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Alternative Transportation Refueling Infrastructure in the U.S. 2014:

Status and Challenges

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Howard H. Baker Jr. Center for Public Policy

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Table of Contents

Alternative Transportation Refueling Infrastructure in the U.S. 2014:

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Abstract

Lack of adequate refueling infrastructure is a major barrier to the success of alternative motor fuels. A transition from fossil petroleum to alternative, low-carbon transportation fuels appears to be necessary to mitigate the adverse impacts of global warming, strengthen energy security and meet air quality standards. Finding effective combinations of business models and public policies to accomplish a transition to alternative fuels poses a new and difficult challenge. Focusing on highway vehicles, this paper reviews the motivation for transition to alternative fuels, the current status of alternative fuel refueling infrastructure in the U.S., the costs of such infrastructure and business models and policies that have been proposed to achieve a successful transition. The goal of this paper is to serve as a basis for innovative thinking and discussion rather than as a comprehensive analysis of the issue. Infrastructure for producing and delivering fuels to refueling stations is equally important but is outside the scope of this paper.

I. Background

Society has compelling reasons for supporting a transition from fossil petroleum to alternative fuels: limiting global climate change by reducing greenhouse gas emissions, enhancing energy security, and improving air quality while reducing other environmental impacts. The Global Energy Assessment (GEA/IIASA, 2012) concluded,

> "…that a sustainable energy future requires a transformation from today's energy systems to those with: (i) radical improvements in energy efficiency, especially in end use, and (ii) greater shares of renewable energies and advanced energy systems with carbon capture and storage (CCS) for both fossil fuels and biomass."
>
> "An effective transformation requires immediate action." (GEA/IIASA, 2012, p. xv)

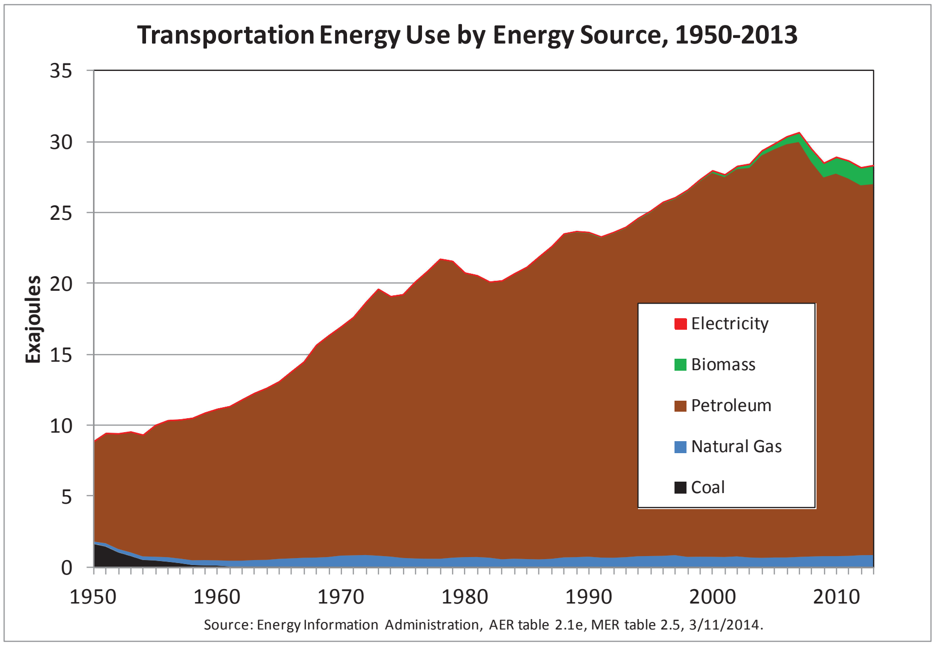
The U.S. National Academy of Sciences report, *America's Energy Future* noted that,

> "The long-term reliability of traditional sources of energy, especially oil, remains uncertain in the face of political instability and limitations on resources." (NAS, 2009, p. vii)

Although U.S. net oil imports steadily decreased from a peak of 60% in 2005 to 33% in 2013, oil prices dramatically increased and remained high through the Fall of 2014. From 2011 to 2013 the cost of oil to U.S. refiners remained above $100 per barrel, twice the 2005 level (EIA, 2014b, tables 3.1 and 9.1). Thus, despite much lower imports the cost of oil dependence to the U.S. economy remained high. Late in winter 2014 oil prices fell, reaching $40-$50 per barrel in January 2015. Volatility has been a hallmark of oil prices since 1973 and is likely to remain so in the future. Climate change, oil dependence, and air pollution cost the U.S. economy hundreds of billions of dollars each year (Greene et al., 2013; NRC, 2009; IWGSCC, 2013).

Transportation and motor vehicles are major contributors to these problems. Transportation emits more carbon dioxide than the industrial, residential or commercial sectors of the economy (NAS, 2012). And nearly all of transportation's greenhouse gas (GHG) emissions are comprised of CO_2 from the combustion of petroleum. The transportation sector remains 92% dependent on petroleum for energy. Highway vehicles use 80% of transportation energy and light-duty vehicles are responsible for 60%. Transportation accounted for 70% of U.S. petroleum use in 2013 and a larger share of the high-value petroleum products that drive the world oil market (EIA, 2014b, table 3.7). There is an urgent need to begin a transition to energy sources that drastically reduce GHG emissions but there is also a role for fuels that offer modest reductions in GHGs but contribute to improving energy security and air quality.

Breaking petroleum's dominance of transportation energy use will be difficult. For the past half century, petroleum has provided nearly all of transportation's energy with the exception of small amounts of natural gas, most of which has been used to power natural gas pipelines rather than motor vehicles (Figure 1)[1]. To date, the greatest penetration of non-petroleum energy has been achieved by blending ethanol with gasoline, largely driven by the Renewable Fuels Standard (RFS) (NRC, 2011). Over the past ten years, biofuel use in transportation has increased from 0.3 to 1.2 quads (out of 27.0 quads) and natural gas use has increased from 0.6 to 0.8 quads (EIA, 2014b, table 2.5). However, ethanol blending in gasoline has effectively reached the 10% limit for many vehicles. Further displacement of petroleum with low-carbon alternatives appears to require a combination of advanced "drop-in" gasoline and diesel replacements made from biomass and alternatives that will require new refueling infrastructure.



Source: Energy Information Administration, AER table 2.1e, MER table 2.5, 3/11/2014.

Figure 1. History of Transportation Energy Use by Fuel Type, 1950-2013.

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[1] The Energy Information Administration includes energy used by pipelines in the data for the transportation sector. The majority of natural gas use in Figure 1 is used to power the compressors of natural gas pipelines.

Deploying sufficient alternative fuel refueling infrastructure to support a market for alternative fuel vehicles has been a major barrier to the success of alternative fuels and vehicles in the past and remains so today (McNutt and Rodgers, 2004). If refueling infrastructure is scarce, the majority of car buyers perceive alternative fuel vehicles as risky and inconvenient. If alternative fuel vehicles are scarce, fuel providers are likely to see investments in refueling infrastructure as risky.

Previous efforts to promote alternative fuel vehicles and infrastructure in the U.S. were largely unsuccessful. Learning the lessons of the past is the most effective way to overcome what Kahneman (2011) calls the "planning fallacy", the tendency for even experts to underestimate the time and effort required to complete a complex new project. Learning from experience should be the first step to developing new strategies and policies. U.S. alternative fuels policies implemented through 2003 were analyzed by McNutt and Rodgers (2004). They summarized the outcomes of these policies as follows:

- "No significant change in alternative fuel use
- Cleaner conventional fuels and significantly lower vehicle emissions
- Expanded oxygenate fuel use
- Millions of alternative fuel compatible vehicles on the road, dominated by ethanol compatible vehicles
- Better understanding of alternative and conventional fuel markets, and consumer-producer behavior." (McNutt and Rodgers, 2004, p. 169)

Key lessons learned include: 1) incumbent energy systems will respond to the challenge by alternative fuels in many ways, including improving their own performance, 2) success in niche markets does not necessarily become success in mass markets and, 3) additional policies are likely to be required to make the transition from fleets to private vehicles. The record of U.S. alternative fuels infrastructure from 1988 to 2003 shows very limited unregulated and unsubsidized private investment. Investors have been reluctant to build infrastructure in advance of the growth of the market for alternative fuels and, McNutt and Rodgers (2004, p. 175) note, those who did were usually disappointed. A key conclusion is that for the mass market success of alternative fuels "…infrastructure development may be the limiting factor." (McNutt and Rodgers, 2004, p. 178).

Although the barriers to transition seem great, they are likely to be small relative to the ultimate benefits. The National Research Council's (NRC) Committee on Transitions to Alternative Vehicles and Fuels analyzed the technologies and policies that could achieve an 80% reduction in petroleum use and greenhouse gas (GHG) emissions by U.S. light-duty vehicles by 2050 (NRC, 2013). Their findings indicate that a transition to alternative fuels, including a major role for electric drive vehicles, is required. While acknowledging that the costs and benefits of such transitions are highly uncertain, the NRC committee's estimates imply that the benefits are likely to exceed the excess costs by approximately an order of magnitude. How to reflect potentially large but uncertain future benefits in current policies to promote alternative fuels is a major challenge. Accomplishing major energy transitions for the public good may require a new public policy paradigm (Greene et al., 2014).

Figure 2 shows the NRC committee's estimates of the net present value, by future year, of a transition that successfully met the 80% reduction goals (future costs and benefits discounted at 2.3%/yr.). Although additional costs (purple line, Figure 2) exceed benefits early in the transition and tens of billions of dollars of subsidies are required, benefits in GHG mitigation (blue line), eventual elimination of petroleum dependence (red line), energy savings not considered by car buyers at the time they purchase a new vehicle (green line) and increased consumer satisfaction with the range of vehicle choices (orange line) eventually swamp the upfront costs of subsidies. Consumer satisfaction grows over time as consumers learn about alternative vehicles and fuels and overcome their aversion to the risk of unfamiliar products. If the NRC study's estimates are approximately correct, breaking the barriers to alternative fuels will pay off many times over. The estimated total net present value (dashed line) is easily an order of magnitude greater than the cost of subsidies.

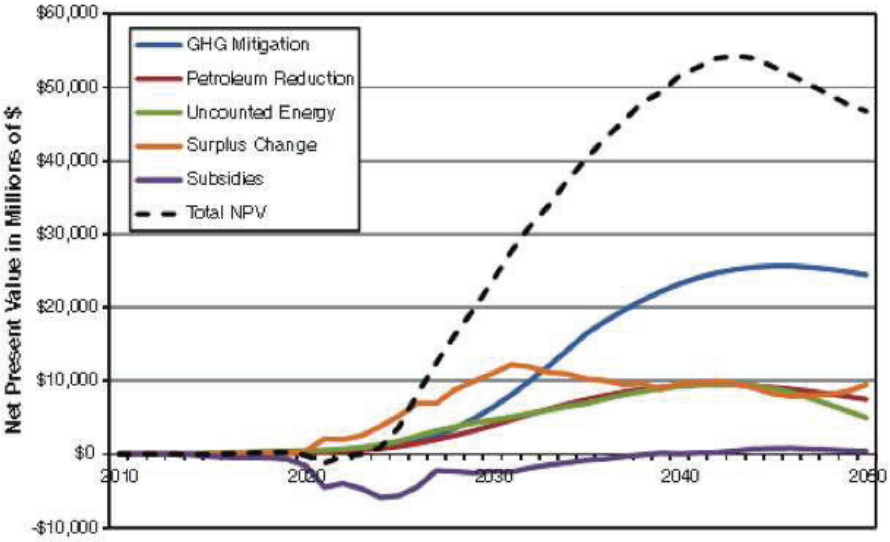


Figure 2. Estimated Components of the Net Present Value of an Energy Transition Light-duty Vehicles. Future annual values discounted at 2.3% per year. (Source: NRC, 2013).

Alternative fuels infrastructure begins with feedstock production and transport, and includes conversion into automotive fuel, distribution and refueling. While this paper focuses on refueling infrastructure, upstream factors can determine the social benefits of alternative fuels and thereby society's willingness to support refueling infrastructure. Broadly defined, alternative fuels infrastructure includes not only the physical, but the institutional and human capital necessary for the functioning of the fuel system. Institutional and human capital are especially important for refueling infrastructure. Codes, standards and regulations influence safety, convenience and cost. Finally, alternative fuels and their infrastructure are unfamiliar to the public. Social learning about alternative fuels infrastructure and gaining confidence in their reliability and safety through experience and education are also important conditions for success in the marketplace.

II. Current Status of Alternative Fuels Infrastructure in the U.S.

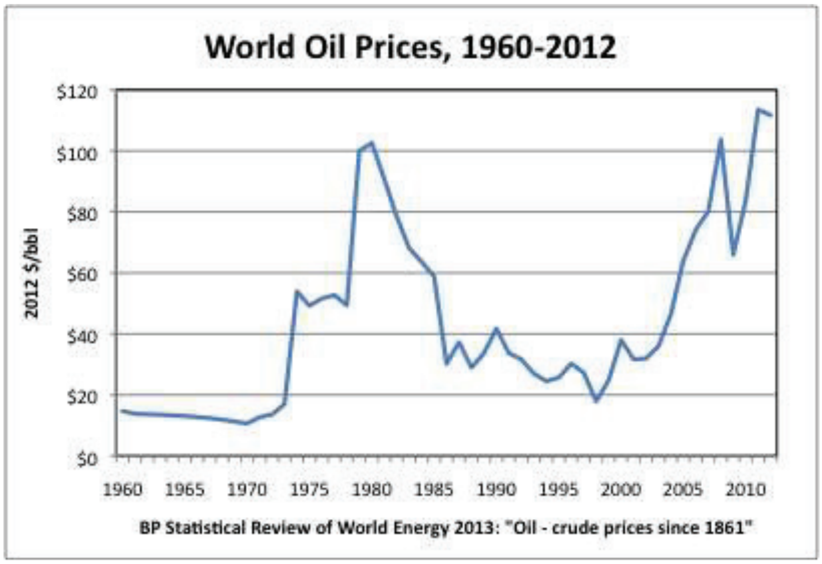
Alternative refueling infrastructure exists across the U.S. but it is scarce in comparison to the petroleum refueling infrastructure. The U.S. Department of Energy's Alternative Fuels Data Center (AFDC) continuously updates counts and locations of publicly accessible outlets for alternative fuels in the U.S. (a complete accounting by state as of August 18, 2014 can be found in appendix Table 1). There are approximately 150,000 gasoline refueling stations ubiquitously distributed throughout the U.S. (Davis et al., 2013, table 4.18). As of August 18, 2014, there were 8,427 public electric vehicle recharging stations with 20,296 outlets in the U.S. (AFDC, 2014). Of these, 1,835 stations and 5,274 outlets were located in California alone. Texas had the second greatest number: 557, followed by Florida with 474 charging stations. Only twelve public hydrogen refueling stations are listed, ten of which are in California However, construction of 29 more stations was recently funded by the state of California and funding has been committed to support 100 hydrogen stations (Gagliano, 2013). The geography of E85 refueling stations is very different; the majority of the 2,418 stations are concentrated in the upper Midwest. Of the 290 biodiesel stations in the U.S., 91 are in the Pacific coast states of California, Oregon and Washington, while 64 are in the southeastern states of Tennessee, North Carolina and South Carolina. Among the hydrocarbon alternative fuels, there are the greatest number of public propane stations (2,714) followed by compressed natural gas (CNG) (737) and liquefied natural gas (LNG) (58). There are approximately 500 private CNG refueling stations serving commercial and government fleets (ANGA & AGA, 2014). Maps illustrating the geographical distribution of publicly available refueling stations for alternative fuels as of May, 2014 are provided in appendix 4.

