CHAPTER FIVE

INFRASTRUCTURE

INTRODUCTION

One of the hallmarks of the U.S. transportation system is its ease of use. Not only are the vehicles cost-efficient, safe, and reliable, but the infrastructure to support them is widespread, efficient, and easy to use. Service stations and truck stops serve a growing fleet of light-duty (LD) and heavy-duty (HD) vehicles.

For alternative fuel vehicles to achieve a significant market penetration, consumers need to be reasonably assured that they will be able to refuel without undue inconvenience. Vehicle fleet modeling in the LD and HD sector analyses of this study assumed the sufficient and steady-state availability of fuel and fueling infrastructure to support alternative fuel-vehicle systems. This chapter discusses the cost of providing fuel infrastructure, transition hurdles for infrastructure deployment, and potential strategies to minimize the impact of transition hurdles.

The LD and HD vehicle integrated economic analyses suggest that once a fuel-vehicle system has achieved commercial scale and infrastructure utilization is high, infrastructure costs are likely to be a small portion of the total cost of driving. However, the transition to these potential future states presents a significant hurdle for several fuel-vehicle systems. Concurrent development of both new fuel-vehicle systems and corresponding fuel infrastructure is a major challenge. Widespread deployment of fueling infrastructure without sufficient demand could result in an extended period of low utilization of fuel infrastructure. This chapter also addresses strategies for mitigating transition issues, which include the use of existing infrastructure, targeted deployment, and use of multi-fuel vehicles.

BACKGROUND: CURRENT GASOLINE AND DIESEL FUEL INFRASTRUCTURE

As used in this section, “fuel infrastructure” refers to all fixed investments required for fuel production, transmission, distribution, and dispensing systems to support a fuel-vehicle system. While all elements of infrastructure are essential to achieve a viable supply chain, the primary focus of this chapter is on dispensing infrastructure, because this is the area where more significant transition challenges exist for most alternative fuels.

The current gasoline and diesel fuel infrastructure (including refineries, pipelines, terminals, and service stations) covers the entire country and operates at very large scale. There are approximately 160,000 service stations and 5,000 truck stops in the United States, which supply ~380 million gallons of gasoline per day (blended with ethanol) and ~140 million gallons of diesel per day (blended with biodiesel).[1] Currently there are 0.65 fueling stations per 1,000 LD vehicles. This ratio has been decreasing slowly over time as lower volume stations have closed. The typical gasoline station has four or more dispensers and operates well below its maximum dispensing capacity so that customer waiting time is minimized during peak usage periods. According to the American Petroleum Institute (API), 97% of stations are owned by small businesses. “The major integrated oil companies own about 3% of the retail stations and operate less than half of the retail stations that they do own. The vast majority of branded stations are owned and operated by

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[1] Station count from *NPN MarketFacts 2008*; truck stop count from America’s Independent Truckers’ Association Inc. (website) Truck Stop Locations (http://www.aitaonline.com/TS/Locations.html); and liquid fuels consumption data from Energy Information Administration’s *Annual Energy Outlook 2012 Early Release.*

independent retailers licensed to represent that brand. According to the National Association of Convenience Stores (NACS), more than half of the retail stations in the U.S. are owned by an individual or family. Through various branding agreements, approximately 37% of the retail stations in the U.S. sell fuel under API members' brands."[2]

METHODOLOGY

The integrated LD and HD vehicle analyses required evaluation of dispensed fuel costs for all alternative fuels, including fixed and variable infrastructure costs, distribution costs, dispensing costs, motor fuel taxes, and others. The infrastructure analysis considered each fuel supply chain individually and assessed the costs for providing widely accessible alternative fuels for transport use. All investments and costs are from published sources, and are consistent with the pathways assessed in the individual fuel-vehicle system supply chain chapters.

Figure 5-1 provides a summary of the elements that comprise the dispensed fuel cost for the various fuels considered in this study. Costs depicted in the blue shaded boxes are from the Energy Information Administration's Annual Energy Outlook 2010 (AEO2010); including dispensed gasoline and diesel price, electricity price for transportation, and industrial natural gas price. The cost elements outside the blue shaded boxes were developed and combined with electricity and natural gas prices to develop dispensed fuel costs for electricity, compressed natural gas (CNG), liquefied natural gas (LNG), and hydrogen. To the extent possible, assumptions were normalized to estimate the levelized cost for each of the fuel pathways under review. The infrastructure assessment builds off the three existing distribution infrastructures: electricity, natural gas, and petroleum. Commodity prices (transport gasoline/diesel price, industrial gas price, transportation sector electricity) are from AEO2010 through 2035, and are assumed to include all upstream capital and variable production costs. The cumulative aggregate growth rate from 2030 to 2035 in AEO2010 is used to extrapolate commodity prices from 2035 to 2050. Fuel production (where applicable), distribution, and dispensing fixed and variable costs were assessed as described in detail in Appendix 5A at the end of this chapter. A range of infrastructure costs was used for some pathways, such as hydrogen, where there is greater uncertainty in dispensing infrastructure investment requirements.

Some assumptions were normalized across pathways for consistency. All dispensing fixed infrastructure investments were *levelized* (i.e., converted to dollars per unit of dispensed fuel), assuming a 10% real weighted average cost of capital and a 20-year economic life for the infrastructure. The infrastructure was assumed to be utilized at full design capacity at all times in this analysis. The sensitivity to underutilization was assessed separately, and is described in this chapter. Federal and state motor fuel taxes for CNG, electricity, hydrogen, and biofuels were assumed to be equivalent to gasoline in cents/mile. Federal and state motor fuel taxes for LNG were assumed to be equivalent to diesel in cents/mile. Details on the tax assumptions are provided in Appendix 5A. A summary of the levelized infrastructure cost ranges for all fuels through 2050 is provided in Appendix 5A (see Table 5A-1).

Infrastructure transition costs were not quantitatively included in the dispensed fuel cost buildup. The infrastructure costs assessed here should therefore be viewed as the *minimum* infrastructure costs for alternative fuel pathways.

