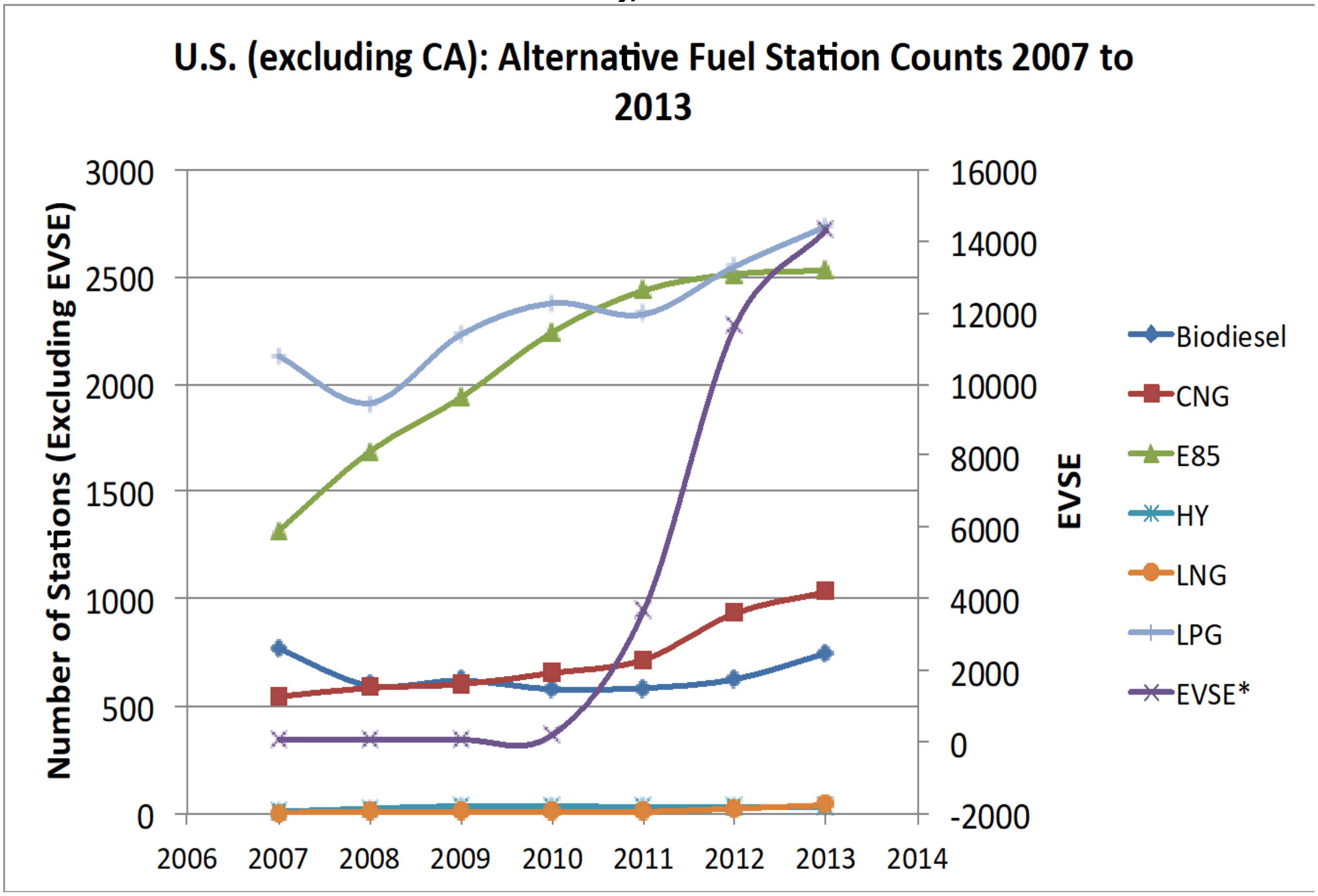
Figure 1: Number of Alternative Fuel Stations and EVSE in California, 2007—2013



***EVSE, are counted once for each outlet available. Includes legacy chargers (such as inductive paddles) but does not include residential or private electric charging infrastructure.**

Source: Alternative Fuel Center Data Station Locator

Figure 2: Number of Alternative Fuel Stations and EVSE Nationally (Excluding California), 2007—2013



Source: Alternative Fuel Center Data Station Locator

Alternative Fueling Infrastructure Cost/Benefit Analysis

The alternative fueling infrastructure cost/benefit analysis provided here is a high-level assessment of a successful transition to efficient vehicles and alternative fuels in California. In includes hypothetical fuel supply infrastructure requirements and the associated capital investment in retail infrastructure that will be needed as the for light duty vehicle market shifts to lower-carbon, alternative fuels. Comparable trends can be identified for medium- and heavy-duty vehicle markets, as reviewed at the national level in the 2012 Transportation Energy Future study's infrastructure expansion report.[10]

California has developed a number of planning scenarios to envision the transformations in light duty vehicles and driving patterns that will be needed to meet its long-term climate goal of reducing GHG emissions in the transportation sector 80 percent below 1990 levels by 2050. Other studies have developed scenarios to investigate needed changes in the transportation sector on a national level. Two of these studies have been used in this report to provide bounding estimates of the types of light duty vehicles, and associated fueling infrastructure,

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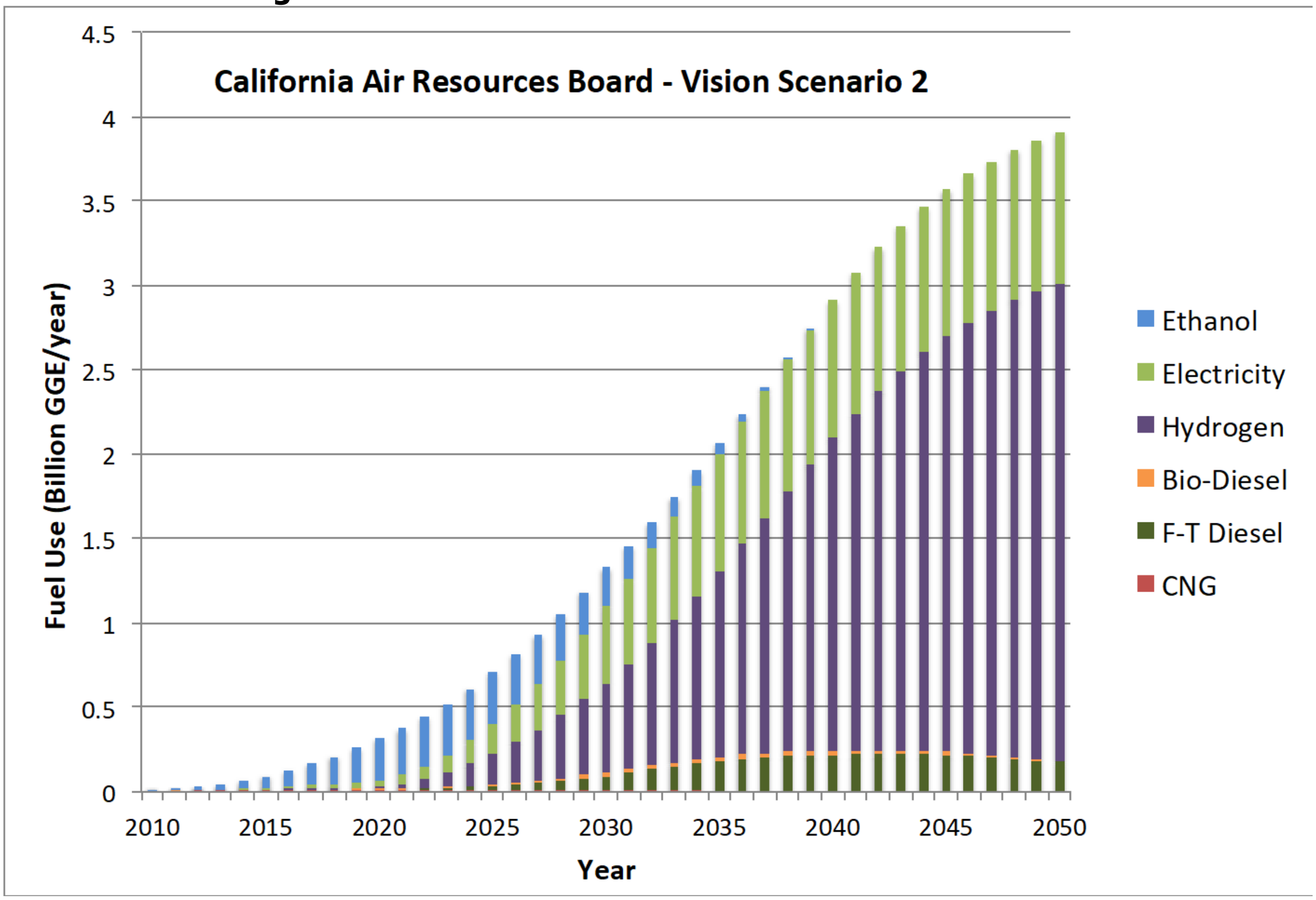
[10] Melaina, M.W.; Heath, G.; Sandor, D.; Steward, D.; Vimmerstedt, L.; Warner, E.; Webster, K.W. (April 2013). *Alternative Fuel Infrastructure Expansion: Costs, Resources, Production Capacity, and Retail Availability for Low-Carbon Scenarios.* Transportation Energy Futures Series. Prepared for the U.S. Department of Energy by the National Renewable Energy Laboratory, Golden, CO. DOE/GO-102013-3710. 101 pp.

that would be required to meet the California transportation sector climate goal. The California *Vision for Clean Air: A Framework for Air Quality and Climate Planning* Scenario 2 envisions a scenario in which, by 2040, all light duty vehicles sold in California are ZEVs that are fueled primarily by electricity and hydrogen.[11] The Transportation Energy Futures study Portfolio Scenario is a national study that achieves the same goal through aggressive improvements in vehicle fuel economy and vehicle miles traveled (VMT) reductions using a broad mix of low carbon fuels.[10] The Transportation Energy Futures Portfolio Scenario 2010 fuel use was normalized to the 2010 total California fuel use in the California Air Resources Board (ARB) vision study to allow comparison of the two scenarios[12]. The envisioned fuel use changes over time are presented for the two scenarios in Figure 3 and Figure 4.

Figure 3: Fuel Use in the California Vision Scenario 2

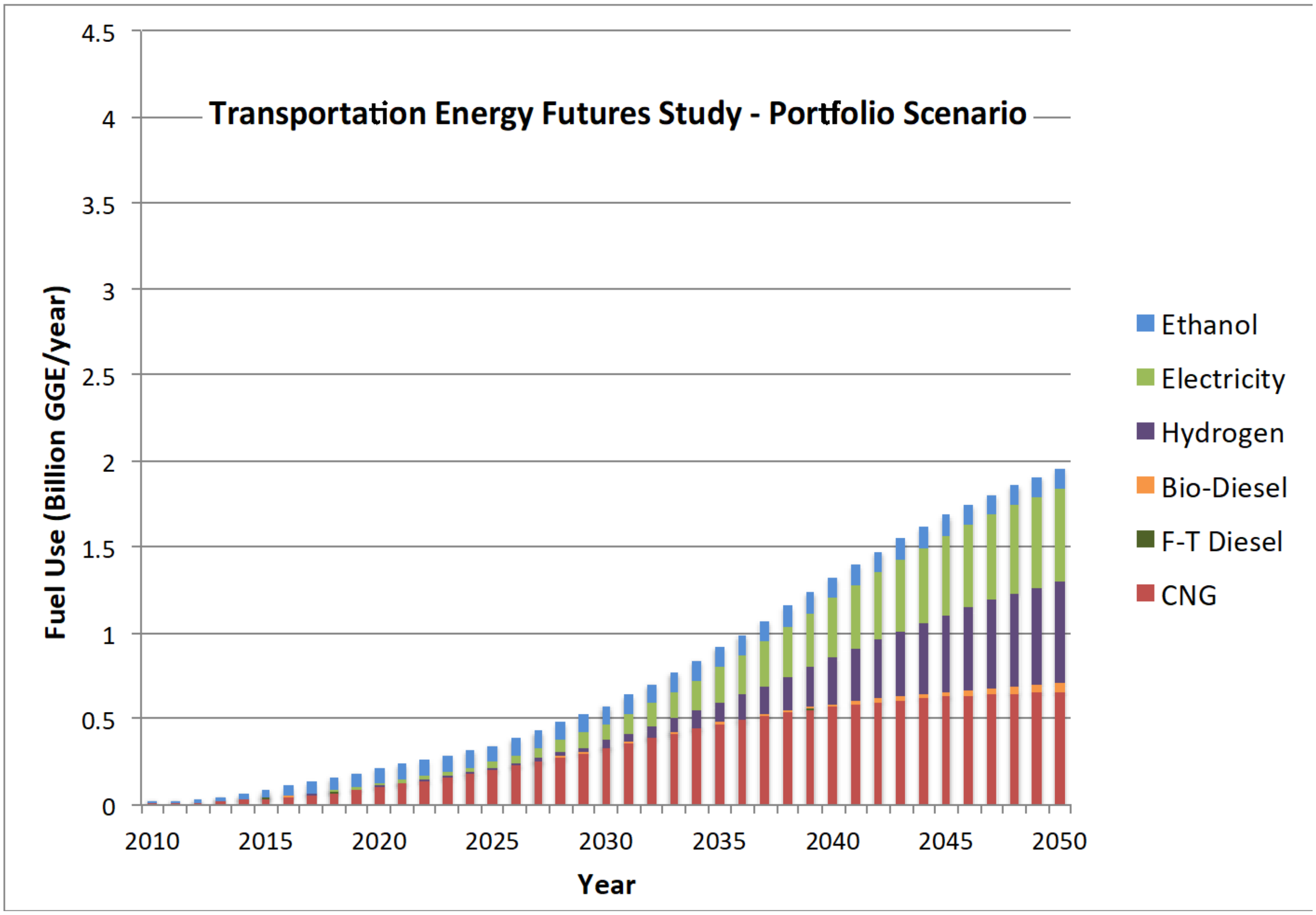


Source: CARB

[11] California Air Resources Board, South Coast Air Quality Management District and the San Joaquin Valley Unified Air Pollution Control District, Public Review Draft June 27, 2012 Vision for Clean Air: A Framework for Air Quality and Climate Planning https://www.aqmd.gov/home/air-quality/clean-air-plans/vision-for-clean-air

[12] California Air Resources Board, South Coast Air Quality Management District and the San Joaquin Valley Unified Air Pollution Control District, Appendix to the June 27, 2012 Draft Vision for Clean Air: A Framework for Air Quality and Climate Planning *Scenario Assumptions and Results*.
http://www.arb.ca.gov/planning/vision/vision.htm

Figure 4: California Fuel Use in the Transportation Energy Futures Study Portfolio Scenario



Source: NREL

Both scenarios begin by assuming the current fuel mix in 2010, which is almost entirely conventional gasoline for light duty vehicles but diverge sharply as they pursue different strategies to achieve the 2050 goal.

The ARB Vision Scenario assumes that by 2040, all passenger vehicles sold in California will be ZEVs. Phase-out of sales of flex-fuel vehicles will occur by 2030 and conventional gas, gasoline hybrid, and plug-in hybrid vehicle sales will be completely phased out by 2040. The scenario assumes that the electric grid capacity will grow to meet new demands, but that it will also be substantially cleaner with heavy reliance on either renewables or carbon capture and storage.

The Transportation Energy Futures Portfolio Scenario states that "a wide variety of low-carbon end-use and fuel technologies are assumed to achieve commercial success." The scenario assumes government support for less competitive fuels and technologies so that a broad range of vehicle types are commercially available in the long term. All of the low carbon scenarios in the Transportation Energy Futures study, including the Portfolio Scenario used here, also assume a 10 percent reduction in light duty vehicle VMT and aggressive improvements in fuel efficiency.

Retail fueling infrastructure distribution and cost assumptions are also adapted from the Transportation Energy Futures study. The Transportation Energy Futures study relied on the current distribution of retail gasoline stations to develop a simplified estimate of the density of retail fueling infrastructure that would be sufficient to meet consumer needs for station availability. Availability and distributions for EVSE infrastructure were also developed for the Transportation Energy Futures study. To simplify the analysis, only the battery electric vehicle (BEV) values were used. Station size distributions and associated costs were estimated for two future time points, 2020 and 2050. The ARB Vision Scenario did not present infrastructure cost estimates. Therefore, the Transportation Energy Futures 2020 and 2050 infrastructure distribution and cost estimates were used to develop estimated total and yearly infrastructure costs for California based on the 2020 and 2050 fuel use values for both scenarios.

Total infrastructure costs for 2020 and incremental infrastructure costs from 2020 to 2050 were calculated from the 2020 and 2050 light duty vehicles fuel use values from the two scenarios. Infrastructure costs for the two scenarios for each fuel type and station size and the total capital investment needed per year to 2020 are presented in Table 4. The table also shows total gasoline dispensed for each fuel type, represented in gasoline gallon equivalent (gge).

Incremental infrastructure costs for the two scenarios for each fuel type and station size and the total capital investment needed per year from 2020 to 2050 are presented in Table 5.

The two scenarios provide a range of required infrastructure investment between about $540 million and $800 million by 2020. As discussed earlier, the ARFVTP has invested approximately $30 to $40 million per year in alternative fuel infrastructure. Both the Transportation Energy Futures Portfolio Scenario and the ARB Vision Scenario assume that a steep ramp-up of investment in alternative fuel infrastructure would continue to be required after 2020. The ARB Vision Scenario would require a ten-fold increase in yearly infrastructure investment after 2020 and the Transportation Energy Futures Portfolio Scenario would require about a six-fold increase. This suggests that investments required to sustain successful market growth, similar to the CARB Vision or Transportation Energy Futures Portfolio scenarios, would far exceed ARFVTP funding levels by approximately 2020.

Fuel cost savings to consumers are potentially very significant, especially due to increased vehicle efficiency and successful cost reductions for alternative fuel supply. For example, after 2050, the Transportation Energy Futures study calculates a cost savings in fuel of approximately $17 per dollar of infrastructure investment. While this value includes infrastructure for medium-duty and heavy-duty vehicles as well as marine, rail, and air in addition to light duty vehicle infrastructure, it provides a rough estimate of the yearly savings that might be realized in a low-carbon transportation future. For the Transportation Energy Futures Portfolio Scenario in California, this equates to about $5 billion per year net savings in fuel costs.

These high-level scenarios provide some insight into the scale and potential cost and benefits of widespread adoption of alternative fuel vehicles in California. More detailed analyses are required to better understand the role of the CEC and other state agencies in facilitating this transition. The sections below provide additional information on each of the major alternative fuels.

Table 4: 2010-2020 Infrastructure Costs for the ARB Vision and Transportation Energy Futures Portfolio Scenarios

	ARB Vision Scenario			Transportation Energy Futures Portfolio Scenario		
	Total Fuel Dispensed (million gge/year)	Number of Stations/ EVSE	Capital Cost ($1000)	Total Fuel Dispensed (million gge/year)	Number of Stations/E VSE	Capital Cost ($1000)
Ethanol	247.7	217	$158,577	93.0	82	$59,923
Hydrogen (small station)	5.8	32	$54,400	1.9	10	$17,000
Hydrogen (large statin)	5.8	14	$43,400	1.9	5	$15,500
BEV EVSE Level 1 Residence	15.8	190,918	$143,189	5.5	65,913	$49,435
Level I Apartment	5.9	14,319	$10,739	21	4,944	$3,708
Level II Residence	11.9	110,485	$254,116	4.1	38,144	$87,731
Level II Work	5.9	16,573	$116,011	2.1	5,722	$40,054
CNG (small station)	4.9	14	$15,960	51.0	142	$161,880
CNG (large station)	4.9	5	$11,400	51.0	47	$107,160
Biodiesel/ Fischer-Tropsch Diesel	5.6	5	$3,654	1.5	1	$731
		Total	$811,445		Total	$543,122
Total (2010-2020)			$81,144,502	Total (2010-2020)		$54,312,180

Source: NREL

Table 5: 2020—2050 Incremental Infrastructure Costs for the ARB Vision and Transportation Energy Futures Portfolio Scenarios

	ARB Vision Scenario			Transportation Energy Futures Portfolio Scenario		
	Total Fuel Dispensed in 2050 (million gge/year)	Incremental Number of Stations/ EVSE	Capital Cost for Incremental Infrastructure (1000$)	Total Fuel Dispensed in 2050 (million gge/year)	Incremental Number of Stations/ EVSE	Capital Cost for Incremental Infrastructure (1000$)
Ethanol	-	-	$0	117	21	$15,346
Hydrogen (small station)	1,413	7,816	$8,597,600	295	1,626	$1,788,600
Hydrogen (large station)	1,413	3,448	$6,896,000	295	717	$1,434,000
BEV EVSE Level I Residence	360	4,930,102	$2,465,051	217	3,014,366	$1,507,183
Level I Apartment	135	225,729	$112,865	81	139,444	$69,722
Level II Residence	270	2,770,089	$4,986,160	163	1,694,513	$3,050,123
Level II Work	135	199,470	$1,196,820	81	124,227	$745,362
CNG (small station)	0	-	$0	196	401	$409,020
CNG (large station)	0	-	$0	456	375	$765,000
Biodiesel/ Fischer-Tropsch Diesel	186	158	$115,462	58	49	$35,808
		Total	$24,369,957		Total	$9,820,164
Total per Year (2020—2050)			$812,331,908	Total per Year (2020—2050)		$327,338,808

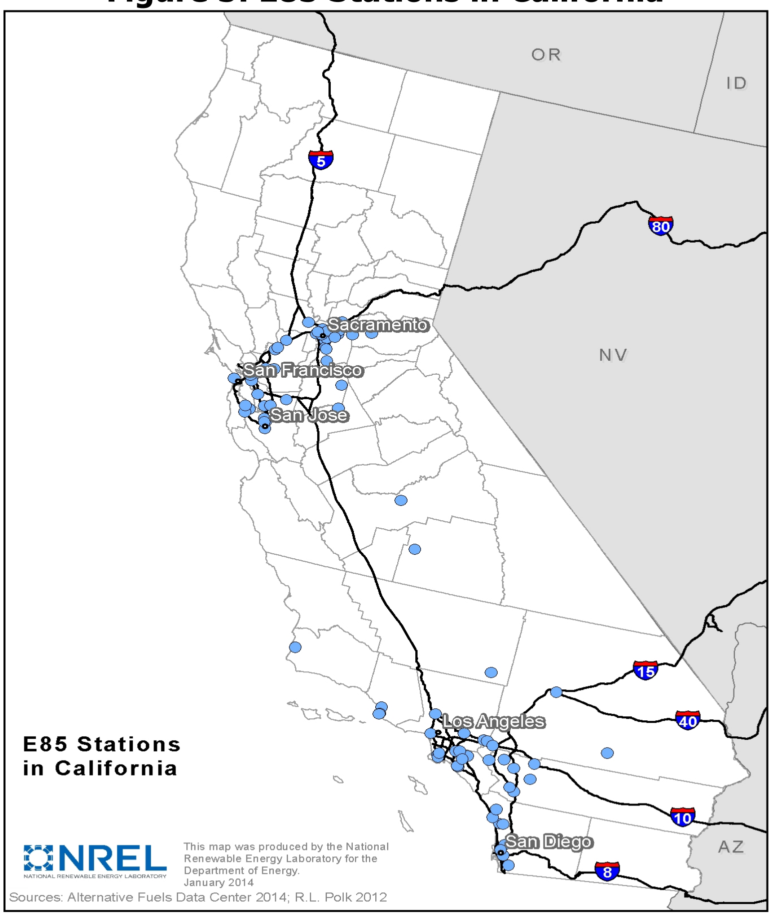
Source: NREL

CHAPTER 2: Ethanol Fueling Infrastructure

Background

Ethanol is commonly referred to at E85 (fuel containing 85 percent ethanol). E85 is a marketing term referring to a high-level gasoline blend meeting American Society for Testing and Materials fuel quality standard D5798 containing 51 percent to 83 percent ethanol, depending on geography and time of year. On average, ethanol content in E85 in California is at the upper end of this range.[13] As of October 2014, there were about 93 fueling stations (74 public and 19 private) in California offering E85.[14] The privately-owned stations are typically installed at government facilities to primarily serve government fleets. Figure 5 illustrates the geographic distribution of these facilities. Most of the stations are concentrated in urban areas and along major highways.

Figure 5: E85 Stations in California



Source: NREL

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[13] CEC. "California Retail Fuel Outlet Annual Report". Accessed December 2013, https://www.energy.ca.gov/data-reports/energy-almanac/transportation-energy/california-retail-fuel-outlet-annual-reporting

[14] Alternative Fuel Data Center Station Locator database https://afdc.energy.gov/stations/#/find/nearest

Ethanol blender pumps allow flexible fuel vehicle (FFV) owners to select a discrete range of ethanol-blended fuels including selections such as E20, E30, and E85 – are increasingly available at stations across the nation. However, none are available in California. In 2010, the United States Environmental Protection Agency (U.S. EPA) approved E15 for use in model year 2001 and newer light-duty cars and trucks, but only about 65 stations are selling it nationwide, and none of them are in California. There are several requirements required to sell E15 that do not apply to E85.[15]

Key Suppliers

California-based Propel Fuels is the major E85 distributor in the state. Currently, the company owns two stations and distributes E85 to 36 branded stations (Chevron, G&M, Phillips 76, Shell, and Valero).[8] Propel Fuels stations offer both conventional and alternative fuels, as well as several other sustainable transportation services such as free air for tires, carbon offset offerings, rideshare and community transportation resources, bicycle tuning stations, and recycling at the pump.[16] Propel Fuels' partners include the U.S. Department of Energy, California Department of General Services, CEC, and Clean Cities Coalitions. Its leading fleet partners include the U.S. Postal Service, CALTRANS, Department of Veterans' Affairs, California Highway Patrol, and Enterprise Fleet Services. Pearson Fuels and Interstate Oil Co. also distribute E85 to 12 and 4 stations respectively. Most terminals store gasoline and E98 and are capable of delivering E85 to customers if requested.

Market Information

E85 consumption on highways in California is estimated to be between 10 million and 15 million gallons per year. However, the potential sales volume is around 240 million gallons per year if all FFV owners refueled solely with E85.[17] According to 2012 Energy Information Administration (U.S. EIA) data, California led all other states in both gasoline and ethanol consumption with an estimate of 28.9 million barrels (~1.24 billion gallons of ethanol) consumed in the transportation sector.[18] Most of the ethanol is sold as E10, and California has reached the blend wall where the E10 market is saturated; any additional ethanol sales will need to be higher blends such as E85 or E15. The data suggest that E85 represents approximately 1 percent of California ethanol sales, which is consistent with nationwide estimates.

According to R.L. Polk data, there are nearly 752,000 FFVs registered in California as of 2012, which represent more than 2 percent of all registered light-duty vehicles in California.[19] The top ten selling vehicles in California represent 25 percent of total sales in the state, but only

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[15] Clean Cities. "Handbook for Handling, Storing, and Dispensing E85 and Other Ethanol-Gasoline Blends". Accessed January 9, 2014 http://www.afdc.energy.gov/uploads/publication/ethanol_handbook.pdf

[16] Propel. "Company Overview". Accessed January 2014. https://propelfuels.com/about_us

[17] CalETC. "California's Low Carbon Fuel Standard: Compliance Outlook for 2020." Last accessed January 9, 2014 https://caletc.com/lcfsreport/

[18] U.S. EIA, U.S. States Profiles and Energy Estimates. Table F4: Fuel Ethanol Consumption Estimates 2012. Last accessed January 9, 2014 http://www.eia.gov/state/seds/data.cfm?incfile=/state/seds/sep_fuel/html/fuel_use_en.html.

[19] R.L. Polk data. NREL purchases R.L. Polk data sets and is approved to publish state level data. https://www.polk.com.

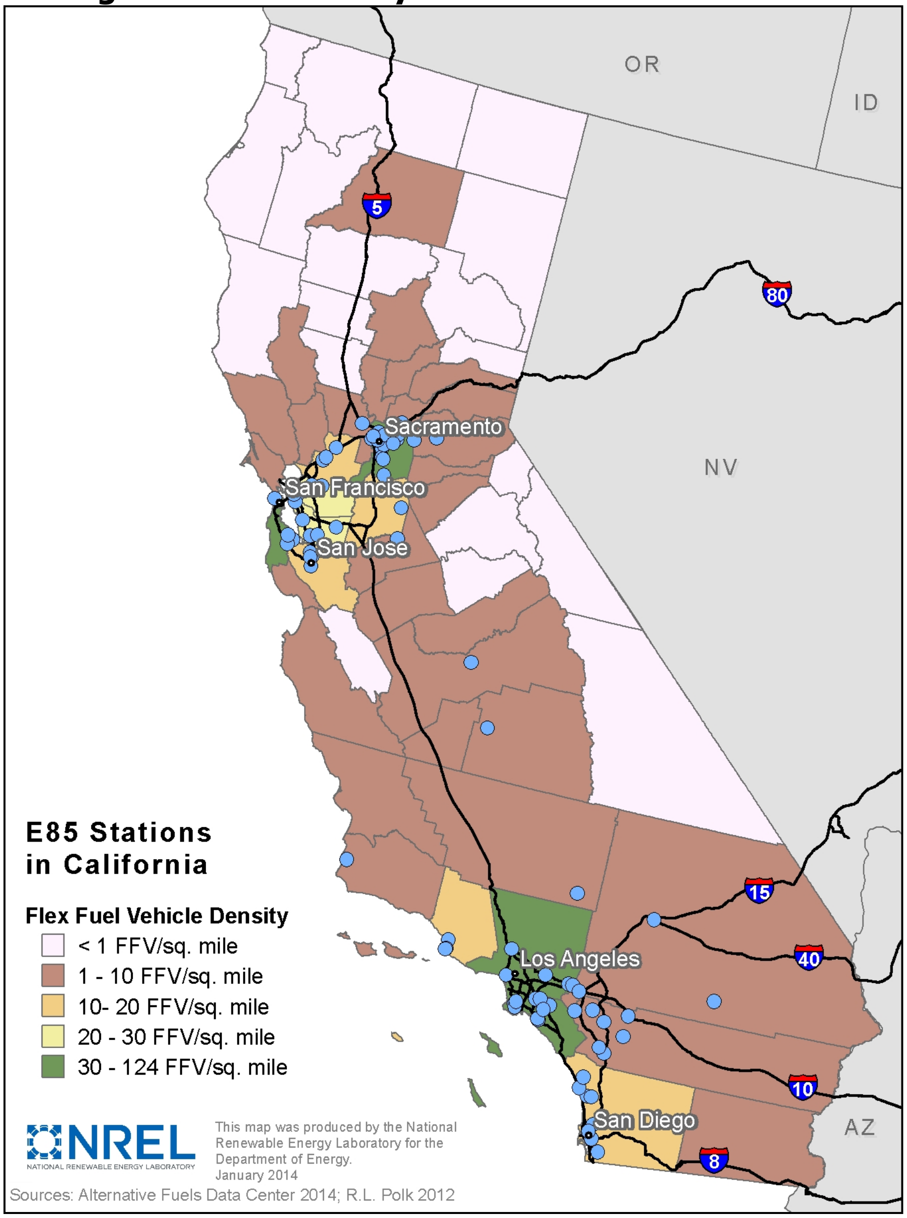
one of those offerings is available with an FFV option – the Ford F-Series.[17] Thirty-nine of 70 public E85 stations are located in counties with higher concentrations of E85 vehicles. Counties with the highest density of FFVs have few or no E85 stations (see Table 6). There is a market opportunity for retail stations to offer E85 in counties with high concentrations of FFVs, and especially in areas with federal fleets required to use the fuel, as illustrated in Figure 6.