III. Capital and Operating Costs of Alternative Fuels Infrastructure

Alternatives to conventional petroleum fuels face substantial economic barriers to initial market success. Foremost among these is the “chicken or egg” problem: lack of refueling infrastructure discourages sales of alternative fuel vehicles and lack of alternative fuel vehicles undermines the profitability of investments in refueling infrastructure. But there are additional barriers. Low sales volumes make it difficult to achieve scale economies in vehicle or fuel production, hinder the development of competitive supply chains and delay cost reductions via learning by doing. Low initial sales volumes cause a lack of diversity of choice in vehicle types, makes and models, further limiting demand. The majority of consumers is averse to the perceived risk of new technology and will wait until time and experience have proven its reliability. In addition there are institutional barriers, codes and standards designed for conventional rather than alternative fuels and infrastructure.

Analyses have shown that the natural market barriers enumerated above are large and take years, and possibly decades to overcome (Greene, 2014; NRC, 2013; Greene et al., 2008). At the same time, sales of alternative fuel vehicles and deployment of infrastructure create strong positive feedbacks and network external benefits that reinforce the transition process (Struben and Sterman, 2008). While governments are accustomed to designing policies to address negative externalities, developing policies to internalize positive externalities and capitalize on positive feedbacks during the transition process in the face of uncertainty about the ultimate outcome is a new challenge.

The economics of alternative fuels infrastructure appears to dictate that in the early phases of market development it will be difficult to create profitable business models in the absence of public policy support. In large part this is because important benefits of alternative fuels, such as the potential for greatly reduced GHG emissions and enhanced energy security, are public goods. Business models for alternative fuel refueling infrastructure are complex and uncertain. In principle, the profitability of alternative refueling investments, like any other, depends on capital and operating costs and revenue flows. However, because of the hurdles to new fuels and the importance of public rather than private benefits, public policy plays a key role. Public policies at the federal, state and local levels can be both complex and uncertain. In addition, developing a new market implies uncertain future demand and therefore revenues. Further complicating matters is the fact that the price of the competing, incumbent fuel has proven to be inherently unpredictable (Figure 3) (Hamilton, 2009). Oil prices in the vicinity of $100 per barrel create a price advantage for fuels such as electricity and natural gas. But if oil prices were to fall to the range of $20-$40 per barrel that prevailed as recently as 1986-2003, alternatives like biofuels and hydrogen would be at a substantial disadvantage. Despite efforts to standardize, codes and standards still vary by state and municipality and demand will vary with the nature of local traffic and socioeconomics.



BP Statistical Review of World Energy 2013: "Oil - crude prices since 1861"

Figure 3. World Oil Prices, 1960-2012.

There are many sources of information on the costs of infrastructure for alternative fuels and estimates can vary greatly depending on a study's premises. Costs frequently vary importantly from location to location and are changing over time as technologies improve and learning through experience leads to more efficient design and implementation. This section is mainly based on recent reports by the National Research Council (NRC, 2013) and studies by the National Renewable Energy Laboratory that considered current and future infrastructure costs but estimates from other sources are also included. While the findings of the studies are presented here as useful reference points it is recognized that there are other valid sources of whose premises, assumptions and results differ. The NRC report emphasized the importance of infrastructure costs to the adoption of alternative fuels and vehicles.

> "The investment costs to build the fuel infrastructure are sizable for all of the alternative fuel and vehicle pathways. In fact, these costs remain among the most important barriers to rapid and widespread adoption of alternatives." (NRC, 2013, p. 45)

E85 & Biodiesel

Nearly all recently installed underground gasoline tanks at fueling stations are compatible with E85 but must be cleaned prior to filling with E85. Specialized dispensing equipment with metals and seals resistant to ethanol is required. Johnson and Melendez (2007) adopted costs of converting at least one pump to E85 of $60,000 if a new E85 tank must be added and $20,000 if an existing tank could be cleaned and utilized. The most economical option was converting an existing mid-grade gasoline tank to E85 and adding a system for blending regular and premium. Typical equipment life was estimated to be 15 years. Operation and maintenance costs were assumed to consist of $2,000 of fixed costs annually and approximately $0.05/gallon of variable costs. If an existing gasoline tank is converted to E85, there could be opportunity costs in lost gasoline sales if inventories cannot be maintained at sufficient levels to satisfy periods of peak demand. Assuming throughput of E85 was 70,000 gallons per year, the required margin for profitable sales of E85 was estimated to be between $0.15 and $0.19 per gallon of E85. These calculations do not consider the potential for increased sales of non-fuel merchandise.

Adding biodiesel blends from 20% to 100% requires minor changes. Existing tanks and lines must be cleaned, otherwise biodiesel will absorb contaminants that conventional diesel would not (AFDC, 2014c). The EPA requires that tank manufacturers certify their tanks for compatibility with biofuels, as they do for E85 (EPA, 2014). According to the AFDC, all tank manufacturers have certified their tanks for biodiesel. These tanks should be comparable in cost to E85 tanks, discussed above. Historically, biodiesel has been dispensed using conventional diesel dispensers. However, dispensers certified for biodiesel by Underwriters Laboratories are now available and are recommended to ensure that codes, standards and regulations are complied with.

Electricity

Plug-in electric vehicles have the advantage of a ubiquitous electricity network yet lack a ubiquitous network of electric vehicle supply equipment (EVSE). EVSE is defined as,

> The conductors, including the ungrounded, grounded, and equipment grounding conductors, the electric vehicle connectors, attachment plugs, and all other fittings, devices, power outlets or apparatuses installed specifically for the purpose of delivering energy from the premises wiring to the electric vehicle.

Although EVSE equipment is quite diverse, it is generally grouped into three categories (levels) according to the rate at which electricity can be delivered into the vehicle. Level 1 (AC) charging is usually done at 120 Volts and provides 2 to 5 miles of range per hour of charging (depending on the vehicle) (AFDC, 2014b). Level 2 (AC) charging takes place at 240 Volts and requires a dedicated circuit of 20 to 80 amperes. Level 2 can add 10 to 20 miles of range per hour. DC fast charging (sometimes referred to as level 3, typically requires 480 Volts and can add 60 to 80 miles of range in 20 minutes.

Table 1. Charging Station Cost Estimates in 2011 (NRC, 2013, table G.7)

Charger Type	Equipment Cost (Range)	Equipment Cost	Installation Cost (Range)	Installation Cost	Total Cost
Level 1	$450-$995	$479	$0-$500	$200	$679
Level 2 (Home)	$490-$1,200	$892	$300-$2,000	$1,300	$2,192
Level 2 (Public)	$1,875-$4,500	$2,477	$1,000-$10,000	$2,500	$4,977
Level 3	$17,000-$44,000	$34,200	$7,000-$50,000	$20,000	$54,200

The NRC (2013) Committee assumed that the infrastructure costs for electric vehicle chargers would decline at about 1.5% to 2% per year through 2050. The NRC's costs are somewhat lower than those reported by Botsford (2012) who estimated $1,500 to $2,000 for an installed home charger (Table 1). For level 2 public chargers, Botsford put the equipment cost at $1,500 to $5,000 based on prices published by the General Services Administration, with installation costs ranging from $3,000 to $10,000 for a single port configuration but only 20% higher for dual ports on the same pole. Installation costs are highly dependent on locations and local codes and standards. Adapting building codes to require compatibility with EV charging would help reduce installation costs, especially in multi-unit dwellings and parking facilities.

Hydrogen

Hydrogen can be transported to a refueling station by pipeline, by truck in liquid or gaseous form, or can be produced onsite by steam methane reforming (SMR) or electrolysis. The station must have storage, compression and dispensing equipment. The NRC Transitions study (NRC, 2013, p. 59) provides a hydrogen station cost estimate in terms of dollars per gallon of gasoline equivalent energy (approximately 1 kg) per day of $2,345. Thus, a station with a capacity of 1,000 kg/d would cost $2. 3 million. This estimate includes "…all costs associated with building grass-roots new stations that include hydrogen storage, compression, and dispensing…" On-site distributed natural gas reforming was estimated to add $700/gge/day, or $700,000, making the cost of an on-site SMR station about $3 million (a gge is the energy equivalent of one gallon of gasoline). Similarly, on-site electrolysis was estimated to add $860/gge/d.

Capital costs for a range of hydrogen station types and sizes were provided by Ogden and Nicholas (2011). Small (100 kg/d) mobile refueling systems were estimated to cost $0.4 to $1 million. Fixed stations of 100 kg/d capacity with delivery by compressed gas trucks were estimated to cost $2.1 to $2.2 million. The capital cost for 1,000 kg/d stations using on-site SMR were estimated to be between $4.9 and $7.8 million; 1,000 kg/d stations using electrolyzers were estimated to cost from $5.6 to 9.3 million. Both estimates appear to be considerably higher than those of the NRC (2013) which may reflect progress in station designs or better information about costs. Ogden and Nicholas' estimates include $2 million per station for site preparation, permitting, engineering, utility installation and buildings which may be higher for stations built in California than in other states. Stations of 1,000 kg/d capacity dispensing hydrogen delivered in the liquid state by cryogenic trucks were estimated to cost $2.6 to $3.2 million. For the smaller stations, annual O&M costs are 13% of capital costs plus $130,000. For the larger stations O&M costs are a smaller fraction of capital costs:

1. 11% of capital cost + $360,000 for liquefied delivery
2. 7% of capital cost + $360,000 for onsite SMR or electrolysis

Melaina and Penev (2013) put the capital cost of a state-of-the art 2011-12, 160 kg/d hydrogen refueling station at $2.65 million, and estimated that future costs during the 2014-16 period for 450 kg/d stations would be only $2.8 million (Table 2). Beyond 2016 they estimated the capital costs of a 600 kg/d station at $3.1 million and a 1,500 kg/d station at $5.1 million. For California in the period from 2014 to 2015, Brown et al. (2013) report capital costs of $1 million for 180 kg/d stations with gaseous delivery and $2 million for 400 kg/d stations with liquid delivery.

Table 2. Capital Costs ($ millions) for Gaseous (GH2) and Liquid (LH2) Truck Delivery, Onsite SMR, and Onsite Electrolysis Stations from the H2A Production and HDSAM Models (Melaina and Penev, 2013).

Station	Truck Delivery		Onsite SMR		Onsite Electrolysis	
Capacity	Gaseous	Liquid	Current	Future	Current	Future
100 kg/d	$1.4	$0.9	$1.1	$0.7	$1.1	$0.8
400 kg/d	$2.0	$1.7	$2.1	$1.4	$2.1	$1.5
1,000 kg/d	$4.1	$3.4	$4.0	$2.7	$4.4	$3.0

Notes: Current cases refer to 2010 technology status, with deployment in 2015, and Future cases refer to 2020 and 2025 for onsite SMR and 2025 and 2030 for onsite electrolysis for technology status and deployment years, respectively. Truck delivery costs are for current cases.

Natural Gas

Natural gas is generally delivered to a CNG refueling station via pipeline, dried, compressed, stored and dispensed into vehicles at about 3,000 psi. LNG is typically delivered to refueling stations by tank trucks equipped to handle cryogenic liquids. An LNG station requires cryogenic storage, a system for handling boil-off, and an LNG dispenser. If CNG is also provided, a vaporizer is also required along with CNG dispensing equipment. The NRC (2013, p. 327) study reports capital cost estimates for four types of natural gas refueling stations:

1. Time filling (approx. 8 hours, mostly home use, does not require storage)
2. Cascade filling (public access with on-site gas storage)
3. Central fast-fill (buffered, for large vehicles)
4. Combined CNG/LNG stations

Liquefied natural gas (LNG) stations were estimated to cost between $350,000 and $1 million for equipment alone (land and buildings excluded), which compares with $150,000 for a gasoline station of similar size. CNG station costs were estimated including land, buildings and equipment at $1.3 million for a station serving 1,000 vehicles per day. CNG stations costs were judged to scale linearly with capacity beyond that point. Home refueling stations were estimated to cost about $4,500 plus installation. However, home refueling raises question about the quality of the natural gas available at residences.

Natural gas refueling infrastructure costs for municipal fleets has been estimated by Johnson (2010). Incremental costs were estimated to be $1.9 to $2.2 million for delivery of 50,000 diesel gallons equivalent energy (DGE) per day to $4.2 to $5.5 million for 250,000 DGE. The ranges reflect differences in the time available for refueling; the more time available the lower the equipment costs. Operating and Maintenance costs increase from about $12,700 at 50,000 diesel gallons equivalent (DGE) to $17,300 at 250,000. O&M costs were summarized as a function of DGE dispensed in the following equation.

$$\text{Cost} = -0.0000002225*(\text{DGE})^2 + 0.125*(\text{DGE}) + 7014.3$$

Costs of CNG stations were also estimated by TIAX (2014a) for fast-fill and time-fill configurations (Table 3). TIAX also noted that costs vary substantially according to location and local codes and standards.

Table 3. Estimated CNG Station Costs (TIAX, 2014).