RESULTS AND DISCUSSION

Total Required Infrastructure Investment

Total required investment provides an indication of the magnitude of the fuel infrastructure challenge. Available literature shows a broad range of values for the minimum number of refueling stations required to support the commercial deployment of alternative fuel vehicles. Table 5-1 shows estimated investment required for fuel production, distribution, and dispensing infrastructure to displace one-third of current gasoline use for gasoline alternatives, and one-third of current diesel use for LNG as a diesel alternative. The data included in this table are derived from the individual fuel-vehicle system sections of this report. One-third of gasoline/diesel consumption is used in the table simply as a common benchmark to compare the relative total cost of displacing a large gasoline/diesel fraction (see

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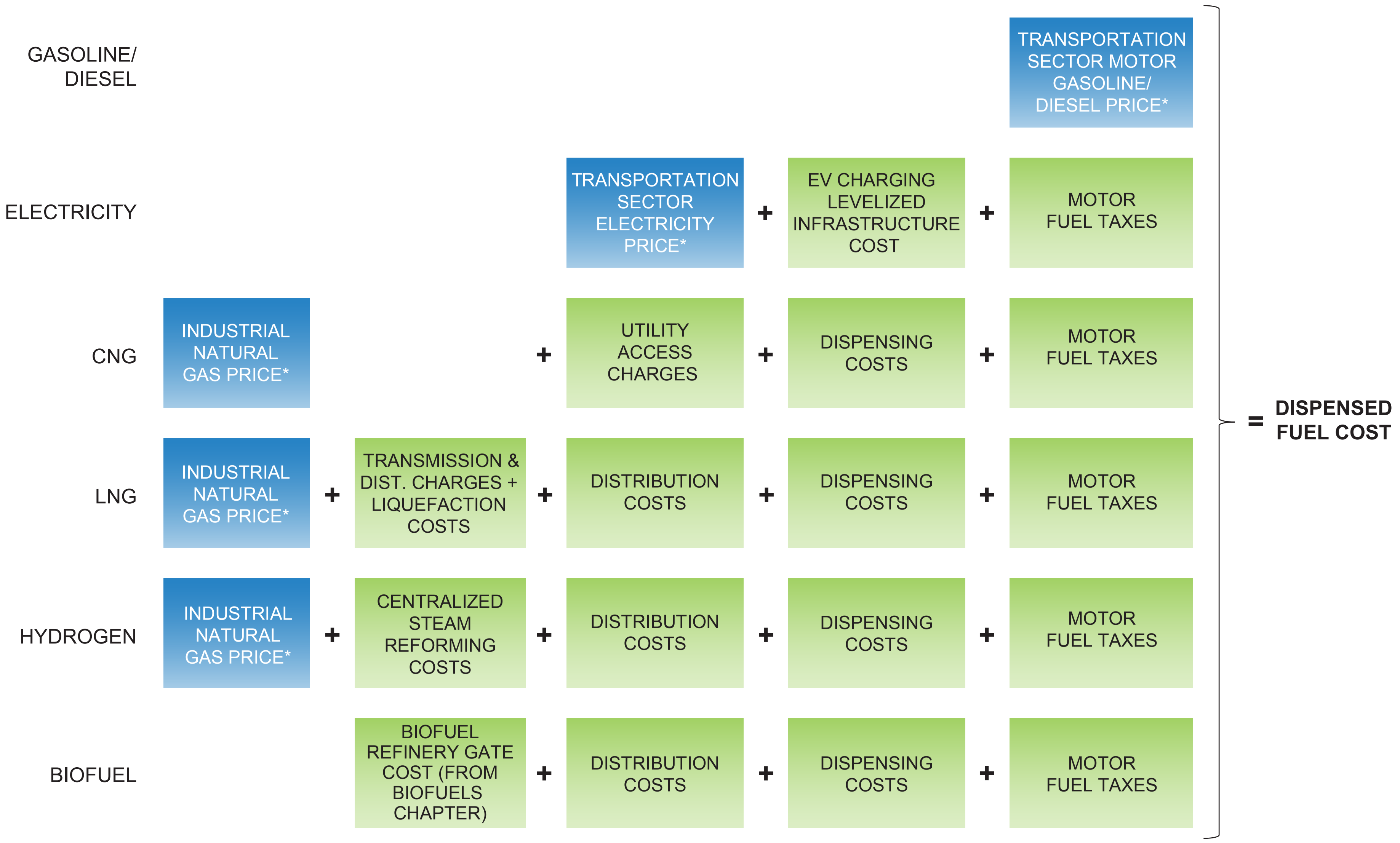
[2] API website, Oil & Gas Overview: Service Station FAQs, http://www.api.org/oil-and-natural-gas-overview/consumer-information/service%20station%20faqs.aspx.



*Source: Energy Information Administration's Annual Energy Outlook 2010 (AEO2010) for values through 2035. Cumulative aggregate growth rate from 2030 to 2035 in AEO2010 is used to extrapolate commodity prices from 2035 to 2050. Dispensed fuel cost for biofuels assumed to be same as that of transport sector gasoline or diesel, in which the biofuel is blended.

Note: Commodity prices from AEO2010 (high, low, and reference oil price cases) are assumed to include all upstream capital and variable production costs. Gasoline/diesel price also includes distribution and dispensing costs and motor fuel taxes.

Figure 5-1. *Dispensed Fuel Cost Buildup for Future Transportation Fuels*

Fuel	Fuel Production (billion 2008$)	Dispensing (billion 2008$)
Compressed Natural Gas	Not estimated	100–200
Hydrogen	30–90* (Hydrogen from new Centralized Steam Methane Reforming)	275–430
Electricity	Not estimated	70–130
Advanced Biofuels	150–300	20–40 (includes distribution)
Liquefied Natural Gas†	40–60	10–20

* This estimate is based on new steam methane reforming facilities. If surplus industrial-grade hydrogen is available, the required investment would be lower. However, some investment would be needed to purify hydrogen for fuel-cell vehicle applications.
† Diesel consumption is used as benchmark for LNG instead of gasoline consumption.

Table 5-1. *Range of Distribution and Dispensing Infrastructure Investment to Displace One-Third of Current Gasoline Consumption*

Appendix 5B for assumptions). Feedstock production is excluded from this analysis. For alternatives that have relatively higher vehicle efficiency, such as hydrogen fuel cell electric vehicles (FCEVs) and other electric vehicles, this analysis accounts for the fact that not as much energy is required to drive the same number of miles. Although the dispensing infrastructure costs are relatively low on a per-mile basis, the aggregate investment required for each fuel pathway is substantial.