Table 6: E85 and Retail Stations by County

County	# of E85 Stations	# of Public E85 Stations	# of Retail Stations	% of Retail Stations Offering E85
FFV concentrations of 30—124 per square mile				
Los Angeles	14	14	1,914	0.73%
Orange	4	4	635	0.63%
San Francisco	1	0	95	0.00%
San Mateo	3	1	198	0.51%
FFV concentrations of 20—30 per square mile				
Alameda	7	5	341	1.47%
Contra Costa	2	1	276	0.36%
Santa Clara	4	4	383	1.04%
FFV concentrations of 10—20 per square mile				
San Diego	8	6	750	0.80%
San Joaquin	1	1	216	0.46%
Solano	3	2	155	1.29%
Ventura	3	1	196	0.51%

Sources: NREL

Figure 6: FFV Density and E85 Station Locations



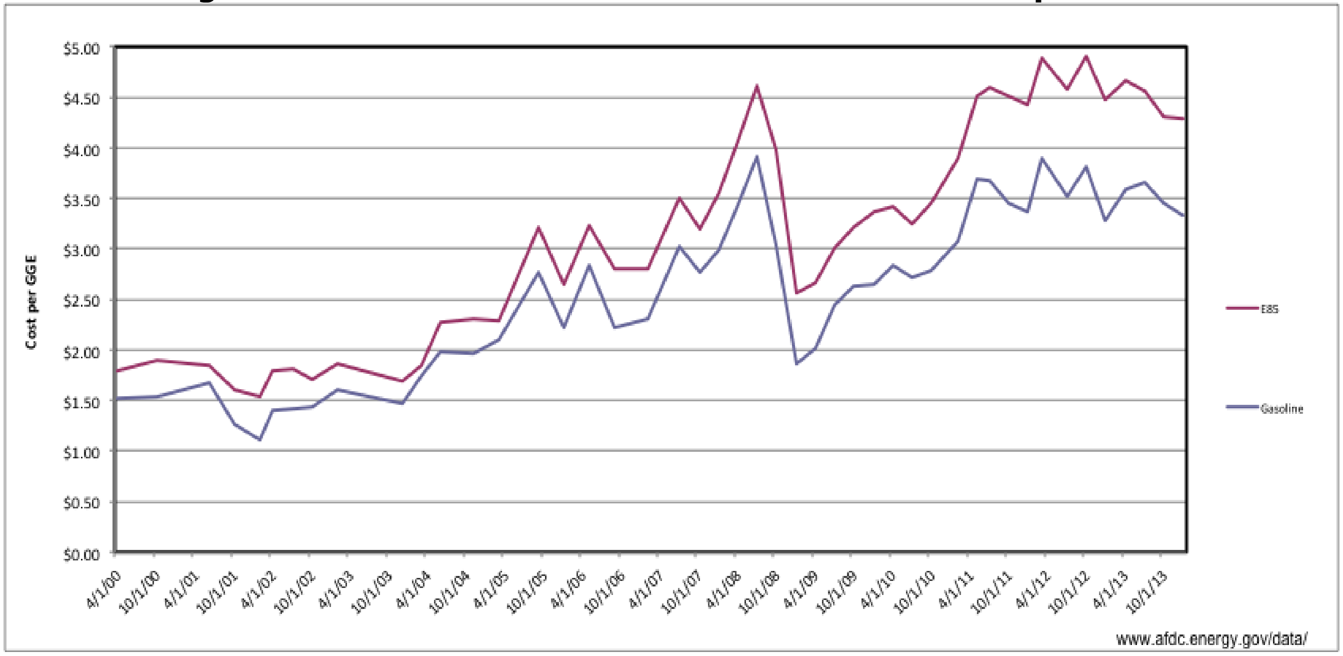
Sources: NREL

E85 in general has a lower fuel economy rating than gasoline because it contains about 27 percent less energy content per gallon compared to gasoline, and because FFVs are calibrated to run on the lower octane of E10.[20] There is an expectation that pricing should be consistently below gasoline prices to reflect the lower energy content. E85 generally is lower priced, but not usually low enough to compensate for the lower energy content in most of the country, with the exception of the Midwest, which typically has the greatest discount between E85 and gasoline prices. Figure 7 illustrates that on a gge basis, E85 costs more than gasoline

[20] E85 refers to fuel that is between 51 percent and 83 percent ethanol which will impact fuel economy depending on the proportion of ethanol in the fuel.

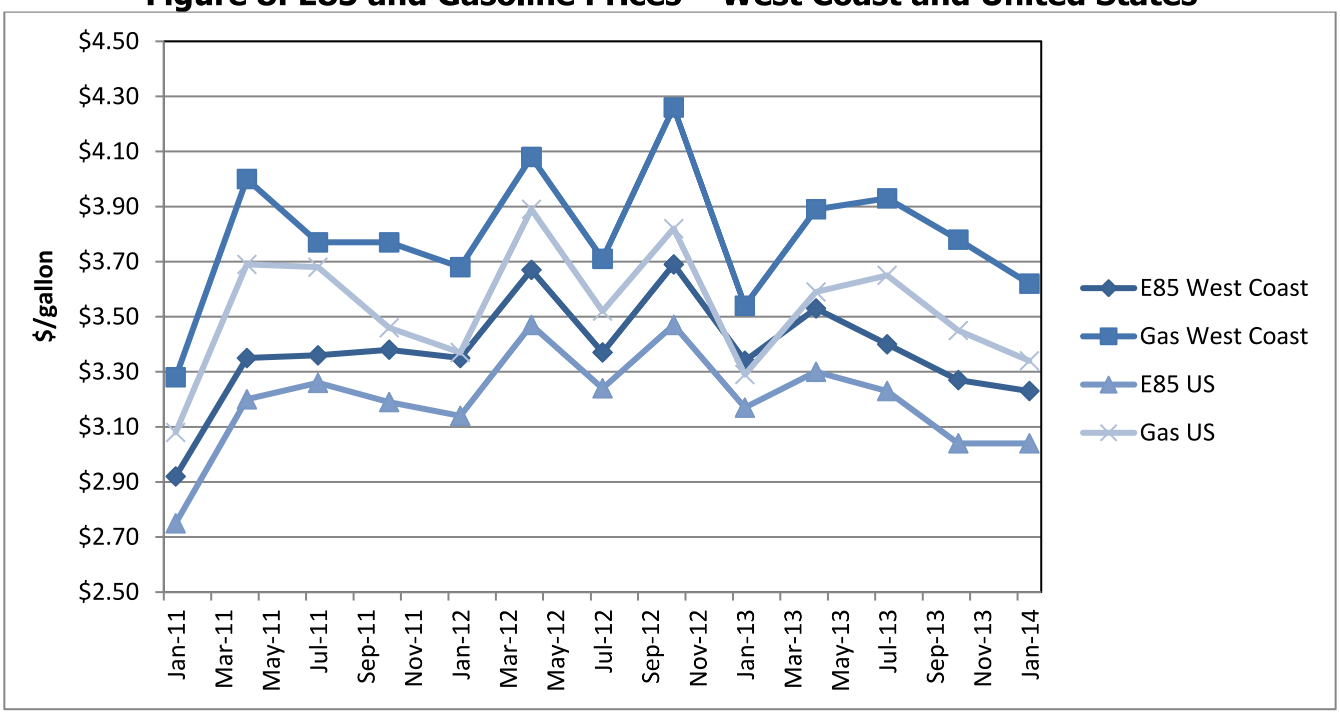
does. Figure 8 shows recent E85 and gasoline prices for both the United States and the West Coast[21] (where the majority of E85 stations are located in California).

Figure 7: E85 and Gasoline Prices – Gasoline Gallon Equivalent



Source: Alternative Fuels Data Center

Figure 8: E85 and Gasoline Prices – West Coast and United States



Source: Clean Cities Alternative Fuel Price Reports

[21] U.S. DOE Alternative Fuels Data Center Fuel Price Reports Accessed March 2014. https://afdc.energy.gov/publications/search/keyword/?q=alternative%20fuel%20price%20report

Refueling Equipment and Requirements

There is no single agency that regulates all equipment at a retail service station. Authorities having jurisdiction (AHJs), most often fire departments in the case of retail stations, are regulating organizations, offices, or individuals responsible for overseeing codes and standards. AHJs are responsible for enforcing codes to ensure public health and safety at fueling stations and will want to know which types of fuels are stored on-site. Some examples of AHJs include local fire marshals; state energy and environment offices; air and water boards; and similar organizations or offices. Jurisdictions and approval agencies vary in their roles and responsibilities.

AHJs have a preference for third-party listed equipment, and Underwriters Laboratory is the only independent third party offering testing and listing of refueling equipment in the United States. The Occupational Safety and Health Administration requires certain equipment to have third-party listing for the fuel being dispensed and this includes dispensers, breakaways, and nozzles (see Figure 9). Underwriters Laboratory offers listings for many, but not all, types of equipment at the service station through a series of testing standards, and biofuels test fluids are available for some standards. Underwriters Laboratory Subject 87A is a testing protocol for mostly above-ground refueling equipment with listings for ethanol blends between E10 and E85. California has specific regulations for stations dispensing E85, which are implemented by the State Water Resources Control Board.[22]

Because Underwriters Laboratory listed E85 equipment was not available prior to 2011, most stations selling E85 are using conventional gasoline refueling equipment often with a waiver from the local AHJ. Available Underwriters Laboratory listed E85 equipment is shown in Table 7 and Table 8[23]. Some manufacturers have equipment for blends between E10 and E25 – this is their conventional gasoline equipment that they submitted to Underwriters Laboratory for testing and listing for use with blends up to E25. The differences in costs for conventional, E25, and E85 Underwriters Laboratory listed equipment are shown in Table 9. E25 equipment either costs the same or is minimally more expensive than conventional gasoline equipment, while E85 equipment is significantly more expensive because it requires specialized metals (usually nickel plated) due to the corrosive nature of the fuel. Stations adding E85 should use Underwriters Laboratory listed equipment to comply with The Occupational Safety and Health Administration standards. Additionally, tanks should be cleaned prior to storing E85. Costs to retrofit an existing station for E85 range between $2,500 and $30,000.[24]

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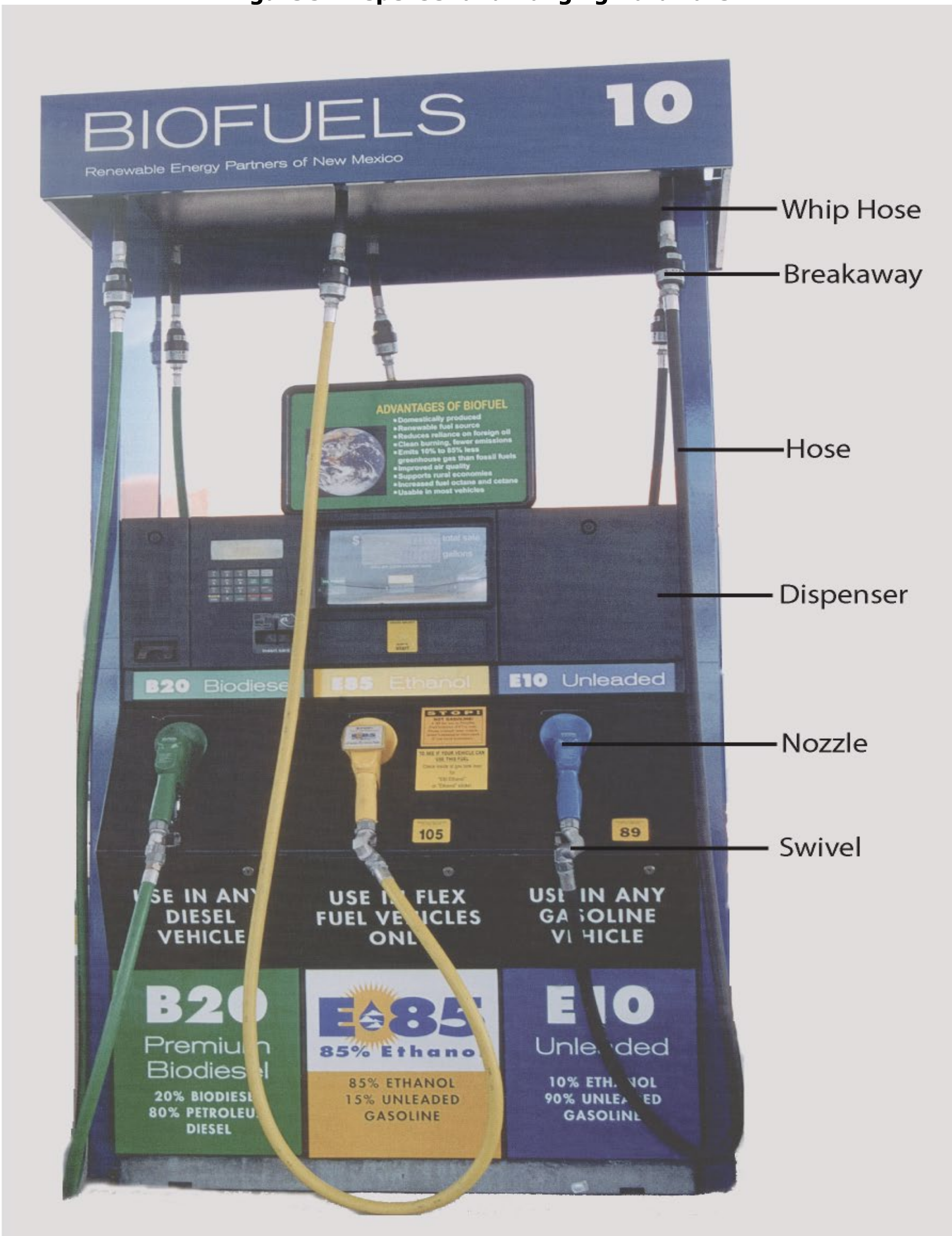
[22] Contact California Water Board for specific station regulations for storing and dispensing E85 or biodiesel blends above B5. State Water Resources Control Board http://www.waterboards.ca.gov/ust/.

[23] Clean Cities. "Handbook for Handling, Storing, and Dispensing E85 and Other Ethanol-Gasoline Blends". Accessed January 9, 2014: http://www.afdc.energy.gov/uploads/publication/ethanol_handbook.pdf.

[24] NREL. March 2008. "Cost of Adding E85 Fueling Capability to Existing Gasoline Stations: NREL Survey and Literature Search." Accessed March 2014: http://www.afdc.energy.gov/pdfs/42390.pdf

Figure 9: Dispenser and Hanging Hardware



Source: NREL

Table 7: Underwriters Laboratory Listed E85 Dispensers

Manufacturer	Model
Wayne	G520
Wayne	G610
Wayne	G620
Wayne	Ovation E
Gilbarco	Encore 300
Gilbarco	Encore 500
Gilbarco	Encore 550
Gilbarco	Encore 700
Gilbarco	Encore NJ2
Gilbarco	Encore NJ4
Gilbarco	Encore NL3
Gasboy	Atlas E85

Source: NREL

Table 8: Underwriters Laboratory Listed E85 Hardware

Equipment	Manufacturer	Model	
		E85*	E25
Breakaway	OPW Fueling Systems	66V-0492	66V-0300
Hose	Veyance	Flexsteel Futura Ethan-all	
Nozzle	OPW Fueling Systems	21GE and 21GE-A	
Swivel	OPW Fueling Systems	241TPS-0492	241TPS-0241, 241TPS-1000, 241TPW-0492

***All E85 equipment is also Underwriters Laboratory listed for E25.**

Source: NREL

Table 9: Prices for Conventional, E25, and E85 Underwriters Laboratory Listed Equipment

Equipment	Conventional	E25	E85
Nozzle	$50	not available	$155
Breakaway	$35	$35	$100
Swivel	$30	$30	$56
Hose	$90	not available	Starting at $357
Whip hose	$32	not available	Starting at $138
Dispenser	$15,000—$17,000*	$400—$700** more or $660*** factory per inlet or $1,950 per inlet in field	$5,000—$8,000**** more
Shear valve	$95	not available	$120

***Dispensers can range from $10,000 to $25,000 or more depending on features and number of products dispensed.**

****Estimate of premium over conventional equipment (Wayne).**

*****Actual costs for equipment at factory for a new dispenser or for a retrofit kit for an existing dispenser.**

******Premium depends on options such as how many fuels it dispenses.**

Source: NREL

The U.S. EPA's Office of Underground Storage Tanks regulates tanks storing petroleum and biofuels under Subtitle I of the Solid Waste Disposal Act, and Federal Code 40 Part 280 requires that the underground storage tank system be compatible with the fuel stored. California, like all states, administers the U.S. EPA's underground storage tank regulations. In 2011, Office of Underground Storage Tanks issued "Guidance – Compatibility of underground storage tank Systems with Biofuel Blends" to provide options to underground storage tank owners to comply with the federal compatibility regulation.[25] The guidance applies to blends above E10 (ethanol) and B20 (20 percent biodiesel and 80 percent petroleum diesel). The guidance gave the option for manufacturers to issue a letter with an affirmative statement confirming compatibility. All existing tank manufacturers issued letters stating compatibility with various ethanol blends. All steel tank manufacturers issued letters stating compatibility with ethanol blends up to E100. Fiberglass tank manufacturer Containment Solutions stated that all tanks it has manufactured are compatible with blends up to E100, while Xerxes and Owens Corning (California has many Owens Corning tanks but the company stopped manufacturing tanks in 1995) have determined compatibility with ethanol blends based on the year the tanks were built and whether they were single or double walled (see Table A-1 in Appendix A). In addition, many other manufacturers of pipes and associated underground storage tank equipment issued letters stating compatibility (Table A-2 in Appendix A).

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[25] U.S. EPA Office of Underground Storage Tanks. 2011. "Guidance - Compatibility of Underground Storage Tank Systems with Biofuel Blends." Accessed January 2014: http://www.epa.gov/oust/altfuels/biofuelsguidance.htm.

CHAPTER 3: Biodiesel and Renewable Diesel Fueling Infrastructure

Background

There are about 84 fueling stations (53 public and 31 private) in California offering various biodiesel blends, primarily B20 and above, as of October 2014.[9] The name "B20" implies a mix of 20 percent biodiesel and 80 percent petroleum diesel, "B5" means 5 percent biodiesel and 95 percent petroleum diesel, and so on. The privately-owned stations primarily support government fleets. Figure 10 illustrates the geographic distribution of these facilities. Most of the stations are concentrated in urban areas and along major highways.

Renewable diesel is in the very early stage of development with currently limited production volumes. Given that renewable diesel is similar to petroleum diesel in chemical makeup and therefore is considered a "drop-in" fuel, it is anticipated that it could utilize the existing petroleum fuels pipeline distribution system.

Key Suppliers

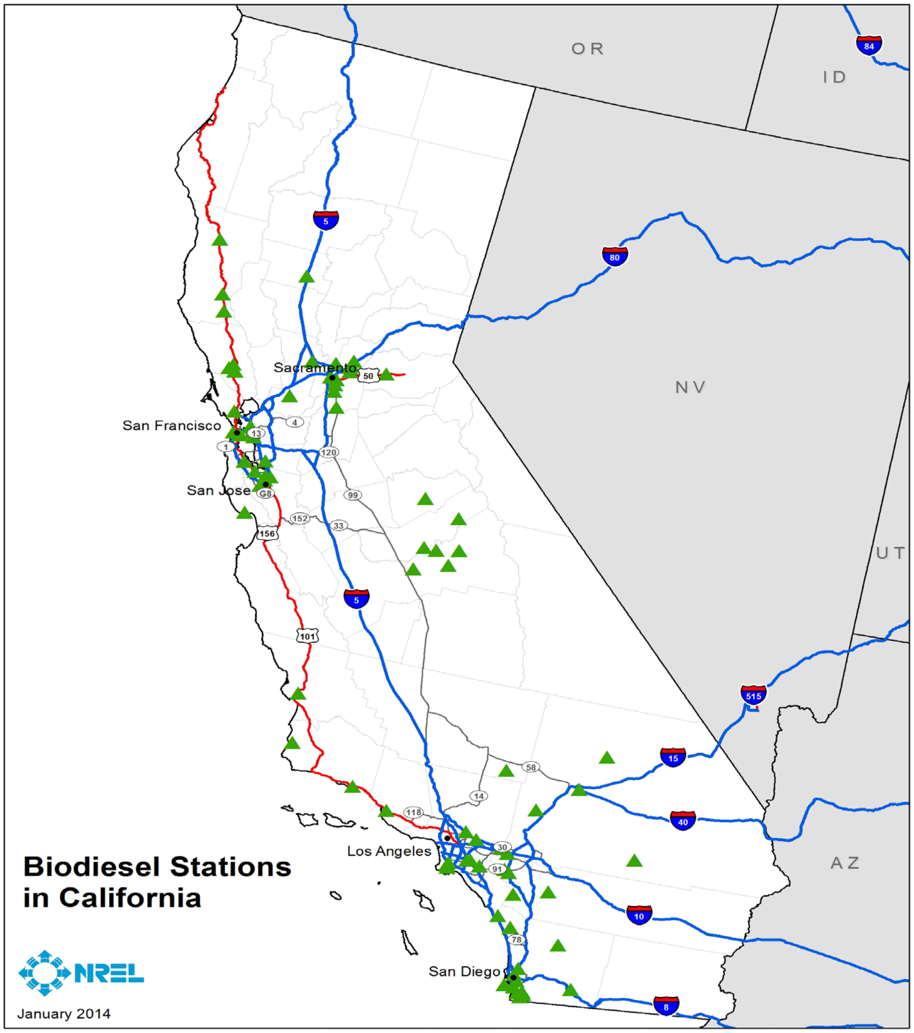
California-based Propel Fuels is the major biodiesel distributor in the state. The company owns two stations that sell biodiesel and distributes it to 27 other stations that are branded (e.g., Shell, Chevron, 76, Valero) but owned by individuals. As mentioned earlier, local renewable diesel supply is limited, with some imports by Neste Oil reported in California.[26] Currently there are three pilot-scale companies in the state working toward developing "drop-in" biofuels: Amyris, LS9, and Solazyme. More information about the feedstock and conversion processes used by these and other entities is available from the associated report "Advanced Fuel Production Technology Market Assessment" prepared by NREL for the CEC[27] and from an upcoming Bioenergy Market report from U.S. DOE.[28]

[26] ICF International. "California's Low Carbon Fuel Standard: Compliance Outlook for 2020". June 2013. https://efiling.energy.ca.gov/GetDocument.aspx?tn=71788&DocumentContentId=36085

[27] Smagala, T. G.; Christensen, E.; Christison, K. M.; Mohler, R. E.; Gjersing, E.; McCormick, R. L. (2013). Hydrocarbon Renewable and Synthetic Diesel Fuel Blendstocks: Composition and Properties. Energy and Fuels. Vol. 27(1), 17 January 2013; pp. 237-246; NREL Report No. JA-5400-55042. http://dx.doi.org/10.1021/ef3012849.

[28] Bioenergy Market Report, U.S. Department of Energy, Forthcoming.

Figure 10: Biodiesel Retail Locations in California



Source: NREL

Market Information

Diesel consumption on highways in California has been about 2.6 billion gallons annually during the last several years.[29] The state is second only to Texas and accounts for about 7 percent of total U.S. diesel use. This estimate is close to a survey conducted by the CEC in 2011, which revealed that the state consumed about 2.46 billion gallons of diesel on highway that year.[30] About 59 percent of these sales occurred to end users at retail stations, including truck stops[31], and the remaining sales were consumed by commercial fleets. Counties with the

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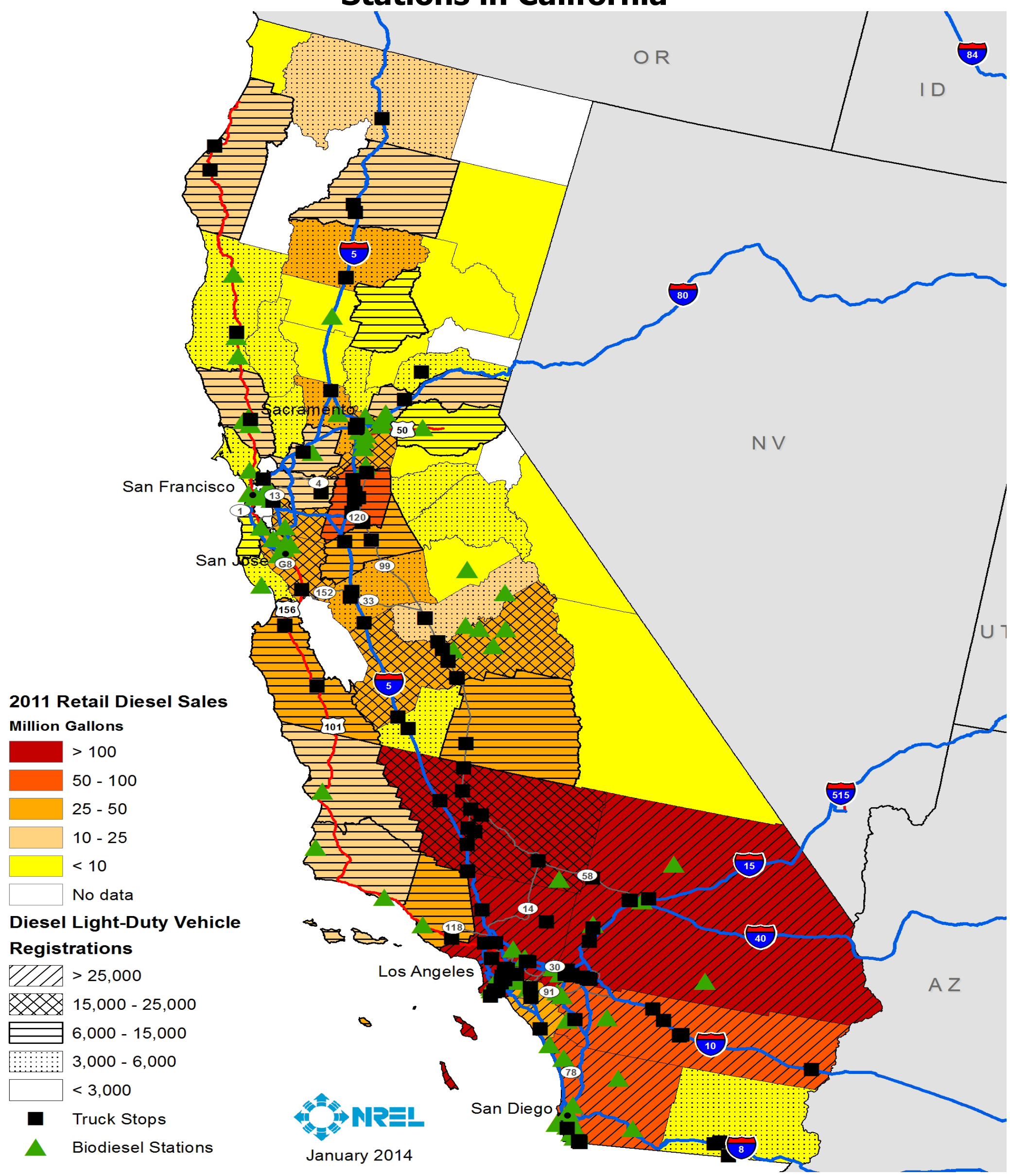
[29] U.S. EIA. Sales of Distillate Fuel Oil by End Use, November 2013, http://www.eia.gov/dnav/pet/pet_cons_821dst_a_EPD2D_VHN_Mgal_a.htm.

[30] CEC. "California Retail Fuel Outlet Annual Report". Accessed December 2013, https://www.energy.ca.gov/data-reports/energy-almanac/transportation-energy/california-retail-fuel-outlet-annual-reporting

[31] Truck Stop Guide, Truck Stops by State. Accessed January 2014. http://www.truckstopguide.com/Search_State.aspx

highest retail diesel sales in 2011 included Los Angeles, San Bernardino, Kern, Riverside, San Joaquin, and San Diego (Figure 11). Figure 11 illustrates only diesel sales at retail stations – not those consumed by commercial fleets – and only light-duty diesel vehicle registrations[32], defined as cars and trucks with gross vehicle weight of 14,000 lb or less. Trucks include vehicles up to class 3 so there are some commercial vehicles in the count. The relatively large consumption of diesel in the state presents a market opportunity for both biodiesel and renewable diesel. Not surprisingly, as shown in Figure 11, most biodiesel stations are strategically located in counties with high diesel consumption.

Figure 11: Diesel Consumption, Vehicle Registrations, Truck Stops, and Biodiesel Stations in California

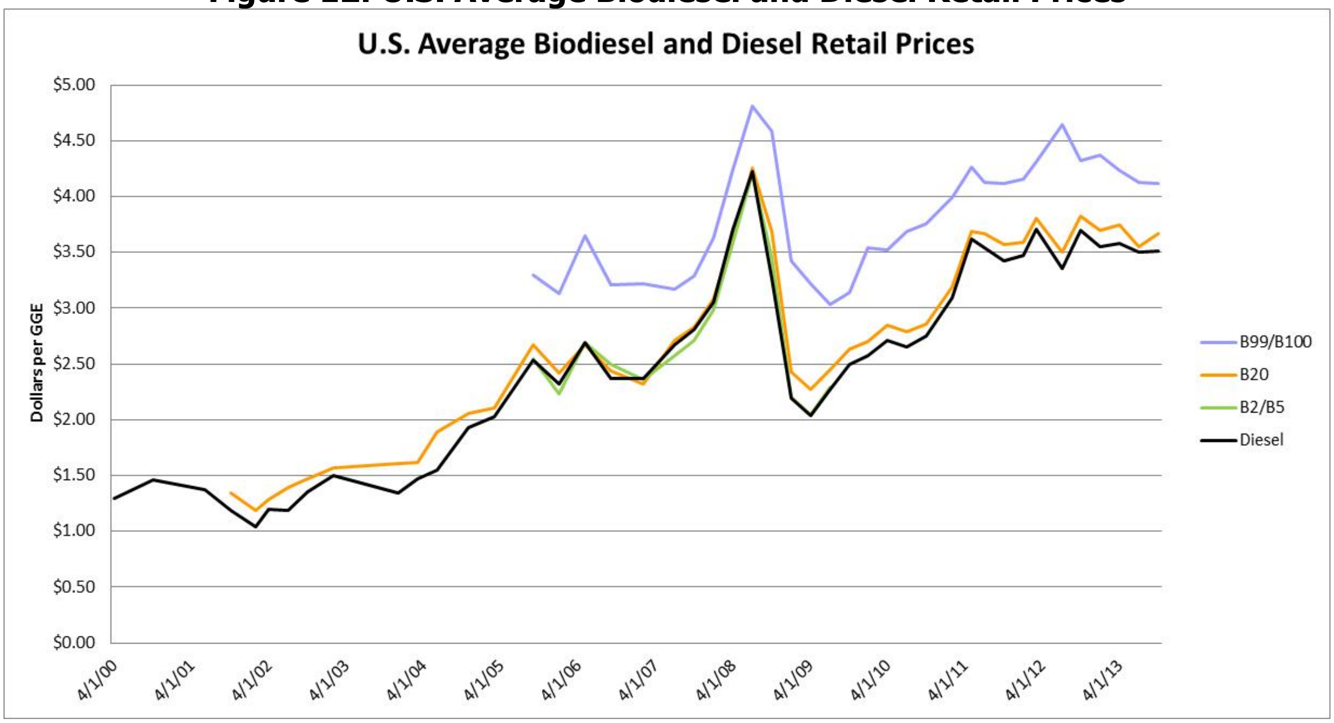


Sources: NREL

[32] Polk, Vehicles in Operation Data 2012. https://ihsmarkit.com/products/automotive-market-data-analysis.html

The biodiesel price varies depending on geographic area, source, and supplier. The price of lower blends (B2/B5 and B20) is typically about the same as the price of petroleum diesel, while higher blends are more expensive (see Figure 12). The price gap between conventional diesel and B100 was closing during 2007—2008 due to higher crude oil prices; however, it has increased again in recent years given low crude oil prices. Fuel prices in California are generally higher than the national average, and biodiesel appears to follow that trend as indicated by recent entries at [AltFuelPrices.com](http://www.altfuelprices.com/stations/BD/California/) (http://www.altfuelprices.com/stations/BD/California/). For example, the price of B5 and B20 at a station in Fullerton was reported at $3.93 per gallon in June 2013 while the national average for that month was $3.55 per gallon. It is expected that price variations exist within the state; however, detailed data were available at the time this report was written.