	Fast Fill	Time Fill
Equipment	$650,000	$375,000
Installation	$350,000	$300,000
Total	$1,000,000	$675,000
Capacity (DGE per hour)	15-20 DGE	3.8 DGE

LNG station costs are are strongly correlated with storage capacity, the most expensive component of an LNG station (TIAX, 2014b). Whether LNG is trucked in and stored cryogenically or natural gas is liquefied on site, LNG stations costs are typically an order of magnitude greater than diesel station costs. The cost of an LNG station based on onsite storage ranges from about $560,000 at 10,000 gallons of onsite storage capacity to $1.63 million at 40,000 gallons. Despite high capital costs, dispensed LNG would cost less than diesel fuel, assuming natural gas priced at $5/mmBtu and operation near full capacity (Figure 4).

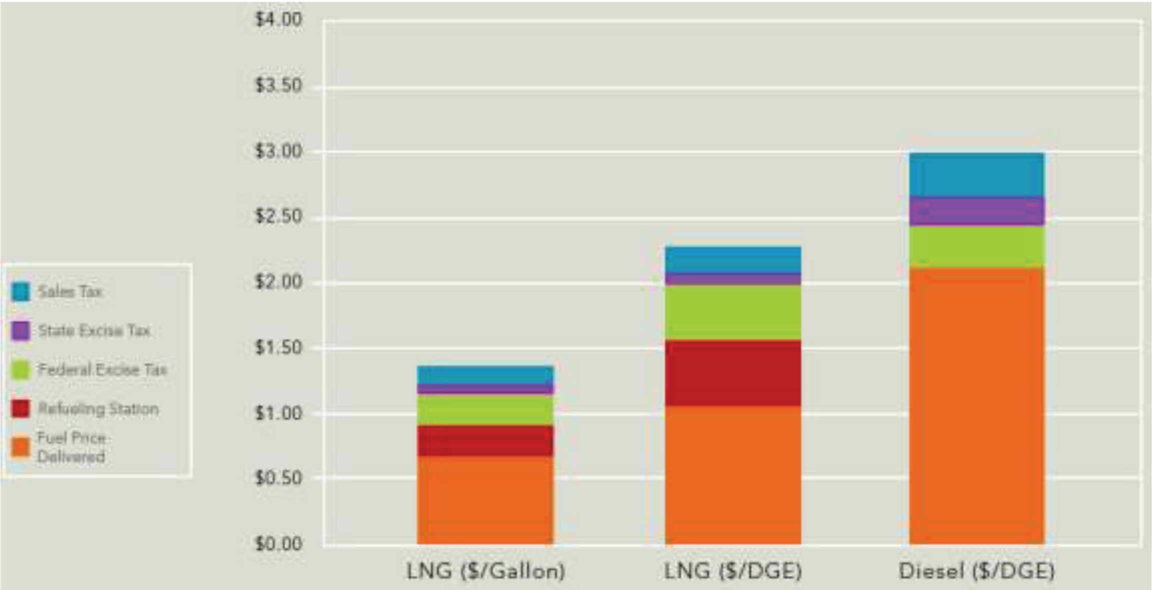


Figure 4. Estimated Cost of Dispensed LNG for a 5,000 Gallon/Day Station, $5/mmBtu Gas (TIAX, 2014b)

Renewable natural gas (RNG) or biomethane is produced from biogas, a product of anaerobic digestion of organic matter (NREL, 2014). Sources of biogas include landfills, municipal wastewater, animal manure and other sources of organic waste. Biogas can be upgraded to RNG by removing CO_2, water, and other trace gases. Once upgraded, biogas can be used just as natural gas would, including as a vehicle fuel. RNG qualifies as an advanced biofuel under the Renewable Fuels Standard. The potential for producing biomethane from all sources is approximately 7.9 million metric tons or 3.5 billion gallons of gasoline equivalent per year. It is estimated that about ten times as much Biomethane could be produced from fermentation or thermochemical conversion of lignocellulose. Of course, there are many competing uses of lignocellulosic biomass that will limit the availability of biomethane from this source.

Propane

The capability to produce, store and transport propane is nearly ubiquitous in the U.S. In most parts of the U.S. propane fueling infrastructure can rely on an existing, local source of supply. Dispensing requires a low pressure storage tank, pump and dispenser (AFDC, 2014d). Equipment purchase and installation cost from $37,000 to $175,000 depending on the local situation and requirements. Propane dispensers can be collocated alongside dispensing equipment for conventional or other alternative fuels. It is even possible to refuel most propane vehicles at existing retail sites that customarily sell in small volumes to fill barbecue grills and other consumer needs.

Summary of Alternative Fuels Infrastructure Costs

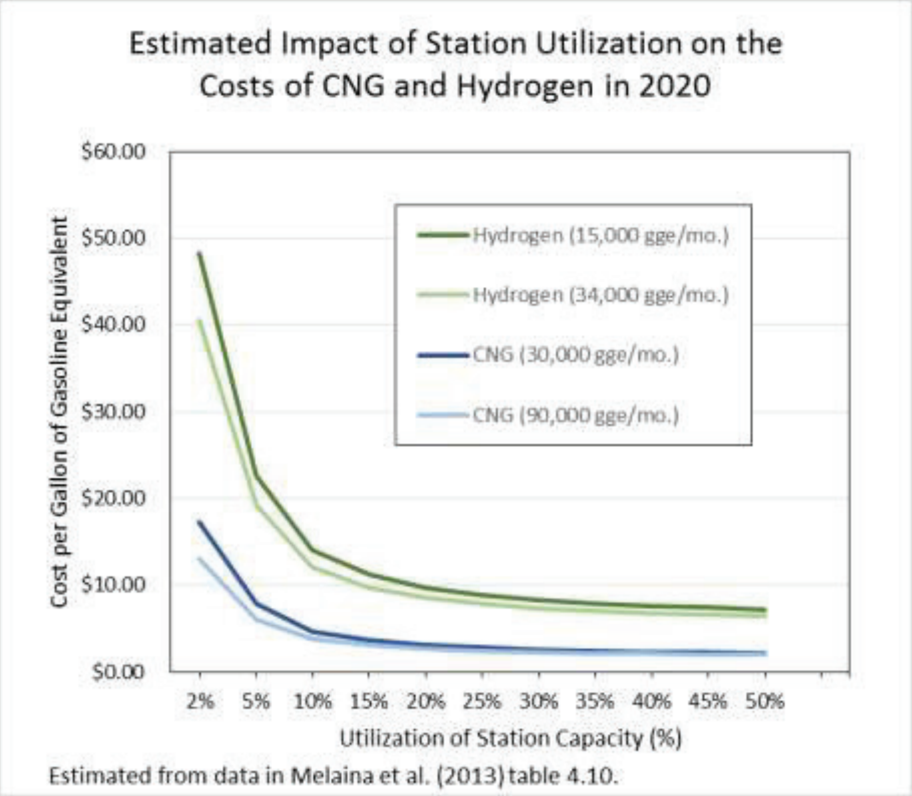
Estimated high-volume costs of producing and dispensing alternative fuels based on the National Research Council's (2013) comprehensive study of alternative transportation fuels for light-duty vehicles are shown in table 4. The costs shown are amortized costs per vehicle for fuel infrastructure investments, including fuel production, distribution and retailing. The estimates for gasoline include the costs of new refineries, as well as transportation, storage and refueling stations. The NRC study assumed one charger per plug-in vehicle, including PHEVs. Recent empirical data indicate that the NRC assumptions overestimated the take rates for residential electric chargers, by approximately a factor of two for PHEVs. All fuels are assumed to be at a high level of market penetration with retail outlets operating at full capacity. However, only gasoline has the benefits of a mature industry and a century of learning by doing.

Table 4. 2030 Fuel Infrastructure Initial Investment Costs per Vehicle (NRC, 2013, table 3.3).

Alternative Fuel	2030 Investment Cost	Light-duty Vehicle Fuel Use/Day	Infrastructure Investment Cost ($/vehicle)
Electricity (BEV)	$330/kWh/day	8.9 kWh	$2,930
Electricity (PHEV 40)	$530/kWh/day	5.4 kWh	$2,880
Electricity (PHEV 10)	$370/kWh/day	1.75 kWh	$650
Hydrogen (with CCS)	$3,890/gge/day	0.45 gge	$1,750
CNG	$910/gge/day	0.89 gge	$810
Biofuel (Thermochemical)	$3,100/gge/day	0.89 gge	$2,760
Gasoline	$595/gge/day	0.89 gge	$530

NRC assumed 13,000 mi/yr and 40 mpgge (miles per gge) for gasoline, biofuel and CNG vehicles, 80 mpgge for hydrogen and 4.0 mi/kWh for miles driven by electricity. PHEV 10 is assumed to have 20% electric miles and the PHEV 40, 60%.

The effect of capacity utilization on cost varies widely by fuel and is illustrated in Figure 5 for only CNG and Hydrogen (Melaina et al. 2013). For these fuels at least, utilization of capacity is far more important than station size in determining the economics of fuel retailing.



Estimated from data in Melaina et al. (2013) table 4.10.

Figure 5. Estimated impact of capacity utilization on the costs of dispensed CNG and Hydrogen (Based on data from Melaina et al., 2013, table 4.10)

Utilization rates will also strongly influence infrastructure costs per kWh for plug-in vehicles. Melaina et al. (2013, table 4.9) provides levelized infrastructure cost estimates ranging from $0.01 for highly utilized level 1 chargers to $0.15/kWh for a level 2 charger at a single family residence.

Table 5. Estimated Retail Costs of Alternative Fuels in 2020 and Infrastructure Cost Shares

Fuel & Station/Charger	Station/Charger ($/gge)	Fuel ($/gge)	Retail Cost ($/gge)	Infrastructure Share (%)
Gasoline (95,000 gge/mo.)	$0.10	$2.76	$2.86	3%
Electricity				
Level 1 Residence	$2.19	$3.64	$5.83	38%
Level 1 Apartment	$0.36	$4.01	$4.37	8%
Level 2 Residence	$5.10	$3.64	$8.75	58%
Level 2 Workplace	$4.37	$3.64	$8.02	55%
Natural Gas				
CNG (30,000 gge/mo.)	$0.63	$1.52	$2.15	29%
CNG (90,000 gge/mo.)	$0.46	$1.52	$1.98	23%
Hydrogen				
H2 (15,000 gge/mo.)	$1.71	$5.50	$7.21	24%
H2 (34,000 gge/mo.)	$1.42	$5.00	$6.42	22%

Dollars per kWh were converted to $/gge by multiplying by (124,340 Btu/gal)/(3412 Btu/kWh) = 36.442. Based on Melaina et al., 2013, tables 4.9 and 4.10. Retail costs per gge do not match table values due to the use in this table of the 36.442 gge/kWh conversion factor for all categories of electrical charging.

IV. Business Models

This section provides a brief review of business models for each alternative fuels. A business model is a description of the logic of how an organization, creates, delivers and captures value. Value implies demand: customers' willingness to pay for the good or service created. The capture of value by the firm requires a sharing of the added value between the customer and the firm. One archetypical business model is the linear "pipes" model, in which products are produced upstream and sold downstream to the customer. With the advent of the information age, many firms have developed more complex "platform" business models that utilize the internet to facilitate interactions between customers and firms to take advantage of intelligent systems, network effects and self-improving systems. One example is websites that interface with in-vehicle navigation systems to provide not only locations of alternative fuel stations but routing options and sometimes reservations. Chargers that recognize the customer have been used by Tesla to bundle fast recharging with the vehicle purchase. Given the sparseness of existing alternative refueling infrastructure, interactive information systems have become an important component of most alternative fuel business models.

In its simplest form, the value chain for alternative fuels is comprised of four linked components.

Although all four can be important in defining the product, only the refueling infrastructure and customer service components will be considered here. The nature of the business environment for alternative fuels is far more complex than the simple diagram above. It may be useful to distinguish several dimensions that can lead to different business models.

1. Is future demand known (e.g., fleet) or uncertain?
2. Who owns the refueling equipment and how is it financed?
3. Who operates the refueling equipment?
4. Who bills for service and how?
5. Who pays for service and how?
6. Is service bundled with other goods and services (e.g., car purchase)?
7. What indirect or spin-off benefits can be captured?
8. What public policy support is available?

With the possible exception of municipal and business fleets, future demand will be highly uncertain. Uncertainty of demand magnifies risk which discourages investment. Several studies of the cash flows of infrastructure investments have introduced uncertainty by evaluating the known demand business model under alternative scenarios of the evolution of future demand (e.g., Ogden and Nicholas, 2010; Eckerle and Garderet, 2012). A more difficult but potentially more realistic approach would incorporate the interdependence of refueling infrastructure and the demand for vehicles and fuels.

To the extent that markets overestimate the risk of alternative fuels infrastructure investments or underestimate the energy savings they can produce, innovative methods of financing can help create viable business models. Financing methods that have had success promoting energy efficient and renewable energy equipment in other sectors include, 1) leasing equipment to operators to reduce the risk of ownership, 2) energy service performance contracts to reduce the risk of unexpected price fluctuations and 3) clean energy banks that use public funds to make loans directly to finance clean energy systems or leverage private investment by reducing risk to private investors (Dougherty and Nigro, 2013).

How service is billed and paid can also change the business model. For example, is recharging paid and billed per event or per kilowatt-hour, or is it paid by monthly or annual subscription? Does the user pay or does the provider pay as a means of attracting customers for other services or providing benefits to employees? Alternative fuel can be sold separately or bundled with the sale or lease of a vehicle or a battery. For conventional gasoline stations, attracting customers to a convenience store is more important to profitability than selling gasoline. The value to commercial businesses or employers of providing EV charging or alternative fuel refueling is not yet fully understood.

Finally, public policy support can come in many different forms with different implications for successful business models. Policy support may consist of direct and indirect subsidies, mandates or non-monetary privileges such as HOV lane access or free parking. Not only the design and quantity of policy intervention but its dependability can make or break early infrastructure investments. Policies that investors are confident will remain stable for several years are likely to be more effective than policies that must be renewed frequently.

The following subsections briefly describe selected business models that have been tried for each of the alternative fuels.