Capital investments for gasoline and diesel production and dispensing have been made gradually over decades. The petroleum refining investment to produce one-third of current gasoline would be approximately $100 billion.[3] Since service stations cost well over $1 million per site, including real estate, replacing 50,000+ service stations would cost over $50 billion. The cost to completely reproduce the petroleum infrastructure would be much larger.

There is significant variation in distribution and dispensing investments required across alternative fuel-vehicle systems, with biofuels, LNG, and electricity having the lowest distribution and dispensing investment cost. Investments required for biofuels production are expected to be high. Investments for biofuel dispensing, however, are relatively low and are not expected to be a long-term barrier. Dispensing infrastructure upgrades are expected be a short-term challenge for individual service stations during transition. Most service stations today do not have equipment that has been certified for ethanol contents above 10%. A typical retail facility having four or more dispensers would pay roughly $80,000 for new pumps that could dispense fuel blends with higher ethanol. Replacing underground equipment requires permits and involves roughly an order of magnitude additional cost.

Dispensing Infrastructure Cost Per Mile

Figure 5-2 shows the percentage of the cost of driving of a new vehicle that is attributable to fuel dispensing infrastructure in 2050. This figure shows a range for new small cars—liquid ICEs, plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), CNG vehicles, and FCEVs—and for new trucks—LNG vehicles (LNGVs).[4]

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[3] National Petroleum Council website, *Hard Truths* study, Topic Paper #16, "Refining & Manufacturing," http://www.npc.org/Study_Topic_Papers/16-STG-RefiningManu.pdf.

[4] Vehicle costs are amortized over 112,000 discounted miles for small cars (light duty), 754,000 discounted miles for LNG Class 7&8 trucks, and 154,000 miles for LNG Class 3-6 trucks. Calculations are based on an assumed 3-year time horizon (described in the light-duty and heavy-duty analysis chapters of this report). The utility factors for PHEV10 and PHEV40 with ubiquitous charging are 0.5 and 0.8, respectively (PHEV10 allows up to 10 miles of driving in all-electric mode and PHEV40 allows up to 40 miles of driving in all-electric mode). Dispensing infrastructure costs shown for PHEV are for electricity only. Liquid ICE is the total cost of driving for a mix of 65% conventional and 35% hybrid vehicles powered by a gasoline-biofuel blend. Infrastructure costs shown for liquid ICE are incremental levelized dispensing infrastructure costs to accommodate higher (E10+) biofuel blends.

Consistent with integrated analysis calculations, the "cost of driving" (vehicle plus fuel costs) does not include cost components such as insurance and vehicle maintenance. The analysis below is based on cost estimates derived from available literature, as described in the individual fuel-vehicle system chapters of this report, and summarized in Appendix 5C.

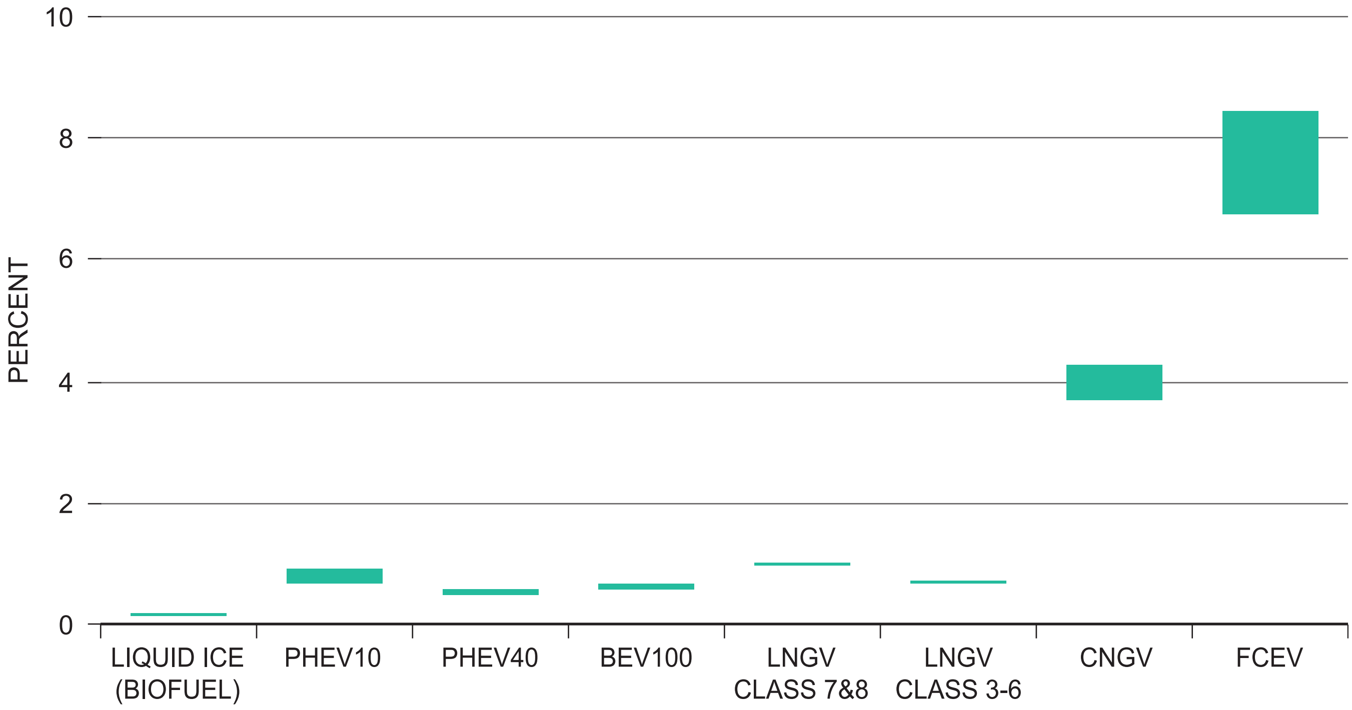
Once a pathway has achieved commercial scale and infrastructure utilization is high, it is unlikely that dispensing infrastructure costs will be a significant portion of the cost of driving because infrastructure costs will be amortized over a large dispensed fuel volume. The fraction of total cost of driving attributable to dispensing infrastructure ranges from 1 to 8% of the cost of driving, depending on the pathway.

Dispensed fuel costs, inclusive of taxes, are a small share of the total cost of driving as compared to vehicle costs. This suggests that reducing vehicle costs is more critical for improving the long-term economics of alternatives fuel-vehicle systems (e.g., a 10% reduction in vehicle cost will have a much greater impact on total cost of driving than a 10% reduction in dispensing infrastructure cost).