Figure 12: U.S. Average Biodiesel and Diesel Retail Prices



Source: Alternative Fuels Data Center

A study by ICF International analyzes recent developments in the transportation sector and presents three scenarios to meet the goal of California's Low Carbon Fuel Standard (LCFS) by 2020.[26] The study points out the following:

> "Although biodiesel consumption in California has been modest in recent years, there is significant potential to blend biodiesel at lower levels (e.g., 5 percent to 20 percent by volume) with conventional diesel and generate a substantial number of LCFS credits. Infrastructure providers are already responding to this potential, and based on ICF research and stakeholder consultation, the industry is rapidly increasing the ability to store and blend biodiesel at petroleum terminals and at refineries." (p. 2)

The report goes on to estimate total blending capacity based upon industry trends:

> "Kinder Morgan made significant investments to expand biodiesel storage and delivery capacity at its Fresno and Colton terminals, with a reported throughput of 19 to 20

> million gallons per year at each facility. As of late last year (2012), Kinder Morgan informed wholesalers that it will only sell B5 (a blend of 5 percent biodiesel with conventional diesel) at its Fresno and Colton facilities. Chevron made a similar announcement regarding the exclusive delivery of B5 at its facility in Montebello. Interviews with industry representatives indicate that at least four (4) refiners within California have proprietary terminals at which they are or have the capacity to blend biodiesel. ICF research indicates that there are at least 230,000 barrels of biodiesel storage capacity in California today. If we assume conservatively that these storage tanks have about 75 turns per year (i.e., the number of times each tank is emptied and filled) and that biodiesel represents about 15 percent of throughput at these facilities, then we estimate a biodiesel blending capacity of around 110 million gallons annually." (p. 36)

Milbrandt et al. note, however, that biodiesel faces some technical limitations that may direct future industry decisions toward more infrastructure-compatible renewable diesel:

> "While the lower-level biodiesel blends (B20 and below) can be used in traditional diesel vehicles without engine modifications, higher-level blends may require engine modifications and other usage considerations. More importantly, biodiesel is currently transported from the production sites to petroleum terminals where it is blended with petroleum fuels, via truck or rail and occasionally, by barge. These modes are much more expensive than transportation by pipeline, which is used for most petroleum fuels. The potential for biodiesel to contaminate jet fuel is preventing widespread pipeline transport. Hydrocarbon renewable diesel is likely to be easily transported in existing pipelines already utilized for petroleum-based fuels."[33]

The CEC's survey estimates that of the approximately 9,710 retail stations in California, about 49 percent sell diesel. This is an increase from 2008 when about 45 percent of the stations reported sales of diesel. Diesel use is predominately related to the trucking industry's consumption pattern, not to that of the general population as it is in the case of gasoline. This is why, broadly speaking, most retail stations offering diesel are located along major roads. This is also the reason why biodiesel stations are also situated primarily in urban centers and along major highways (Figure 11). Those outside of these locations are predominately private stations serving the fleets of the Department of Defense, other federal agencies, and local governments.

A recent trend in California is the growth in registrations of diesel passenger cars and sport utility vehicles. The state had a 55 percent growth in this category between 2010 and 2012, which placed it first in the nation, with 84,106 diesel cars and sport utility vehicles registered in 2012.[34] If pickup trucks and vans are included, the number of registered diesel vehicles in California totals 572,303 in 2012, only second after Texas. Figure 11 illustrates the light-duty

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[33] Milbrandt, A., Kinchin, C., McCormick, R. "The Feasibility of Producing and Using Biomass-Based Diesel and Jet Fuel in the United States", December 2013. http://www.nrel.gov/docs/fy14osti/58015.pdf.

[34] Diesel Technology Forum. "U.S. Diesel Car Registrations Increase By 24%, Hybrids Up 33%; Total Car Market Registrations Increase Just 2.7% Since 2010". April 2013. http://www.dieselforum.org/news/u-s-diesel-car-registrations-increase-by-24-hybrids-up-33-total-car-market-registrations-increase-just-2-7-since-2010.

diesel vehicle registrations by county. The highest number of registered vehicles is in the southern, most populated part of the state: Los Angeles, San Diego, Riverside, Orange, and San Bernardino counties.

Given that freight trucks are the major consumer of diesel both nationwide and in California, the trucking industry could provide a strong business opportunity for biodiesel and renewable diesel producers. California has about 122 truck stops located along the state's major highways.[33] Increasing the sales of biodiesel and renewable diesel at truck stops could boost these alternative fuels' production, lower their cost, and improve the environmental footprint of the trucking industry and the state of California as a whole.

Refueling Equipment and Requirements

The Occupational Safety and Health Administration requires certain equipment have third-party listing for the fuel being dispensed and this includes dispensers, breakaways, and nozzles. Underwriters Laboratory offers listings for many, but not all, types of equipment at the service station through a series of testing standards, and biofuels test fluids are available for some standards. Underwriters Laboratory Subject 87B, released in 2010, is a testing protocol for mostly above-ground refueling equipment with listings for B20 or B100. Blends of B5 are considered the same as petroleum diesel and can be dispensed in all existing diesel infrastructure. California has specific regulations for stations dispensing biodiesel blends above B5, which are implemented by the State Water Resources Control Board.[35]

Because Underwriters Laboratory listed B20 equipment became available at the start of 2014, most stations selling biodiesel blends are using conventional diesel refueling equipment, often with a waiver from the local AHJ. There were issues with the introduction of ultra-low-sulfur diesel and existing equipment, which led to equipment upgrades. These upgrades were beneficial for both diesel fuel and biodiesel fuel, as some of the same updated conventional diesel equipment is also Underwriters Laboratory listed for B20. B20 equipment is either the same price as or marginally more expensive than conventional equipment, although exact pricing is unavailable at this time. The following equipment is Underwriters Laboratory listed for B20:

- Hose: Veyance Flexsteel Futura
- Hanging hardware: OPW has listed equipment in this category but model numbers are not available
    - Nozzles: Husky models 1+VIII, 1+VIIIS
    - Breakaway: Husky 5812
    - Swivel: Husky 4860
- Dispenser

[35] State Water Resources Control Board. "Underground Storage Tank Program – Interim Regulations for Underground Storage Tank Systems Storing Biodiesel Blends up to B20". Accessed January 2014 http://www.waterboards.ca.gov/ust/regulatory/biodiesel_regs.shtml

    - Gilabarco – all conventional models sold as of 2014 are Underwriters Laboratory listed for B20
    - GE Wayne – expects to have a product available in 2014
- Shear valve: Franklin Fueling model 662; OPW has listed shear valves but model numbers are not available
- Submersible turbine pump: Franklin Fueling all models.

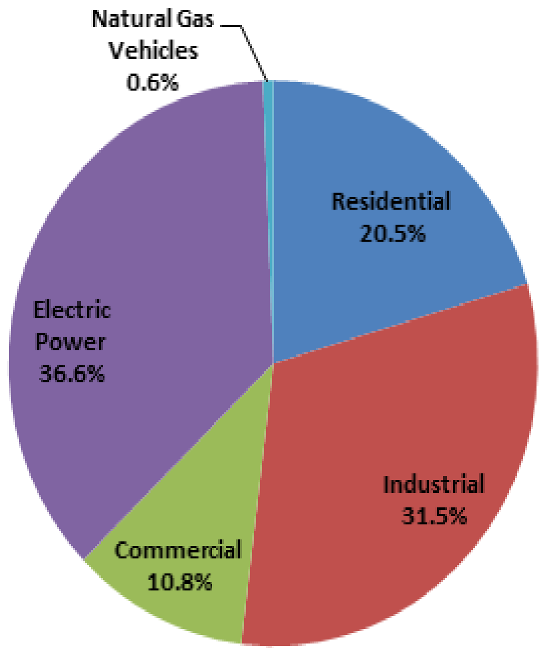
As mentioned earlier (Chapter 2), the U.S. EPA's Office of Underground Storage Tanks regulates tanks storing petroleum and biofuels. All existing tank manufacturers issued letters stating compatibility with all biodiesel blends up to B100 per Office of Underground Storage Tanks Biofuels Guidance (see Chapter 2). There are many Owens Corning tanks in California, but the company stopped manufacturing tanks in 1995 and had never tested them with biodiesel fuel. As such, Owens Corning could not provide a statement on compatibility. In addition, many other manufacturers of pipes and associated underground storage tank equipment issued letters stating compatibility. Lists of compatible tanks and associated equipment are available in Appendix B.

CHAPTER 4: Natural Gas Supply and Fueling Infrastructure

Background

Natural gas represents the largest energy source in California, accounting for 2,197 trillion British thermal units or 28 percent of all of the energy used for transportation, electricity generation, and heat in the state. The industrial and electric power sectors are the largest users of natural gas in California accounting for more than two thirds of demand. Only about 0.6 percent of natural gas demand comes from the transportation sector[36] as illustrated in Figure 13.

Figure 13: Natural Gas Demand in California by Sector – 2012



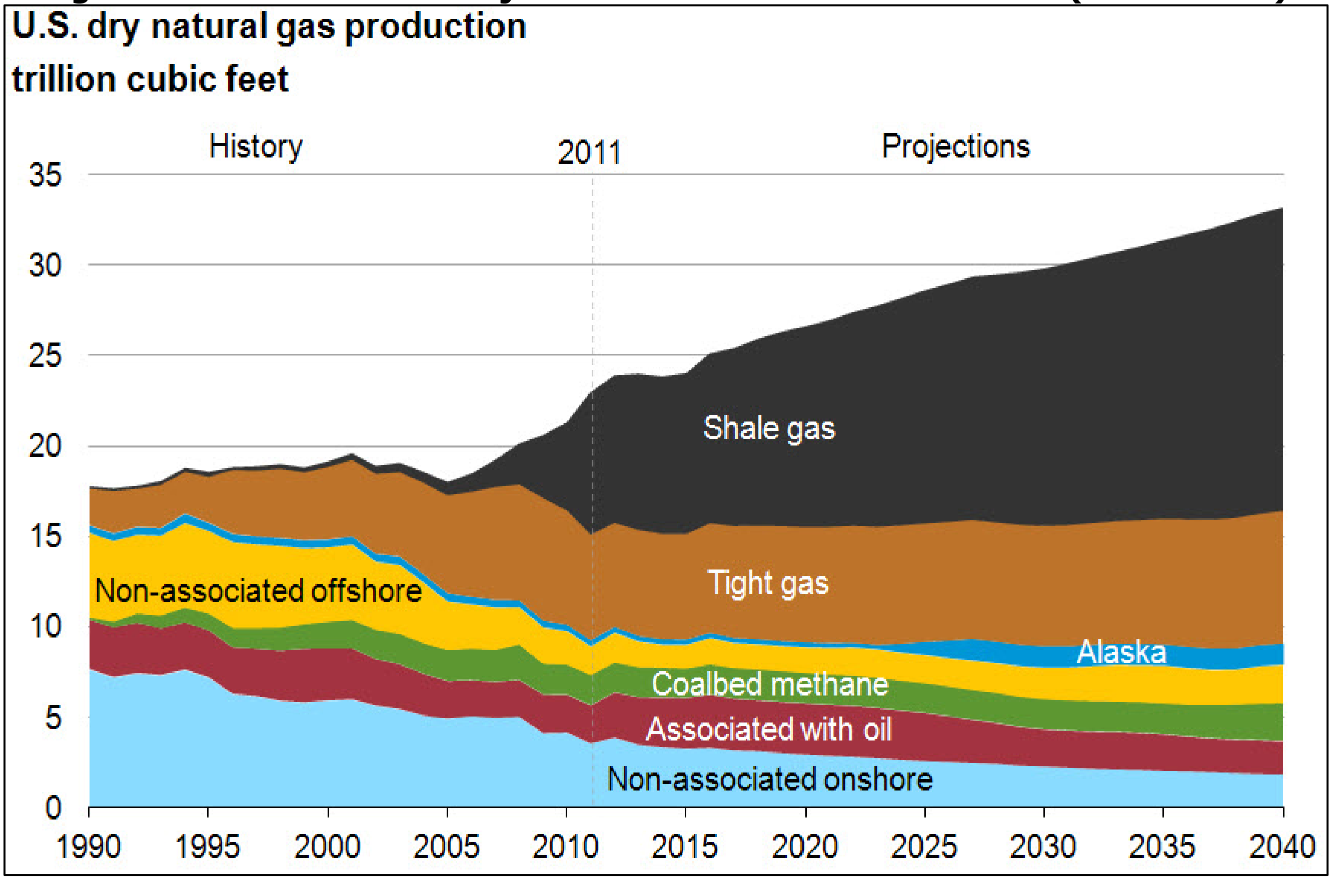
Source: U.S. EIA

Natural gas is a domestically produced resource that is extracted from a variety of basins across the United States. Dramatic increases in shale gas have vastly expanded estimates of the nation's recoverable gas in the near to mid-term as shown in Figure 14. The most recent estimate from U.S. EIA projects the nation's annual natural gas production to increase by 44 percent to 33.1 trillion cubic feet between 2011 and 2040.

California has a number of gas-producing basins, both conventional and unconventional, which are located in the Sacramento–San Joaquin River Delta and around the greater Los Angeles area. In 2012, California ranked 13th in the nation in marketed natural gas production, producing about 247 million cubic feet or 254 trillion British thermal units.

[36] U.S. EIA. 2013. "Annual Energy Outlook, 2013 Early Release". (U.S. Energy Information Administration).

Figure 14: Historical and Projected U.S. Natural Gas Production (1990—2040)



Source: EIA

Most of the gas that is used in California comes from other states. As of 2012, 40 percent of the gas used in California came from basins in the Rocky Mountain region, 35 percent came from basins in the Southwestern United States, and 16 percent came from Canadian basins. Roughly 9 percent of the natural gas used in California was generated from in-state basins.

Natural gas is also derived from renewable sources in what is called renewable natural gas (RNG) or biomethane. RNG is naturally produced from a variety of sources including landfills, wastewater treatment plants, and dairies and must be upgraded and purified to meet certain specifications (depending on the use and transport mode). RNG can be used as a direct replacement for natural gas in vehicle fueling or it can be blended with traditional natural gas. Unlike fossil-based natural gas, RNG can qualify as an advanced biofuel under the federal Renewable Fuel Standard.

Gathering lines move gas from production fields to larger inter- or intra-state pipelines where it is then distributed either directly to industrial facilities, such as natural gas liquefaction plants, or to gas processing facilities. From these locations, natural gas is routed through local distribution companies, which provide gas service to individual industrial, commercial, and residential locations. Upstream of the local distribution companies are market hubs, which facilitate transactions among pipelines as well as natural gas trading activities. California currently has two market hubs, operated by Southern California Gas Company and Pacific Gas and Electric.

While natural gas itself is a traded commodity at the bulk level, natural gas service is regulated for most parts of California and is provided to consumers by nine local distribution companies across various service territories shown in Figure 15[37]. Natural gas service rates and the price of related services such as pipeline distribution, storage, and metering are set by the California Public Utilities Commission.

Figure 15: California Natural Gas Utility Service Areas

Source: CEC

Natural gas is used in two forms for transportation purposes – as a compressed gas and as a super-cooled liquid. CNG is used for a variety of purposes that range from passenger vehicles to delivery vehicles to transit buses and serves as a substitute for either gasoline or diesel fuel. LNG is typically used for larger vehicles such as Class 8 trucks where driving range and energy density are more critical. LNG has been discussed as a viable fuel for rail and marine operations. LNG is also used in natural gas peaker plants to provide incremental generation

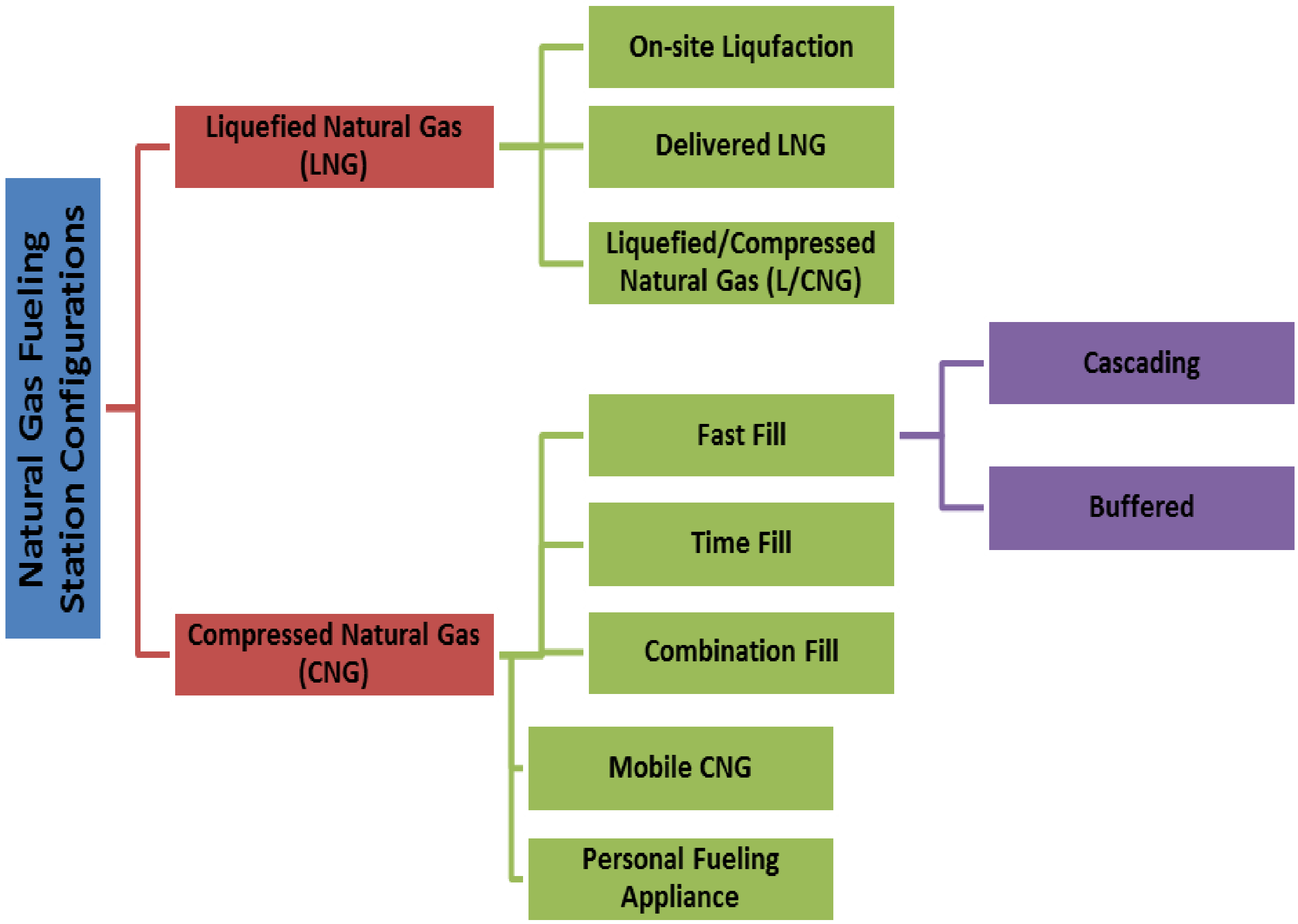
[37] CEC. "California Energy Maps." *Energy Maps of California*. 27 January 2014.

during peak demand and is being proposed as the means to allow for increased transcontinental natural gas exports.

Natural Gas Fueling Infrastructure

Commercial natural gas fueling operations have a variety of configurations that vary depending on the type of fuel needed (CNG and/or LNG) and the level of service needed for a given vehicle population. Additionally, there are both mobile and small-scale fueling solutions that can provide flexibility in fueling activities. Figure 16 details the various commercial configurations for providing natural gas as a transportation fuel either as a liquid or a compressed gas.

Figure 16: Natural Gas Fueling Station Configurations

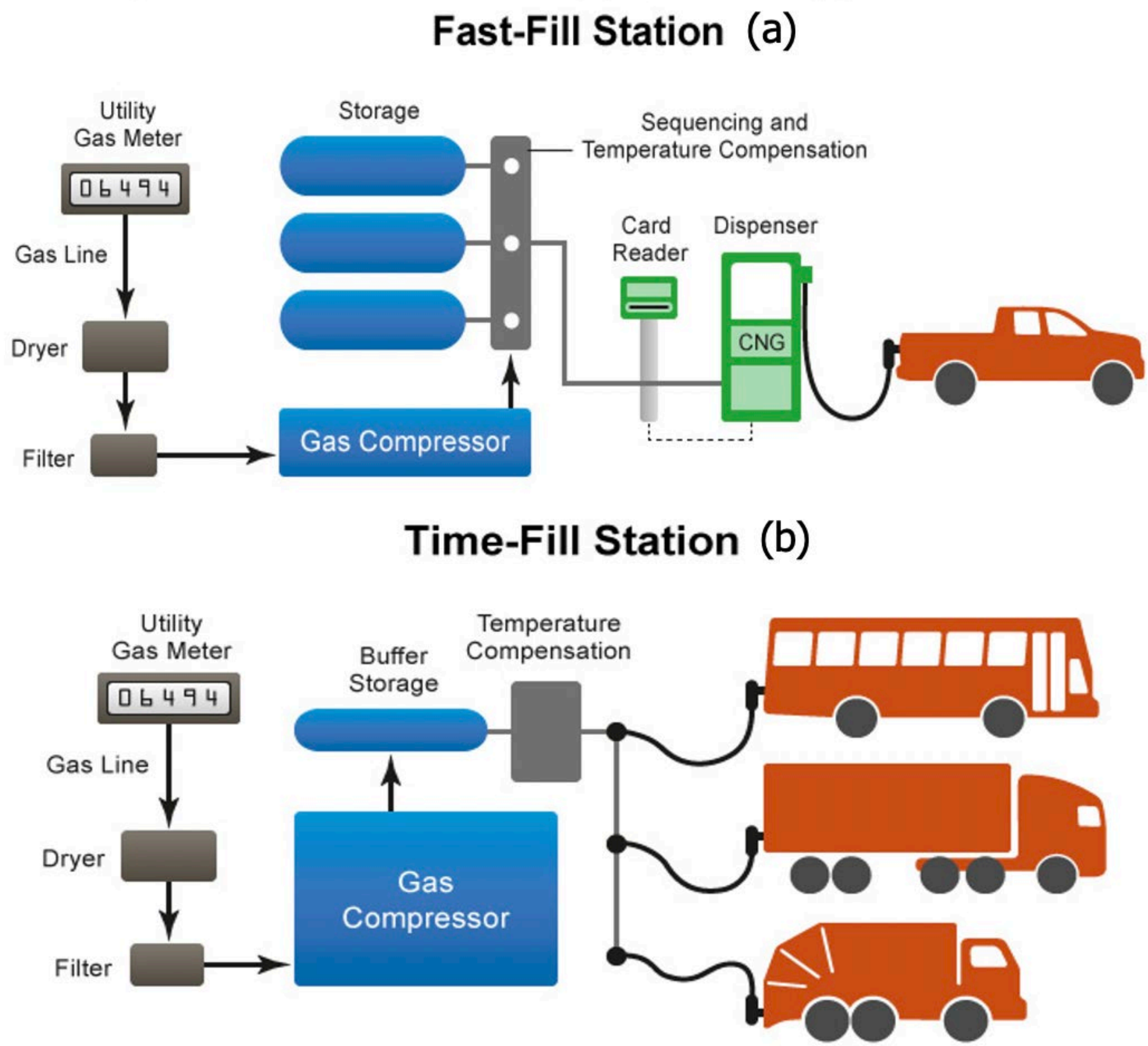


Source: NREL

Compressed Natural Gas

CNG is currently dispensed to a fill pressure of up to 3,600 pounds per square inch (psi), but it can be dispensed at various rates, generically referred to as time-fill and fast-fill capabilities. These two configurations can exist independently or in combination to provide flexibility in accommodating varying operational needs. Figure 17 provides a simplified schematic of each station type. A fast-fill station provides a fill time that is similar to that of gasoline and diesel fueling stations and based on the application, draws natural gas either from on-site storage vessels or directly from the compressor. Cascade-fill systems use CNG that is stored in cylinders that are dispensed and refilled as needed and are often employed in retail applications where fueling activity can be sporadic. Buffered-fill systems dispense fuel directly into the vehicle from the compressor and are often used in situations where high volumes of fuel are needed over a sustained period of time such as a transit operation. Time-fill stations are employed in operations where a vehicle is parked for sustained periods of time. Vehicles are generally filled with gas provided directly from a compressor. Vehicle fleets with central, return-to-base operations such as refuse trucks typically use this configuration, as illustrated in Figure 18.

Figure 17: Schematic of fast fill (a) and time fill (b) CNG stations



Source: Alternative Fuels Data Center

Figure 18: CNG Vehicles Using the Time-Fill Posts

Photo credit: NREL

A combination fill station can provide both fast-fill and time-fill services. Typically, these configurations fill vehicles initially with natural gas from storage tanks. Once the storage tanks are unable to provide the required fill pressure, vehicles are filled with gas that is fed directly from the compressor.

Liquefied Natural Gas

Most LNG fueling facilities in California receive LNG via truck where the fuel is offloaded and stored in cryogenic vessels that are typically 15,000 or 30,000 gallons. In many cases, the LNG needs to be conditioned before it is stored so that the fuel can be dispensed at a predetermined pressure, which is often about 100 psi. Whether or not LNG needs to undergo this "conditioning" depends on the application of the fuel. Most LNG stations are unique designs that are built for specific applications under varying regulations and requirements. Because LNG is often received directly via truck, it may not involve transactions with the gas local distribution companies.

Although less common, small-scale liquefaction technologies allow for the production of LNG on-site. The station operates exactly the same as a delivered LNG station does, although transportation costs are reduced because the LNG does not need to be delivered via truck. Gas is delivered through local distribution pipelines to the facility where it is condensed into liquid form through a variety of processes (dependent on the particular technology being used).

LNG stations can also be co-located with CNG stations in what are referred to as L/CNG stations. These facilities are capable of dispensing LNG and also converting LNG to CNG. L/CNG stations warm LNG through a vaporizer, which brings the fuel closer to ambient temperature and a state change from a liquid fuel to a gaseous fuel. From there, the gas is stored in storage cylinders and the stations function similarly to cascade fast-fill stations. These stations also provide a means to dispense CNG at locations that do not have access to natural gas pipelines.

Mobile refueling options exist for both CNG and LNG applications and can remove the need for on-site fueling infrastructure or provide a solution for vehicles while infrastructure is under construction or out of operation. CNG mobile fueling units often utilize the same fuel storage tanks found in vehicles, which then dispense compressed gas directly into a vehicle at high pressures. This practice is also known as "wet hosing."

With a majority of California having access to residential gas service, personal or home fueling devices can provide a convenient solution for owners of natural gas vehicles (NGVs) to fuel their vehicles from home or other locations such as a parking garage or the workplace. There are limited options for these devices and refueling time is slower than that of a commercial fueling station. Personal refueling appliances currently are available only for CNG.

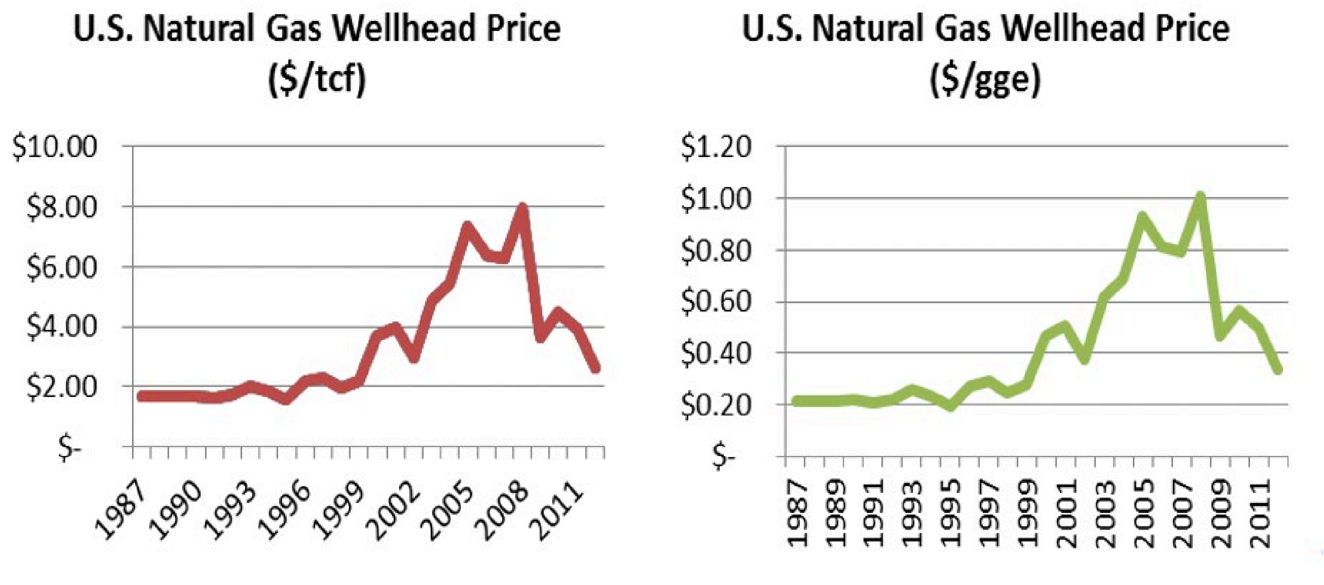
As mentioned previously, natural gas does not occur naturally in a liquid form, so dedicated production facilities are required that can refrigerate natural gas down to its boiling point. Because this required temperature is so low, pipeline transport, particularly over long distances, is not practical. Because of this and benefits of scaling these facilities to large capacities, LNG is often transported via truck to fueling facilities. The cost of transporting LNG to fueling stations can create geographic limitations on the fuel availability.