E85 & Biodiesel

Converting one or more pumps that currently dispense mid-grade of gasoline or diesel fuel is a common business model for E85 or B20 biodiesel refueling (Johnson and Melendez, 2007). Retail margins for gasoline and diesel sales are slim and sales of convenience products are the major source of revenue for many stations. Thus, if offering biofuel can attract additional customers it may generate sufficient revenues to be a profitable investment. Among the competitive advantages suggested for offering biofuel include attracting fleet customers and the perception of being green, patriotic, pro-farmer and cutting-edge (Clean Cities, 2008). On the other hand, only about 14-16 million out of 227 million light-duty vehicles on U.S. roads are capable of safely using E85 (EIA, 2014). Thus, only 7% of the total light-duty market are potential customers (RFA, 2014). All diesel vehicles can use up to B20 without engine or fuel system modifications, although not all manufacturers cover use of B20 in their warrantees (AFDC, 2014c).

Although there are only a few peer-reviewed econometric studies of E85 demand, they generally support the view that E85 sales are very sensitive to the price difference between E85 and gasoline on an energy equivalent basis (Liu and Greene, 2014; Anderson, 2012) and the same is probably true for biodiesel. Thus, price competitiveness must be a key component of successful business models.

Federal grants have played an important role in the deployment of biofuel infrastructure. For example, the Department of Energy’s Clean Cities Program used grants to support the creation of the “planet’s longest biofuels corridor” along I-75 from Sault Ste. Marie, Michigan to Miami, Florida. Both E85 and biodiesel are available along the corridor with no two stations more than 200 miles apart (Chattanoogan, 2014). Established fuel retailers accepted the grants and installed biofuel pumps at their existing stations. Policies supporting the production and sale of biofuels, such as the Renewable Fuels Standard or California’s Low Carbon Fuels Standards have also been critical to biofuel’s market share by creating monetize-able value in the form of renewable identification number (RIN) credits that can be sold and bought to meet federal Renewable Fuels Standards.

Electricity

Electric vehicle recharging can be accomplished at almost any location and a by means of a wide range of equipment with very different capital costs. Planners have identified a hierarchy of needs for EV charging (Langford and Cherry, 2013). Single family home recharging is the lowest level, where the greatest amount of EV charging is done. Approximately half of U.S. households could charge EVs at home. Next comes charging at multi-family dwellings, followed by workplace charging, fleet charging, charging at public places in metropolitan areas and finally intercity charging. Researchers at UC Davis’ Plug-in Hybrid and Electric Vehicle Research Center summarized the challenge of EVSE business models:

“A central problem for developing a system is that there is still no good way to make money on selling electricity to drivers.” (PHEVRC, 2012). Communities and firms are innovating and experimenting at all levels of the hierarchy above home recharging and learning from experience in an effort to discover viable business models. .

The EV charging value chain begins with the source of electricity and the utility company and requires an EVSE infrastructure owner and charging station operator. These may be the same or separate entities. In addition, the owner of the property where the EVSE is located may choose to own or lease the EVSE. Alternatively, a service company could provide the equipment and recharging service for a fee.

The EV charging value chain does not deliver a differentiated product. This fact, in combination with IT technology allows mass customization of access and payment options at no additional cost (ABB, 2011). The kinds of business models EVSE providers can create will be shaped by four factors: 1) drivers need to charge more frequently (every 100 miles or so), 2) charging can be made available almost anywhere by almost anyone, 3) fully charging an EV battery is inexpensive: the cost of electricity to fully charge the 24 kWh battery of a Nissan Leaf, for example, is only $2.40 at $0.10/kWh and $4.80 at $0.20/kWh and, 4) the faster the charge the more it costs to provide (ABB, 2011). To this list could be added the fact that service times are relatively long, on the order of 0.33 to 10 hours. However, EVs can go at least twice as far per unit of on-board energy than conventional vehicles: the cost of electricity to travel the same distance as a conventional vehicle consuming 1 gallon of gasoline is only $0.86 in the state of Washington and up to $2.15 in New York (DOE, 2014).

Existing business models for EV recharging were reviewed by Wells and Nieuwenhuis (2012). In the EU, a common business model is EVSE purchased by property owners, such as retailers or restaurants, who charge for EVSE use either by length of time spent charging or electricity use, with payment by credit card (IEA, 2013). Other businesses provide free charging as a way of attracting customers. Third-party vendors, including utilities, may also own and operate EVSE while charging monthly or annual fees for membership in a recharging network.

Establishing viable business models remains challenging because it is not yet clear what price the market is willing to pay for EV charging, especially in areas where home charging is widely available (IEA, 2013). The rate of growth and ultimate size of the market are also unclear. The failures of Ecotality and Better Place contributed to concerns that there may be no unsubsidized, profitable business model for EV charging (Voelcker, 2013). On the other hand, the jury is still out on many other approaches. Tesla (2014) has bundled vehicle purchase with free access to a network of fast charging stations. Eighty-six fast chargers strategically located across the U.S. to facilitate long distance travel were completed in April 2014. Tesla plans to extend the network so that 98% of Americans will be no more than 100 miles from a fast charger. Bundling this premium service enhances the value of Tesla’s premium electric automobile, which is presumably where the company intends to recapture the value of its EVSE investments. ChargePoint, the largest operator of EVSE stations has a network of 17,000 charging points across the U.S. Unlike former competitors, ChargePoint sells and operates chargers but does not own them, thereby reducing the capital investment required (Tilley, 2014; Hernandez, 2014).

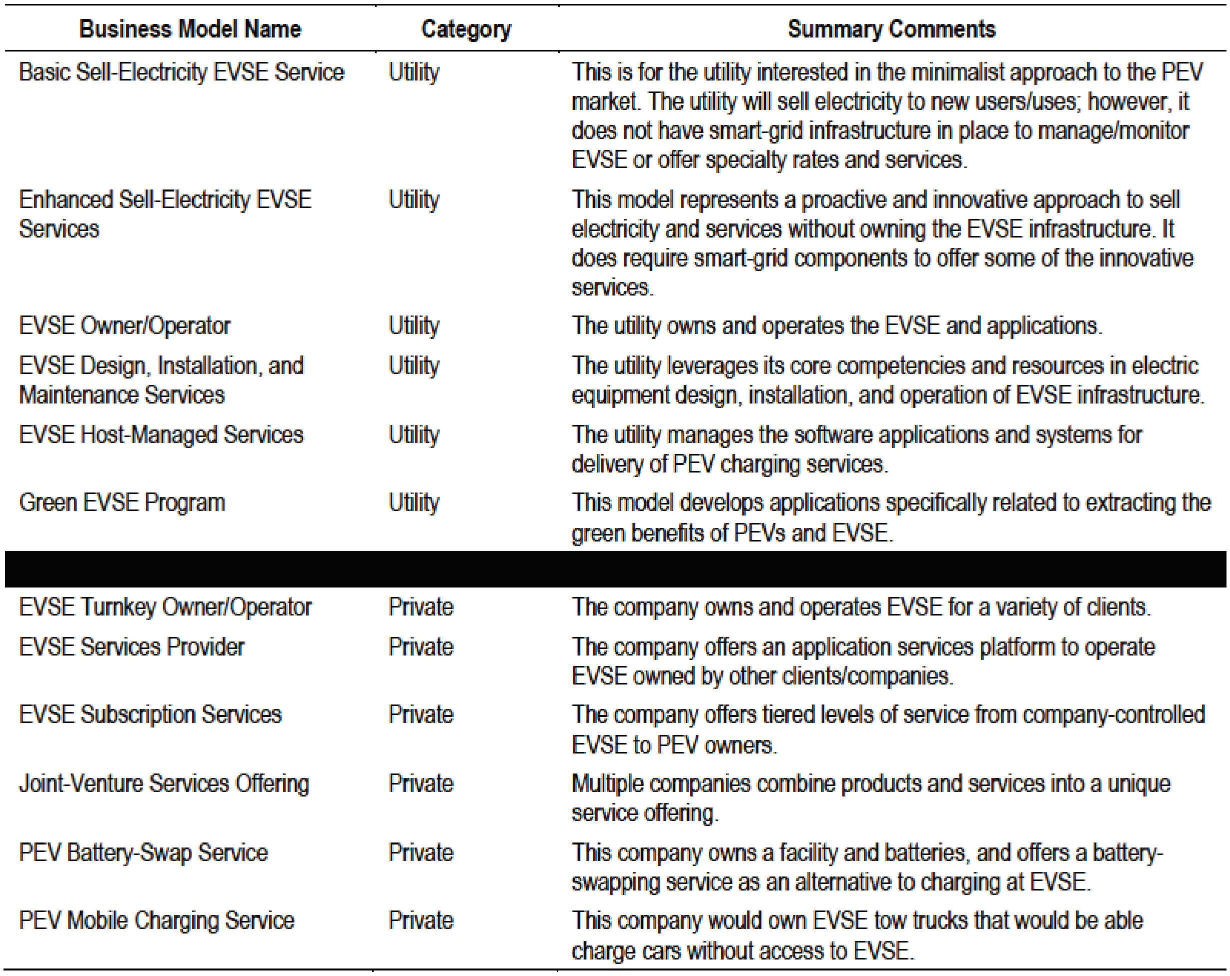
The Texas River Cities Plug-in Electric Vehicle Initiative conducted an extensive examination of potential business models for EVSE infrastructure (UTSA, 2013). Their assessment which was vetted with key stakeholders produced six key findings, summarized below.

1. The PEV industry will continue to develop over the next ten years. The market will likely grow slowly until PEVs achieve price parity with conventional vehicles.
2. The slow growth of the market poses a challenge for the EVSE industry but allows more time to prepare and execute well thought out business models.
3. PEVs offer the single largest potential for energy sales growth for the utility industry.
4. Unsubsidized, large-scale EVSE infrastructure owner/operator business models will have negative returns for years, especially with the higher capital cost fast charger equipment. However, there are strategic and opportunistic ways to build up EVSE infrastructure by partnering with retailers, workplaces and utilities.
5. Even at this early stage of EVSE development, clear trends are emerging to separate software services from EVSE hardware and the consolidation of hardware suppliers to achieve scale economies.
6. Extensive PEV owner research is needed to understand owner habits, likes and dislikes.

The Texas River Cities study focused on two types of business models: 1) utility models and 2) private company models. The models described and analyzed in detail in their report are summarized in table 6. The utility models are distinguished by whether the utility simply provides electricity, adds smart services, owns and operates EVSE equipment, operates it as a service to the owners, provides EVSE support services to owner operators or offers green incentives to encourage PEV ownership and charging. The private company models are distinguished according to whether the company owns and operates a turnkey EVSE service, provides services to EVSE owner/operators, sells a subscription EVSE service to PEV owners, forms a joint venture with a vehicle security company, provides a battery swap service (e.g., Better Place), or provides a mobile recharging service.

Templates were developed to evaluate the cash flows of each business models under various assumptions. Although the results depend critically on the evolution of the stock of PEVs and other factors, in general, business models that involved selling electricity or services only appeared to be profitable from startup while those that involved owning and operating EVSE equipment proved much more challenging.

Table 6. Business Model Summary (UTSA, 2013, table 5-3)



Business Model Name	Category	Summary Comments
Basic Sell-Electricity EVSE Service	Utility	This is for the utility interested in the minimalist approach to the PEV market. The utility will sell electricity to new users/uses; however, it does not have smart-grid infrastructure in place to manage/monitor EVSE or offer specialty rates and services.
Enhanced Sell-Electricity EVSE Services	Utility	This model represents a proactive and innovative approach to sell electricity and services without owning the EVSE infrastructure. It does require smart-grid components to offer some of the innovative services.
EVSE Owner/Operator	Utility	The utility owns and operates the EVSE and applications.
EVSE Design, Installation, and Maintenance Services	Utility	The utility leverages its core competencies and resources in electric equipment design, installation, and operation of EVSE infrastructure.
EVSE Host-Managed Services	Utility	The utility manages the software applications and systems for delivery of PEV charging services.
Green EVSE Program	Utility	This model develops applications specifically related to extracting the green benefits of PEVs and EVSE.
EVSE Turnkey Owner/Operator	Private	The company owns and operates EVSE for a variety of clients.
EVSE Services Provider	Private	The company offers an application services platform to operate EVSE owned by other clients/companies.
EVSE Subscription Services	Private	The company offers tiered levels of service from company-controlled EVSE to PEV owners.
Joint-Venture Services Offering	Private	Multiple companies combine products and services into a unique service offering.
PEV Battery-Swap Service	Private	This company owns a facility and batteries, and offers a battery-swapping service as an alternative to charging at EVSE.
PEV Mobile Charging Service	Private	This company would own EVSE tow trucks that would be able charge cars without access to EVSE.

Natural Gas

The Drive Natural Gas initiative identified three fundamental business models for natural gas refueling based on the ownership of the equipment and whether the customers are fleets or the general public (ANGA & AGA, 2014).

1. Fleet or End-user Ownership
2. Local Distribution Company Ownership
3. Third Party Ownership

Fleet or end-user ownership applies when an entity has vehicles it wishes to refuel with natural gas and prefers to own the refueling infrastructure. The entity may use its own personnel to maintain and operate the infrastructure or contract with a third party for those services. The owner may then contract with a utility or a third party for delivery of the gas to the refueling station.

A CNG refueling station may be owned and operated by a utility or local distribution company. In general, this means that the price charged for the CNG will be regulated at a rate that allows recovery of capital, operating and material costs but no profit. Approximately one third of the public CNG refueling stations in the U.S. follow this model (ANGA & AGA, 2014).

In the third party ownership model a commercial for-profit entity owns the refueling station and operates it for a profit. Some third party stations are owner-operated while others are not. This model requires a location with a sufficiently high level of private CNG demand to allow profitability.

Propane

The most common business model for propane is a centrally fueled business or government fleet. Because of the relatively low cost of propane dispensing equipment, fleets with suitable vehicle usage patterns often find conversion and operation of propane refueling to be profitable (AFDC, 2104d).

Hydrogen

A focus group of fourteen large fuel retailers reviewed five alternative configurations of hydrogen refueling stations at a California workshop in 2010. In addition to commenting on the five examples, the retailers made several general observations about the economics of their industry. First, fuel retailers now rely more on profits from their convenience stores than fuel sales, although profits from fuel sales are still important. Second, station owners must see a payback in 3-5 years to justify investment in alternative fuels infrastructure. Third, consumer demand, the price of gasoline and government policies are the most important factors influencing investments in alternative fuel infrastructure. The value of a green public image has little impact, in the opinion of the retailers.

Regarding the example station business models, the focus group participants judged that “The capital costs of all the configurations are too high without government support.” Rather than building entirely new stations, they considered a preferable approach to be adding one dispenser of hydrogen to an existing gasoline station then expanding as demand warranted. The key concern was minimizing risk in the face of uncertain demand.