The modeling analysis assumed fuel costs based on fully utilized production, distribution, and dispensing infrastructure (see Appendix 5A). With these conditions, all fuel-vehicle pathways achieved significant market penetration under at least some scenarios. This indicates that steady-state infrastructure costs should not be an impediment to the penetration of alternative vehicles, assuming an effective transition from nascent to highly utilized infrastructure can be implemented. Transition phase fuel costs were not considered in the quantitative analysis but are discussed qualitatively in the section below.

Infrastructure Technology Readiness

Table 5-2 shows the infrastructure technology readiness for each fuel pathway and is based on the technology assessment described in Chapter Four, "Priorities for Technology Investment." Technology



Note: Graph shows range for new small car (liquid ICE, PHEV, BEV, CNGV, and FCEV) and new truck (LNGV).

Figure 5-2. *Dispensing Infrastructure Cost as a Percentage of Cost of Driving in 2050*

	Infrastructure Technology Readiness Status		
	Production	**Distribution**	**Dispensing**
Corn Ethanol	🟦	🟦	🟦
Advanced Biofuels	🟥 🟨	🟦	🟦
Electricity	🟦	🟦	🟦
Hydrogen	🟦	🟦	🟥
Natural Gas	🟦	🟦	🟦

🟥 RED: Ranges from Basic Research to Technology Demonstration. These hurdles require invention or have high uncertainty.

🟨 YELLOW: Ranges from Technology Development to Technology Demonstration. For these hurdles, a pathway for success has been demonstrated and significantly tested, but sustained effort is required to achieve wide scale material volumes.

🟦 BLUE: Systems commissioning or operational. These hurdles have minimal or no barriers to wide scale material volumes.

Table 5-2. *Infrastructure Technology Readiness*

hurdles for each fuel-vehicle system were assessed using criteria described in Chapter Four. Hurdles identified for each fuel-vehicle system were categorized as either red, yellow, or blue based on these criteria. The table defines the criteria for this categorization and shows the results of this analysis for fuel production, distribution, and dispensing technologies for each of the fuel pathways analyzed.

For most pathways, there are no red or yellow technology hurdles for fueling infrastructure. Corn ethanol and biodiesel pathways are already commercial, and there were no technology hurdles identified that impede deployment of CNG, LNG, and electricity fuel infrastructure. However, the study's technology assessment identified two areas for technology development for fueling infrastructure. Advanced biofuels production requires technology advancement to achieve commercial scale, and hydrogen compression and storage at a fueling station require advancements to reduce equipment costs and land requirements.

Transition Challenges

Providing fuel infrastructure for new alternative fuel-vehicle systems is much more challenging during the transition to commercial scale. A quantitative treatment of LD and HD infrastructure transition was not possible due to uncertainty in transition variables (e.g., scale and utilization), and the differing complexities of infrastructure transition for each fuel pathway (e.g., regional vs. national). The cost and transition time to commercial scale can also vary depending on a number of factors including: vehicle and fuel technology improvement rates, consumer value proposition, penetration rate needed to achieve commercial scale, competition between other alternatives, scope of infrastructure build-out, and ability to use existing infrastructure. There is considerable difference among the pathways in these factors. The wide-scale availability of the conventional fueling infrastructure took many decades to evolve (e.g., railroad, ICE/gasoline/diesel, ethanol). Small-scale introductions of alternative fuel infrastructure can occur much more quickly in small segments (e.g., a natural gas city bus refueling system).

The infrastructure hurdles that need to be overcome for a fuel-vehicle system to be deployed at commercial scale were assessed, and a summary is shown in Table 5-3. Many hurdles deal with the availability of fueling stations and the significant challenge of attracting investment capital when the accumulated vehicle population is low.

Hurdle	Tech/ Non-Tech	Description	Steps to Address Hurdle
Light-Duty CNG			
Modular CNG dispensing islands	Tech	Reduce cost and increase dispensing capacity. Will improve functionality of CNG upgrades to existing retail locations.	Cost reduction of upgrades to existing retail locations.
Fuel station availability	Non-Tech	Major expansion required. Initially target fleet markets with new, dedicated CNG stations. Expansion to consumer market could be supported by modular upgrades.	Investment in refueling to support accelerated growth of fleet markets. Infrastructure expansion to support consumer market transition.
Heavy-Duty Natural Gas			
Fuel Station Availability	Non-Tech	Limited infrastructure today. Growing but pace of acceleration is key to market growth.	Investment in refueling to support major freight corridors. Infrastructure expansion to support broader markets.
LNG liquefaction capacity expansion	Non-Tech	Expanded availability of LNG required, primarily through new liquefaction plants.	Investment to support fuel throughput.
Small scale liquefaction	Tech	Cost reduction of small-scale liquefaction systems to support fuel availability.	Engineering demonstration deployment scale up.
Biofuels			
Crop collection/ densification/ storage	Tech	Crop collection – low density and concentration of biomass.	Develop low-cost pelletization or briquetting system for storage and transport.
Electricity			
Multiple dwelling units (MDU)/ commercial/ public charging business models	Non-Tech	Insufficient justification for installing MDU/commercial/public charging infrastructure.	Align business models, regulations, codes and standards, and processes to enable third-party providers to install and charge for MDU, workplace, commercial, and public charging at a reasonable return on investment.
Hydrogen			
Compression and storage technologies	Tech	Land requirements for compression, storage equipment, and permitting/setback requirements can limit scale up of fueling capacity.	Fueling equipment fits into most existing stations. Fueling capacity scales within real estate limitations.
Fuel station availability	Tech	Insufficient fueling locations for material consumer adoptions and lack of compelling economics for early infrastructure deployment.	Sufficient early stations for demonstration fleets. Sufficient early stations to avoid consumer concerns of fuel availability.