California is host to one liquefaction facility, which is operated by Clean Energy in Boron. The plant currently can produce up to 160,000 gallons of LNG a day and has a 1.5-million-gallon storage tank on-site. The facility was built in a way that will allow production to scale up to 240,000 gallons per day. Applied Natural Gas Fuels has an LNG production facility near Lake Havasu that has a production capacity of 86,000 gallons per day and provides access to LNG for parts of California. The facility is currently being upgraded to double production by mid-2014.

Market Information

Natural gas is a regulated commodity in that a market sets the commodity price and the delivered cost of natural gas service is regulated by the Public Utilities Commission. Commodity prices of natural gas have been relatively low over the past few years due in large part to the increased production referenced earlier. For comparison's sake, the pricing data is provided in units of thousand cubic feet as well as gasoline gallon equivalent (126.67 thousand cubic feet) in Figure 19 below.

Figure 19: Historical Wellhead Natural Gas Prices (per thousand cubic feet and gge)



Source: EIA

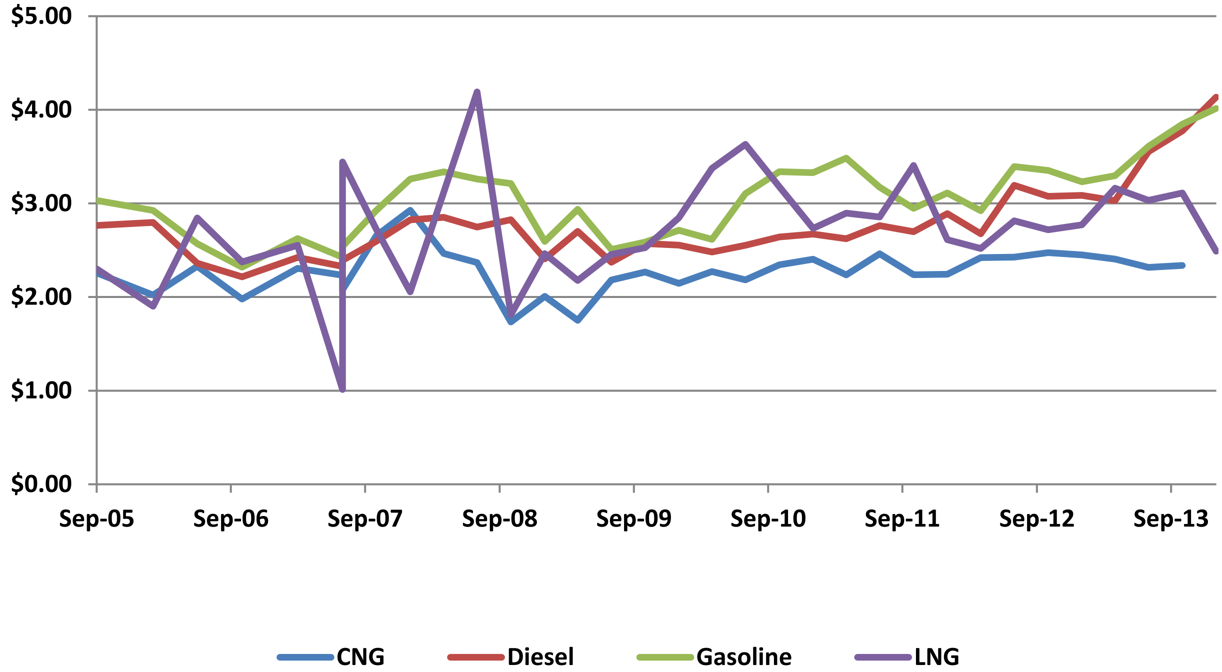
As the data below show, the regulated nature of natural gas provides some price stability that isn't seen in gasoline and diesel fuel, which can be particularly valuable for fleets.

The cost of LNG and CNG is made up of several key components, some of which are static and others that are market-based. These include the commodity cost of natural gas, pipeline and distribution costs, operations and maintenance associated with the fueling infrastructure (including electricity costs), amortization of the infrastructure investment, and applicable fuel and sales taxes.[38] For LNG operations, these costs vary in some cases in which the natural gas can be purchased directly from a producer, bypassing the local distribution companies and instead paying a transportation charge for delivering the fuel.

Overall, CNG prices in California have been relatively stable over the past 5 years while LNG prices have displayed more volatility. Figure 20 shows prices for CNG, LNG, gasoline, and diesel on a gasoline gallon equivalent basis for uniform comparison.

[38] While these costs represent the basic elements of the components of natural gas as transportation fuel, they may be structured differently based on a given utility's tariff and rate schedule.

Figure 20: Historical Prices for Various Fuels ($/gge)



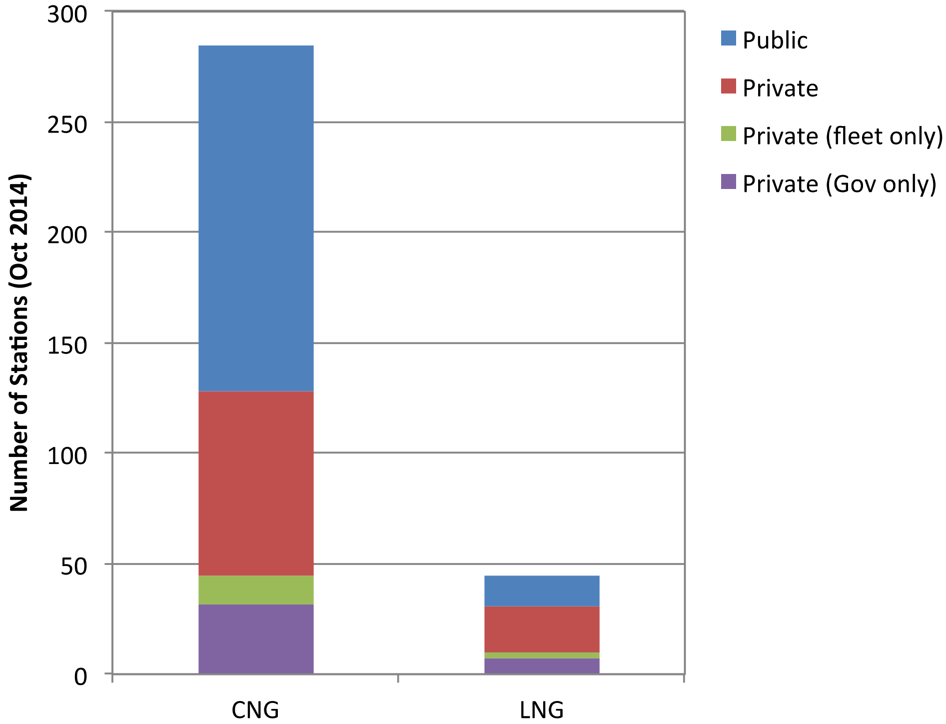
Source: Alternative Fuels Data Center

Figures 19 and 20 may appear inconsistent at first. Figure 19 illustrates a natural gas wellhead peak price of about one dollar per gge, while Figure 20 indicates significantly higher prices. However, Figure 20 focuses on retail prices (instead of wellhead prices), which include distribution costs, compression costs, and profit margin.

Station Availability

California, as of October 2014, has about 290 compressed natural gas and 45 liquefied natural gas fueling stations and about 33,000 natural gas vehicles registered in the state. While many of these stations are open for public access, a number are restricted to exclusive or limited access for private vehicle fleets. LNG infrastructure in particular has limited public access, with only one-third of all stations open to the public. Most of the CNG stations in California offer 3,600 psi service, with 16 stations offering 3,000 psi service (of these only three are public). Of the 43 LNG stations in California, 12 are L/CNG stations (only one of which is open to the public). Figure 21 breaks out the number of CNG and LNG stations in California by public or private station types. L/CNG stations are identified as LNG stations for the purpose of this chart.

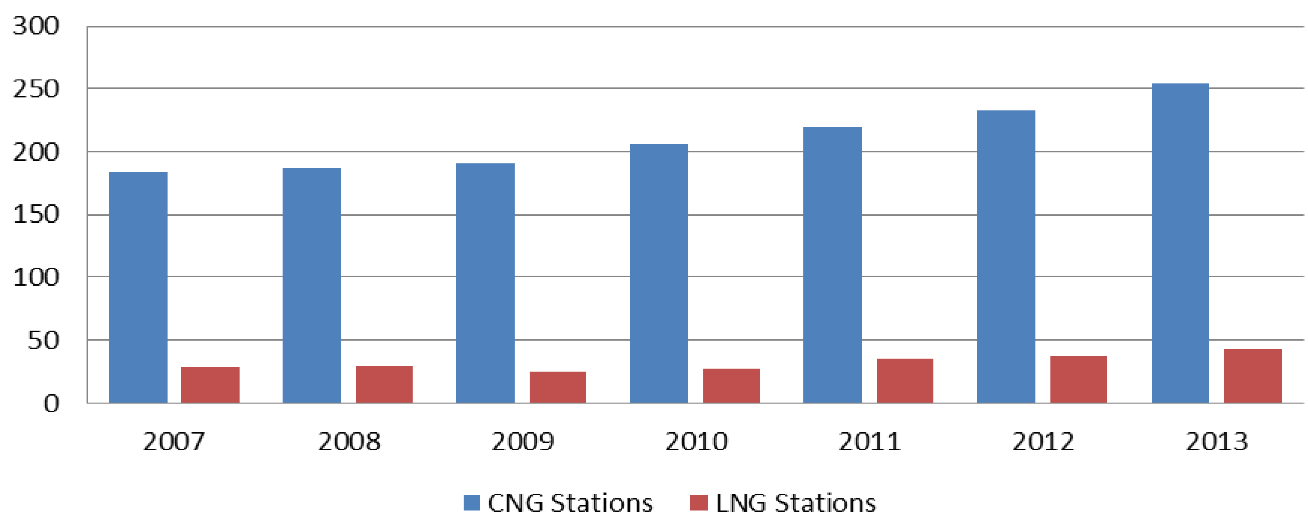
Figure 21: Natural Gas Fueling Stations in California (October 2014)



Source: Alternative Fuels Data Center

The availability of natural gas fueling infrastructure has been steadily increasing in California. The first public natural gas fueling station in California was a compressed natural gas station, which opened in Concord in 1990. In 2007, there were 184 CNG stations and 28 LNG stations. By 2013, this number increased to 254 and 43 respectively, which is equivalent to a 38 percent increase in the number of CNG fueling stations in and 54 percent increase in the number of LNG stations over that time period (see Figure 22). By October of 2014 there were 285 CNG stations reported to the Alternative Fuels Data Center.

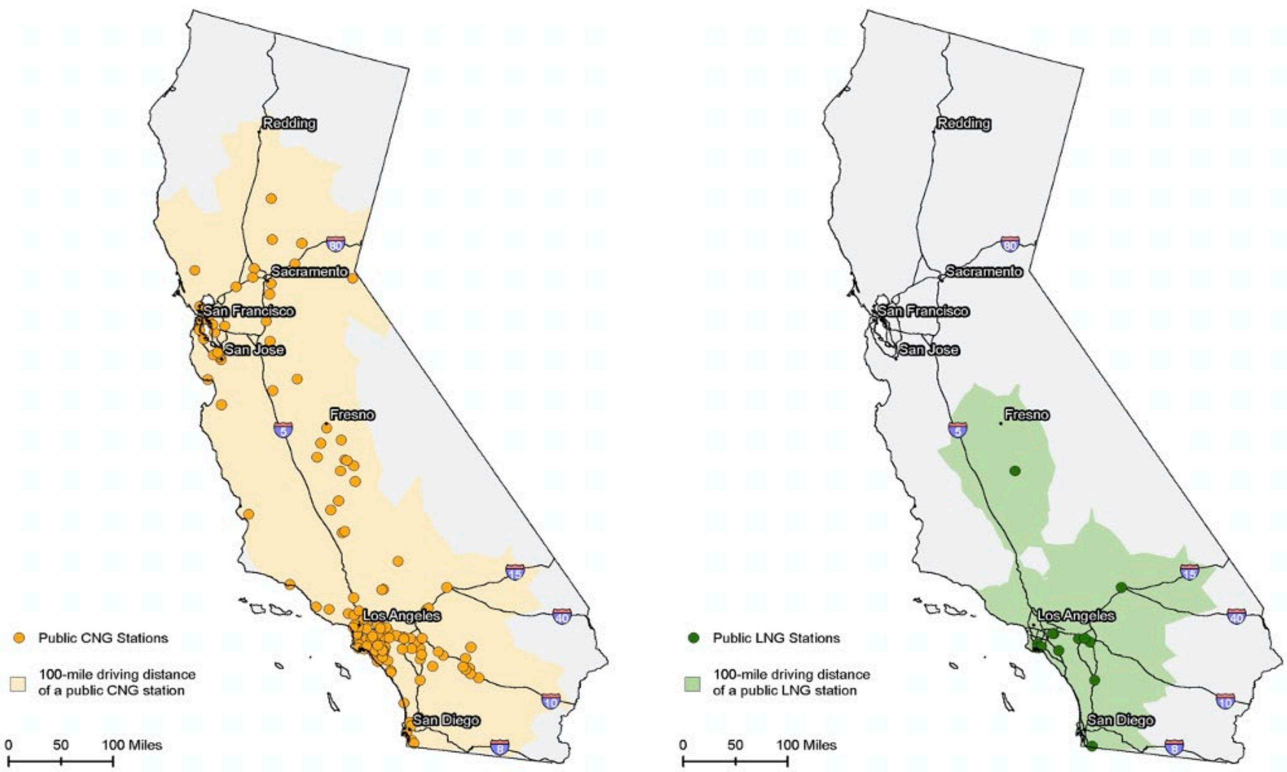
Figure 22: Natural Gas Fueling Stations in California (2007—2013)



Source: Alternative Fuels Data Center

While California has the largest number of both CNG and LNG stations in the country, the state ranks 13th and 3rd among states in the number of CNG and LNG stations per capita respectively. As Figure 23 illustrates, much of the natural gas fueling infrastructure in California is concentrated near the greater Los Angeles and San Francisco Bay areas; however, most parts of the state are within 100 miles of public CNG fueling. From a practical perspective, the availability of fueling infrastructure can be viewed in two ways: (1) as a corridor that facilitates intra- and inter-state transportation and (2) as a hub that facilitates return-to-base/home trips.

Figure 23: Public Natural Gas Fueling Corridors in California – January 2014



Source: NREL

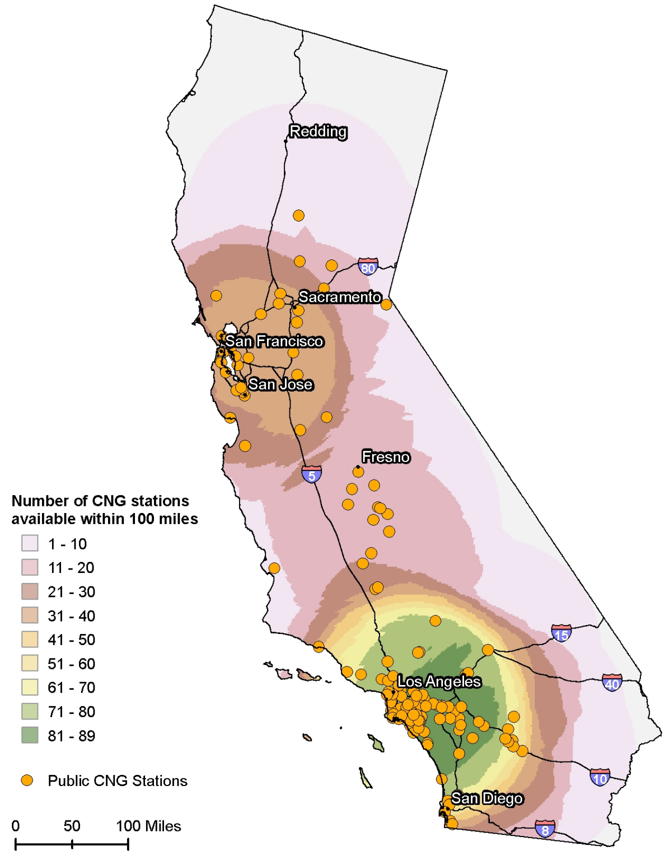
Natural Gas Fueling Corridors in California

Public natural gas fueling corridors exist in the central and southern parts of California for LNG and across most of the state for CNG. In fact, CNG is available at least every 100 miles at a public station between Redding and San Diego. LNG on the other hand is primarily only publicly available in the great Los Angeles area as well as Fresno, with two routes connecting those corridors. While these maps help to provide an overview of travel across California, they do not account for stations that are across state lines that may facilitate interstate operations, nor do they include private stations.

Natural Gas Fueling Hubs in California

As discussed earlier, the current economics and infrastructure availability of CNG facilitate return-to-base and return-to-home trips, which in most cases would require a localized concentration of infrastructure for basic convenience and availability of refueling. Figure 24 depicts the infrastructure density for CNG in California. The Los Angeles metro area has the greatest concentration of stations of any part of the state.

Figure 24: Density of CNG Fueling Infrastructure in California – January 2014



Source: NREL

Natural Gas Vehicle Market in California

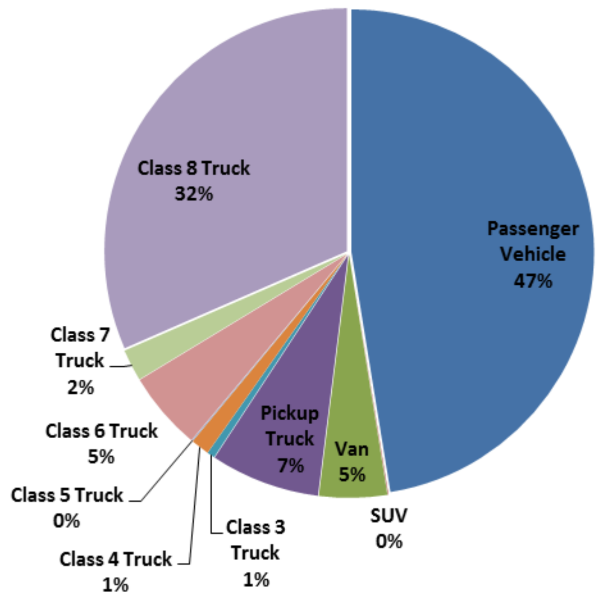
As with many alternative fuels, a key indicator of the market for alternative fuel infrastructure viability is the presence of vehicles that are capable of running on alternative fuels. Natural gas vehicles have been in existence since the 1930s and are a relatively mature technology. Their adoption in California has been partly spurred by air quality regulations and petroleum dependency concerns and more recently due to a relatively significant difference in the fuel cost between natural gas and gasoline and diesel.

There are three types of natural gas vehicle technologies that allow for varying fueling flexibility: (1) a dedicated natural gas vehicle that is only capable of running on CNG or LNG; (2) a bi-fuel vehicle that can run on natural gas and either gasoline or diesel independently; and (3) a dual-fuel vehicle that runs on natural gas but also requires diesel fuel for portions of the drive cycle. The range of a given vehicle will often correlate to the type of natural gas fueling system, with a dedicated CNG vehicle typically having the lowest range of these options, and thus, likely having the greatest need for fueling infrastructure. Bi-fuel vehicles can operate on multiple fuels independently, which can create additional options for refueling and provide for a greater "effective range."

As of 2013, California had roughly 33,000 natural gas vehicles registered in the state; about one-third of those fall into medium- and heavy-duty vehicle classes, while the remaining two-thirds are light-duty vehicles[39] (see Figure 25). Within each of these two segments, passenger vehicles (47 percent) and Class 8 trucks (32 percent) make up the largest portion of the state's NGV fleet by a substantial margin.

California accounts for a significant portion of the national natural gas vehicle market. While numbers aren't available for 2013, the most recent numbers published by U.S. EIA cited approximately 122,000 natural gas vehicles in operation nationally as of 2011.

Figure 25: Market Share of Natural Gas Vehicles in California



Source: NREL

Technology Assessment of Natural Gas Fueling

Most technology used in commercial natural gas fueling infrastructure is relatively mature, particularly that used in CNG stations. A list of key suppliers and technology developers/providers for commercial CNG and LNG infrastructure is in Appendix C.

Clean Energy Fuels is the largest operator of CNG stations in California as well as nationally. Nationally, the company operates about 500 natural gas fueling stations and is vertically integrated, providing production facilities as well as CNG and LNG services and station and vehicle components. Trillium CNG is the second largest operator of CNG stations and has worked primarily with local governments, transit agencies, and private companies in California. In addition, several companies such as Waste Management and Southern California Gas Company operate their own stations.

Clean Energy Fuels operates the largest network of LNG stations in California. Waste Management also operates 10 LNG fueling facilities, which are limited to private access. Several of the above providers also provide station development for LNG fueling solutions.

While many natural gas fueling stations in California accept common forms of payment like Visa, MasterCard, and American Express, there are several payment card systems that are

[39] Polk, R.L. *POLK_ VIO_DETAIL_2012.* National Renewable Energy Laboratory, January 2014

commonly used by fleets. Wright Express and Voyager cards are the largest fleet fuel purchasing cards used at natural gas fueling stations. Clean Energy also issues a fueling card to its customers. Several public fueling stations only accept one of these specialized payment options.

Technology Opportunities for Natural Gas Fueling Infrastructure

To limit the scope to technologies directly relevant to natural gas as a transportation fuel, this paper discusses only technologies that exist on the fueling site itself; however, some of the larger technological barriers and opportunities, particularly for LNG, exist upstream.

Small-Scale On-site Liquefaction

Because LNG currently is required to be transported via truck, it's unable to leverage existing infrastructure and the relative low transport cost provided by gas pipelines. An economic, small-scale solution to natural gas liquefaction can help to utilize existing infrastructure and allow access to LNG in places where it was previously cost prohibitive.

Several technologies exist and have been demonstrated that convert natural gas on-site in quantities that are more appropriately scaled for a vehicle fueling operation. The Gas Technology Institute has demonstrated the use of a mixed refrigerant liquefier to provide a solution that can produce between 5,000 and 30,000 gallons per day. The technology is currently being used in the United Kingdom, Australia, and in Altamont, California, at a Waste Management facility that converts landfill gas into LNG. Several other companies, such as GE and Dresser-Rand, have brought small-scale, modular LNG production units to the market recently.

There are inherent challenges in on-site liquefaction due to the fact the pipeline gas is odorized and would need to be purified prior to liquefaction. On-site liquefaction also does not allow for the flexibility that a centralized, large-scale facility would have to accommodate varying market demand and/or overall growth.

Personal Refueling Appliances

While there are commercial personal refueling appliances, their cost can often be prohibitive compared to other personal appliances such as electric vehicle charging units. Several companies, notably GE, have invested in research to provide a low-cost natural gas home fueling solution. Doing so would provide a much greater degree of flexibility in fueling locations and also ease some of the limitations inherent in current on-vehicle natural gas storage technologies. America's Natural Gas Alliance recently unveiled a series of CNG vehicles with "pony-tanks" that provide 3 to 5 gge of storage. The vehicles operate on a similar principle to the Chevrolet Volt in that they leverage relatively easy access to fueling to downsize and lower the costs of the components required for electrification (or in this case, compressed natural gas).

Adsorbed Natural Gas Storage

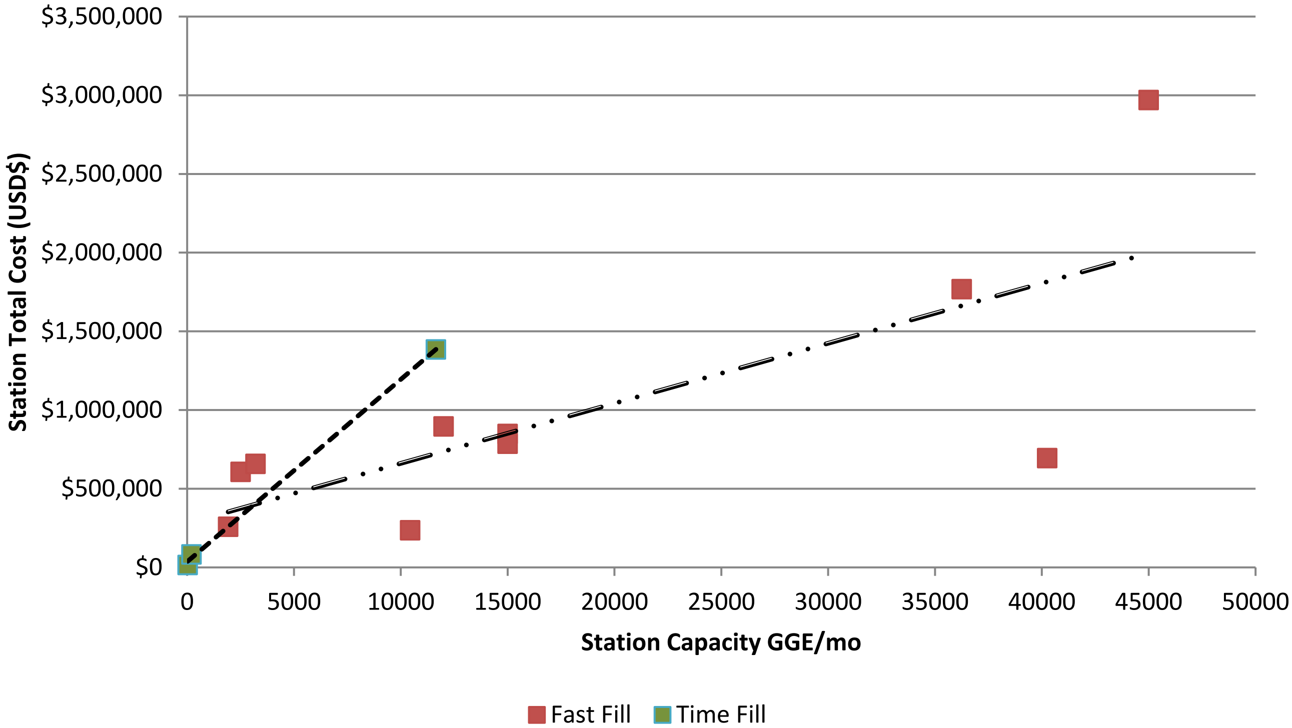
Current on-board storage for vehicles requires natural gas to be either compressed or liquefied in order to obtain a useful energy density. A third approach that is being investigated is adsorbed natural gas storage, where natural gas molecules bond to a high-surface-area "framework" that provides much greater storage capacity than a traditional cylinder or tank. While the actual energy density may not be as great as that of LNG, it can be achieved at ambient temperature and at lower pressures than CNG.

Factors Affecting Natural Gas Fueling Station Installation, Operation, and Maintenance Costs

Station costs can vary substantially depending on a number of factors such as siting, configuration, codes and standards, utility rates, and existing infrastructure. Installation is generally more streamlined for CNG stations than for LNG stations, and there are a number of companies that offer turnkey solutions.

The data in Figure 26 show the variation in the costs of natural gas fueling stations installed through project awards provided by the U.S. DOE. The data suggest a rough correlation between capacity and station cost.

Figure 26: CNG Fast-Fill and Time-Fill Station Cost Comparison from U.S. DOE-Awarded Projects



Source: NREL

LNG stations are less common than CNG stations and can vary substantially in cost. The chart in Figure 27 is taken from a report assembled by TIAX for America's Natural Gas Alliance on LNG infrastructure[40]. The trends shown suggest that for LNG stations with smaller storage capacities there is a stronger correlation between station cost and storage capacity. The data begin to fan out at storage capacities greater than 40,000 gallons.

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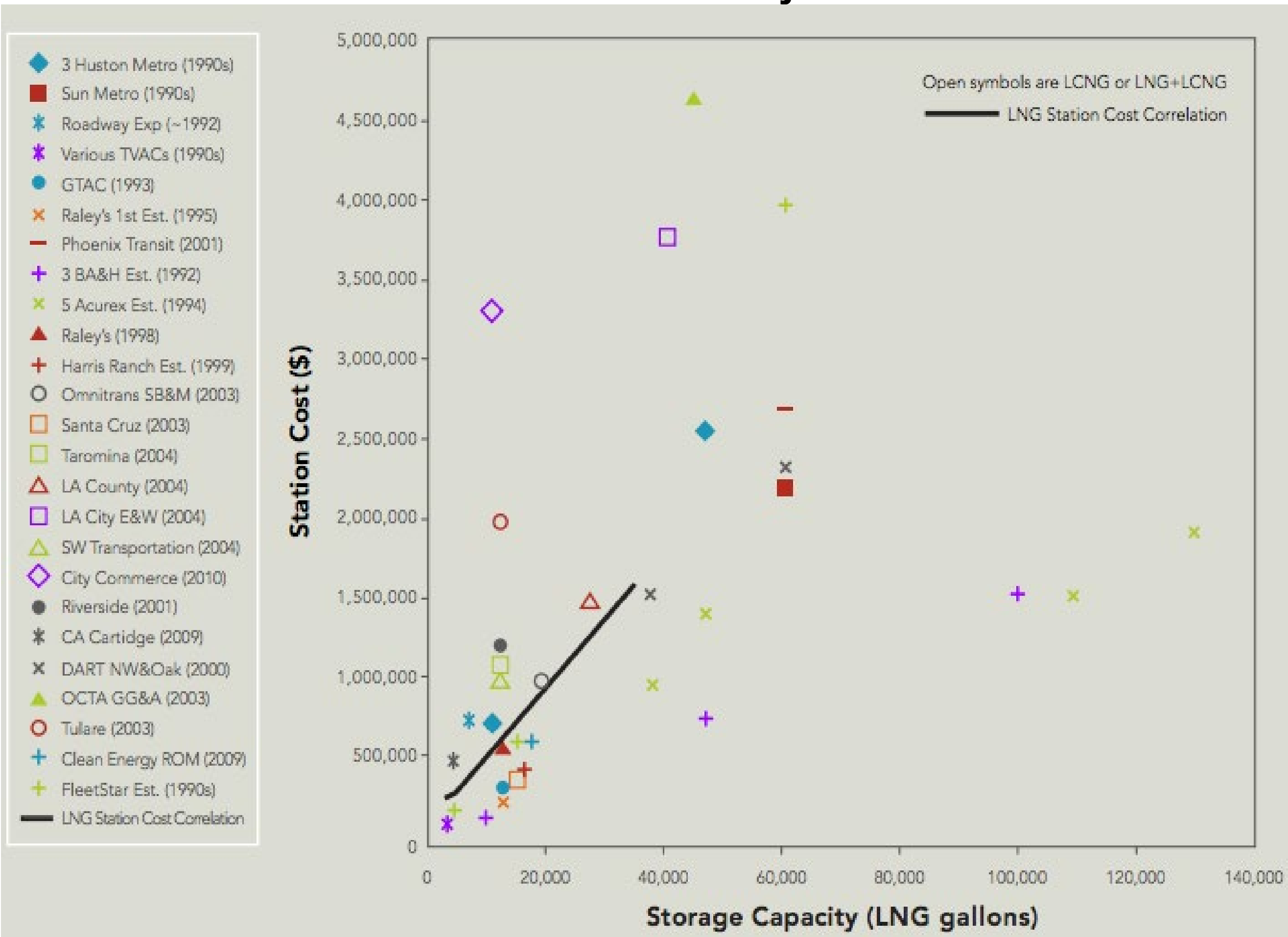
[40] TIAX. U.S. and Canadian Natural Gas Vehicle Market Analysis: Compressed Natural Gas Infrastructure. America's Natural Gas Alliance (2012).