Using the station cost assumptions of Ogden and Nicholas (2010), Eckerle and Garderet (2012) estimated cash flow models for 250 kg/d and 400 kg/d hydrogen refueling stations in southern California. Three demand scenarios were based on estimates of FCV sales under the ZEV mandate. The proposed business model was based on a “cash flow incentive” to be given to station operators to negate estimated cash flow losses. A typical 400-500 kg/d station was estimated to require a cash flow incentive of $1.67 million, given the default assumptions about sales margin per kg, demand growth, financing, and investment lifetime. Sensitivity analysis showed that the required cash flow incentive was highly sensitive to capital costs, actual utilization rates, the margin on hydrogen sales and the term of the financing loan. Since utilization rates and sales margins are likely to be uncertain, even with a cash flow incentive equal to the expected present value cash flow losses, investment in a hydrogen refueling station would involve substantial risk.

A detailed assessment of the profitability of 68 hydrogen refueling stations planned for California by 2015 indicated that depending on the rate of growth in FCV sales refueling stations might achieve a positive cash flow in 2017 assuming optimistic growth of the fuel cell vehicle fleet, or in 2020 assuming growth in FCV sales equivalent to one tenth of the historical rate of growth of HEVs in California (Brown et al, 2013). However, the 68 stations would require external financial support ranging from $33 million to $80 million. A key assumption of the analysis was that more stations would not be added to the original 68 over the time period of the analysis. Adding more stations greatly reduces the return on investment of the original 68 stations and lengthens the time to profitability. As noted above, low utilization rates greatly increase the cost per gge of fuel dispensed (see Figure 5). On the other hand, adding more stations would make FCVs more attractive to potential buyers and increase the demand for hydrogen. At present, the nature of this potential transition problem is not well understood. How to bridge the gap between the initial government-subsidized stations and a sustainable retail market is likely to be a major challenge.

California's ZEV mandate creates an incentive for automobile manufacturers not only to bring vehicles to market but to insure that fuel is available for them. Toyota is reported to have provided capital support to First Element, a company that won state support to build and operate 19 hydrogen stations in California (Ohnsman, 2014). Hyundai is bundling free hydrogen with the lease of its 2015 fuel cell Tucson SUV (Edmunds, 2014). Although Hyundai is not itself building hydrogen refueling infrastructure, making hydrogen costless to drivers helps insure a market for fuel retailers. In the future, alternative fuel business models may include greater participation from automobile manufacturers subject to policy-driven requirements or incentives to sell AFVs.

Dimensions of Alternative Fuel Business Models

Alternative fuel business models have several dimensions. Who owns and who operates the refueling equipment are commonly used to describe alternative business models. Because capital investment and the return to it are critically important, the method of financing should be another key dimension. Because business models are about making money, sources of revenue are also an essential element. These four dimensions and illustrative categories along each dimension are listed in Table 7. The categories are not intended to be exhaustive. They are there to stimulate creative thinking about potentially viable business models. Because of the strong public interest in alternative fuels and the major economic hurdles to the deployment of infrastructure during the early stages of market development, public policy forms a critical fifth dimension that will be discussed in the following section. The potential diversity of business models can be illustrated by the fact that there are nearly 800 different combinations of just the alternatives listed in table 6. Since there can be multiple sources of financing and revenue, and since this list is not complete, the actual number of potential business models is far greater.

Table 7. Dimensions of Alternative Fuels Infrastructure Business Models

Ownership	Operator	Financing	Revenue Sources
Energy Supplier Fuel Retailer State Government Municipal Gov't. Other	Owner Retailer Third party	Financial Institution Government Energy Company/Gov't. Gov't/AVF Manufacturer AVF Manufacturer Stock Market Crowd Sourcing Employer Fleet Owner/Operator Energy Supplier Retailer	Energy Sales Per unit Flat fee Energy Bundled e.g., Tesla, Hyundai Indirect Traffic generator Advertising Credit Markets (ZEV, LCFS, RFS, GHG) Intangibles Employee benefit Public relations

V. Policies

Most alternative fuel infrastructure will require some form of public policy support during the initial phase of market development. With the possible exception of vehicles that can be adequately refueled at a central location, the refueling infrastructure necessary for alternative fuel and vehicle market development must exceed economical levels for at least several years while the on-road fleet of alternative fuel vehicles increases. This makes achieving positive net present values for early infrastructure investments difficult or impossible in the absence of external support. If this assertion is correct it raises two Inter-related questions. What policies should be used to subsidize refueling infrastructure? What business models can efficiently use those subsidies?

Public policy support can take various forms. Capital costs may be subsidized by cost-sharing grants or tax policies ranging from credits or deductions to depreciation rules. Regulations or mandates can require firms to provide alternative fuels, essentially requiring them to cross-subsidize the capital investments from other business activities. Alternative fuel sales can be subsidized by exemption from excise or sales taxes, via rebates or by relaxing other regulations (e.g., CAFE credits). Sales of alternative fuels can be mandated. The American Recovery and Reinvestment Act provided approximately $5 billion to support the deployment of electric vehicles, batteries, components and chargers. By June of 2013, deployment of 500 stations had been supported with plans for 20,000 more by the end of the year.

California's efforts to deploy hydrogen refueling infrastructure in advance of ZEV requirements provides another example of how public policies can inspire innovative business models for alternative fuel infrastructure. The California Energy Commission has announced awards of $46.6 million to fund up to 90% of the capital cost of 28 stationary and 1 mobile hydrogen refueling stations in California (Schilling, 2014) and funding has been committed for a total of 100 stations. Cost sharing of O&M costs of up to

$100,000 per station per year for up to three years was also offered. The awards went to eight different applicants who submitted bids to build and operate refueling stations. Among the criteria the CEC used to evaluate proposals was location. Potential bidders were provided a government analysis of preferred locations but were able to propose alternatives they considered preferable.

FirstElement, a start-up company that won grants for 19 stations, was able to obtain financial backing from Toyota Motor Corporation (Ohnsman, 2014). The exact terms of Toyota's financial support have not been disclosed but the capitalization amounts to at least $7.2 million. The ZEV requirement obligates Toyota to sell zero emission vehicles in California and it will obviously be easier to sell hydrogen fuel cell vehicles if hydrogen fuel is available. In this way, the ZEV policy may be creating an opportunity for fuel suppliers to create viable business models by collaborating with automobile manufacturers. A Toyota spokesman summarized Toyota's position: "Through this financial arrangement with FirstElement, Toyota is showing its full commitment to deploy zero-emission fuel-cell vehicles here." (Ohnsman, 2014)

In addition to direct subsidies or mandates, alternative fuels can be supported indirectly. Competing fuels can be taxed to reflect their social costs. Alternative fuel vehicles may be subsidized or mandated (e.g., ZEV mandates). California's zero emission vehicle (ZEV) mandates require manufacturers to sell plug-in electric or fuel cell vehicles, creating the basis for a market for recharging and hydrogen refueling infrastructure. The Corporate Average Fuel Economy (CAFE) standards incentivized the production of millions fuel flexible vehicles capable of using E85 by basing manufacturers' CAFE numbers on the assumption that E85 would be used 50% of the time and by not including the energy content of ethanol in a vehicle's MPG estimate. The California Air Resources Board's (CARB) Clean Fuel Outlet regulation required sellers of petroleum fuels to also provide alternative fuels but was later modified to focus on funding the construction of hydrogen refueling stations (ARB, 2014).

The DOE's Clean Cities EV Readiness Project highlighted the importance of local and state policy support in the form of harmonized codes and standards, planning, and low-cost incentives (Langford and Cherry, 2013). Possible low-cost incentives include waiving or reducing the cost of EVSE permitting fees, offering preferred parking, free parking or HOV lane access for users of EVSE infrastructure, and offering tax rebates or credits on EVSE installation. Such incentives have been shown to be important. Six out of seven plug-in vehicle owners who received rebates from the state of California also have an HOV sticker for their vehicle (Tal and Nicholas, 2014).

The NRC (2013) report highlights the need for continued technological progress and government support for research and development. For many alternative fuels, refueling infrastructure is a relatively mature technology but for others it is not. In addition, cost reductions and performance improvements to alternative fuel vehicles will indirectly benefit alternative fuels infrastructure by enabling a more rapid expansion of fuels markets.

Unfortunately, public policy for support of alternative fuels infrastructure in both the short and long run remains unsettled. The EU's Global EV Outlook (IEA, 2013) seems to imply unqualified support for public-private cost-sharing during initial infrastructure deployment combined with an expectation that the private sector must be responsible for the long-term viability of EVSE infrastructure (IEA, 2013, p. 28). The transition to alternative fuels and vehicles not only poses a new challenge for public policy, but society will have a continuing interest in the public good benefits of alternative fuels well beyond the early stages of a transition. Accomplishing the transition will require matching innovative business models for alternative fuels infrastructure with strong public policies to induce the transition and durable policies to sustain it.

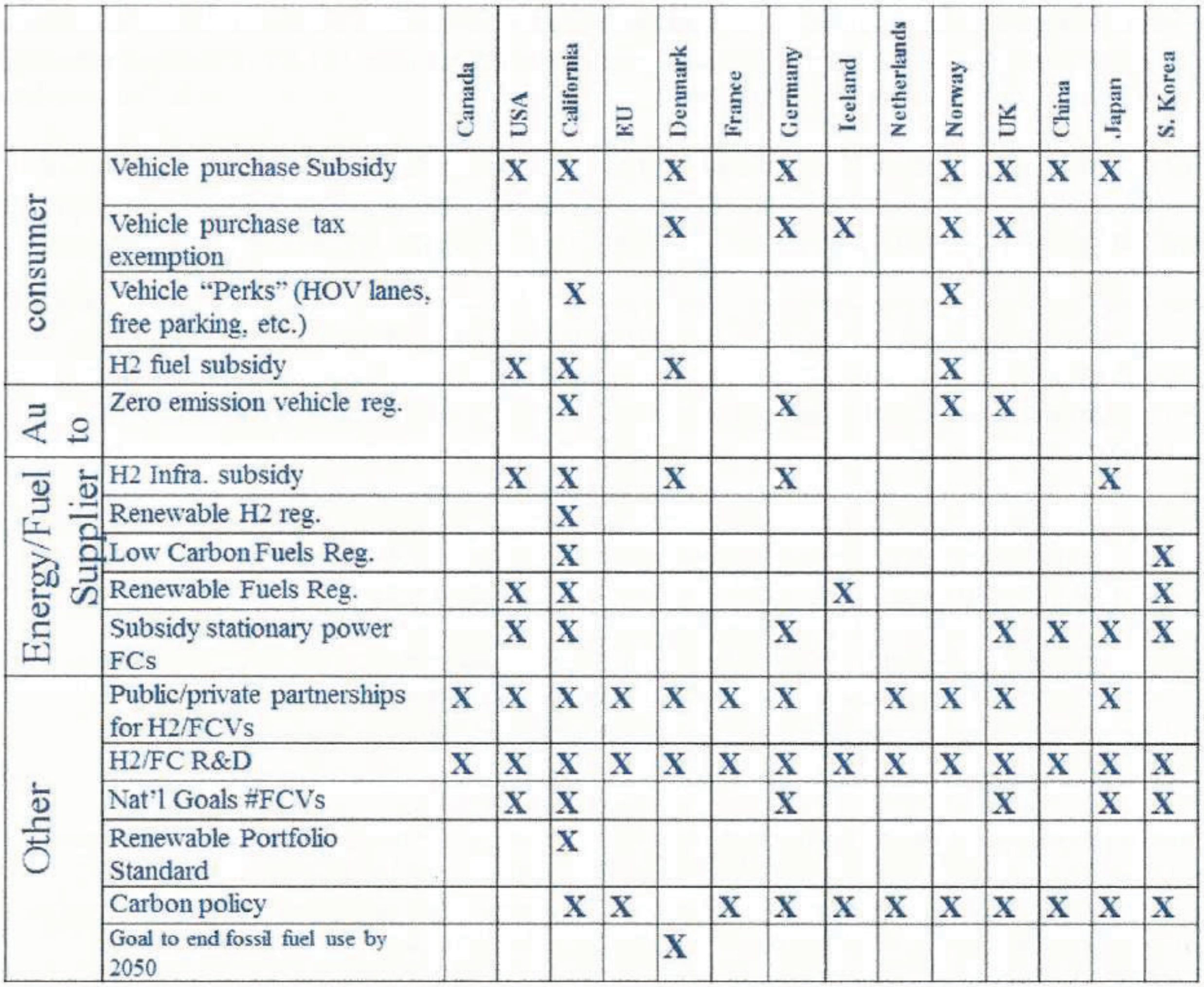
Dimensions of Policy Support

Public policy is an important component of most alternative fuels business models because of the riskiness of investments during early market development and the strong public interest in the success of alternative fuels. Public policies can create or enhance revenue sources for alternative fuel infrastructure. Subsidies for alternative fuels can be a direct source of revenue as can grants directly supporting infrastructure investment. Loan guarantees can reduce risk. Mandates require firms to cross-subsidize alternative fuels with revenues from their other products. Policies that promote the purchase and use of alternative fuel vehicles speed up growth of the market, reducing the time to profitability for refueling infrastructure. Non-monetary incentives such as HOV lane access or preferred parking privileges can stimulate demand for both vehicles and fuels. The following list of policy options is not intended to be exhaustive.

- Fuel subsidies or mandates
    - Tax exemption
    - Other
- Grant or loan guarantee
    - Capital
    - O&M
- Vehicle subsidies or mandates
    - ZEV
    - Tax credit
    - Rebate/Feebate
    - Other
- Non-monetary incentives
    - HOV access
    - Parking privileges
    - Other

Public policies to promote hydrogen fuel cell vehicles in thirteen countries and the state of California were summarized by Ogden et al. (2014) and are shown in table 8. Similarly diverse policies have been or could be used to support other alternative fuels.