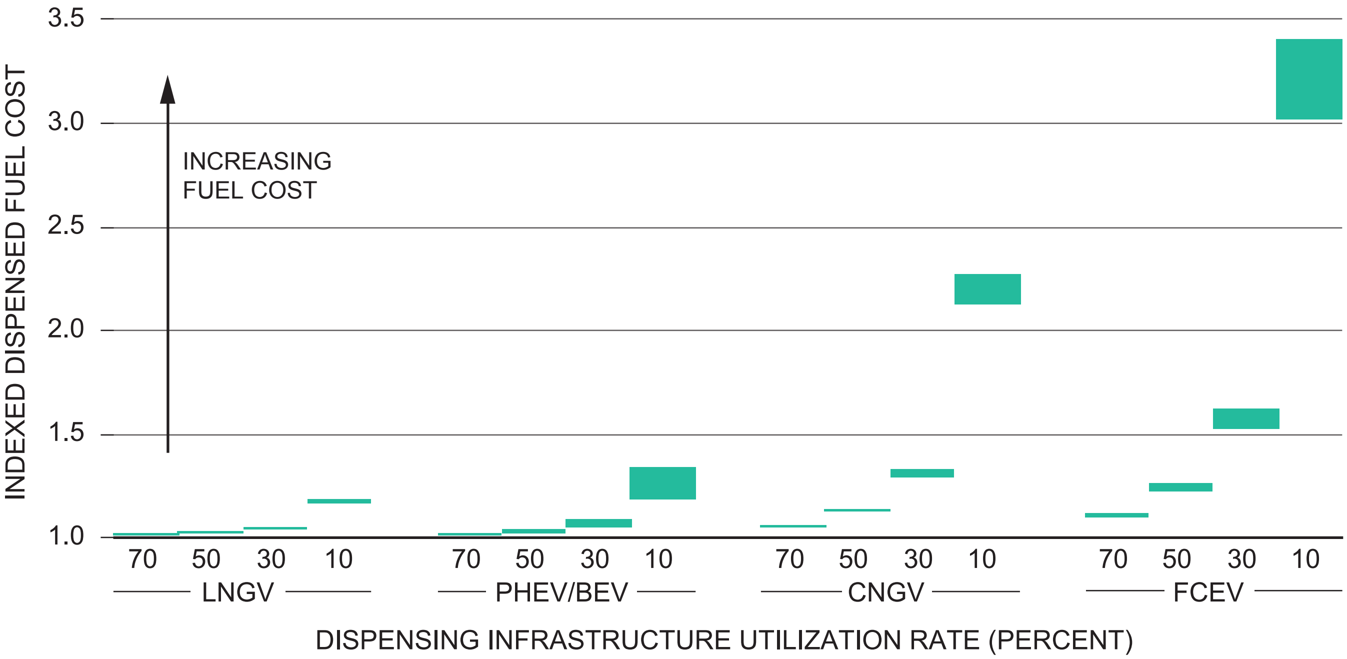
Table 5-3. *Key Priorities to Facilitate Widespread Deployment of Infrastructure*

Concurrent development of both new vehicles and fuel infrastructure is a major transition challenge for new fuel-vehicle system adoption. Widespread deployment of fueling infrastructure without sufficient demand could result in an extended period of low utilization of fuel infrastructure. Figure 5-2 assumed that fueling infrastructure is available and fully utilized, and that vehicle production is at scale. Introduction of vehicles without convenient access to fueling infrastructure is likely to hinder vehicle adoption by consumers and reduce the ability of the vehicle manufacturer to reach production volumes that would lead to cost reductions and increased market penetration. This concurrence conundrum leads to uncertainty about infrastructure investment and vehicle purchases, which contributes to the infrastructure transition barrier.

Low Utilization

Concurrent deployment of vehicles and fuel infrastructure has the potential to lead to low initial capacity utilization of fuel infrastructure. This dynamic could result in a transition period during which dispensing infrastructure is underutilized or there are fewer fueling sites than needed to support vehicle introduction. Initial low fuel demand also provides little incentive for new alternative fueling infrastructure investment. Figure 5-3 illustrates the sensitivity of dispensed fuel cost to infrastructure utilization levels by depicting the relative cost of fuel as a function of dispensing capacity utilization in 2050. Costs are normalized to the corresponding dispensed cost of fuel at 100% design-capacity utilization in 2050. At lower utilization, infrastructure costs are assumed to be recovered over the lower dispensed volume base, resulting in increased dispensed fuel costs.

Figure 5-3 compares the relative fuel cost required for a range of dispensing infrastructure utilization levels from full capacity down to 10% design capacity. It assumes all dispensing infrastructure costs are recovered through increases in dispensed fuel costs. The graph is normalized to the fuel cost for each pathway at 100% design capacity utilization. The duration and extent of



Notes: Graph is normalized to fuel cost at 100% design capacity utilization.
The value shown for “PHEV/BEV” is the average of PHEV10, PHEV40, and BEV100 in the ubiquitous charging scenario (there is minimal impact of under-utilization in residential-only charging scenario).

Figure 5-3. *Relative Cost of Fuel as a Function of Fuel Dispensing Infrastructure Utilization Levels in 2050* underutilization of dispensing facilities is likely to be different for each pathway. If the infrastructure is significantly underutilized, dispensed fuel costs would rise and may contribute significantly to the total cost of driving.

Some pathways have the option to deploy smaller stations or modular islands in existing gasoline retail facilities during transition to minimize the risk of underutilization. While the risk may be partly mitigated by this strategy, the cost per unit for these smaller facilities is likely to be higher due to lack of economies of scale. In the case of BEVs, infrastructure cost estimates are sensitive to assumptions of charger density. The risk of underutilization of public/commercial charging facilities will depend on the accuracy of the projection of the total number of plug-in electric vehicles (PEVs) and the ratios of electric vehicle supply equipment to vehicles. The potential for underutilization is lower for PEVs using residential charging.

It is noteworthy that different fuels have different sensitivities to utilization level, even at the improved installation costs assigned to systems in 2050. LNG is less sensitive to utilization due to the throughput volumes at HD vehicle fueling sites. Fuel cost for electric vehicles is less impacted by low utilization of dispensing infrastructure because recharging costs are modeled to decrease significantly with time. Similar cost reductions are modeled for hydrogen (see Chapter Fifteen, "Hydrogen," as well as Chapter Thirteen, "Electric," and Appendix 5A of this chapter). If the projected reductions in infrastructure costs are not realized, the dispensing costs for BEVs and FCEVs and their sensitivity to underutilization could potentially be greater. The fuel cost for FCEVs is most impacted by low utilization. Although compressed natural gas vehicles (CNGVs) and FCEVs both use natural gas as the primary energy input for fueling, the impact of underutilization of hydrogen infrastructure is high because infrastructure costs represents a larger share of total dispensed fuel cost.