Figure 27: CNG Fast-Fill Station Cost Comparison from American Recovery and Reinvestment Act Projects



Source: TIAX

While neither of these datasets allow for far-reaching conclusions, several common factors that influence the cost of natural gas fueling infrastructure are described below.

The configuration of a CNG, LNG, or L/CNG station will have a significant impact on installation and operational costs. Because of the need for storage and, in some cases, on-demand compression, a fast-fill CNG station is more costly to install and operate than a time-fill station with a similar capacity. For both LNG and CNG stations, the volume of throughput required will drive up costs as more or larger compressors (for CNG) and storage capacity (for both CNG and LNG) are required.

The level of gas pressure provided by utilities will affect both capital and operating costs for CNG stations. Access to higher-pressure gas will allow for smaller-sized compressors and/or lower electric demand for operations. Broader system-wide considerations must be considered when looking at enhanced natural gas pressures. Several California gas utilities have approved rate tariffs for providing high-pressure gas to retail stations.

As was discussed earlier, most natural gas that is provided in California is provided via a regulated utility. The specific rates for natural gas and electricity as well as other tariffs, such as demand charges, along with any on-site electricity generation, will affect operational and product costs. Utility costs for a CNG or LNG station can also impact the overall utility expenses of a given facility depending on how rates are structured, and facility operations are metered.

The readiness of a given site to connect to the appropriate level of electric and gas service will affect up-front capital investments. Factors that will influence these costs include proximity to existing utility infrastructure; the capacity of existing utility infrastructure and required electric and gas service; and trenching and construction requirements for connecting to utilities. For CNG stations, both gas and electric infrastructure need to be considered, whereas for LNG stations, electric infrastructure is of primary interest unless liquefaction is being done on-site.

Because California is a home rule state, meaning that local jurisdictions are free to set a number of their own codes and standards, there likely will be variability in the costs required to meet various local codes and standards for natural gas fueling stations. These expenses will be tied to the type of natural gas fueling installation as well as other factors such as whether indoor fueling is required. LNG vehicles have varying requirements, which can lead to variation in the specifications of a fueling facility.

Because of the relatively large above-ground footprint needed for both CNG and LNG stations, the particular siting of a facility may have economic and/or operational implications. Additional site-related considerations are reflected elsewhere, such as codes and standards and access to utility service mentioned above.

If a station is being built for either commercial or private use, anticipating future growth can help to save costs over the lifetime of the station. Examining the need for additional space, larger compressors and/or storage, as well as utility upgrades can provide cost benefits if these items are planned for during the initial construction of a project. While this may present an additional initial cost, often the savings over the life of the project are net positive.

A number of natural gas fueling stations incorporate redundant compressors, which allow for continued operation of a fueling facility should a compressor require maintenance or stop working. This approach provides for a more reliable overall operation but also increases capital expenses. Depending on how the compressor is powered, some station operators will also install backup generation in the case of a power outage. These generators are often diesel powered.

Methane Leakage

One of the advantages of natural gas as an alternative fuel is its relatively low carbon content compared to conventional fuels. Compared with gasoline, use of CNG as a transportation fuel results in a roughly 29 percent reduction in life cycle GHG emissions per unit of fuel energy.[41] However, as is the case with many life cycle assessment2qzstudies, there are uncertainties around some input parameters and therefore the carbon intensity results. Leakage of methane, which is the primary component of natural gas, is especially of interest for CNG pathways due to its high global warming potential of 28 to 30 times that of carbon dioxide on

[41] CARB 2014, Low Carbon Fuel Standard Lookup Tables, accessed Oct 22, 2014 https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities

a 100-year scale.[42] Most studies of the leakage implications for total life cycle GHG emissions have focused on natural gas for electricity generation, and typically discuss leakage as the total natural gas released to the atmosphere (intentionally or unintentionally) by way of leakage across the supply chain divided by total natural gas produced. Alvarez et al. (2012) estimate that leakage rates greater than 3.2 percent would make electricity from natural gas more carbon intensive than electricity from coal,[43] while the meta-analysis conducted by Heath et al. (2014) suggests a range of leakage rates between 0.53 percent to 6.2 percent.

A well-known tool for estimating transportation fuel life cycle emissions is Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model. An Argonne report examining life cycle shale and natural gas emissions using GREET highlighted the need to better understand upstream methane leakage and venting, as leakage can reduce GHG benefits from using natural gas as an alternative fuel in motor vehicles.[44] A recent presentation by GREET analysts suggests that a leakage rate of approximately 4.5 percent (using a total throughput basis) would make CNGVs equivalent to conventional gasoline internal combustion engine vehicles on a GHG per mile basis, assuming equivalent fuel economies between CNGV and conventional vehicles, and approximately 3.5 percent assuming a (more likely) 5 percent lower fuel economy for CNGVs.[45]

A recent study examining the past 20 years of technical literature on natural gas emissions found that official inventories consistently underestimate actual methane emissions compared with measurement-based estimations, and the study suggests a small number of "super emitters" may be responsible.[46] These "super emitters" may include well sites, processing plants, and storage and distribution systems that are not specific to any one sector or industry, further complicating the life cycle analysis. The study used a 100-year assessment period and did not consider technological evolution and forecasting for engine efficiencies when assessing the impacts that upstream methane leakage may have on the benefits of using natural gas as an alternative fuel.

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[42] Intergovernmental Panel on Climate Change 2013
http://www.climatechange2013.org/images/report/WG1AR5_ALL_FINAL.pdf

[43] Alvarez RA, Pacala SW, Winebrake JJ, Chameides WL, Hamburg SP (2012) *Greater focus needed on methane leakage from natural gas infrastructure*. Proceedings of the National Academy of Sciences, USA 109(17): 6435–6440.

[44] Argonne National Laboratory, Life-Cycle Analysis of Shale Gas and Natural Gas
https://publications.anl.gov/anlpubs/2012/01/72060.pdf

[45] M. Wang, A. Burnham, A. Elgowainy, and H. Cai (2014) Life-Cycle Analysis of Natural Gas Use in Transportation: CNGVs, LNGVs, EVs, and FCVs, Argonne National Laboratory, Presentaiton at the Society of Automotive Engineering 2014 World Congress, Detroit, MI, April 8-10.

[46] Novim, Methane Leaks from North American Natural Gas Systems, 2014
https://static1.squarespace.com/static/5a08c1b88c56a8aa90e8a6d5/t/5a5d8a1471c10bc0943679d2/1516079640250/ScienceSupplement.02.14.14-1.pdf

Some methane emissions, such as those that occur during vehicle refueling and operation, are not well understood but are currently being investigated in greater detail.[47,48,49] CNG vehicle tank venting can occur if the tank is refilled to a high level when temperatures are cool, followed by the tank warming in the sun and exceeding the maximum allowable pressure, thus opening the pressure relief valve. LNG vehicles can also experience tank venting. If vehicles are not regularly used, a portion of the fuel can slowly boil off; this phenomenon is accelerated by elevated temperatures or damage to the tank insulation. Once the maximum allowable tank pressure is exceeded, a pressure relief valve will open, and natural gas is vented. The occurrence of these emissions may depend on the specific fleet's refueling strategy, climate, and the level of training given to operators, resulting in a wide range of secondary emissions. To ensure that natural-gas-fueled vehicles achieve the desired reductions in GHG emissions compared to conventional fuels, fleets should receive appropriate refueling and operational guidance. Efforts should be made to identify and resolve upstream supply chain leakage issues, particularly from "super emitters"; this is an important endeavor for non-transportation natural gas uses as well.

Market Expansion Opportunities and Barriers to Widespread Commercialization and Deployment

California has historically been a leading state in terms of natural gas vehicle use, representing about a quarter of the national market for natural gas vehicles. The technology presents an opportunity for the state to advance a number of objectives: fuel diversification, economic benefits, and positive environmental attributes. This section presents an overview of some of the opportunities and challenges that natural gas fueling infrastructure faces. These reflect current conditions, and many of the barriers can in fact be opportunities if addressed.

Opportunities

Current law allows for natural gas vehicles to use high-occupancy vehicle lanes, which has proven to be a valuable benefit to vehicle sales in California. These lanes are aligned with heavy commuting routes, which presents an opportunity to match natural gas fueling corridor development with traffic patterns, providing both a valuable benefit to NGV owners and a captive market for natural gas station owners.

Prior price volatility in natural gas markets created a disincentive to making capital investments in either natural gas vehicles or fueling infrastructure. Dramatic increases in the nation's estimated supply of economically recoverable gas have both depressed and smoothed natural gas prices. This price stability could encourage longer-term investments by infrastructure providers and/or introduce innovative financing products that exploit the spread between natural gas and diesel prices.

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[47] West Virginia University, New collaborative study at WVU will measure methane emissions associated with natural gas vehicles and fueling stations, 2013 http://wvutoday.wvu.edu/n/2013/03/04/scemr-release

[48] Environmental Defense Fund, The climate impacts of methane emissions, 2012 http://www.edf.org/methaneleakage

[49] Proceedings of the National Academy of Sciences, Greater focus needed on methane leakage from natural gas infrastructure, 2012 http://www.pnas.org/content/early/2012/04/02/1202407109.full.pdf+html

Because of price spread between natural gas and diesel, a number of fleets are making purely economic decisions to use natural gas as a transportation fuel. Fleets such as refuse and transit fleets, which have consistent routes, return to base to fuel, and have relatively high mileage and low fuel economy, can make fairly reliable investments in vehicles and leverage infrastructure investments over a large fuel demand pool. It is not clear, however, that this will correspond to greater availability of public infrastructure.

Cost-effective home fueling presents an opportunity to transform personal transportation using natural gas vehicles by increasing the convenience and availability of fueling options. Provided that these fueling activities occur at night, this technology could also prompt some load shifting of both gas and electricity to off-peak hours. Finally, having access to a greater number of fueling points also could have an influence on future natural gas vehicle designs.

The availability of LNG is currently geographically constrained because of the lack of infrastructure in place to easily and cost-effectively transport it. Leveraging the existing natural gas transmission and distribution system to liquefy natural gas at or closer to the actual demand source could overcome this obstacle. While several current technologies are available, they are not yet widely deployed.

Natural gas is currently the prime feedstock for a majority of hydrogen production in the United States. As California rolls out its requirements for zero-emission vehicles and also supports the installation of hydrogen fueling stations, there are possible synergies that can be leveraged between hydrogen and natural gas fueling infrastructure. These include codes and standards, providing adequate electric and gas service at retail fueling locations, and on-site fuel storage.

Barriers

Perhaps the largest barrier to natural gas fueling infrastructure is not related to the stations themselves, but rather to the relatively high incremental costs of natural gas vehicles. While incremental costs vary across vehicle classes, the greater up-front investment required by businesses and consumers can make it challenging to adequately plan infrastructure, particularly if there is not an anchor fleet customer. Without widespread access to infrastructure, current natural gas vehicle economics tend to favor fleets because they are able to exploit the price spread between natural gas and diesel – assuming fleets have on-site natural gas fueling capability. This in turn can present challenges to growing the availability of public infrastructure.

Current fueling range and storage capacity presents an overall challenge to the natural gas vehicle and fueling infrastructure industries. For passenger vehicles, the Honda Natural Gas Civic has a range of approximately 220 miles. Bi-fuel vehicles such as the Dodge Ram 2500 allow a range of up to 745 miles because of the option to use a 35-gallon gasoline tank (as well as greater overall fuel storage space that’s available), but they do not guarantee petroleum displacement or any emissions benefits from natural gas. Lower range implies the need for either more strategic placement, or a greater number, of natural gas fueling stations. Advanced natural gas storage technologies, such as adsorbed gas, could also benefit on-site storage at refueling facilities for fast-fill stations.

Natural gas pipeline pressure varies across California and among the various types of customers that natural gas utilities serve. With CNG requiring pressures of 3,600 psi, there can be a substantial electrical demand associated with reaching these pressures depending on the starting pressure of the gas service provided to the fueling infrastructure. Having access to higher-pressure gas service reduces compressor demands for CNG stations, which can then lower both up-front capital costs and operational costs for electricity.

New entrants into natural gas fueling, particularly for CNG, may not be familiar with managing electricity demand charges that can be triggered by peak or seasonal electricity use. Given the relatively high electric load required by compressors, their operation during these times can cause substantial increases in the per-unit cost of natural gas fueling (as can other appliances on the same meter). This can be particularly challenging to station operators that are attempting to grow their base of natural gas fueling customers, as initially they have fewer gallons to spread these additional costs across.

As was mentioned previously, the location of a fueling facility relative to adequate electric or gas service can have a significant impact on overall project economics, particularly at existing sites where concrete and existing facilities may be affected by construction. There is some question as to whether or not fueling stations represent an indeterminate load for utilities, which can be a determining factor in whether connecting that facility to a certain class of service can be covered in the rate base. These costs can be a substantial part of total fueling station economics.

With only one large-scale liquefaction facility in the state and the inability to use pipelines for transport, LNG is currently limited in its ability to be cost-effective in California. The limited availability of liquefaction facilities also presents a supply risk to fleets. Financially, large-scale liquefaction facilities are capitally intensive investments, which can serve as a possible limit to the ability and pace of overall market expansion.

There are currently no national standards for natural gas that is dispensed as a motor fuel, though efforts are ongoing through American Society for Testing and Materials International. While there are standards for natural gas being transported through pipelines, these are regional standards and do not necessarily present an optimal specification for natural gas used in transportation. Materials such as water and oil from compressors can make their way into vehicle fueling systems, which can cause problems in engines.

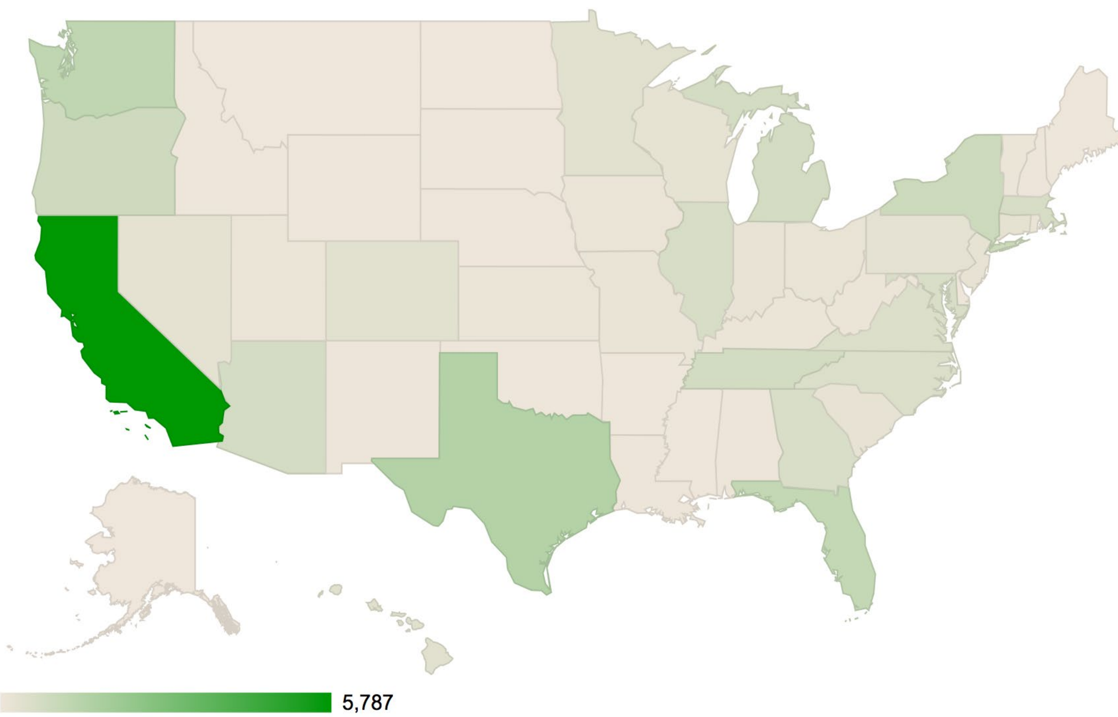
While natural gas vehicles have been successfully deployed around California as a means to help meet air quality targets, emission standards have evolved such that all light duty vehicles (and heavy-duty vehicles) must meet the same emission standards regardless of fuel. Furthermore, there are several studies underway that are examining the life cycle impacts of natural gas with a focus on new production processes and leakage rates in the gas transmission and distribution system. Further research into this area is needed to make definitive statements about air quality and greenhouse gas benefits.

CHAPTER 5: Electric Vehicle Supply Equipment and Electric Vehicle Charging Infrastructure

Background

Charging stations are often referred to as EVSE and are categorized as Level 1 chargers, Level 2 chargers, and fast chargers. Level 1 chargers are generally the least expensive charging option and are the slowest. On the other extreme are fast chargers, which can charge a plug-in electric vehicle (PEV) relatively quickly but are the most expensive. As of October 14, 2014, California has the most public electric charging stations of any state with 1,886 stations and 5,749 charging outlets. Texas and Florida follow it with 555 and 483 stations, respectively. Figure 28 illustrates the relative number of public electric charging outlets by state as of October 14, 2014.

Figure 28: Relative Number of Public Electric Charging Stations by State

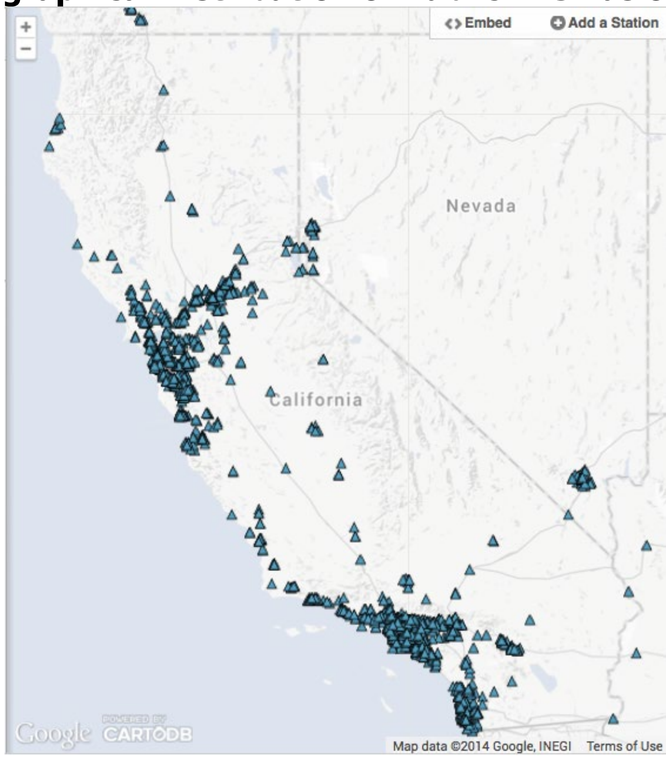


Source: Alternative Fuels Data Center

EVSE availability is reported as both stations and outlets because some stations have more than one outlet. California, for example, has roughly 374 Level 1 stations and 1,696 Level 1 outlets, 1,779 Level 2 stations and 5,485 Level 2 outlets, and 175 fast charger stations and

466 fast chargers outlets that are publicly available.[50] The geographical distribution of public EVSE stations as of October 14, 2014, is shown in Figure 29.

Figure 29: Geographical Distribution of Public EVSE as of October 2014



Source: Alternative Fuels Data Center

Key Suppliers and Technology Developers

There are many companies that manufacture EVSE, and the EVSE range from relatively big commercial charging stations to small residential ones. Some key providers include EVTRONIC, Eaton, AeroVironment, Schneider, Delta Electronics, GE, Siemens, Clipper Creek, Coulomb Technologies, and Leviton. Direct current (DC) fast chargers are still quite expensive (more than $20,000) and not as widespread as Level 1/Level 2 alternating current (AC) chargers; thus, the number of companies that manufacture DC fast chargers is relatively small. Some fast charger manufacturers are ABB, AeroVironment, Delta, Eaton, Ecotality, and Schneider. Tesla has its own proprietary DC fast charger, called Supercharger, for its Model S.

All leading automobile manufacturers are investing in the development of future EVSE technology and standardization in collaboration with utility and power equipment companies. The main technological issues for future EVSE are reverse power flows, such as vehicle-to-grid and vehicle-to-building, and secure communication links among PEV, EVSE, smart meters, and utility companies. Because communication is a critical part in delivering power from PEVs to the electric grid, homes, or buildings, many network equipment or component companies such

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[50] The total number of EVSE stations reported by the CEC's ARFVTP may vary from those reported on the Alternative Fuels Data Center due to reporting protocols. See footnote 9 for the Alternative Fuels Data Center reference.

as Qualcomm, Broadcom, Cisco, D-Link, and Texas Instruments are actively participating in development and standardization of communication networks that will be part of EVSE.

Currently, EVSE operators use their own network to manage charging stations and provide information about charging station location and availability to customers. Two large networks in California are ChargePoint by Coulomb Technologies and Blink Network by Car Charging Group (previously Ecotality). They use their own proprietary cellular networks, and they are not compatible with each other. They can show the locations of EVSE in other networks but cannot get status information from other networks due to incompatibility. The Society of Automotive Engineers (SAE) organizes regular standardization meetings to determine industrial standards for communication that eventually may be used by PEVs and EVSE.

Technology Assessment

An international standard for electrical connectors for EVs is specified by International Electrotechnical Commission 62196. There are three connector types listed in International Electrotechnical Commission 62193. Type 1 was proposed by SAE and standardized as SAE J1772. All PEVs in the United States have a receptacle that is compatible with this type of connector. Type 2 was developed by a German company called Mennekes and is called VDE-AR-E 2623-2-2. Type 3 was proposed by the Electric Vehicle (EV) Plug Alliance, which was formed by electrical companies in France and Italy. In 2013, the European Commission declared type 2 to be a common standard for charging ports in Europe. Pictures of connectors of each type are illustrated in Figure 30.

Figure 30: Pictures of Type 1, 2, and 3 Connectors (from left to right)

Sources: SAE, Mennekes, EV Plug Alliance

Japanese auto companies and the Tokyo Electric Power Company developed a DC fast charging method for PEVs called CHAdeMO. CHAdeMO-compatible EVSE have been installed world-wide (more than 1,000 stations in Japan as of 2012 and 160 in California as of 2013). Nissan and Mitsubishi started to sell LEAF and iMiEV, respectively, with an option for a CHAdeMO receptacle since 2013 in California.

Considering the small number of CHAdeMO stations compared to the number of AC Level 1/ Level 2 stations, Nissan LEAF and Mitsubishi iMiEV vehicles should be equipped with both AC and DC inlets to maximize the DC fast charging capability. In order to compete with this Japanese standard and to be compatible with the existing J1772 AC charging systems, U.S. car manufacturers are working on another DC charging standardization with SAE called J1772 combo. The upper part of the J1772 combo inlet is the same as the J1772 AC inlet, as shown in the right picture of Figure 31; as such, vehicles need to have only one inlet for both AC and DC charging capabilities. J1772 combo fast charge EVSE are not yet available. As mentioned, Tesla has its own proprietary DC fast charger (Supercharger) for its Model S.

Figure 31: CHAdeMO/J1772 AC Receptacle on Nissan LEAF (left) and J1772 Combo Connector and Receptacle (right)

Sources: Alternative Fuels Data Center

Market Information

As of early 2014, the Center for Sustainable Energy reported the cumulative number of PEVs in California at about 63,000.[51] If it is assumed that Center for Sustainable Energy survey results accurately reflect the PEV driver preferences of a broad consumer base, beyond early adopters, then the following survey results are noteworthy for future EVSE deployment activities.[52]

- About 1 of every 40 cars purchased or leased in California during the last quarter of 2012 was a PEV.
- Nearly 85 percent of PEV drivers cited environmental benefits as an important factor in their decision to purchase a PEV.
- While environmental benefits are a factor in purchasing a PEV, clearly economic factors are very important to potential PEV buyers as well based on the following:
    - A rebate program was an important factor in the PEV purchase decision for 95 percent of respondents.
    - Two-thirds of PEV drivers used workplace charging less than once per week if usage fees were charged.
    - Ninety percent of respondents had installed a residential charger; 56 percent had received a free or subsidized Level 2 charger.

[51] California Center for Sustainable Energy, What Drives California's Plug-in Electric Vehicle Owners? Accessed March 2014. https://energycenter.org/article/ca-pev-owners-report-varying-motivations-models-purchased

[52] California Venter for Sustainable Energy, California Plug-in Electric Vehicle Driver Survey Results, March 2014. http://energycenter.org/sites/default/files/docs/nav/transportation/cvrp/survey-results/California_Plug-in_Electric_Vehicle_Driver_Survey_Results-May_2013.pdf

- The single highest "extremely important" factor in determining when PEV owners charge their vehicles is the cost of charging.
    - The data indicate many PEV owners are programming their PEVs to charge when rates are least expensive.
- While PEV drivers desire PEVs with longer all-electric ranges than current models offer, average vehicle use was 28.9 miles per day – consistent with non-PEV drivers having similar demographic profiles to PEV drivers.
- Driver satisfaction with public charging infrastructure is improving, but it is still less than 25 percent.

Based on these survey results, it could be assumed that the PEV market is alive and well in California – at least for the short term. Given the importance of economic subsidies cited by survey respondents, market incentives will be required for the foreseeable future. These incentives, entailing rebates, charger subsidies, minimal charging fees, and visibility of time-of-use charging strategies, will likely have to be maintained – and possibly increased – to attract future PEV purchasers whose demographics and disposable income may be different than the typical PEV early adopter.

The near-term outlook of "for-profit" EVSE does not appear particularly lucrative, given PEV drivers' unwillingness to pay for charging (less than one-half of respondents would be willing to pay $1 per hour for daily Level 2 charging).

One potential market is charging operation and management. At this point, charging operations are mainly focused on charging station information such as station location and availability. With the introduction of smart EVSE having the capability to communicate with utility companies and ongoing efforts for vehicle-to-grid/vehicle-to-building, charging management should see more features and functionalities. Markets for those services and for smart EVSE systems are expected to grow as consumers may come to view their PEVs not only as a vehicle, but as a money-making system capable of providing power to the grid or a building. Additionally, retailers may endorse on-site EVSE as a way to create a captive customer while the vehicle is charging.

A more extensive discussion of technology assessment and market status can be found in the May 2014 *California Statewide Plug-in Electric Vehicle Infrastructure Assessment* report. More recent information on technology and market trends can be found at the PEV Collaborative and CES websites.

CHAPTER 6: Hydrogen Fueling Infrastructure

Background

A fuel cell electric vehicle (FCEV) generates the electricity needed to run an electric motor propulsion system using an on-board fuel cell that operates on hydrogen fuel. A hydrogen-fueled FCEV directly emits only water vapor during operation and is recognized as a ZEV in California. While an FCEV emits no carbon dioxide or local air pollutants or precursors at its point of use, local criteria air pollutants and GHG emissions may be generated during the production of the hydrogen fuel. In this manner hydrogen is an energy carrier like electricity, the production of which may also involve GHG and criteria emissions from upstream processes. The initial FCEVs being developed for the emerging commercial market store hydrogen on-board the vehicle as a compressed gas. FCEVs can have a driving range similar to that of conventional gasoline vehicles, around 300 miles per tank. Hydrogen refueling times for FCEVs are expected to be similar to gasoline refueling times, at 3 to 5 minutes for a complete fill of approximately 5 kilograms (kg) of hydrogen, and hydrogen will typically be dispensed from retail outlets that resemble conventional gasoline stations.[53]

FCEVs are just becoming commercially available now, with initial leases of the Hyundai Tucson in June of 2014 and a number of auto manufacturers intending to sell FCEVs in targeted markets as early as 2015. One of the largest hurdles for FCEVs entering and expanding into the light-duty vehicle market is the required coordinated rollout of hydrogen production and fueling infrastructure to satisfy the fueling needs of a growing FCEV fleet. Today, an extensive network of approximately 156,000 retail petroleum-based fueling stations is available to fuel gasoline and diesel vehicles.[54] Replicating this number of hydrogen fueling stations to support expansion of FCEVs into the light-duty vehicle market is neither necessary nor economically or practically feasible. The challenge for FCEVs to achieve market expansion will be to develop a hydrogen infrastructure path extending into the future that cost-effectively meets the needs of a growing FCEV fleet.

Hydrogen as a transportation fuel has a broad applicability to a wide variety of on-road vehicle platforms (see Figure 32). Hydrogen can be used as a transportation fuel in both FCEV configurations and in hydrogen-powered internal combustion engine vehicles. Given the performance characteristics of fuel cell systems, fuel cell-based propulsion systems are expected to be suitable for the full range of light-duty vehicles, from smaller cars to larger cars and sport utility vehicles. As auto manufacturers are focusing their vehicle development on light-duty FCEVs instead of hydrogen-powered internal combustion engine vehicles or medium/heavy duty vehicle markets, this report concentrates on the hydrogen fueling needs of light-duty FCEVs.

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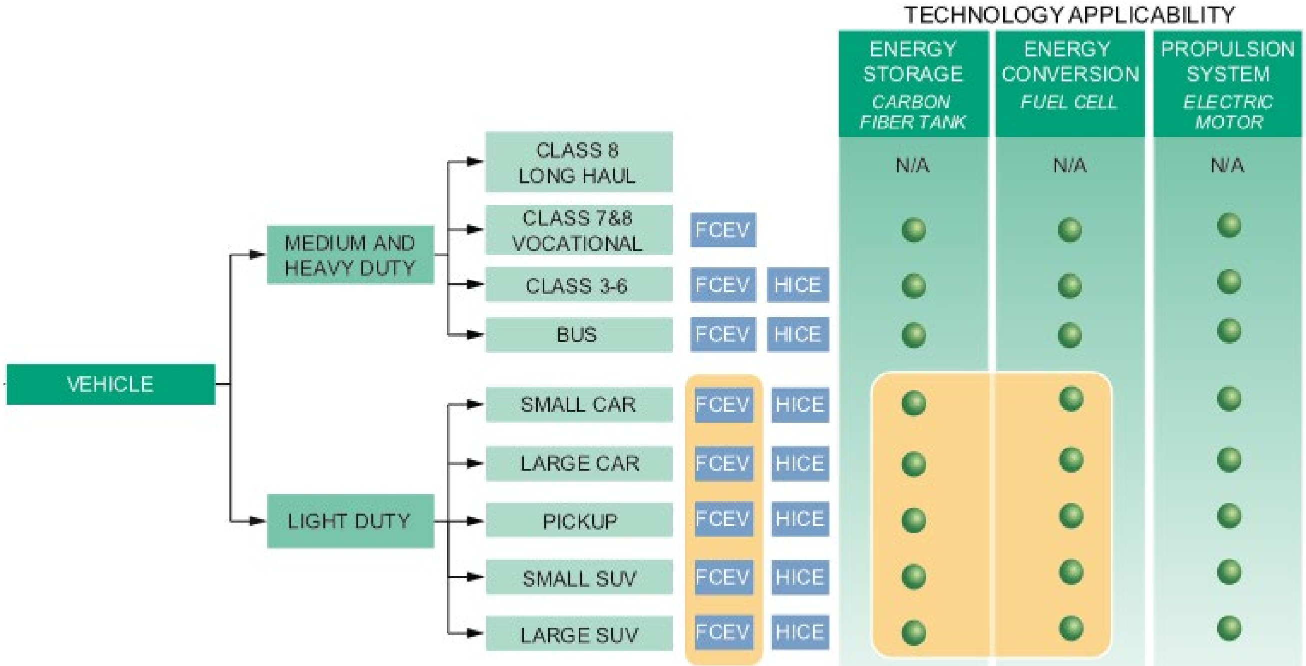
[53] A kilogram of hydrogen contains approximately the same amount of energy as a gallon of gasoline.