Table 8. Hydrogen and Fuel Cell Vehicle Related Policies in Various Countries (Ogden et al., 2014)



		Canada	USA	California	EU	Denmark	France	Germany	Iceland	Netherlands	Norway	UK	China	Japan	S. Korea
consumer	Vehicle purchase Subsidy		X	X		X		X			X	X	X	X	
	Vehicle purchase tax exemption					X		X	X		X	X			
	Vehicle "Perks" (HOV lanes, free parking, etc.)			X							X				
	H2 fuel subsidy		X	X		X					X				
Auto	Zero emission vehicle reg.			X				X			X	X			
Energy/Fuel Supplier	H2 Infra. subsidy		X	X		X		X						X	
	Renewable H2 reg.			X											
	Low Carbon Fuels Reg.			X											X
	Renewable Fuels Reg.		X	X					X						X
	Subsidy stationary power FCs		X	X				X				X	X	X	X
Other	Public/private partnerships for H2/FCVs	X	X	X	X	X	X	X		X	X	X		X	
	H2/FC R&D	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Nat'l Goals #FCVs		X	X				X				X		X	X
	Renewable Portfolio Standard			X											
	Carbon policy			X	X		X	X	X	X	X	X	X	X	X
	Goal to end fossil fuel use by 2050					X									

Combining policy options with the dimensions of ownership, operation, financing and revenue sources creates an enormous number of potential business models. If alternative fuels are to succeed, policy/business model combinations must be found that are cost-effective and sustainable, both economically and politically.

VI. Summary

This overview of alternative fuels infrastructure challenges and opportunities points to three fundamental generalizations. First, the public has a strong interest in the success of alternative fuels, derived from the need to mitigate global climate change, enhance energy security and create a sustainable energy system. The public interest has been expressed in the form of policies ranging from subsidies to mandates, to a variety of non-monetary incentives. Second, during the early stages of the transition to alternative vehicles and fuels, it will be difficult if not impossible for firms to profitably invest in alternative fuels infrastructure without some form of external support. Cash flow analyses of early alternative fuels infrastructure investments typically show several years of losses while the stock of alternative fuel vehicles grows to a level of demand capable of profitably sustaining unsubsidized investments. Finally, the alternative fuels market is subject to considerably uncertainty. Uncertainties about future energy prices, public policies and vehicle technology create a risky context for investment.

Given these premises, the challenge for alternative fuels infrastructure providers is how to create efficient business models that monetize incentives for alternative vehicles and fuels to allow alternative fuels markets to quickly become profitable. Conversely, the challenge for government is how to structure cost-effective public policies that create monetize-able incentives for alternative fuels infrastructure. Both business models and policies must be sufficiently durable to survive a transition period that will likely last a decade or more.

The choice of the “chicken or egg” metaphor to describe the alternative fuels infrastructure challenge may be an unfortunate one. The problem is not one of providing a fully developed refueling infrastructure before the first vehicle is sold nor is it one of replacing all conventional petroleum-powered vehicles with alternative fuel vehicles before the first station is built. Rather, it is a problem of creating the conditions under which vehicles and fuels can co-evolve. We now understand that the co-evolution of alternative vehicles and fuels induces strong positive feedbacks and network external benefits that create path-dependencies and tipping points in the energy system. In reality, neither the chicken nor the egg came first. Instead, evolution progressed through interaction of the organism with its environment. If a transition to a sustainable energy system is indeed essential, then the challenge is to create an environment in which alternative fuels can evolve to become an incumbent energy system that better serves the needs of current and future generations.

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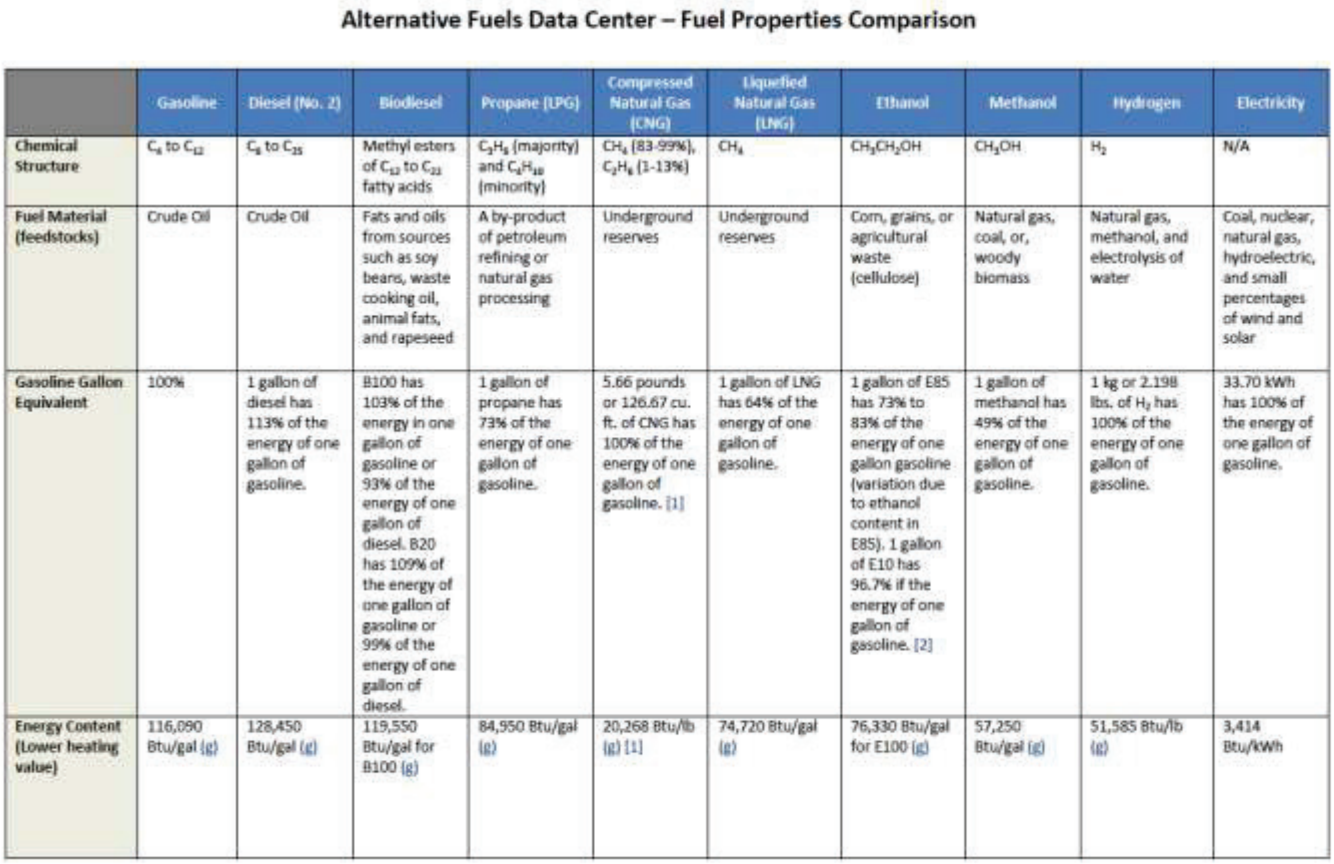
Appendix 1. Definition of Alternative Fuels

The Energy Policy Act of 1992 defines an alternative fuel as:

- Biodiesel (B100)
- Natural gas and liquid fuels domestically produced from natural gas
- Propane (liquefied petroleum gas)
- Electricity
- Hydrogen
- Blends of 85% or more of methanol, denatured ethanol, and other alcohols with gasoline or other fuels
- Methanol, denatured ethanol, and other alcohols
- Coal-derived, domestically produced liquid fuels
- Fuels (other than alcohol) derived from biological materials
- P-Series fuels

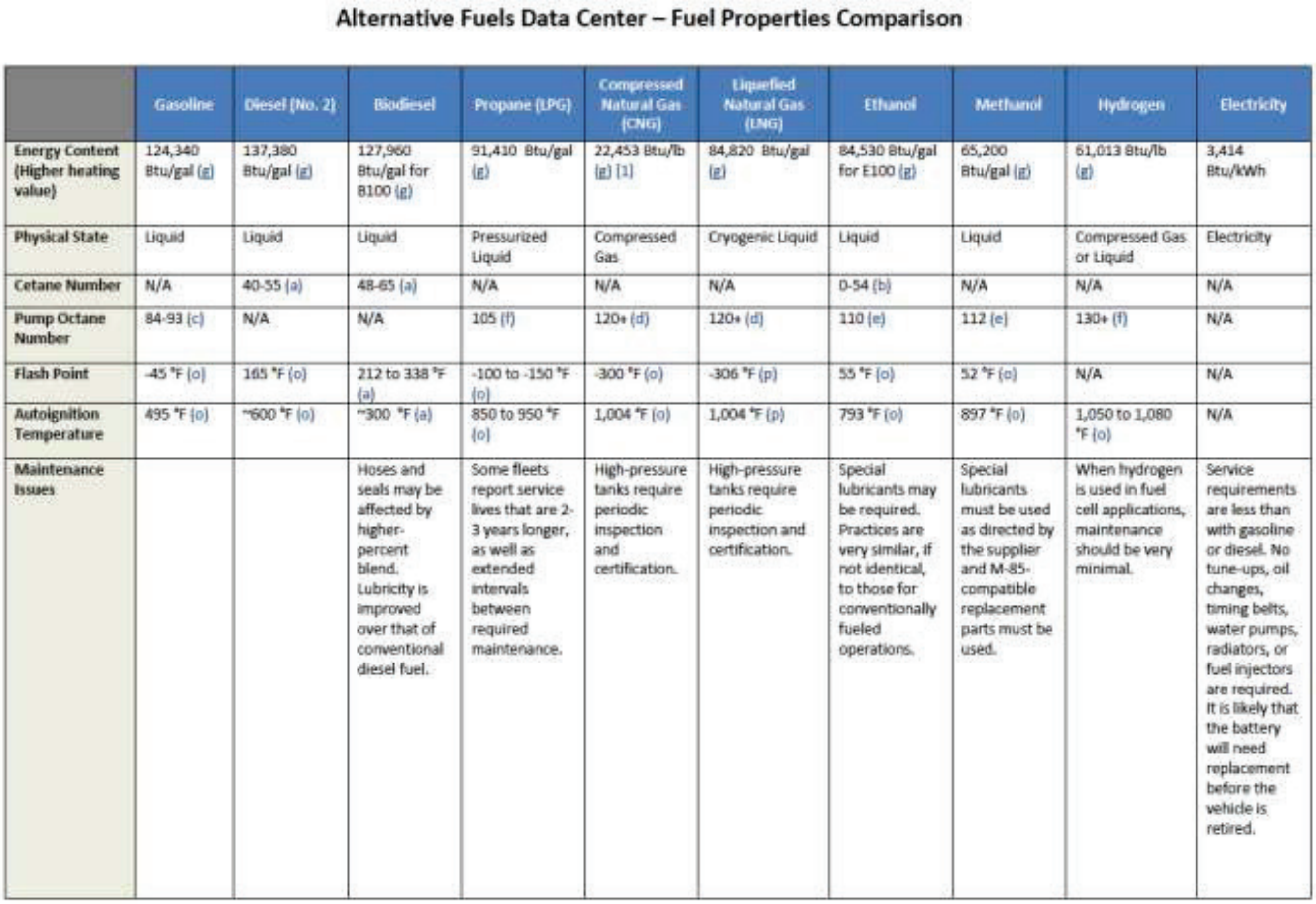
This paper covers biodiesel blends as low as B20, natural gas, propane, electricity, hydrogen and E85.

Appendix 2. Properties of Alternative Fuels (AFDC, 2014)



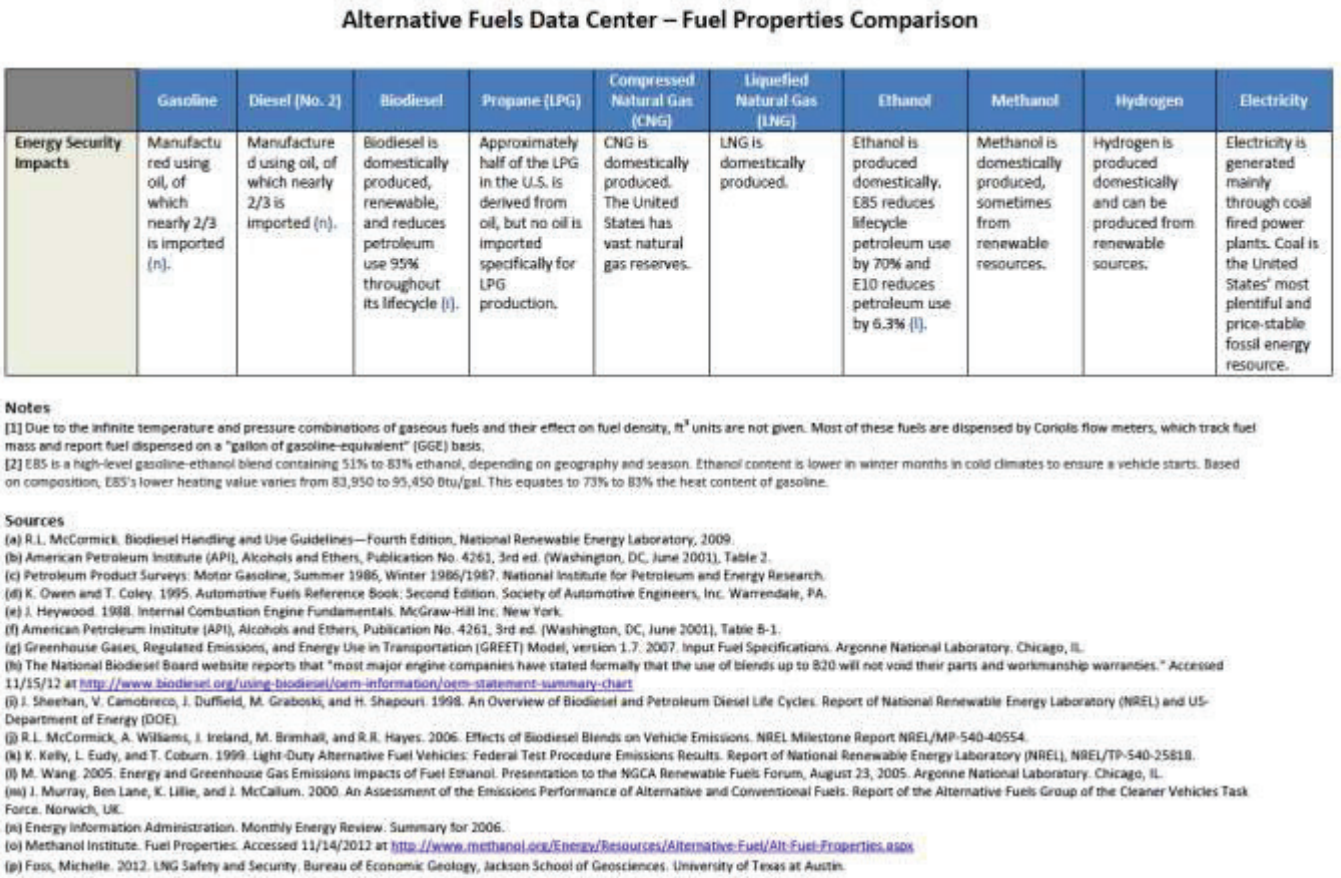
Alternative Fuels Data Center – Fuel Properties Comparison