Mitigation Strategies for Transition Issues

While there are significant challenges to be overcome to widely deploy alternative fuels, there are potential strategies that can help mitigate transition issues. These strategies include but are not limited to the following:

- Leverage infrastructure that is already in place for build-out of alternative fuel infrastructures
- Target initial infrastructure deployments to specific geographic areas, transit corridors, fleets, or other niche application vehicles
- Use vehicles that can run on more than one fuel, such as flexible-fuel vehicles or PHEVs.

It should be noted that these strategies may be used independently or combined in order to mitigate transition issues.

Build Off Existing Infrastructure

Current infrastructure can be leveraged to potentially reduce initial investment and facilitate a faster transition. The extent to which different fuel supply chains can leverage existing infrastructure during transition varies by fuel type. Biofuels (if infrastructure-compatible biofuels are developed) and electricity have the greatest opportunity, followed by natural gas and then hydrogen.

Biofuels

Existing petroleum terminals and service station networks can continue to be used for distributing biofuels. A significant infrastructure is in place for transporting and blending biofuels at terminals. If biofuel demand increases, then additional investment may be needed for rail transportation and other distribution infrastructure. While there are no technical hurdles for retrofitting existing service stations to dispense ethanol blends above 10%, in the near term the investment required may pose a challenge for station owners.

Electricity

There is already an extensive electric power generation, transmission, and distribution infrastructure in the United States. According to AEO2010, the current U.S. electricity consumption across all sectors is 12.3 quadrillion BTU. Assuming electricity displaced a third of current gasoline consumption in LD vehicles, an additional 1.9 quadrillion BTU[5]—approximately 15% of current

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[5] Only 1.9 quadrillion BTU of electricity is needed to displace 5.7 quadrillion BTU of gasoline, due to ~3x higher tank-to-wheel efficiency of plug-in electric vehicles (on electricity), relative to gasoline LD vehicles.

consumption—of delivered electricity would be needed. This rough estimate accounts for the higher efficiency of electric vehicles. In perspective, AEO2010 projects that an additional 3.6 quadrillion BTU of delivered electricity across all other sectors will be required through 2035. Assuming that a substantial portion of BEV charging occurs overnight during off-peak times, transportation demand for electricity could potentially leverage existing electricity production and transmission infrastructure. As described in Chapter Thirteen, capacity can be added to support increased transportation demand within existing business practices.

Some vehicle owners have convenient access to electrical outlets for vehicle charging. These outlets could enable the charging of certain plug-in hybrids. However, the widespread adoption of vehicles with larger batteries such as BEVs will most likely require higher-capacity, more-costly home charging and potentially public charging infrastructure.

Natural Gas

An extensive natural gas distribution infrastructure also exists today. According to AEO2010, current U.S. natural gas consumption across all sectors is 21.2 quadrillion BTU. Assuming natural gas displaced 30% of current fuel for LD and HD transport, an additional 6–7 quadrillion BTU of natural gas, approximately 30% of current consumption would be needed. In perspective, AEO2010 projects that an additional 2.3 quadrillion BTU of delivered natural gas across all other sectors will be required through 2035. In the near term, the existing natural gas distribution network is expected to be adequate to support transitional LD vehicle CNG demand for transportation. However, in the long term, significant investments in production, transmission and distribution infrastructure will be needed to support widespread deployment of natural gas in transport. A Department of Energy study estimates this investment to be on the order of 100–200 billion dollars.[6]

For near-term LD vehicle natural gas dispensing, a modular approach could be taken that would add CNG fueling capability to existing service stations. This approach minimizes the potential for underutilization of dispensing facilities, while keeping infrastructure investments manageable. However, it does not take advantage of economies of scale benefits. When demand increases, larger more capital intensive dedicated CNG stations could emerge and capture benefits of scale.

LNG production and distribution is a mature technology. Many existing LNG "peak-shaving" facilities are used to store surplus natural gas that is distributed by truck to meet local demand during peak consumption periods. LNG stations for HD vehicle fueling will likely be deployed similar to the way diesel fuel is deployed—through large truck fueling stations or at truck depots for individual trucking companies. LNG could also be used to provide CNG fuel for LD vehicle applications.

Hydrogen

Industrial grade hydrogen production is a mature technology, and there are existing hydrogen production facilities that may be utilized in the early stages of hydrogen FCEV deployment. Additional investments may be needed to produce commercial quantities of high-purity hydrogen for FCEV use. New hydrogen plants that manufacture hydrogen via steam methane reforming could leverage the existing natural gas distribution network for feedstock. However, of all the alternative fuels addressed in this study, hydrogen would be least capable of taking advantage of the existing distribution and dispensing infrastructure. While dispensing infrastructure costs could be reduced by deploying dispensers at current service stations, significant new investment in dispensing infrastructure would be required.

Local, Corridor, or Niche-Application Deployment

Another transition strategy is to minimize required infrastructure investment by targeting initial deployments to specific geographic areas, transit corridors, fleets, and/or other niche-application vehicles (e.g., buses, delivery trucks, etc.). Focused deployment of infrastructure can improve utilization of infrastructure during transition, thereby helping to overcome the transition barrier described previously. This strategy could be most effective in high-volume freight corridors for natural gas fueled

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[6] G. A. Whyatt, *Issues Affecting Adoption of Natural Gas Fuel in Light- and Heavy-Duty Vehicles,* PNNL-19745, prepared by Pacific Northwest National Laboratory for U.S. Department of Energy, September 2010.

HD vehicles, and in regions with high population density for LD vehicles. Ethanol is an example of a regionally focused deployment of infrastructure. Gasoline-ethanol blends were first introduced in the Midwest, near corn supply and ethanol production facilities, and gradually spread to other areas of the country. This was made possible because the existing vehicle inventory was able to use ethanol blends, and ethanol was able to leverage the existing hydrocarbon liquid distribution system.

To improve infrastructure utilization, alternative fuels are often targeted to fleets with centralized fueling facilities (e.g., buses, taxis, commercial fleets, etc.). Medium-duty (MD) and HD vehicles are more likely to be centrally fueled than LD vehicles and access to the public is often limited, but during an initial transition period, alternative LD vehicles may be able to use fleet dispensing infrastructure.