[54] U.S. EIA Petroleum and Other Liquids Data page https://www.eia.gov/petroleum/data.php

For more than a decade, the United States, Europe, Japan, and Korea have been conducting research and demonstration programs to support the development of FCEV technologies and the development of the necessary hydrogen fueling infrastructure for FCEVs.[55] During that time, there have been significant advances in both FCEV technology and hydrogen production and delivery technology. However, the need to build and deploy a complex network of hydrogen production, delivery, and dispensing infrastructure, including the deployment of significant numbers of hydrogen fueling stations, remains a significant hurdle[56].

Figure 32: Applicability of Hydrogen as a Fuel for Various On-Road Highway Vehicle Platforms



Source: National Petroleum Council

Hydrogen Supply and Infrastructure Overview

To provide hydrogen fuel for the commercialization of FCEVs, existing hydrogen infrastructure must be leveraged initially, and eventually a network of hydrogen production, distribution, and dispensing facilities must be developed. Overall, the development of a robust hydrogen production, distribution, and dispensing infrastructure throughout the United States is a significant challenge that must be met to enable full commercialization of hydrogen-powered FCEVs.

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[55] National Academies of Science (NAS), 2013. *Transitions to Alternative Vehicles and Fuels*. National Research Council, Committee on Transitions to Alternative Vehicles and Fuels, Board on Energy and Environmental Systems, Division on Engineering and Physical Sciences. The National Academies Press, Washington, DC.

[56] National Petroleum Council (NPC), 2012. *Advancing Technology for America's Transportation Future*, Part Two – Fuel and Vehicle System Analyses. Washington, DC
https://www.hydrogen.energy.gov/pdfs/htac_nov12_11_boccanfuso.pdf

This report section provides an overview of these hydrogen infrastructure elements and discusses existing infrastructure and technologies. Other than the overview in this section, upstream hydrogen production and distribution is not discussed in depth in this report.

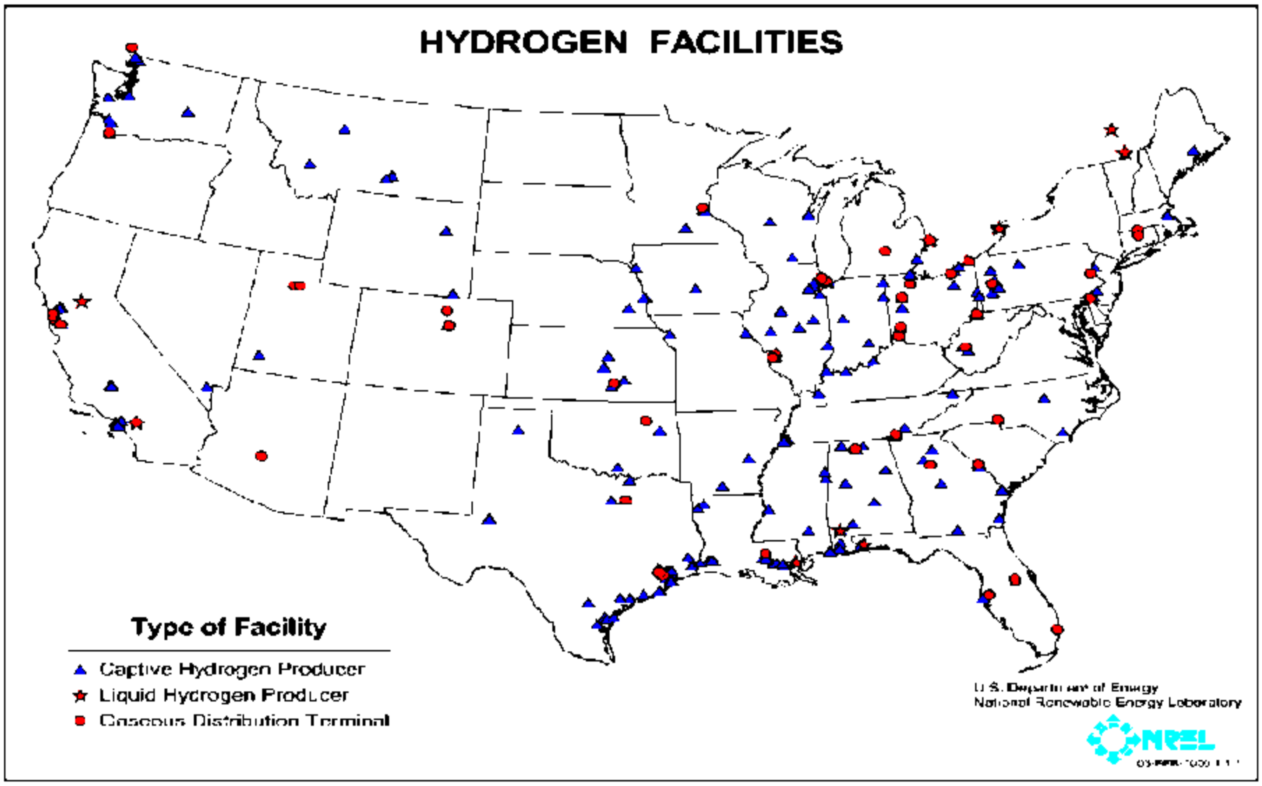
Hydrogen Production

Unlike petroleum, natural gas, or other fossil fuels, hydrogen is not an energy source. Instead, it is an "energy carrier" like electricity and can be produced from a variety of energy resources. The U.S. DOE reports that more than 9 million metric tons of hydrogen is produced annually in the United States for both captive and merchant markets.[57] With the exception of supporting pre-market demonstrations of FCEVs and for early market applications such as fuel cell-powered material handling equipment ("forklifts"), hydrogen is not used as a transportation fuel but rather as an industrial gas. Produced in large scale for more than 50 years, hydrogen is used in such industrial applications as petroleum refining, chemical production, food processing (e.g., hydrogenation), electric generator cooling, and steel and glass making.

More than 95 percent of U.S.-produced hydrogen is made in central plants from natural gas using a steam methane reforming process, with small amounts of hydrogen produced from refinery off-gases, coal, and water electrolysis. The National Petroleum Council reports that large hydrogen production facilities (with capacities of more than 18,000 kg of hydrogen per day) operate in nearly every state (see Figure 33).[56] The existing hydrogen production infrastructure can be leveraged to support the initial commercialization of FCEVs, though there is little excess hydrogen production capacity.[56] As commercialization of FCEVs progresses, new hydrogen production capacity will need to be built.

[57] U.S. DOE, 2012. DOE Hydrogen and Fuel Cells Program Record #12014. "Current U.S. Hydrogen Production", Originated by Fred Joseck http://www.hydrogen.energy.gov/program_records.html

Figure 33: Hydrogen Production and Distribution Facilities in the United States



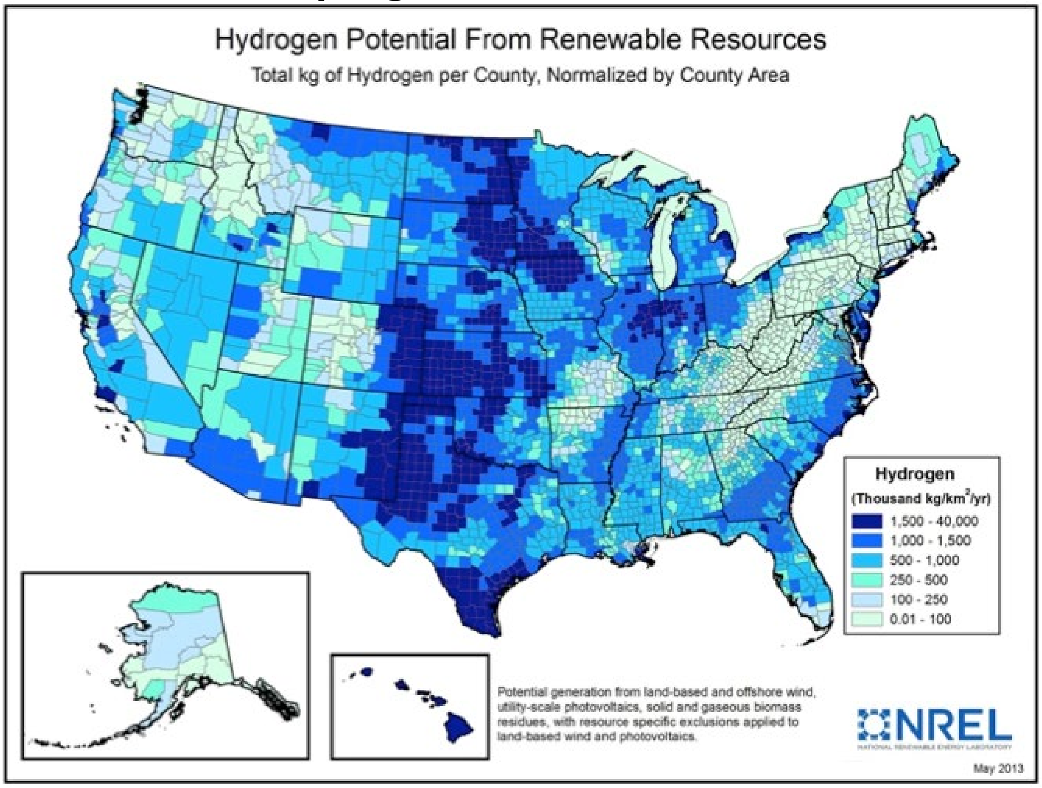
Source: NREL

In the early stages of commercialization, expanded hydrogen production will likely rely upon natural gas feedstock converted to hydrogen with the steam methane reforming process, as this approach offers a low-cost pathway to producing hydrogen. Over time, the hydrogen fuel feedstock mix could evolve from this natural gas dominance to a more diversified production mix, such as a lower-carbon production mix that includes natural gas reformation with carbon capture and storage, coal with carbon capture and storage, biofuels, waste resources, nuclear, and water electrolysis using renewable electric power. This shift is anticipated because it is expected that there will be a significant push to de-carbonize transportation fuels.

Hydrogen gas as a fuel is already fully carbon free, and there are no carbon emissions at the point of use of hydrogen in FCEVs. Carbon emissions from hydrogen as a transportation fuel are primarily associated with the production of hydrogen. Thus, in a low-carbon future, hydrogen produced from fossil fuels would increasingly rely upon carbon capture and storage systems. Carbon capture and storage is a process in which carbon dioxide emissions from production processes are captured and compressed, and the resulting compressed carbon dioxide gas is injected and stored in deep geologic caverns such that it is prevented from re-entering the atmosphere.

Hydrogen may also be produced from renewable energy resources and waste streams using low-carbon-emitting processes, and such production is expected to expand as part of de-carbonizing transportation fuels. Production of renewable hydrogen from biomass gasification, water electrolysis using renewable electricity, and reformation of renewable natural gas are established low-carbon production pathways. The U.S. DOE is also researching hydrogen production via fermentation of biomass hydrocarbons, biological water splitting, and photoelectrochemical water splitting, among other advanced production pathways. NREL estimates that on a technical basis, more than a billion metric tons of hydrogen can be produced annually in the United States using wind, solar, and biomass resources, although these renewable resources have an economic production potential closer to 120 million metric tons per year.[58, 59] See Figure 34 for hydrogen production potential from renewable sources in the United States.

Figure 34: Renewable Hydrogen Production Potential in the United States



Source: NREL

Hydrogen Distribution

According to the U.S. DOE, most of the hydrogen consumed in the United States is produced at or near the large industrial sites where it used.[60] Unlike natural gas or petroleum products (gasoline and diesel), distribution of hydrogen in large quantities over long distances is not typical. As a result, hydrogen distribution technologies currently serve relatively small markets and hydrogen distribution represents a significant portion of the total delivered cost of hydrogen, or cost "at the pump". Overall, the hydrogen delivery and distribution infrastructure

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[58] Levene, J., Mann, M., Margolis, R., and Milbrandt, A., 2007. "An Analysis of Hydrogen Production from Renewable Electricity Sources", *Solar Energy*. Vol. 81, Issue 6, June 2007.

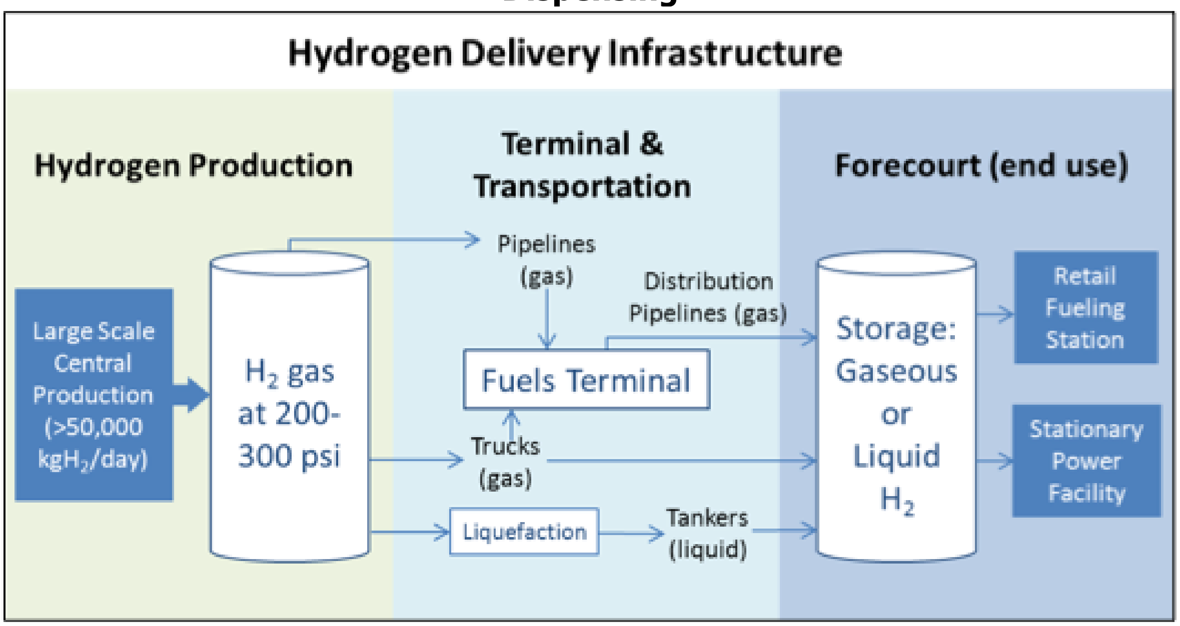
[59] Melaina, M., Penev, M., and Heimiller, D., 2013. *Resource Assessment for Hydrogen Production – Hydrogen Production Potential from Fossil and Renewable Energy Resources*, National Renewable Energy Laboratory, Technical Report NREL/TP-5400-55626, Golden, CO.

[60] U.S. DOE, 2010. "Hydrogen Distribution and Delivery," Energy Efficiency and Renewable Energy (EERE) Information Center. November 2010.

includes transport elements (e.g., trucks and pipelines), storage elements (terminals, large scale geologic storage, on-site storage), and fuel dispensing[61] (see Figure 35).

Following production in centralized facilities, hydrogen can be distributed as a compressed gas via pipelines or it can be distributed as either a compressed gas or super-cooled liquid (-253°C) via roadways, rail, and barge. The least expensive method of distributing large quantities of hydrogen is by pipelines, but relatively little hydrogen pipeline infrastructure is in place in the United States – less than 1,200 miles of pipeline in total, mainly near large refineries and chemical plants along the Gulf Coast and in Illinois and California.[56] Over shorter distances (generally less than 200 miles), hydrogen can be delivered cost effectively over the road as a compressed gas in tube trailers with a payload of about 250 kg of hydrogen. For longer distances and for larger quantities when pipelines are not available, liquefied hydrogen can be delivered via cryogenic liquid tanker trucks (up to about 4,000 kg of liquid hydrogen), though the energy penalty for liquefying hydrogen is significant.

Figure 35: Elements of a Hydrogen Delivery Infrastructure from Production to Dispensing



Source: U.S. DRIVE

New truck-based delivery technologies are under development, including high-pressure composite/carbon-fiber tube trailers that can deliver up to 1,000 kg of hydrogen at 50 megapascal (~7,200 psi), and dual-phase liquid tankers with on-board vaporizers that can carry hydrogen as a liquid but dispense it as a 70 megapascal (~10,000 psi) compressed gas.[56]

To accommodate variability in hydrogen demand, including seasonal demand variability, hydrogen delivery infrastructure may need to include large-scale storage of hydrogen in geologic formations including both natural formations and mined formations such as abandoned salt mines. Currently, only three geologic hydrogen storage facilities are in

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[61] U.S. Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability (U.S. DRIVE), 2013. *Hydrogen Delivery Technical Team Roadmap*. U.S. DRIVE Partnership, June 2013.

operation, all in Texas. Hydrogen storage, including both compressed gaseous hydrogen storage and cryogenic liquid hydrogen storage, can also be provided at hydrogen distribution terminals. The United States currently has 40 gaseous hydrogen storage terminals and nine liquid hydrogen terminals.[56]

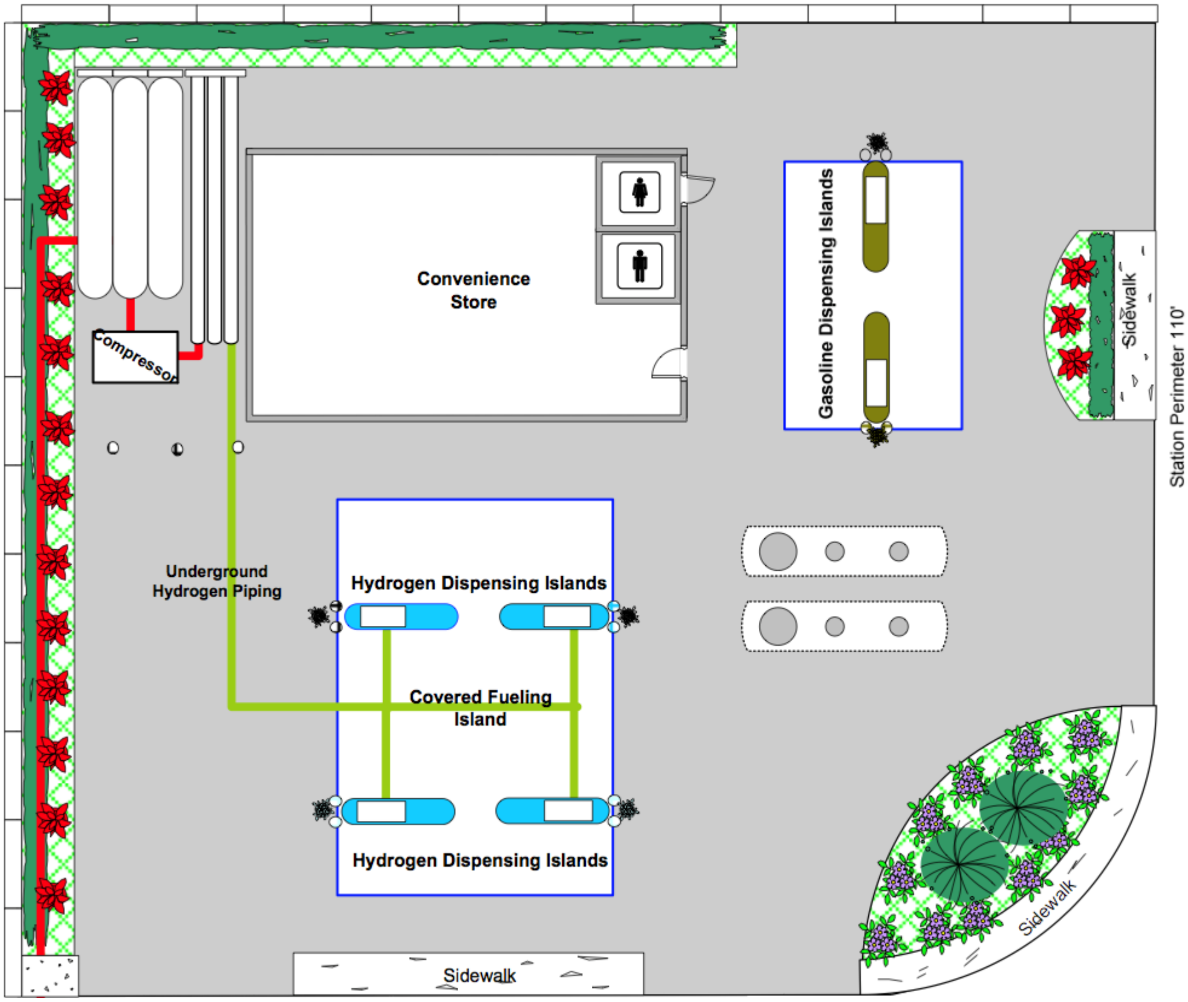
Infrastructure Needs for Hydrogen as a Transportation Fuel

Early, pre-market hydrogen vehicles included both hydrogen-powered internal combustion engine vehicles and FCEVs. The hydrogen-powered internal combustion engine vehicles stored hydrogen as a cryogenic liquid. In contrast, the initial FCEVs stored hydrogen on-board as a compressed hydrogen gas at a nominal pressure of 35 megapascal (350 bar, or about 5,000 psi). During the FCEV commercialization period beginning in 2015, the latest hydrogen vehicles will be FCEVs using on-board storage of gaseous hydrogen at 70 megapascal (700 bar, or about 10,000 psi).

Though home hydrogen refueling systems have been investigated, it is likely that the initial hydrogen fueling infrastructure developed to support the commercialization of FCEVs will be in the form of public fueling stations similar to today's retail gasoline stations. The exact model for hydrogen fueling stations may vary. For instance, hydrogen fueling stations may be integrated with existing retail gasoline stations[62] (see Figure 36 for an example layout of such a station).

[62] Nexant, Inc., 2008. *Hydrogen Delivery Infrastructure Options Analysis*. DOE Award DE-FG36-05GO15032; Principal Investigator: Tan-Ping Chen. May 2008.

Figure 36: Example Layout of Hydrogen Fueling Integrated with a Retail Gasoline Station



Source: Nexant

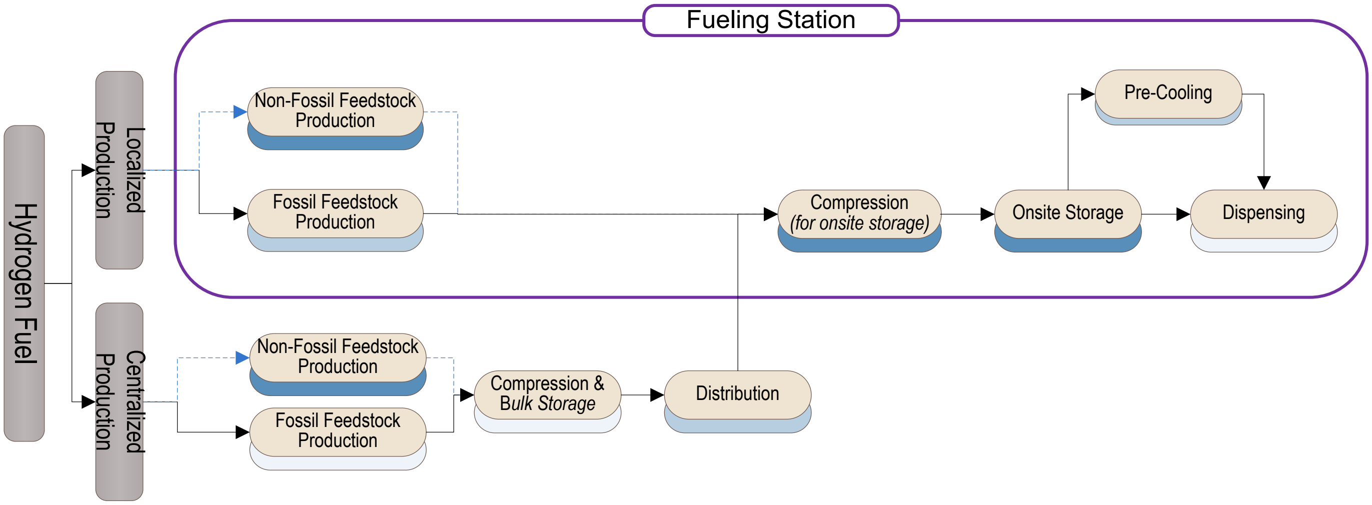
Alternatively, hydrogen stations may be standalone stations where hydrogen fuel is the primary product or they may be integrated with other businesses or facilities, such as the hydrogen station at AC Transit. Regardless of the configuration, the early market hydrogen fueling network is expected to include stations offering both 35 megapascal and 70 megapascal dispensing.

Hydrogen Fueling Infrastructure – Overview

Overview of Hydrogen Fueling Networks

There are two general approaches to provide hydrogen as a transportation fuel for highway vehicles (see Figure 37). In the centralized approach, hydrogen is produced in large central production facilities and is then distributed to individual fueling stations where it is stored and dispensed to hydrogen-fueled vehicles. Production of hydrogen as a transportation fuel under the centralized approach mirrors the current large-scale production of hydrogen for industrial applications. Centralized hydrogen production facilities might have daily production capacities in the tens of thousands of kilograms during the early commercialization phase, or they may have capacities of several hundred thousand kilograms of hydrogen per day as the market for FCEVs matures.

Figure 37: Centralized and Distributed Hydrogen Fueling Infrastructure Approaches



Source: National Petroleum Council

In the early years of commercialization, centralized production facilities generally will be located at the city-gate (within 30-60 miles of the city limits) to keep distribution costs down. Hydrogen from these centralized facilities will likely be distributed mainly by truck at first (either by gaseous tube trailers or by liquefied hydrogen trucks), with a network of hydrogen pipelines developing over time. In a highly mature market (potentially after ~2030), hydrogen production facilities may include both smaller city-gate facilities and larger regional production facilities, with hydrogen distributed mainly from a network of pipelines.

Distributed, localized, or "onsite" hydrogen production represents the second approach to providing hydrogen as a transportation fuel. Under this approach, hydrogen is produced in a distributed fashion at the fueling station itself. (Using the British term for fueling station, this is often called "forecourt" production.) Distributed production of hydrogen is likely to be based mainly on steam methane reformation of natural gas or grid-based water electrolysis, though on-site reformation of ethanol or bio-oil is also a potential pathway. As in the centralized approach, distributed hydrogen fueling stations will need hydrogen storage and dispensing facilities. Eventually, distributed hydrogen production might also include home fueling systems and neighborhood dispensing facilities, though these pathways are not expected to be cost effective in the early years of commercialization.

Distributed production facilities at hydrogen fueling stations may have capacities in the range of 100-250 kg/day in the early years of commercialization, expanding to more than 1,000 kg/day as the FCEV market matures. With smaller production capacities compared to centralized facilities, distributed production facilities will not be able to leverage larger economies of scale, and as a result they can be expected to have higher production costs on a per kg produced basis. However, distributed production stations avoid the need for hydrogen delivery and hence may be the most cost-effective option when hydrogen distribution costs are high (e.g., when stations are located far from production plants) or during the early years of commercialization when local demand does not justify larger stations.

Overview of Hydrogen Fueling Stations

As noted above, both the centralized approach and the distributed approach require the development of hydrogen refueling stations that will have several common system elements aimed at storing and dispensing hydrogen. The commercialization phase beginning in 2015 centers around FCEVs that store hydrogen as a compressed gas with a nominal fill pressure of 70 megapascal, though earlier generations of FCEVs stored hydrogen at 35 megapascal and onboard liquid hydrogen storage has some advantages. To accommodate these early FCEVs, hydrogen stations will include three basic system elements: hydrogen compression, storage, and dispensing.

Hydrogen stations must include some amount of onsite storage to meet hourly, daily, weekly and annual variations in consumer refueling schedules and the resulting demand profiles at any given location. Moreover, during the early market introduction phase, demand is expected to increase over time as greater numbers of vehicles are deployed. Hydrogen produced on-site under the distributed approach is generally stored as a compressed gas. Centrally produced hydrogen generally is delivered either via a gaseous hydrogen pipeline, as a compressed gas on gas-truck tube trailers, or as a cryogenic liquid by liquid tanker trucks. When hydrogen is delivered by truck as a liquid, it is then stored on-site as a cryogenic liquid and later vaporized to a hydrogen gas when needed. Gaseous hydrogen is generally stored in bulk at the station in steel tube cylinders at pressures of about 15—20 megapascal. A smaller amount of hydrogen is pressurized to higher levels (up to 85—90 megapascal) for dispensing to FCEVs in a cascade storage system using carbon-fiber storage cylinders.

To provide compressed hydrogen to FCEVs, hydrogen stations require compression equipment to compress stored hydrogen to pressures of about 85—90 megapascal for dispensing into 70 megapascal FCEVs. Hydrogen produced in a distributed approach on-site generally exits the production sub-system at pressures of about 2 megapascal or less. Hydrogen delivered via a network of transmission and distribution pipelines is typically at pressures of about 2—10 megapascal (though higher pipeline pressures are possible). Therefore, to achieve on-site storage pressures of 85—90 megapascal, hydrogen stations utilize compressors that operate over a wide range of inlet pressures.

In addition to hydrogen storage and compression systems, hydrogen stations require high-pressure gaseous hydrogen dispensers to handle 35 and 70 megapascal dispensing to FCEVs. To meet relevant codes and standards for the dispensing of high-pressure hydrogen, pre-cooling systems are incorporated into hydrogen dispensers to enable safe dispensing of hydrogen to FCEVs at a rate that meets customer expectations for rapid refueling (generally 5 minutes or less). A typical hydrogen dispenser is illustrated in Figure 38.

Figure 38: Hydrogen Dispenser at Newport Beach Station

Photo credit: NREL

Hydrogen fueling will be implemented under the SAE J2601 standard together with the SAE J2799 standard on wireless dispenser communications. After 12 years of work, the J2601 standard was finalized in June 2014 and will provide a safe fueling protocol allowing 70 megapascal filling of hydrogen in 3-5 minutes.[63] Worldwide hydrogen fueling infrastructure, including fueling stations in the United States, Europe, and Japan, will use the J2601 protocol.

In addition to the baseline compression, storage, and dispensing systems required at all hydrogen fueling stations, distributed production stations require additional equipment and sub-systems for the on-site production of hydrogen. In the early years of hydrogen station development, on-site production of hydrogen is likely to be accomplished through either the steam methane reforming of natural gas or the splitting of water via electrolysis. Overall, the cost of on-site steam methane reforming is expected to be less than the cost of producing hydrogen from water electrolysis, as discussed below.