	Gasoline	Diesel (No. 2)	Biodiesel	Propane (LPG)	Compressed Natural Gas (CNG)	Liquefied Natural Gas (LNG)	Ethanol	Methanol	Hydrogen	Electricity
Chemical Structure	C_4 to C_{12}	C_8 to C_{25}	Methyl esters of C_{12} to C_{22} fatty acids	C_3H_8 (majority) and C_4H_{10} (minority)	CH_4 (83-99%), C_2H_6 (1-13%)	CH_4	CH_3CH_2OH	CH_3OH	H_2	N/A
Fuel Material (feedstocks)	Crude Oil	Crude Oil	Fats and oils from sources such as soy beans, waste cooking oil, animal fats, and rapeseed	A by-product of petroleum refining or natural gas processing	Underground reserves	Underground reserves	Corn, grains, or agricultural waste (cellulose)	Natural gas, coal, or, woody biomass	Natural gas, methanol, and electrolysis of water	Coal, nuclear, natural gas, hydroelectric, and small percentages of wind and solar
Gasoline Gallon Equivalent	100%	1 gallon of diesel has 113% of the energy of one gallon of gasoline.	B100 has 103% of the energy in one gallon of gasoline or 93% of the energy of one gallon of diesel. B20 has 109% of the energy of one gallon of gasoline or 99% of the energy of one gallon of diesel.	1 gallon of propane has 73% of the energy of one gallon of gasoline.	5.66 pounds or 126.67 cu. ft. of CNG has 100% of the energy of one gallon of gasoline. [1]	1 gallon of LNG has 64% of the energy of one gallon of gasoline.	1 gallon of E85 has 73% to 83% of the energy of one gallon gasoline (variation due to ethanol content in E85). 1 gallon of E10 has 96.7% if the energy of one gallon of gasoline. [2]	1 gallon of methanol has 49% of the energy of one gallon of gasoline.	1 kg or 2.198 lbs. of H_2 has 100% of the energy of one gallon of gasoline.	33.70 kWh has 100% of the energy of one gallon of gasoline.
Energy Content (Lower heating value)	116,090 Btu/gal (g)	128,450 Btu/gal (g)	119,550 Btu/gal for B100 (g)	84,950 Btu/gal (g)	20,268 Btu/lb (g) [1]	74,720 Btu/gal (g)	76,330 Btu/gal for E100 (g)	57,250 Btu/gal (g)	51,585 Btu/lb (g)	3,414 Btu/kWh



Alternative Fuels Data Center – Fuel Properties Comparison

	Gasoline	Diesel (No. 2)	Biodiesel	Propane (LPG)	Compressed Natural Gas (CNG)	Liquefied Natural Gas (LNG)	Ethanol	Methanol	Hydrogen	Electricity
Energy Content (Higher heating value)	124,340 Btu/gal (g)	137,380 Btu/gal (g)	127,960 Btu/gal for B100 (g)	91,410 Btu/gal (g)	22,453 Btu/lb (g) [1]	84,820 Btu/gal (g)	84,530 Btu/gal for E100 (g)	65,200 Btu/gal (g)	61,013 Btu/lb (g)	3,414 Btu/kWh
Physical State	Liquid	Liquid	Liquid	Pressurized Liquid	Compressed Gas	Cryogenic Liquid	Liquid	Liquid	Compressed Gas or Liquid	Electricity
Cetane Number	N/A	40-55 (a)	48-65 (a)	N/A	N/A	N/A	0-54 (b)	N/A	N/A	N/A
Pump Octane Number	84-93 (c)	N/A	N/A	105 (f)	120+ (d)	120+ (d)	110 (e)	112 (e)	130+ (f)	N/A
Flash Point	-45 °F (o)	165 °F (o)	212 to 338 °F (a)	-100 to -150 °F (o)	-300 °F (o)	-306 °F (p)	55 °F (o)	52 °F (o)	N/A	N/A
Autoignition Temperature	495 °F (o)	~600 °F (o)	~300 °F (a)	850 to 950 °F (o)	1,004 °F (o)	1,004 °F (p)	793 °F (o)	897 °F (o)	1,050 to 1,080 °F (o)	N/A
Maintenance Issues			Hoses and seals may be affected by higher-percent blend. Lubricity is improved over that of conventional diesel fuel.	Some fleets report service lives that are 2-3 years longer, as well as extended intervals between required maintenance.	High-pressure tanks require periodic inspection and certification.	High-pressure tanks require periodic inspection and certification.	Special lubricants may be required. Practices are very similar, if not identical, to those for conventionally fueled operations.	Special lubricants must be used as directed by the supplier and M-85-compatible replacement parts must be used.	When hydrogen is used in fuel cell applications, maintenance should be very minimal.	Service requirements are less than with gasoline or diesel. No tune-ups, oil changes, timing belts, water pumps, radiators, or fuel injectors are required. It is likely that the battery will need replacement before the vehicle is retired.



Alternative Fuels Data Center – Fuel Properties Comparison

	Gasoline	Diesel (No. 2)	Biodiesel	Propane (LPG)	Compressed Natural Gas (CNG)	Liquefied Natural Gas (LNG)	Ethanol	Methanol	Hydrogen	Electricity
Energy Security Impacts	Manufactured using oil, of which nearly 2/3 is imported (n).	Manufactured using oil, of which nearly 2/3 is imported (n).	Biodiesel is domestically produced, renewable, and reduces petroleum use 95% throughout its lifecycle (i).	Approximately half of the LPG in the U.S. is derived from oil, but no oil is imported specifically for LPG production.	CNG is domestically produced. The United States has vast natural gas reserves.	LNG is domestically produced.	Ethanol is produced domestically. E85 reduces lifecycle petroleum use by 70% and E10 reduces petroleum use by 6.3% (l).	Methanol is domestically produced, sometimes from renewable resources.	Hydrogen is produced domestically and can be produced from renewable sources.	Electricity is generated mainly through coal fired power plants. Coal is the United States' most plentiful and price-stable fossil energy resource.

Notes

[1] Due to the infinite temperature and pressure combinations of gaseous fuels and their effect on fuel density, ft^3 units are not given. Most of these fuels are dispensed by Coriolis flow meters, which track fuel mass and report fuel dispensed on a "gallon of gasoline-equivalent" (GGE) basis.

[2] E85 is a high-level gasoline-ethanol blend containing 51% to 83% ethanol, depending on geography and season. Ethanol content is lower in winter months in cold climates to ensure a vehicle starts. Based on composition, E85's lower heating value varies from 83,950 to 95,450 Btu/gal. This equates to 73% to 83% the heat content of gasoline.

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Appendix 3. Table A-3. Total Public Alternative Fueling Station Counts (AFDC, 2014)

STATE	Biodiesel	CNG	E85	Electric* (stations/outlets)	HY	LNG	LPG	Totals** by State
US Totals by fuel	**290**	**737**	**2,418**	**8,427 / 20,296**	**12**	**58**	**2,714**	**26,525**
Alabama	4	8	25	34 / 45	0	1	112	195
Alaska	0	1	0	0 / 0	0	0	6	7
Arizona	5	10	23	275 / 693	0	1	66	798
Arkansas	1	7	36	21 / 32	0	1	37	114
California	51	155	73	1,835 / 5,274	10	14	223	5,800
Colorado	7	18	77	165 / 328	0	0	48	478
Connecticut	0	7	1	148 / 263	1	1	15	288
Delaware	0	1	0	11 / 19	0	0	6	26
District of Columbia	0	0	1	56 / 121	0	0	0	122
Florida	6	13	45	474 / 1,066	0	1	59	1,190
Georgia	6	14	45	235 / 529	0	2	59	655
Hawaii	9	0	0	158 / 362	0	0	3	374
Idaho	2	2	6	12 / 20	0	6	25	61
Illinois	2	15	207	297 / 606	0	1	102	933
Indiana	3	18	173	93 / 179	0	2	59	434
Iowa	8	4	187	45 / 87	0	0	17	303
Kansas	4	5	24	56 / 114	0	0	36	183
Kentucky	2	4	51	26 / 87	0	0	46	190
Louisiana	0	16	6	26 / 45	0	1	31	99
Maine	2	0	0	16 / 23	0	0	9	34
Maryland	3	2	14	243 / 572	0	0	17	608
Massachusetts	3	11	8	235 / 586	0	0	19	627
Michigan	11	15	196	260 / 676	0	0	69	967
Minnesota	8	9	274	162 / 351	0	0	30	672
Mississippi	0	4	2	17 / 19	0	0	109	134
Missouri	1	5	95	83 / 154	0	0	60	315
Montana	1	0	0	2 / 5	0	0	49	55
Nebraska	3	5	67	18 / 33	0	0	21	129
Nevada	2	7	17	85 / 244	0	2	36	308
New Hampshire	1	1	0	26 / 37	0	0	11	50
New Jersey	1	8	3	99 / 197	0	0	9	218
New Mexico	3	5	8	19 / 53	0	0	46	115
New York	6	38	70	416 / 885	0	0	53	1,052
North Carolina	24	20	9	214 / 482	0	0	84	619
North Dakota	1	0	55	3 / 4	0	0	20	80
Ohio	7	22	111	111 / 177	0	2	59	378
Oklahoma	0	79	22	19 / 28	0	1	144	274
Oregon	23	4	7	373 / 883	0	1	31	949
Pennsylvania	4	26	30	151 / 267	0	0	51	378
Rhode Island	3	3	0	61 / 148	0	0	6	160
South Carolina	17	5	57	118 / 207	1	1	36	324
South Dakota	0	0	87	7 / 19	0	0	18	124
Tennessee	23	9	51	304 / 730	0	2	90	905
Texas	5	51	94	557 / 1,453	0	9	457	2,069
Utah	3	44	4	50 / 94	0	7	26	178
Vermont	2	1	0	38 / 82	0	0	2	87
Virginia	3	5	10	179 / 488	0	0	51	557
Washington	17	7	6	432 / 1,193	0	1	68	1,292
West Virginia	0	3	5	18 / 87	0	0	12	107
Wisconsin	3	43	130	137 / 235	0	1	53	465
Wyoming	0	7	6	7 / 14	0	0	18	45

*Includes legacy chargers, but does not include residential electric charging infrastructure.
**Totals by States indicate the total number of stations for all fuel types combined. Individual stations are counted multiple times if the station offers multiple types of fuel. For Electric, the total number of charging outlets was used in the calculation.

Legend

Biodiesel-B20 and above
CNG-Compressed Natural Gas
E85-Ethanol Flex Fuel
Electric-Electric Vehicle Supply Equipment (EVSE)
HY-Hydrogen
LNG-Liquefied Natural Gas
LPG-Propane (Liquefied Petroleum gas)

Appendix 4. Geography of Alternative Fuel Refueling Stations in the U.S. in August 2014

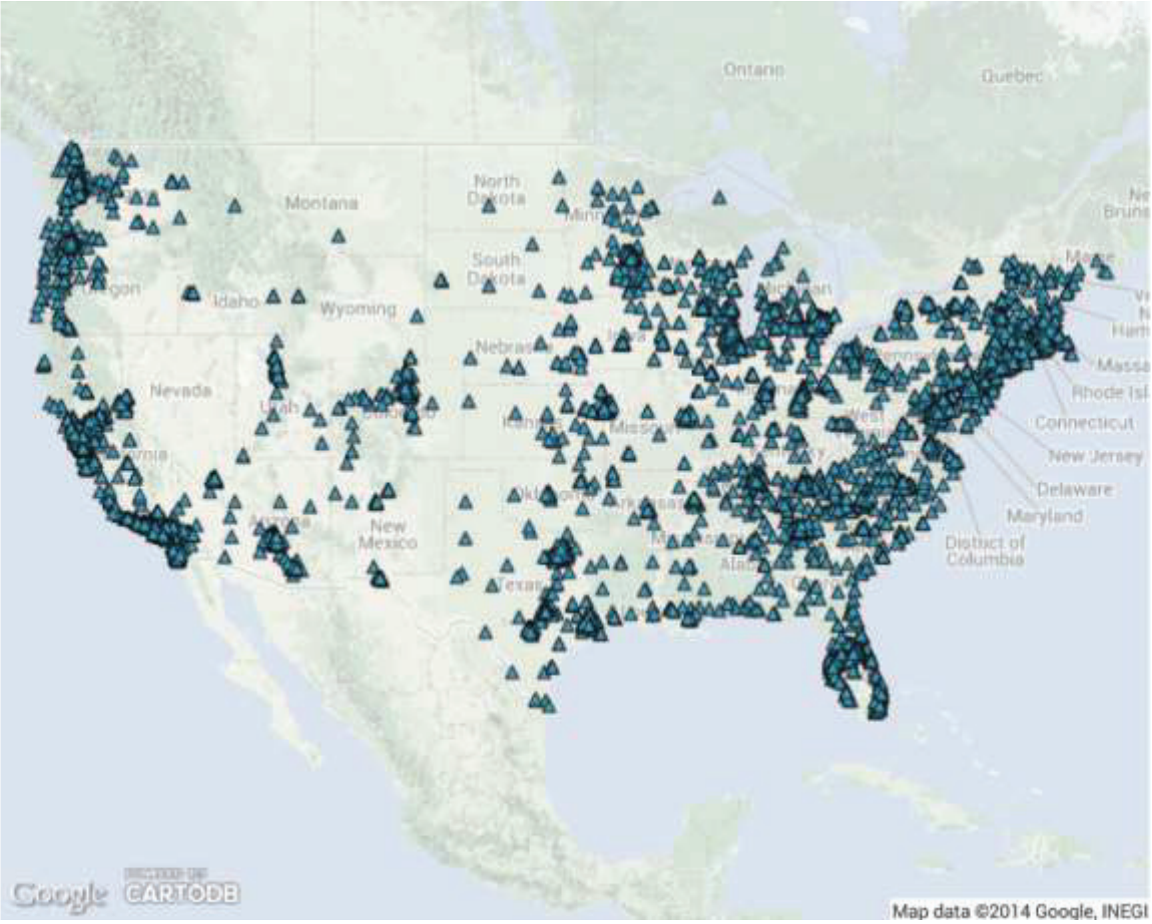

Figure A4-1. 8,353 Public Electric Vehicle Recharging Stations (21,199 electrical outlets).