There are distinct differences between LD and HD vehicle fueling practices and transportation economics. The following could reduce the infrastructure transition barriers for natural gas in MD and HD vehicles:

- A substantial number of HD trucks have high annual mileage, with some trucks traveling over 200,000 miles per year. A higher annual fuel cost means quicker payback for less expensive alternative fuels, providing economic incentive to overcome the transition barrier.
- Class 7&8 combination vehicles tend to fuel at major truck stops and at centralized depots. Both fueling locations typically dispense large volumes of fuel, shortening the payback period for station operators/investors. With a limited number of high-volume fueling stations, it would be easier to reach a certain threshold percentage of stations with a new fuel.

Multi-Fuel Vehicles

Flexible-fuel, bi-fuel, and plug-in hybrids also facilitate transition by allowing vehicle deployment prior to widespread fuel supply, and by allowing the build-out of fueling infrastructure to be better matched to vehicle sales to increase infrastructure utilization. There are, however, vehicle cost and technical limitations to this strategy. Bi-fuel vehicles add additional cost and weight to the vehicle to provide capability for two separate fuels. Flexible-fuel gasoline/ethanol vehicles have been introduced widely in Brazil and the United States, and require additional vehicle cost compared to a conventional vehicle.

Pathway Transition Issue Summary

Each alternative fuel pathway has unique advantages and disadvantages in leveraging these strategies and overcoming the challenges described. Tables 5-4 and 5-5 provide summaries of advantages and disadvantages of the various fuel options for LD and HD vehicles.

FINDINGS

1. Widespread availability of fuel infrastructure and concurrent development of both new vehicles and fuel infrastructure is necessary for the adoption of alternative fuel-vehicle systems.
2. Once a pathway has achieved commercial scale and infrastructure utilization is high, infrastructure costs are likely to be a small part of the total cost of driving.
3. Significant investments are needed for wide-scale availability of each alternative fuels infrastructure.
4. The need for concurrent development of both new vehicles and fueling infrastructure is a significant transition barrier because fuel infrastructure design capacity utilization would be low in the early years and, therefore, fuel costs would be higher than those projected at steady state.
5. There are strategies for mitigating transition issues:
   - Build off existing infrastructure to potentially minimize initial investment and facilitate a faster transition.
   - Use localized, corridor, or niche-application deployment to maintain higher dispensing infrastructure utilization levels during transition.
   - Use flexible-fuel, bi-fuel, and plug-in hybrids to facilitate transition by allowing vehicle deployment prior to widespread fuel supply.

	Potential Infrastructure Disadvantages	Potential Infrastructure Advantages
Biofuels	• Costs to retrofit existing dispensers and to upgrade underground equipment to accommodate higher level biofuel blends. • Additional distribution costs relative to conventional fuels. • Technology hurdles that need to be overcome to commercialize advanced biofuel pathways.	• Potential to leverage existing petroleum product blending terminals. • Growing number of vehicles with flex-fuel capability.
Natural Gas (CNG)	• Insufficient LD vehicle natural gas demand generates risk of underutilization. • Lower range of CNG vehicles creates greater need for convenient access to refueling; smaller, geographically dispersed dispensing facilities are more expensive than large, dedicated stations at equivalent total dispensed volume.	• Potential to leverage existing natural gas production and distribution network, minimizes upfront investment in production and distribution infrastructure. • Potential to leverage fleet/HD natural gas infrastructure for LD vehicles.
Electricity	• Low electric vehicle inventory creates poor incentive for investment in public/workplace charging infrastructure due to risk of under utilization.	• Existing residential Level 1 charging capability in some homes, and plug-in hybrids enable early adoption of PEVs. • PEV fuels costs are less sensitive to infrastructure utilization levels. • Potential to leverage existing grid, minimizes upfront investment in electricity generation, transmission and distribution to meet early transport demand.
Hydrogen	• Insufficient LD vehicle hydrogen demand generates risk of infrastructure underutilization. Dispensed hydrogen costs are more sensitive to infrastructure utilization levels than other fuels. • Technology hurdles that need to be overcome to minimize footprint for hydrogen compression, storage and distribution; lower footprint is needed to enable retrofit of most retail establishments.	• Production technology is well established on commercial scale for industrial grade (low purity hydrogen), which may be leveraged during initial deployment. However, additional investment may be needed to produce commercial quantities of high purity hydrogen for FCEVs. • Can build off of natural gas infrastructure to provide feedstock for hydrogen production.

Table 5-4. *Summary of Infrastructure Advantages and Disadvantages for Light-Duty Vehicles*

	Potential Infrastructure Disadvantages	Potential Infrastructure Advantages
Biofuels	• Limited supply of biofuel for diesel vehicles.	• Potential to leverage existing petroleum product pipeline network, and blending terminals. • Growing number of vehicles with capability to handle biofuel blends.
Natural Gas (CNG/LNG)	• Low heavy-duty inventory of natural gas vehicles creates risk of underutilized infrastructure.	• Concentration on freight corridors increases likelihood of higher utilization. • Return-to-base fleets (e.g., city buses, garbage trucks, taxis, etc.) enable centralized refueling with high utilization. • LNG production and distribution technology is well established. • Potential to leverage existing natural gas production and distribution network, minimizes upfront investment in production and distribution infrastructure.

Table 5-5. *Summary of Infrastructure Advantages and Disadvantages for Heavy-Duty Vehicles*

APPENDIX 5A:
DISPENSING INFRASTRUCTURE COST ASSUMPTIONS AND SUMMARY

INFRASTRUCTURE AND DISPENSED FUEL COST ASSUMPTIONS

- Infrastructure calculations assume design capacity is fully utilized. (Dispensing infrastructure costs in $/gallon gasoline equivalent can be found in Table 5A-1.)
- Dispensed fuel cost ($/gallon gasoline equivalent) includes all production, distribution, and dispensing costs, and fuel taxes.
  - Assumes commodity price (gasoline price, industrial gas price, transportation electricity) includes upstream capital and variable production costs.
  - In the LD/HD quantitative analysis, biofuels pump price was assumed to be same as that of gasoline or diesel, into which the biofuel was blended.
  - Taxes for CNG, electricity, biofuels, and hydrogen assumed equivalent to gasoline in cents/mile.
  - Taxes for LNG assumed equivalent to diesel in cents/mile.
- Dispensing infrastructure investments leveled (i.e., converted to 2008$/gallon gasoline equivalent) assuming 10% real weighted average cost of capital and 20-year economic life.
- Fuel costs through 2035 from the Energy Information Administration's AEO2010; extrapolation to 2050 uses AEO compound annual growth rate from 2030 to 2035.
  - Transportation gasoline, diesel and electricity, industrial natural gas price for natural gas and hydrogen.
  - High and low defined by AEO2010 High Oil Price Case and Low Oil Price Case, respectively.