Hydrogen Station Economics

Hydrogen Station Capital Cost Estimates

Current costs for hydrogen fueling stations, whether they employ distributed production or dispense centrally-produced hydrogen, are significant, with installed costs exceeding $2 million for a single station, not including land costs or convenience store costs. Table 10 shows the capital investment for a number of distributed production and central production hydrogen fueling stations that were awarded grants by the CEC and California Air Resources Board. As the dispensing capacity of stations varies, capital costs are often normalized on a dollars per

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[63] Jesse Schneider, 2014. "Hydrogen Fueling Standardization for Fuel Cell Electric Vehicles," Presentation to the U.S. DRIVE Fuel Operations Group, February 6, 2014. SAE International.

kg/day capacity basis. On this basis, the initial hydrogen station awards in California range from $8,000 to $20,000 per kg/day for compression, storage, and dispensing-only stations (centralized production approach) to as much as $40,000 per kg/day capacity for distributed production stations.

Table 10: Capital Investment for Hydrogen Stations Under Development in California

Centralized Approach Station Cost			
Funding Agency	**Location**	**Capacity (kg/day)**	**Capital Investment Without Production (2011$ millions)**
CEC	Irvine, CA	100—250	$1.96
CEC	Santa Monica, CA	100—250	$2.04
CEC	Beverley Hills, CA	100—250	$2.00
CEC	Los Angeles, CA	100—250	$2.00
CEC	Hermosa Beach, CA	100—250	$2.01
CEC	Irvine, CA	100—250	$2.03
CEC	Diamond Bar, CA	100—250	$1.99
CEC	Hawthorne, CA	100—250	$2.00
Distributed Approach Station Cost			
ARB	Newport Beach, CA	100	$4.00
ARB	Los Angeles, CA	140	$4.30

Source: National Petroleum Council

FCEVs are in an early commercial stage, and most of the hydrogen stations planned and implemented to date have been demonstration stations or early deployment stations using state-of-the-art technologies with higher overall costs than are expected as hydrogen infrastructure technology and implementation practices mature. Early cost projection estimates from the 1990s of expected future hydrogen station costs ranged from $2,000 to $3,400 per kg/day capacity for on-site natural gas steam methane reforming stations to $3,200 to $5,600 per kg/day capacity for on-site electrolysis stations, depending on station size.[64] Since those early cost projections, the U.S. DOE has developed a set of H2A ("hydrogen analysis") models, based on industry input and feedback, that provide mature-market cost estimates for

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[64] Melaina, M. W., Steward, D., Penev, M., McQueen, S., Jaffe, S., & Talon, C. (2012). *Hydrogen Infrastructure Market Readiness: Opportunities and Potential for Near-term Cost Reductions,* National Renewable Energy Laboratory, Technical Report BK-5500-55961, Golden, CO.

hydrogen production and hydrogen delivery.[65] The U.S. DOE's H2A Production models estimate costs for both centralized production facilities and distributed, on-site production and dispensing facilities. The H2A Delivery models report costs for hydrogen delivery infrastructure, including compression, storage, and dispensing-only hydrogen fueling stations (centralized production approach) and on-site production stations. Based on these models, for currently available hydrogen technologies deployed in a mature market, NREL estimates station capital costs of $5,000 to $5,500 per kg/day capacity for on-site production stations, $2,200 to $2,700 per kg/day capacity for compression, storage, and dispensing-only stations employing gaseous hydrogen storage, and $1,300 per kg/day capacity for liquefied hydrogen storage and dispensing stations.[66]

To better understand hydrogen fueling station costs as the technologies progress from state-of-the-art stations to larger stations in a mature market, NREL developed a Hydrogen Station Cost Calculation tool to elicit input from experts and industry stakeholders. This study also included a compilation of opportunities to reduce station costs as conveyed through a facilitated expert workshop held in February of 2011.[64] Quantitative input received through the Hydrogen Station Cost Calculation analysis estimates station capital costs for post-2016 stations at $3,400 to $5,200 per kg/day, depending on station size. In the nearer term, the Hydrogen Station Cost Calculation analysis estimates station capital costs in the 2014—2016 timeframe to be $6,200 per kg/day capacity. In comparison, the National Petroleum Council's transportation fuels study evaluated the station costs experienced in California and estimated that considering cost reductions expected from experience, the next group of similar delivered-hydrogen refueling stations would have capital costs of $4,000 per kg/day capacity.[56] In a follow-up study, NREL compared the Hydrogen Station Cost Calculation results to various other estimates, including those from a multi-stakeholder study conducted by the University of California at Davis and costs reported through recent ARFVTP station awards.[67] The resulting cost reduction trend, in units of dollars per kg/day capacity, is indicated in Figure 39 from the California Fuel Cell Partnership (CaFCP) 2014 Road Map.[68] This figure compares capital cost estimates from station awards to the cost reduction trends suggested by Hydrogen Station

[65] See U.S. DOE's H2A Analysis website for more details on the H2A Project and the H2A production and delivery models http://hydrogen.energy.gov/h2a_analysis.html

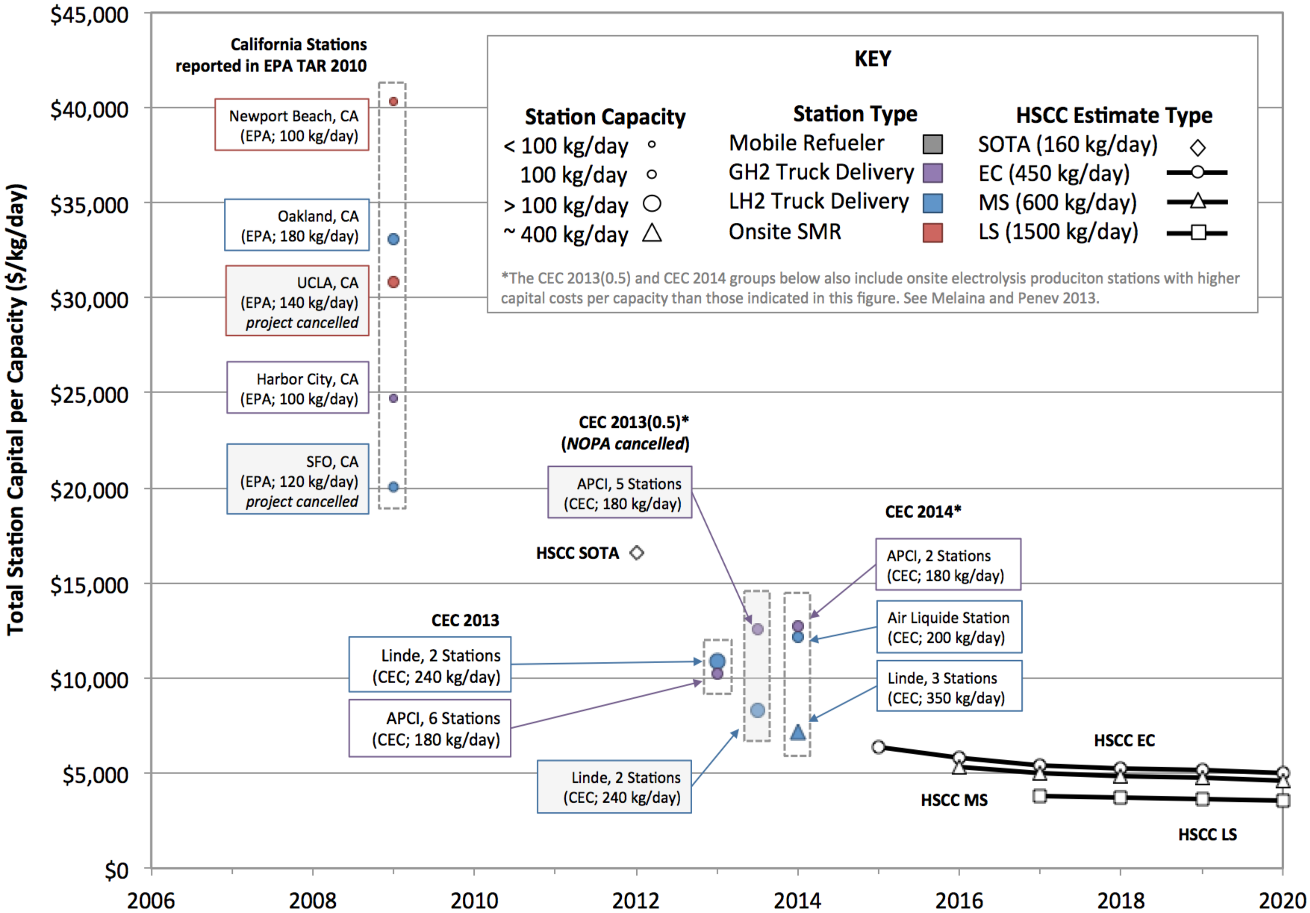
[66] Ramsden, T., Ruth, M., Diakov, V., Laffen, M., and Timbario, T., 2013. *Hydrogen Pathways: Updated Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery, and Distribution Scenarios*, National Renewable Energy Laboratory, Technical Report NREL/TP-6A10-60528 (March), Golden, CO.

[67] Melaina, M. and Penev, M., 2013. *Hydrogen Station Cost Estimates: Comparing Hydrogen Station Cost Calculator Results with Other Recent Estimates*, National Renewable Energy Laboratory, Technical Report NREL/TP-5400-56412, Golden, CO.

[68] CaFCP (2014). A California Road Map: The Commercialization of Hydrogen Fuel Cell Vehicles (pp. 1–31). California Fuel Cell Partnership.
https://cafcp.org/sites/default/files/A%20California%20Road%20Map%20June%202012%20(CaFCP%20technical%20version).pdf

Cost Calculation results for four station types: state-of-the-art, early commercial, more stations, and larger stations.

Figure 39: Trends in Total Station Capital per Capacity



Source: CaFCP

These analyses and station cost trends suggest that nearer-term (2014—2016) stations may have capital costs in the $4,000 to $6,000 per kg/day range (exclusive of land costs). For a station with a capacity of 450 kg/day, this equates to $1.8 million to $2.7 million per station. In the longer term, larger and more mature delivered hydrogen station costs may fall within the range of $2,000 to $3,000 per kg/day capacity (2020 or later in Figure 6-8). For a larger 1,000 kg/day station, this would yield a station capital cost in the range of $2 million to $3 million. Stations based on delivered liquid hydrogen may be less expensive, potentially on the order of $1,500 per kg/day, or a total station cost of $1.5 million for a 1,000 kg/day station.

Hydrogen Fuel Costs

Currently, both FCEVs and hydrogen fueling infrastructure are deployed in an early commercial state. As such, hydrogen fuel for transportation vehicles is not yet offered for retail sale in the United States. As with the capital investment cost evaluations for hydrogen fueling infrastructure, modeling and analyses have been conducted to estimate the cost of the hydrogen fuel itself, both in the near term during the early years of FCEV commercialization and in the longer term during a mature market phase.

Hydrogen fuel costs are generally expressed on a per kilogram basis. A kilogram of hydrogen has roughly the same energy content as a gallon of gasoline, or alternatively a kilogram of hydrogen is about one gge. Fuel cell vehicles are expected to be about twice as fuel efficient as conventional gasoline-powered internal combustion engine vehicles, so hydrogen prices on a gge or per kg basis can be about twice that of gasoline prices and still maintain roughly the same fueling costs to consumers on a per-mile-driven basis.

Overall, hydrogen fuel costs are expected to be high during the early commercialization period beginning in 2015. During this period, small stations are expected to be built to reduce capital investment while providing increased geographic availability for early adopters. During the early transition, station capacity is not expected to be fully utilized as the number of local FCEVs increases over time. Dispensed hydrogen costs are expected to fall fairly quickly as the market for FCEVs matures, due to increased station utilization, economies of scale, and cost reductions through industry learning and experience.[64]

Several other studies have estimated near-term hydrogen costs in terms of the dollars per kg required to cover the cost of fully utilized early-market stations. From 2005 to 2011, the U.S. DOE conducted its FCEV Learning Demonstration to demonstrate and validate FCEV and hydrogen infrastructure technologies.[69] Based on the capital and operating costs of the stations they operated during the demonstration, energy company partners projected the costs of developing and operating larger, 1,500 kg/day stations at high utilization rates. The results of this analysis indicate that the cost of hydrogen using currently available technologies is expected to be in the range of $8—$10/kg from on-site natural gas steam methane reforming stations and $10—$13/kg from on-site electrolysis stations.[70] Similarly, the NPC Future Transportation Fuels study group estimated the cost of dispensed hydrogen in the near term based on the capital and operating costs of early deployment stations in California. Based on a Monte Carlo simulation of potential capital and operating costs, NPC estimates that the total hydrogen cost (excluding fuel taxes) is $8—$11/kg for delivered hydrogen stations (centralized approach) and $14—$24/kg for on-site production stations (distributed approach).[56] A 2011 study of alternative vehicle powertrains in Europe predicted similar hydrogen costs, citing a dispensed hydrogen cost of about $13/kg in 2015 (9.90 Euro/kg).[71] A 2013 study by the National Academies of Sciences estimated early market hydrogen costs at $10/kg (NAS 2013).[55]

Some of these same studies have projected the cost reductions anticipated as hydrogen markets mature, with costs declining due in part to anticipated technology improvements but also to larger station capacities and higher capacity utilization. In addition to the Hydrogen Station Cost Calculation trends discussed above, which are based upon stakeholder estimates rather than techno-economic cost estimates, the U.S. DOE's H2A modeling of currently

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[69] For more information on the Learning Demonstration, see NREL's technology validation analyses. https://www.nrel.gov/hydrogen/hydrogen-infrastructure-analysis.html

[70] Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Ainscough, C., and Saur, G., 2012. *National Fuel Cell Electric Vehicle Learning Demonstration Final Report*, National Renewable Energy Laboratory, Technical Report NREL/TP-5600-54860 (July), Golden, CO.

[71] McKinsey & Company, 2010. *A Portfolio of Powertrains for Europe: A Fact-Based Analysis*. http://www.h2euro.org/publications/featured-publications/a-portfolio-of-power-trains-for-europe-a-fact-based-analysis.

available hydrogen technologies deployed in a mature market indicates that the dispensed cost of hydrogen may fall to $5—$6/kg (untaxed) for hydrogen produced using natural gas reformation under the centralized production approach.[66] Based on its Monte Carlo analysis of future hydrogen station economics considering technology advancements and scale improvements, the NPC estimates untaxed, dispensed hydrogen costs in the range of $5—$6/kg under the centralized approach and $6—$8/kg under the distributed approach.[56] As part of its Transportation Energy Futures study, the U.S. DOE estimates a hydrogen cost of about $5/kg in the 2020—2025 timeframe.[72] The National Academies of Science predicts mature-market hydrogen costs in the range of $3.60—$5.50/kg in the 2020—2025 timeframe.[55]

Other Hydrogen Station Considerations

Fuel cells require highly pure hydrogen for operation and especially for fuel cell stack durability. It is expected that the purity of hydrogen dispensed to a FCEV will need to be very high, on the order of 99.97 percent pure or greater.[61]

In addition to cost-effective station designs and operation allowing for cost-competitive fuel, hydrogen safety is extremely important to consumer acceptance of hydrogen as a transportation fuel. Organizations such as the National Fire Protection Association have developed a variety of hydrogen standards to ensure safety, including flammability in air and ignition energy thresholds.[61] National Fire Protection Association also sets standards for setback distances for a variety of hydrogen infrastructure equipment. These setback distances will affect the overall footprint of a hydrogen fueling station. Station footprints affect both station economics, in terms of the cost of land needed for the station, and station placement, as not all potential sites will have adequate space to contain the hydrogen footprint.

Hydrogen Stations and Infrastructure Suppliers

Current Hydrogen Station Infrastructure

Commercial light-duty FCEVs are just being introduced in significant numbers, though there have been several pre-market demonstrations and limited deployments over the past 5-10 years.[73] The U.S. DOE FCEV Learning Demonstration deployed more than 180 FCEVs as part of its technology validation efforts, and more than 400 FCEVs have been deployed in addition to these U.S. DOE technology validation vehicles.[56] In addition to these light-duty FCEV deployments, more than 40 fuel cell transit buses have been deployed in the United States, including 16 in California, with more than three dozen still in operation.[74] A small number of hydrogen fueling stations have been deployed to support these pre-market FCEVs and fuel cell buses. Twenty-five hydrogen stations were deployed as part of the U.S. DOE FCEV Learning Demonstration, though most of those early stations have been retired.

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[72] Melaina, M.W.; Heath, G.; Sandor, D.; Steward, D.; Vimmerstedt, L.; Warner, E.; Webster, K.W., 2013. *Alternative Fuel Infrastructure Expansion: Costs, Resources, Production Capacity, and Retail Availability for Low-Carbon Scenarios*. Transportation Energy Futures Series. Prepared for the U.S. Department of Energy by National Renewable Energy Laboratory, Golden, CO. DOE/GO-102013-3710 (April).

[73] Oak Ridge National Laboratory, Status and Prospects of the Global Automotive Fuel Cell Industry and Plans for Deployment of Fuel Cell Vehicles and Hydrogen Refueling Industry
https://www.energy.gov/sites/prod/files/2014/03/f9/fcev_status_prospects_july2013.pdf

[74] Eudy, L., and Gikakis, C., 2013. *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2013*, National Renewable Energy Laboratory, Technical Report NREL/TP-5400-60490 (December), Golden, CO.

According to the Alternative Fuels Data Center, there are currently 55 public and private hydrogen fueling stations operating in the United States, 23 of which are in California.[9] Only 10 of all U.S. hydrogen fueling stations offer public fueling, and nine of them are in California (see Figure 39).

Planned Hydrogen Station Infrastructure

Additional hydrogen stations are expected to be deployed to support the commercialization of FCEVs beginning in 2015, especially through the recent CEC awards for 28 new stations supported with $46.6 million in state funds, bringing the total existing and funded stations in California to 54 stations.[75] To ensure adequate hydrogen fueling infrastructure is in place for their customers, auto manufacturers will focus early sales of FCEVs in the key urban markets and geographies targeted through the CEC awards. This will allow adequate hydrogen infrastructure to be deployed to meet the fueling needs of those new FCEVs. Conversely, by concentrating FCEV sales in particular markets, operators of hydrogen fueling stations will have access to a larger local vehicle market. Thus, the likelihood is that hydrogen infrastructure will be deployed in only a few urban markets, and then phased into a wider set of strategic urban areas before it is expanded into a nationwide network.

As reflected in the CaFCP's 2014 California Road Map report, California is planning a launch of 68 hydrogen refueling stations to facilitate FCEV commercialization in 2015 (Dunwoody 2013).[76] These stations will provide station coverage to enable the market launch of FCEVs in California and will support convenient customer fueling in early markets. State support for a broader network of at least 100 stations has been secured through the reauthorization of ARFVTP by Assembly Bill 8, and the allocation of up to $20 million per year for hydrogen stations.[77]

Hydrogen Infrastructure Suppliers

As noted previously, the infrastructure for hydrogen as a transportation fuel is not yet in place and the market overall is in its infancy. A number of industry segments may be part of the supplier network for this infrastructure, based on their involvement in similar transportation fuel businesses or with hydrogen as an industrial gas.

Key companies involved with hydrogen infrastructure include the following:

- **Oil companies**: ExxonMobil, Chevron, Shell, BP
- **Industrial gas companies**: Air Products, Linde, Air Liquide, Praxair
- **Compressor manufacturers**: Mohawk Innovative Technology, Inc., Linde, Haskel International, Pressure Products Industries, PDC Machines
- **Storage system suppliers**: Hexagon Lincoln, Linde, Powertech Labs, CP Industries

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[75] Fuel News Market, 2014. *California Investing Nearly $50 million in Hydrogen Refueling Stations*, 2014, https://fuelsmarketnews.com/california-investing-nearly-50-million-hydrogen-refueling-stations/

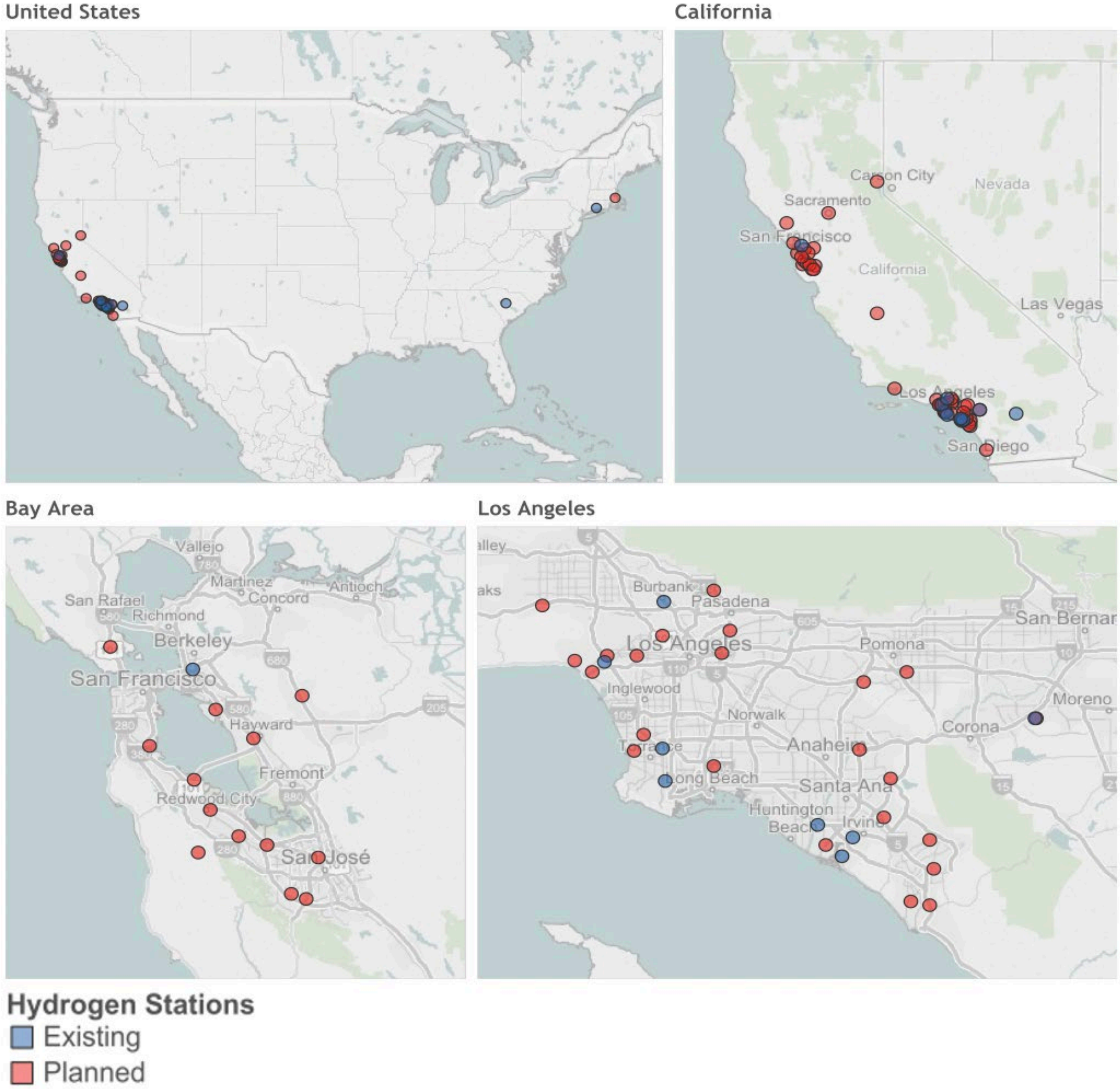
[76] Dunwoody, C., 2013. "Fuel Cell Electric Vehicles and Hydrogen Fuel for California", California Energy Commission IEPR Workshop on Transportation Energy Scenarios, California Fuel Cell Partnership presenation, July 31, 2013.

[77] GCC, 2013. *California legislature passes $2-billion bill extending clean vehicle and fuel incentives through 2023,* Green Car Congress, September 12, http://www.greencarcongress.com/2013/09/20130912-ab8.html

- **Production system suppliers**: Teledyne Energy Systems, Proton, FuelCell Energy, Nuvera

Hydrogen suppliers are expected to include major oil companies that currently provide gasoline fuel to retail stations, many of which are operating or have operated hydrogen stations at the demonstration level. Key players also include industrial gas companies that have been supplying hydrogen for industrial applications and are expected to help supply hydrogen as a transportation fuel. In addition to these industry segments, the hydrogen supply network includes suppliers of hydrogen storage systems, hydrogen dispensers, compressors, and hydrogen production systems.

Figure 40: Existing and Planned Hydrogen Refueling Stations



Source: NREL

CHAPTER 7: Policies and Incentives Impacting Advanced Vehicle Infrastructure

Background

The degree of alternative fuel vehicle adoption is linked to the installation of alternative refueling infrastructure. Infrastructure may be more or less challenging to develop, depending on the fuel type; the cost to install an alternative fuel station can vary from $400 to $5,500 for electric home charging stations to $2-$3 million for a hydrogen refueling station.[78]

Aside from cost challenges, infrastructure can be challenging to deploy given the "chicken or egg" problem, where infrastructure development depends on the number of vehicles deployed, and the number of vehicles deployed depends on the level of infrastructure development. Alternative fuel vehicle deployment is also complicated by the fact that vehicle manufacturers may not want to develop vehicles that consumers are not interested in buying. These issues have been discussed at greater[79] length elsewhere.[80]

In order to address the "chicken or egg" problem, governments have provided incentives for AFV infrastructure – typically through tax credits, grants, or rebates. Yeh outlines a policy matrix for promoting natural gas vehicles in eight countries; one component of promoting NGVs is creating a market on the supplier side, which includes investments in refueling stations and pipeline infrastructure.[81]

The CEC places significant emphasis on AFV infrastructure development. The proportion of infrastructure funding in the ARFVTP investment plan has increased between the 2012—2013 investment plan update[82] and the 2014—2015 proposed plan. In the 2012—2013 fiscal year, infrastructure (electric charging, hydrogen fueling, E85 fueling, and natural gas fueling) funding totaled $21.5 million, or 21.5 percent of the total funding budget. In 2013—2014, infrastructure funding totaled $28.5 million (28.5 percent), and in the proposed 2014—2015

[78] Dougherty, S; Nigro, N. (2013). "Alternative Fuel Vehicle and Fueling Infrastructure Deployment Barriers and the Potential Role of Private Sector Financial Institutions;" U.S. DOE, ADFC. December 20, 2013. https://afdc.energy.gov/files/u/publication/afv_fueling_infrastructure_deployment_barriers.pdf

[79] Melaina, M. and Bremson, J. (2008). "Refueling availability for alternative fuel vehicle markets: Sufficient urban station coverage." Energy Policy, 36, pp. 3233-3241.

[80] Sperling, D. (1988). New Transportation Fuels: A Strategic Approach to Technological Change. Berkeley, CA: University of California Press.

[81] Yeh, S. (2007). "An Empirical analysis on the adoption of alternative fuel vehicles: The case of natural gas vehicles." Energy Policy 35, pp. 5865-5875.

[82] CEC, 2012-2013 Investment Plan Update https://ww2.energy.ca.gov/publications/displayOneReport_cms.php?pubNum=CEC-600-2012-001-LCF

investment plan, infrastructure totals $36.5 million (36.5 percent).[83] The overall increases have been driven primarily by increases in electric charging infrastructure ($7 million in 2013—2014 and $15 million in 2014—2015) as well as hydrogen refueling infrastructure ($9.9 million in 2012—2013 and $20 million in 2013—2014).

In California, public incentives are available at the local, state, and federal level for advanced technology infrastructure. Common incentive types for infrastructure include tax credits and grants or rebates. For example, the CEC is providing $6 million in funds to employers and property owners in California for four categories of EV charging.[84] The types include destination charging, corridor charging, workplace charging, and multi-unit dwelling charging.

The types and ranges of incentives for AFV refueling infrastructure at the federal, state and local/utility level are presented in Table 11. The incentives captured here are in addition to the ARFVT Program and are sourced from the Alternative Fuels Data Center laws and incentives database (www.afdc.energy.gov) and/or through the program links provided below.

Table 11: Summary of Federal, State, and Local Incentives for Refueling Infrastructure

Type	Program Name	Funding Amount	Technology	Program Link
		Federal		
Tax Credit	Alternative Fuel Infrastructure Tax Credit (expired 12/2013)	30% of the cost of fueling equipment, not to exceed $30,000. Consumers may receive up to $1,000.	Fueling equipment for natural gas, propane, electricity, E85, or diesel fuel blends (minimum 20% blend)	Alternative Fuel Vehicle Refueling Property Credit http://www.irs.gov/pub/irs-pdf/f8911.pdf
Grant	The EV Project (expired in March 2013) ($155 million U.S. DOE funding from American Recovery and Reinvestment Act, matched by $115 in private investment)	Free Blink wall mount charger, and in select locations, up to a $400 credit toward installation in exchange for allowing the collection of vehicle and charge information.	EV charger and installation	The EV Project https://www.energy.gov/eere/vehicles/avta-ev-project

[83] CEC, 2014-2015 Proposed Investment Plan https://ww2.energy.ca.gov/publications/displayOneReport_cms.php?pubNum=CEC-600-2013-003-SD

[84] CEC, Grant Solicitation Electric Vehicle Charging Station, PON-13-606 https://www.ourair.org/wp-content/uploads/05-14-energy-comm-grant-att.pdf

Type	Program Name	Funding Amount	Technology	Program Link
Tax Credit	Hydrogen Fuel Infrastructure Tax Credit (expires 12/2014)	30% of the cost of fueling equipment, not to exceed $30,000. Consumers may receive up to $1,000.	Hydrogen fueling equipment	Alternative Fuel Vehicle Refueling Property Credit http://www.irs.gov/pub/irs-pdf/f8911.pdf
Grants and Loan Guarantees	Ethanol Infrastructure Grants and Loan Guarantees (through the Rural Energy for America Program)	Max. loan guarantee is $25 million and the max. grant funding is 25% of project costs.	Flexible fuel pumps, or blender pumps, that dispense intermediate ethanol blends	Ethanol Infrastructure Grants and Loan Guarantees https://afdc.energy.gov/laws/9172
Infrastructure Incentives	Airport Zero Emission Vehicle and Infrastructure Incentives	50% of the cost of ZEVs used exclusively for airport purposes; funding to install infrastructure to support ZEVs.	ZEVs and associated infrastructure	Airport Zero Emissions Vehicle and Infrastructure Pilot Program http://www.faa.gov/airports/environmental/zero_emissions_vehicles/
		State (California)		
Grant	Motor Vehicle Registration Fee Program	Funding for projects that reduce air pollution from on- and off-road vehicles	Unspecified	Motor Vehicle Registration Fee Program http://www.arb.ca.gov/planning/tsaq/mvrfp/mvrfp.htm
Grant	Carl Moyer Memorial Air Quality Standards Attainment Program	Incentives to cover the incremental cost of purchasing engines and equipment that are cleaner than required by law	Heavy-duty fleet modernization, light duty vehicle replacements and retrofits, idle reduction technology, and off-road vehicle and equipment purchases.	Carl Moyer Memorial Air Quality Standards Attainment Program http://www.arb.ca.gov/msprog/moyer/moyer.htm

Type	Program Name	Funding Amount	Technology	Program Link
Grant	Goods Movement Emission Reduction Program	Funding for projects that reduce emissions from freight movement, including heavy-duty truck replacement, repower, or retrofit; and truck stop electrification infrastructure development	Heavy-duty trucks, truck stop electrification	Goods Movement Emissions Reduction Program https://ww2.arb.ca.gov/our-work/programs/proposition-1b-goods-movement-emission-reduction-program
		Local/Utility		
Program (San Francisco, San Jose, and Oakland)	Plug-In Vehicle Charging Infrastructure Promotion (coordinated through the Bay Area EV Corridor Project and the Association of Bay Area Governments)	Incentives for employers and other organizations to install charging infrastructure	PEV infrastructure	Plug-in Vehicle Charging Infrastructure https://steps.ucdavis.edu/wp-content/uploads/2016/10/09-11-2015-Compendium-Narrative-updated-4.15.15.pdf
Rebate (Los Angeles Department of Water and Power)	Electric Vehicle Supply Equipment Rebate	Rebates to commercial and residential customers for purchase of Level 2 or DC fast charger. Residential rebates of $750; commercial rebates of $750, $1,000, or $15,000 depending on charger type	EV charging	Electric Vehicle Supply Equipment Rebate https://www.ladwp.com/ladwp/faces/ladwp/residential/r-savemoney/r-sm-rebatesandprograms?_adf.ctrl-state=szo9b97yh_4&_afrLoop=72806636401552

Type	Program Name	Funding Amount	Technology	Program Link
Rebate (Glendale Water and Power)	Vehicle Home Charge Rebate	$200 rebate for the first 100 single family residential EV owners to install a level 2 240 V charging station with Safety Socket Meter Panel	EV charging	Glendale Water and Power Rebate https://www.glendaleca.gov/home/showdocument?id=48487

Source: Alternative Fuels Data Center

Two federal programs to incentivize AFV infrastructure have recently expired. The Alternative Fuel Infrastructure Tax Credit provided 30 percent of the cost of fueling equipment, not to exceed $30,000, for businesses, or up to $1,000 to individuals; this credit expired at the end of 2013. The EV Project, a program funded by American Recovery and Reinvestment Act, expired in March 2013. The program provided a free wall mount EV charger and, in select locations, up to a $400 credit toward installation. In exchange, participants allowed for collection of vehicle and charge data. Data on charging station location and availability are provided through the Blink network, which includes more than 4,000 public chargers nationwide, with more than 800 located in California.