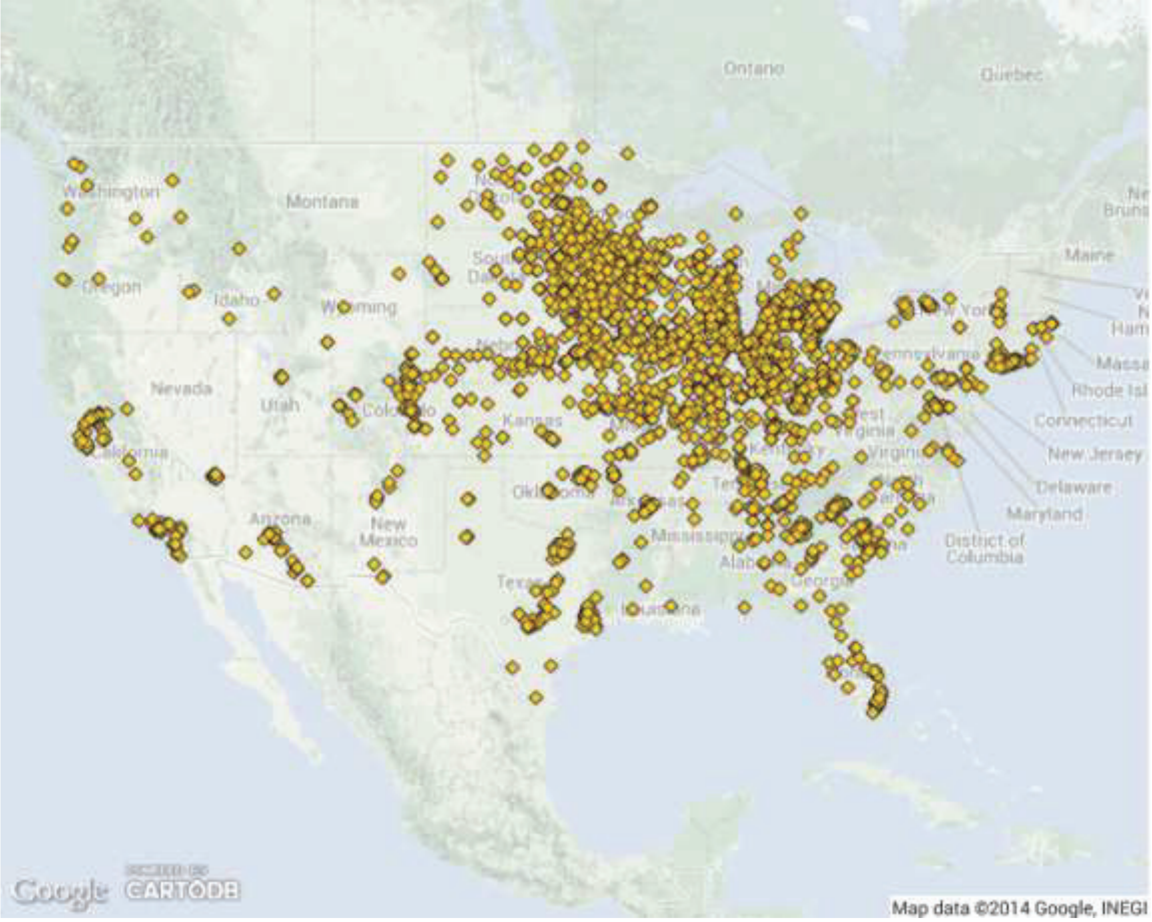

Figure A4-2. 2,418 E85 Refueling Stations.

Figure A4-3. 290 Biodiesel Refueling Stations.

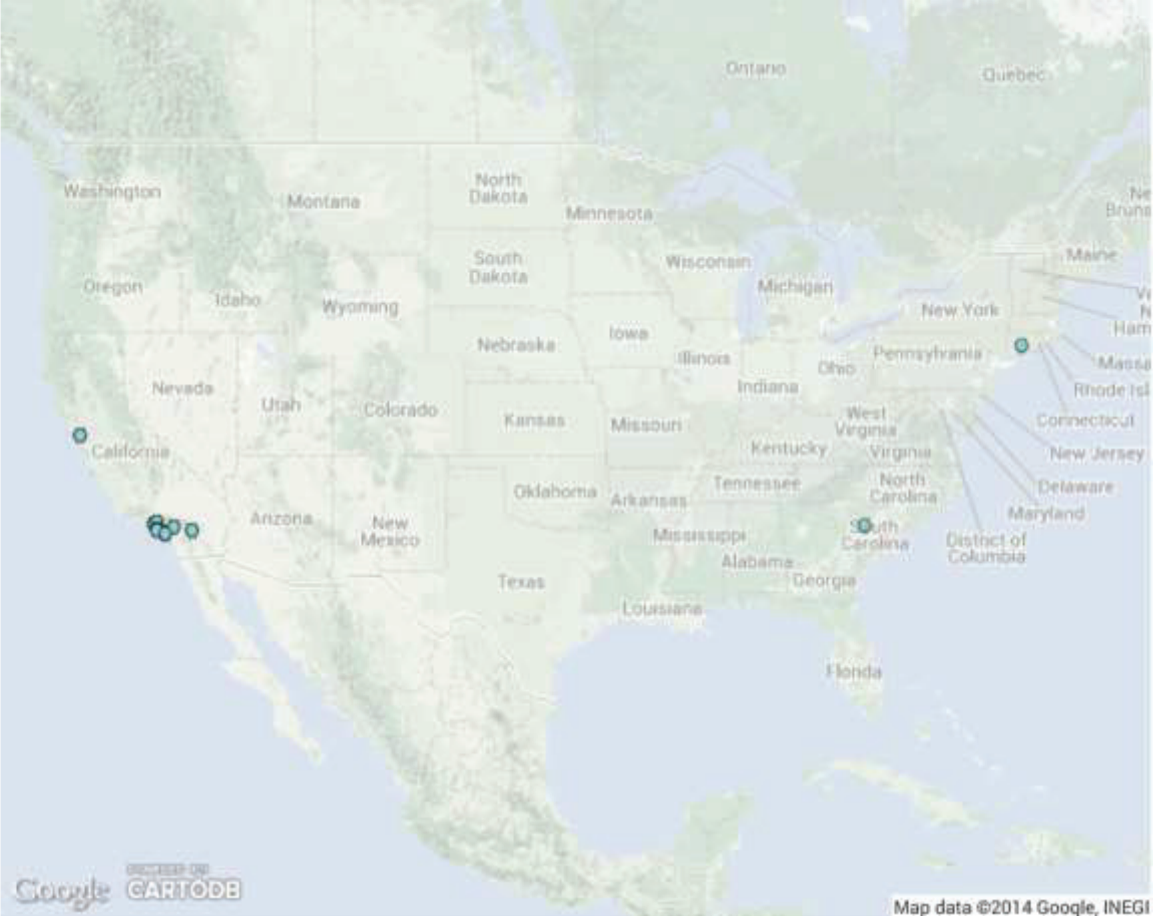

Figure A4-4. 12 Hydrogen Refueling Stations.

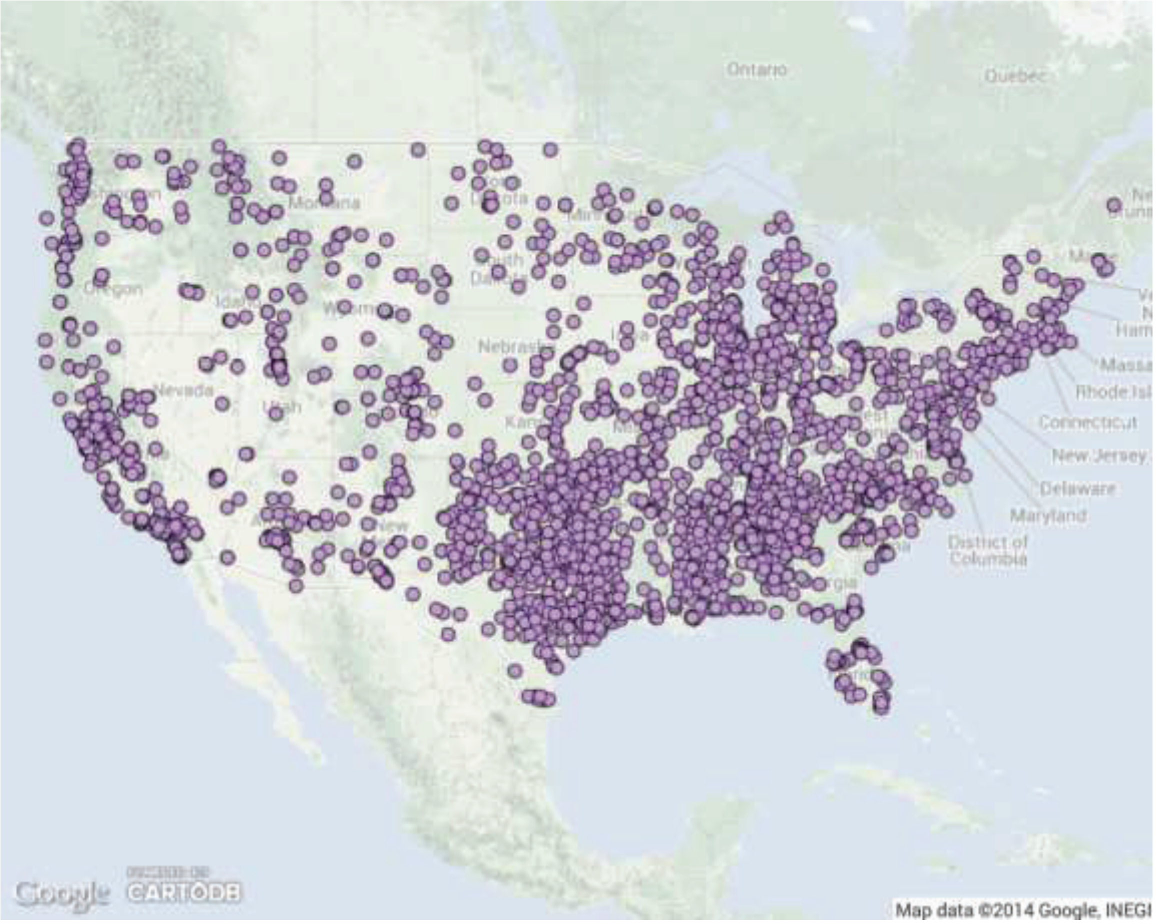

Figure A4.5. 2,714 Propane Refueling Stations.

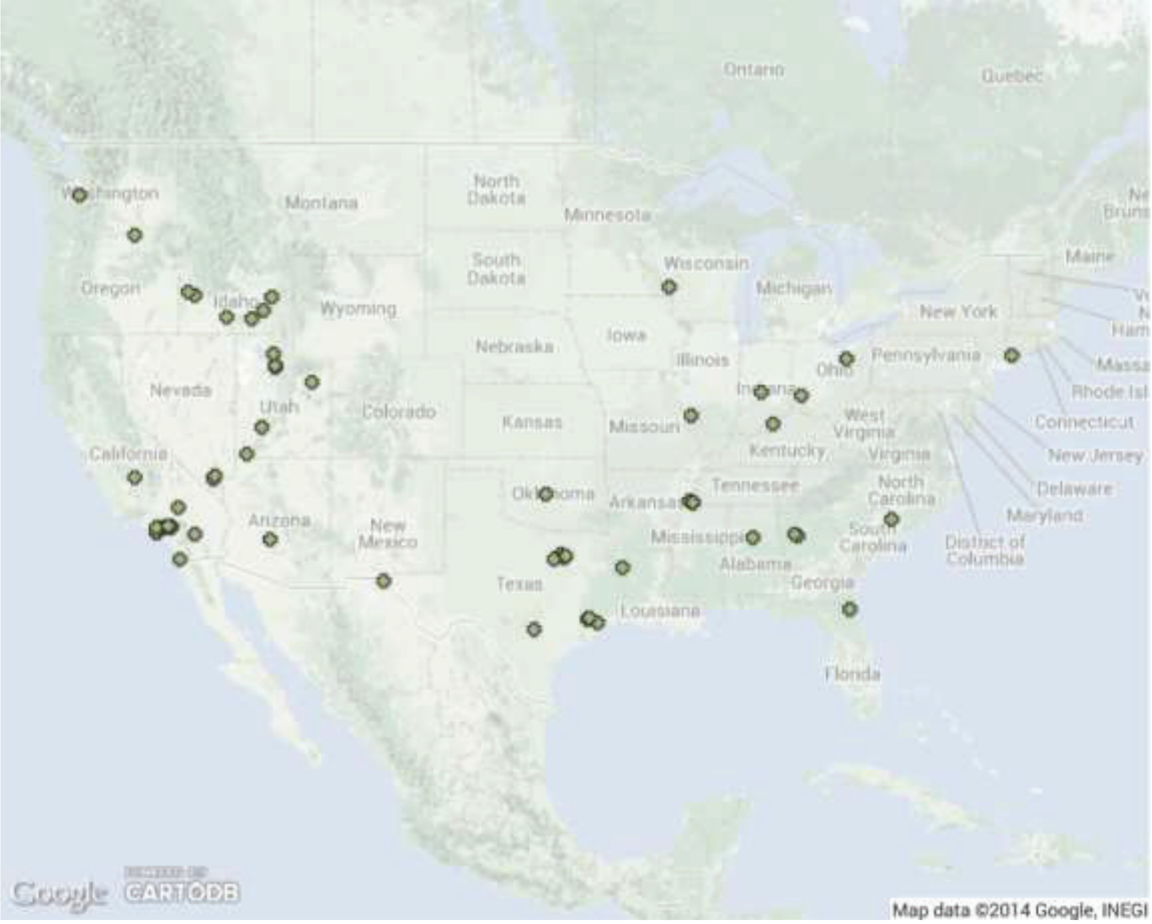

Figure A4-6. 58 LNG Refueling Stations.

Figure A4-7. 737 CNG Refueling Stations.