At the federal level, the Hydrogen Fuel Infrastructure Tax Credit, which provides the same benefits as the Alternative Fuel Infrastructure Tax Credit, is set to expire at the end of 2014.

The federal transition away from providing infrastructure credits or grants may be replaced by local or utility incentives, particularly for EVs. Currently at least two utilities in California offer EV charging rebates. Efforts are also underway in the Bay Area, through the Bay Area Air Quality Management District, to develop incentive programs for EV deployment, including incentives for infrastructure.[85]

Role of Partnerships and Collaboration

Infrastructure development can be coordinated with collaboration between government and the private sector. These types of partnerships are occurring at the federal level and in California. At the federal level, the U.S. DOE launched H_2USA, a public-private partnership between hydrogen fuel suppliers, automakers, government agencies, and clean technology groups. H_2USA is also working with the California Fuel Cell Partnership and a number of other associations. The U.S. DOE also sponsors the National Clean Fleets Partnership, which builds on the Clean Cities program.[86]

At the state level, the California Fuel Cell Partnership relied upon research and computer modeling tools to recommend that hydrogen refueling stations be built in five geographic

[85] Bay Area Air Quality Management District Funding and Incentives https://www.baaqmd.gov/funding-and-incentives

[86] U.S. DOE Clean Cities Coalition Network, Partnerships and Projects https://cleancities.energy.gov/partnerships/

clusters. The clusters were focused in areas where the first customers are likely to live. The following cluster communities were identified were Berkeley, South San Francisco Bay Area, Santa Monica and West Los Angeles, Torrance and nearby coastal communities, and Irvine and southern Orange County. The Partnership's work determined that fuel cell stations must be installed before consumers purchase vehicles, and that customers prefer stations to be located near their home, work, and in weekend destinations, with a 6-minute maximum travel time.[87]

On the EV side, partnerships between private and public entities are helping to coordinate infrastructure development at the regional level. *Ready, Set Charge! California* works with the EV Communities Alliance, Clean Fuel Connection, Inc., Association of Bay Area Governments, and Bay Area Climate Cooperative to, among other things, provide infrastructure guidance to government planners and coordinate Bay Area infrastructure. The Southern California Air Quality Management District and Bay Area Air Quality Management District are also working together under the CALSTART program to share infrastructure ideas between northern and southern California.

Future Outlook for Infrastructure Incentives

A number of key questions exist for the future of infrastructure incentives. Namely, how many AFV refueling stations are needed in order to facilitate growth in AFV markets? The number of AFV refueling stations will depend on a number of factors, including technology type, vehicle range, and station locations. Stations located in dense urban areas may be more profitable and provide greater access than stations in rural areas. However, as noted by the CEC, "corridor charging," which may be located near a highway but in an otherwise rural area, is beneficial to EV drivers traveling long distances.

In addition to determining the optimal number or location of refueling stations, there are questions about what entity should be funding the stations as well as the appropriate mix of public and private stations. For electric and natural gas refueling, it may in some cases be appropriate for the incumbent electric or gas utility to be more engaged in providing infrastructure. For hydrogen and biofuels, it may be appropriate to have different levels of engagement by multiple partners, including station owners, fuel suppliers, automakers, fleet operators and state agencies.

[87] California Fuel Cell Partnership California Road Map
https://cafcp.org/sites/default/files/20120814_Roadmapv%28Overview%29.pdf

GLOSSARY

ALTERNATING CURRENT (AC)—Flow of electricity that constantly changes direction between positive and negative sides. Almost all power produced by electric utilities in the United States moves in current that shifts direction at a rate of 60 times per second.

AUTHORITY HAVING JURISDICTION (AHJ)—An organization, office, or individual responsible for enforcing the requirements of a code or standard, or for approving equipment, materials, an installation, or a procedure.

BATTERY ELECTRIC VEHICLE (BEV)—Also known as an "All-electric" vehicle (AEV), BEVs utilize energy that is stored in rechargeable battery packs. BEVs sustain their power through the batteries and therefore must be plugged into an external electricity source in order to recharge.

CALIFORNIA AIR RESOURCES BOARD (ARB or CARB)— The state's lead air quality agency consisting of an 11-member board appointed by the Governor, and just over thousand employees. ARB is responsible for attainment and maintenance of the state and federal air quality standards, California climate change programs, and is fully responsible for motor vehicle pollution control. It oversees county and regional air pollution management programs.

CALIFORNIA ENERGY COMMISSION (CEC)—The state agency established by the Warren-Alquist State Energy Resources Conservation and Development Act in 1974 (Public Resources Code, Sections 25000 et seq.) responsible for energy policy. The CEC's five major areas of responsibilities are:

1. Forecasting future statewide energy needs.
2. Licensing power plants sufficient to meet those needs.
3. Promoting energy conservation and efficiency measures.
4. Developing renewable and alternative energy resources, including providing assistance to develop clean transportation fuels.
5. Planning for and directing state response to energy emergencies.

Funding for the CEC's activities comes from the Energy Resources Program Account, Federal Petroleum Violation Escrow Account, and other sources.

CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY (Cal/EPA)—A state government agency established in 1991 for unifying environmental activities related to public health protection in the State of California. There are five boards, departments, and offices under the organization of Cal/EPA including the California Air Resources Board (ARB), State Water Resources Control Board (SWRCB) and its nine Regional Water Quality Control Boards (RWQCB), Department of Pesticide Regulation (DPR), Department of Toxic Substances Control (DTSC) and Office of Environmental Health Hazard Assessment (OEHHA). The Cal/EPA boards, departments, and offices are directly responsible for implementing California environmental laws, or play a cooperative role with other regulatory agencies at regional, local, state, and federal levels.19

COMPRESSED NATURAL GAS (CNG)—Natural gas that has been compressed under high pressure, typically between 2,000 and 3,600 pounds per square inch, held in a container. The gas expands when released for use as a fuel.

DIRECT CURRENT (DC)—A charge of electricity that flows in one direction and is the type of power that comes from a battery.

E85—E85 motor fuel is defined as an alternative fuel that is a blend of ethanol and hydrocarbon, of which the ethanol portion is 75-85 percent denatured fuel ethanol by volume and complies with the most current American Society of Testing and Measurements specification D5798.[35]

ELECTRIC VEHICLE (EV)—A broad category that includes all vehicles that are fully powered by electricity or an electric motor.

ELECTRIC VEHICLE MILES TRAVELED (eVMT) - Refers to miles driven using electric power over a given period of time. The more general term, VMT, is a measure of overall miles driven over a period of time.45

ELECTRIC VEHICLE SUPPLY EQUIPMENT (EVSE)—Infrastructure designed to supply power to EVs. EVSE can charge a wide variety of EVs, including BEVs and PHEVs.

FLEX-FUEL VEHICLE (FFV)—FFVs are designed to run on gasoline or gasoline-ethanol blends of up to 85 percent ethanol (E85). Except for a few engine and fuel system modifications, they are identical to gasoline-only models. FFVs experience no loss in performance when operating on E85, and some generate more torque and horsepower than when operating on gasoline. However, since ethanol contains less energy per volume than gasoline, FFVs typically get about 15—27 percent fewer miles per gallon when fueled with E85.[49]

FUEL CELL ELECTRIC VEHICLE (FCEV)—A zero-emission vehicle that runs on compressed hydrogen fed into a fuel cell "stack" that produces electricity to power the vehicle.

GASOLINE GALLON EQUIVALENT (GGE)—The amount of alternative fuel it takes to equal the energy content of one liquid gallon of gasoline. GGE allows consumers to compare the energy content of competing fuels against a commonly known fuel—gasoline. GGE also compares gasoline to fuels sold as a gas (natural gas, propane, and hydrogen) and electricity.

GREENHOUSE GAS (GHG)—Any gas that absorbs infrared radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO2), methane (CH4), nitrous oxide (NOx), halogenated fluorocarbons (HCFCs), ozone (O3), per fluorinated carbons (PFCs), and hydrofluorocarbons (HFCs).

GREENHOUSE GASES, REGULATED EMISSIONS, AND ENERGY USE IN TRANSPORTATION (GREET®)—A full lifecycle model sponsored by the Argonne National Laboratory (U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy). GREET® fully evaluates energy and emission impacts of advanced and new transportation fuels, the fuel cycle from well to wheel, and the vehicle cycle through material recovery and vehicle disposal. It allows researchers and analysts to evaluate various vehicle and fuel combinations on a full fuel-cycle/vehicle-cycle basis.

GROSS VEHICLE WEIGHT (GVW)—The maximum operating weight/mass of a vehicle as specified by the manufacturer including the vehicle's chassis, body, engine, engine fluids, fuel, accessories, driver, passengers, and cargo, but excluding that of any trailers.

KILOGRAM (kg)—The base unit of mass in the International System of Units that is equal to the mass of a prototype agreed upon by international convention and that is nearly equal to the mass of 1,000 cubic centimeters of water at the temperature of its maximum density.

LIQUEFIED NATURAL GAS (LNG)—Natural gas that has been condensed to a liquid, typically by cryogenically cooling the gas to minus 260 degrees Fahrenheit (below zero).

LOW CARBON FUEL STANDARD (LCFS)—A set of standards designed to encourage the use of cleaner low-carbon fuels in California, encourage the production of those fuels, and therefore reduce greenhouse gas emissions. The LCFS standards are expressed in terms of the carbon intensity of gasoline and diesel fuel and their respective substitutes. The LCFS is a key part of a comprehensive set of programs in California that aim cut greenhouse gas emissions and other smog-forming and toxic air pollutants by improving vehicle technology, reducing fuel consumption, and increasing transportation mobility options.

NATURAL GAS VEHICLE (NGV)—An alternative fuel vehicle that uses compressed natural gas (CNG) or liquefied natural gas (LNG).

NATIONAL RENEWABLE ENERGY LABORATORY (NREL)—The United States' primary laboratory for renewable energy and energy efficiency research and development. NREL is the only Federal laboratory dedicated to the research, development, commercialization, and deployment of renewable energy and energy efficiency technologies. Located in Golden, Colorado.[20]

PLUG-IN ELECTRIC VEHICLE (PEV)—A general term for any car that runs at least partially on battery power and is recharged from the electricity grid. There are two different types of PEVs to choose from—pure battery electric and plug-in hybrid vehicles.

POUNDS PER SQUARE INCH (PSI)—A unit of pressure or stress based on avoirdupois units. It is the pressure resulting from a force of one pound-force applied to an area of one square inch.

RENEWABLE NATURAL GAS (RNG)—Or biomethane, is a pipeline-quality gas that is fully interchangeable with conventional gas and thus can be used in natural gas vehicles. RNG is essentially biogas (the gaseous product of the decomposition of organic matter) that has been processed to purity standards. Like conventional natural gas, RNG can be used as a transportation fuel in the form of compressed natural gas (CNG) or liquefied natural gas (LNG).100

SOCIETY OF AUTOMOTIVE ENGINEERS (SAE)—A global association of more than 128,000 engineers and related technical experts in the aerospace, automotive, and commercial-vehicle industries. The leader in connecting and educating mobility professionals to enable safe, clean, and accessible mobility solutions.[112]

UNITED STATES DEPARTMENT OF ENERGY (U.S. DOE)—The federal department established by the Department of Energy Organization Act to consolidate the major federal energy functions into one cabinet-level department that would formulate a comprehensive, balanced national energy policy. DOE's main headquarters are in Washington, D.C.

UNITED STATES ENERGY INFORMATION ADMINISTRATION (U.S. EIA)—An independent agency within the U.S. Department of Energy that develops surveys, collects energy data, and does analytical and modeling analyses of energy issues. The Agency must satisfy the requests of Congress, other elements within the Department of Energy, Federal Energy Regulatory Commission, the Executive Branch, its own independent needs, and assist the general public, or other interest groups, without taking a policy position.

ZERO EMISSION VEHICLE (ZEV)—Vehicles that produce no emissions from the on-board source of power (e.g., an electric vehicle).

APPENDIX A:
E85 Tank and Equipment Compatibility

Table A-1 through A-3 illustrate E85 tank compatibility[88] and equipment compatibility[89] with various ethanol blends.

Table A-1: Fiberglass Tank Manufacturer Compatibility with Ethanol Blends

Manufacturer	Compatibility Statement with Ethanol Blends
Containment Solutions	Tanks manufactured after January 1, 1995, are all compatible with ethanol blends up to 100% (E100) (UL Listed)
Owens Corning Single Wall Tanks	Tanks manufactured between 1965 and 1994 are approved to store up to 10% ethanol (E10)
Owens Corning Double Wall Tanks	Tanks manufactured between 1965 and July 1, 1990, are approved to store up to 10% ethanol (E10)
	Tanks manufactured between July 2, 1990, and December 31, 1994, are warranted to store any ethanol blend
Xerxes Single Wall Tanks	Tanks manufactured prior to 1981 are not compatible with ethanol blends
	Tanks manufactured from February 1981 through June 2005 are designed for the storage of ethanol fuel up to a 10% blend (E10)
	Tanks manufactured from July 2005 to date are designed for the storage of ethanol fuel blends up to 100% (E100) (UL Listed)
Xerxes Double Wall Tanks	Tanks manufactured prior to April 1990 are designed for the storage of ethanol fuel up to a 10% blend (E10)
	Tanks manufactured from April 1990 to date are designed for the storage of ethanol fuel blends up to 100% (E100) (UL Listed)

Sources: PEI and Steel Tank Institute

88 PEI, UST Component Compatibility Library https://www.pei.org/ust-component-compatibility-library

89 Steel Tank Institute, Compatibility of Underground Storage Tanks Storing Gasoline with Ethanol https://www.steeltank.com/Portals/0/Shop%20Fab/SteelAndAlternativeFuels/CA_Water_Boards_ethanol_tank_compatibility_letter.pdf

Table A-2: Steel Tank Manufacturer Compatibility with Ethanol Blends

Manufacturer	Compatibility Statement with Ethanol Blends
Acterra Group Inc.	Compatible with all blends up to 100% (E100)
Caribbean Tank Technologies Inc.	Compatible with all blends up to 100% (E100)
Eaton Sales & Service LLC	Compatible with all blends up to 100% (E100)
General Industries	Compatible with all blends up to 100% (E100)
Greer Steel, Inc.	Compatible with all blends up to 100% (E100)
Hall Tank Co.	Compatible with all blends up to 100% (E100)
Hamilton Tanks	Compatible with all blends up to 100% (E100)
Highland Tank	Compatible with all blends up to 100% (E100)
J.L. Houston Co.	Compatible with all blends up to 100% (E100)
Kennedy Tank and Manufacturing Co., Inc.	Compatible with all blends up to 100% (E100)
Lancaster Tanks and Steel Products	Compatible with all blends up to 100% (E100)
Lannon Tank Corporation	Compatible with all blends up to 100% (E100)
Mass Tank Sales Corp.	Compatible with all blends up to 100% (E100)
Metal Products Company	Compatible with all blends up to 100% (E100)
Mid-South Steel Products, Inc	Compatible with all blends up to 100% (E100)
Modern Welding Company	Compatible with all blends up to 100% (E100)
Newberry Tanks & Equipment, LLC	Compatible with all blends up to 100% (E100)
Plasteel[1]	Compatible with all blends up to 100% (E100)
Service Welding & Machine Company	Compatible with all blends up to 100% (E100)
Southern Tank & Manufacturing Co., Inc.	Compatible with all blends up to 100% (E100)
Stanwade Metal Products	Compatible with all blends up to 100% (E100)
Talleres Industriales Potosinos, S.A. de C.V.	Compatible with all blends up to 100% (E100)
Tanques Antillanos C. x A.	Compatible with all blends up to 100% (E100)
Watco Tanks, Inc.	Compatible with all blends up to 100% (E100)
We-Mac Manufacturing Company	Compatible with all blends up to 100% (E100)

Sources: PEI and Steel Tank Institute

Table A-3: Associated Underground Storage Tank Equipment Manufacturer Compatibility with Ethanol Blends E0—E100

Manufacturer	Product	Model	Ethanol Compatibility
Bravo Systems	Fiberglass fittings	Series F, FF, FPE, FR, F Retrofit-S, RPE Retrofit-Si, F BLR, F D-BLR-S, TBF	E0—E100
Bravo Systems	Spill buckets	B3XX	E0—E100
Bravo Systems	Tank sumps and covers	B4XX	E0—E100
Bravo Systems	Transition sumps (planter, walkover, H-20 rated)	B5XX, B6XX, B7XX, B8XX	E0—E100
Bravo Systems	Transition sumps	B8XX	E0—E100
Bravo Systems	Under dispenser containment sumps	B7XXX, B8XXX, B9XXX	E0—E100
Brugg Pipesystems	Pipes	FLEXWELL-HL, SECON-X, NIROFLEX, LPG	E0—E100
KPS Petrol Pipe Systems	Pipes and associated products	All single and double wall plastic pipes, flexible connectors, plastic fittings, gaskets, couplings, entry boots, containment sumps, leak detector units for filling and refueling	E0—E100
Morrison Bros	Expansion relief valve	076DI, 078DI	E0—E85
Morrison Bros	Frost proof drain valve	128DIS	E0—E85
Morrison Bros	Double outlet vent	155	E0—E85
Morrison Bros	Double tap bushing	184	E0—E85
Morrison Bros	Anodized farm nozzle	200S	E0—E85

Manufacturer	Product	Model	Ethanol Compatibility
Morrison Bros	Emergency vents	244	E0—E85
Morrison Bros	Swing check valves	246ADI, 246DRF	E0—E85
Morrison Bros	Internal emergency valves	272DI, 72HDI	E0—E85
Morrison Bros	Line strainers with Teflon	285	E0—E85
Morrison Bros	Caps	305C	E0—E85
Morrison Bros	Tank monitor adaptor and cap kits	305XPA	E0—E85
Morrison Bros	Float vent valves	317	E0—E85
Morrison Bros	Vapor recovery adaptor with Viton	323	E0—E85
Morrison Bros	Vapor recovery caps	323C	E0—E85
Morrison Bros	External emergency valves	346DI, 346FDI, 346SS, 346FSS	E0—E85
Morrison Bros	Updraft vents	354	E0—E85
Morrison Bros	Flame arrester	351S	E0—E85
Morrison Bros	Anodized drop tubes	419A	E0—E85
Morrison Bros	Spill containers	515/516/517/518	E0—E85
Morrison Bros	Anodized diffusers	539TO, 539TC	E0—E85
Morrison Bros	Pressure vacuum vents	548	E0—E85
Morrison Bros	Extractors	560/561/562/563	E0—E85
Morrison Bros	Ball valves	691BSS	E0—E85

Manufacturer	Product	Model	Ethanol Compatibility
Morrison Bros	Solenoid valves (3” must be all-Teflon version)	710SS	E0—E85
Morrison Bros	Pressure vacuum vents	748, 749	E0—E85
Morrison Bros	Clock gauges	818	E0—E85
Morrison Bros	Anti-syphon valve	912	E0—E85
Morrison Bros	Clock gauge with alarm	918	E0—E85
Morrison Bros	Overfill alarm	918TCP	E0—E85
Morrison Bros	Combination vent/overfill alarm	922	E0—E85
Morrison Bros	Dry disconnect adaptor	927	E0—E85
Morrison Bros	In-line check valve	958	E0—E85
Morrison Bros	Overfill prevention valve	9095A-AV, 9095SS	E0—E85
National Environmental Fiberglass	Dispenser sumps	All	E0—E100
National Environmental Fiberglass	Tank collars	All	E0—E100
National Environmental Fiberglass	Tank sumps and collars	All	E0—E100
National Environmental Fiberglass	Transition sumps	All	E0—E100
National Environmental Fiberglass	Single wall tank and transition sumps	All	E0—E100
National Environmental Fiberglass	Double wall tank and transition sumps	All	E0—E100

Manufacturer	**Product**	**Model**	**Ethanol Compatibility**
NOV Fiberglass Systems	Pipe	Red Thread IIA (UL listed for E0-e100)	E0—E100 (UL Listed)
NUPI Americas	Pipe and fittings	Smartflex	E0—E100 (UL Listed)
Omegaflex	Pipe, fittings, and accessories	DoubleTrac (brass and stainless-steel fittings)	E0—E100 (UL Listed)
Vaporless Manufacturing, Inc.	Leak detectors	99 LD-2000/2200/3000 (must use stainless steel tubing and fittings)	E0—E100
Vaporless Manufacturing, Inc.	Overfill prevention valve	OFP-2/3 (must use stainless steel tubing and fittings)	E0—E100
Western Fiberglass	CO-flex piping	All	E0—E100
Western Fiberglass	Cuff fittings	All	E0—E100
Western Fiberglass	Sumps (tank, dispenser, transition, vapor/vent)	All	E0—E100
Western Fiberglass	Co-flow hydrostatic monitoring systems	All	E0—E100

Source: PEI

APPENDIX B: Biodiesel Tank and Equipment Compatibility

Table B-1 through B-3 illustrate tank compatibility and equipment compatibility with various biodiesel blends.

Table B-1: Fiberglass Tank Manufacturer Compatibility with Biodiesel Blends

Manufacturer	Compatibility Statement
Containment Solutions	Compatible with all blends up to 100% (B100)
Xerxes	Compatible with all blends up to 100% (B100)

Sources: PEI and Steel Tank Institute

Table B-2: Steel Tank Manufacturer Compatibility with Biodiesel Blends

Manufacturer	Compatibility Statement
Acterra Group Inc.	Compatible with all blends up to 100% (B100)
Caribbean Tank Technologies Inc.	Compatible with all blends up to 100% (B100)
Eaton Sales & Service LLC	Compatible with all blends up to 100% (B100)
General Industries	Compatible with all blends up to 100% (B100)
Greer Steel, Inc.	Compatible with all blends up to 100% (B100)
Hall Tank Co.	Compatible with all blends up to 100% (B100)
Hamilton Tanks	Compatible with all blends up to 100% (B100)
Highland Tank	Compatible with all blends up to 100% (B100)
J.L. Houston Co.	Compatible with all blends up to 100% (B100)
Kennedy Tank and Manufacturing Co., Inc.	Compatible with all blends up to 100% (B100)
Lancaster Tanks and Steel Products	Compatible with all blends up to 100% (B100)

Manufacturer	Compatibility Statement
Lannon Tank Corporation	Compatible with all blends up to 100% (B100)
Mass Tank Sales Corp.	Compatible with all blends up to 100% (B100)
Metal Products Company	Compatible with all blends up to 100% (B100)
Mid-South Steel Products, Inc	Compatible with all blends up to 100% (B100)
Modern Welding Company	Compatible with all blends up to 100% (B100)
Newberry Tanks & Equipment, LLC	Compatible with all blends up to 100% (B100)
Plasteel	Compatible with all blends up to 100% (B100)
Service Welding & Machine Company	Compatible with all blends up to 100% (B100)
Southern Tank & Manufacturing Co., Inc.	Compatible with all blends up to 100% (B100)
Stanwade Metal Products	Compatible with all blends up to 100% (B100)
Talleres Industriales Potosinos, S.A. de C.V.	Compatible with all blends up to 100% (B100)
Tanques Antillanos C. x A.	Compatible with all blends up to 100% (B100)
Watco Tanks, Inc.	Compatible with all blends up to 100% (B100)
We-Mac Manufacturing Company	Compatible with all blends up to 100% (B100)

Sources: PEI and Steel Tank Institute

Table B-3: Associated Underground Storage Tank Equipment Manufacturer Compatibility with Biodiesel Blends B0—B100

Manufacturer	Product	Model
Bravo Systems	Fiberglass fittings	Series F, FF, FPE, FR, F Retrofit-S, RPE Retrofit-Si, F BLR, F D-BLR-S, TBF
Bravo Systems	Spill buckets	B3XX
Bravo Systems	Tank sumps and covers	B4XX
Bravo Systems	Transition sumps (planter, walkover, H-20 rated)	B5XX, B6XX, B7XX, B8XX
Bravo Systems	Transition sumps	B8XX
Bravo Systems	Under dispenser containment sumps	B7XXX, B8XXX, B9XXX
Brugg Pipesystems	Pipes	FLEXWELL-HL, SECON-X, NIROFLEX, LPG
KPS Petrol Pipe Systems	Pipes and associated products	All single and double wall plastic pipes, flexible connectors, plastic fittings, gaskets, couplings, entry boots, containment sumps, leak detector units for filling and refueling
Morrison Bros	Expansion relief valve	076DI, 078DI
Morrison Bros	Frost proof drain valve	128DIS
Morrison Bros	Emergency vents	244
Morrison Bros	Swing check valves	246ADI, 246DRF
Morrison Bros	Internal emergency valves	272DI, 72HDI
Morrison Bros	Caps	305C
Morrison Bros	Vapor recovery adaptor with Viton	323
Morrison Bros	Vapor recovery caps	323C
Morrison Bros	External emergency valves	346DI, 346FDI, 346SS, 346FSS

Manufacturer	**Product**	**Model**
Morrison Bros	Updraft vents	354
Morrison Bros	Flame arrester	351S
Morrison Bros	Anodized drop tubes	419A, 539TO, 539TC
Morrison Bros	Spill containers	515/516/517/518
Morrison Bros	Pressure vacuum vents	548, 748, 749
Morrison Bros	Ball valves	691BSS
Morrison Bros	Solenoid valves (3" must be all-Teflon version)	710SS
Morrison Bros	Clock gauges	818
Morrison Bros	Anti-syphon valve	912
Morrison Bros	Clock gauge with alarm	918
Morrison Bros	Overfill alarm	918TCP
Morrison Bros	Combination vent/overfill alarm	922
Morrison Bros	Dry disconnect adaptor	927
Morrison Bros	In-line check valve	958
Morrison Bros	Overfill prevention valve	9095A-AV (except B100), 9095SS
National Environmental Fiberglass	Dispenser sumps	All
National Environmental Fiberglass	Tank collars	All
National Environmental Fiberglass	Tank sumps and collars	All
National Environmental Fiberglass	Transition sumps	All
National Environmental Fiberglass	Single wall tank and transition sumps	All
National Environmental Fiberglass	Double wall tank and transition sumps	All
NOV Fiberglass Systems	Pipe	Red Thread IIA (UL listed for E0-e100)
NUPI Americas	Pipe and fittings	Smartflex

Manufacturer	Product	Model
Omegaflex	Pipe, fittings, and accessories	DoubleTrac (brass and stainless-steel fittings)
Vaporless Manufacturing, Inc.	Leak detectors	99 LD-2000/2200/3000 (must use stainless steel tubing and fittings)
Vaporless Manufacturing, Inc.	Overfill prevention valve	OFP-2/3 (must use stainless steel tubing and fittings)
Western Fiberglass	CO-flex piping	All
Western Fiberglass	Cuff fittings	All
Western Fiberglass	Sumps (tank, dispenser, transition, vapor/vent)	All
Western Fiberglass	Co-flow hydrostatic monitoring systems	All

Source: PEI

APPENDIX C: Key Suppliers and Technology Providers for Commercial CNG and LNG Infrastructure

Table C-1 and C-2 provide lists of key suppliers and technology developers for CNG and LNG infrastructure[90].

Table C-1: Suppliers and Technology Developers for CNG and LNG Infrastructure

Adrianus Resources
All-In-One Fuel, Inc.
Allsup Corp
American Integrated Services, Inc.
Amtek Construction
California Clean Fuels
Cenergy Solutions
Clean Energy Fuels
Clean Fuel Connection
ET Environmental
Evergreen CNG Systems
Exterran
Franzen-Hill
Go Natural Gas
Greenfield Compression
GreenLine Fuel Corp.
Knox Western
Pinnacle CNG Co.
Questar Fueling
Revolution CNG

[90] Southern California Gas Company. "CNG Supplier Directory." January 27, 2014.

S&W Compressors
Trillium CNG
TruStar Energy
U.S. Air - CNG Systems
Vant Hull Construction

Source: Southern California Gas Company

Table C-2: Key Vendors and Component Manufacturers in California for Natural Gas Fueling Stations

Supplier	**Products**
3M Advanced Composites	Storage cylinders
Advance Fuel Systems	Compressors, dispensers
Allied Equipment, Inc.	Storage cylinders
ANGI International	Compressors, control systems, dispensers, gas dryers, storage cylinders
Atlas Copco	Compressors
BRC Gas Equipment	Compressors, personal fueling appliances
Broadluz	Fuel management systems
Clean Energy Fuels	Personal fueling appliances
CNG Cylinders Int'l.	Storage cylinders
CNI Manufacturing	Dispenser hose retractors
Dynetek Industries Ltd.	Storage cylinders
Evergreen CNG Systems	Compressors
Exterran	Compressors
FuelMaker	Compressors, personal fueling appliances
Galileo Natural Gas Technologies	Compressors, dispensers
Greenfield Compression, Inc.	Compressors, dispensers, storage, dryers, control systems
Greenfix America	Compressors and personal fueling appliances
Hurricane Compressors	Compressors,
IMW Industries, Inc.	Compressors, control systems, dispensers

Supplier	Products
Knox Western	Compressors
Lincoln Composites	Storage cylinders
Luxfer Gas Cylinders	Storage cylinders
Pinnacle CNG Company	Compressors, dispensers, storage, dryers
Quantum Technologies	Storage cylinders
S&W Compressors	Compressors
SPX Flow Technology Pneumatic Products	Gas dryers
Structural Composites Industries	Storage cylinders
Tulsa Gas Technologies	Dispensers, hoses, meters

Source: Southern California Gas Company