Dispensing Infrastructure (2008$/GGE*)	2015	2020	2025	2030	2035	2040	2045	2050
CNG	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38
LNG	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
PHEV10 – Residential	1.05	0.86	0.77	0.63	0.49	0.36	0.24	0.15
PHEV40 – Residential	1.25	1.00	0.86	0.71	0.56	0.41	0.27	0.17
BEV100 – Residential	1.52	1.20	1.04	0.86	0.67	0.49	0.33	0.20
PHEV10 – Ubiquitous	1.27	1.05	0.90	0.79	0.69	0.59	0.50	0.42
PHEV40 – Ubiquitous	1.12	0.90	0.77	0.64	0.51	0.39	0.28	0.19
BEV100 – Ubiquitous	1.53	1.20	1.05	0.87	0.68	0.50	0.34	0.21
FCEV – Hydrogen	2.66-4.61	1.79-3.41	1.79-3.41	1.32-1.90	1.32-1.90	1.32-1.90	1.32-1.90	1.32-1.90

*Gallon gasoline equivalent (GGE) = 125,000 BTU.

Table 5A-1. *Summary of Levelized Dispensing Infrastructure Costs (2008$/Gallon Gasoline Equivalent), Assuming Full Utilization of Design Capacity*

MOTOR FUEL TAX ASSUMPTIONS

- Motor fuel taxes for gasoline and diesel in dollars per gallon gasoline equivalent are from the AEO2010 until 2035.
  - Assumes federal taxes are constant in nominal dollars.
  - Assumes state and local taxes are constant in real dollars.
- From 2036 to 2050, gasoline and diesel taxes are extrapolated using VISION's extrapolation factors for total fuel price (which is inclusive of taxes).
- Taxes are normalized to gasoline and diesel on a cents/mile basis.
  - Taxes for CNG, biofuel, hydrogen, and electricity are assumed to be equivalent to gasoline in cents/mile.
  - Taxes for LNG assumed to be equivalent to diesel in cents/mile.
- Average test fuel economies (2015–2050) to calculate taxes in dollar per mile and in dollars per gallon gasoline equivalent are shown in Tables 5A-2 and 5A-3, respectively.
- Miles per gallon gasoline equivalent for gasoline is weighted average of conventional (65%) and hybrid (35%) vehicle fuel economy.
- Taxes (dollars per gallon gasoline equivalent) = Taxes (dollars per mile) * Miles per Gallon Gasoline Equivalent.

	MPGGE*	2010	2015	2020	2025	2030	2035	2040	2045	2050
Gasoline	43	0.010	0.009	0.009	0.009	0.008	0.008	0.009	0.009	0.010
Diesel	38	0.011	0.010	0.010	0.009	0.009	0.009	0.009	0.010	0.010
CNG	43	0.010	0.009	0.009	0.009	0.008	0.008	0.009	0.009	0.010
LNG	36	0.011	0.010	0.010	0.009	0.009	0.009	0.009	0.010	0.010
Biofuel	43	0.010	0.009	0.009	0.009	0.008	0.008	0.009	0.009	0.010
Hydrogen	84	0.010	0.009	0.009	0.009	0.008	0.008	0.009	0.009	0.010
PHEV10 – Electricity	123	0.010	0.009	0.009	0.009	0.008	0.008	0.009	0.009	0.010
PHEV40 – Electricity	128	0.010	0.009	0.009	0.009	0.008	0.008	0.009	0.009	0.010
BEV100 – Electricity	148	0.010	0.009	0.009	0.009	0.008	0.008	0.009	0.009	0.010

*MPGGE = miles per gallon gasoline equivalent.

Table 5A-2. *Motor Gasoline Taxes in Dollars per Mile (2008$)*

	MPGGE*	2010	2015	2020	2025	2030	2035	2040	2045	2050
Gasoline	43	0.42	0.41	0.39	0.38	0.36	0.35	0.37	0.39	0.41
Diesel	38	0.41	0.40	0.38	0.36	0.34	0.33	0.35	0.37	0.40
CNG	43	0.42	0.41	0.39	0.38	0.36	0.35	0.37	0.39	0.41
LNG	36	0.39	0.38	0.36	0.34	0.33	0.31	0.33	0.36	0.38
Biofuel	43	0.42	0.41	0.39	0.38	0.36	0.35	0.37	0.39	0.41
Hydrogen	84	0.82	0.79	0.76	0.73	0.71	0.68	0.72	0.76	0.81
PHEV10 – Electricity	123	1.19	1.16	1.11	1.07	1.03	1.00	1.06	1.12	1.18
PHEV40 – Electricity	128	1.25	1.21	1.17	1.12	1.08	1.04	1.11	1.17	1.23
BEV100 – Electricity	148	1.44	1.39	1.34	1.29	1.24	1.20	1.27	1.35	1.42

*MPGGE = miles per gallon gasoline equivalent.

Table 5A-3. *Motor Gasoline Taxes in Dollars per Gallon Gasoline Equivalent (2008$)*

APPENDIX 5B:
ASSUMPTIONS FOR TABLE 5-1 "RANGE OF INVESTMENT"

- Amount of alternative fuel required to displace one-third of current gasoline use for gasoline alternatives, and one-third of current diesel use for LNG as a diesel alternative (quadrillion BTU) is based on the AEO2010 estimates for 2010 consumption of motor gasoline and diesel fuel, which are ~140 billion gallons per year and ~45 billion gallons per year, respectively.
- Average fuel economy ratio (i.e., ratio of fuel economy of alternative fuel vehicle to conventional vehicle) for CNG, hydrogen FCEV, electric vehicles (PHEV10, PHEV40, BEV) and LNG are assumed to be 1.0, 1.95, 3.1, and 0.95, respectively.
- Production Investment:
  - **CNG.** Industrial natural gas prices (from AEO2010) used in the quantitative analysis are assumed to include levelized capital recovery cost for natural gas production and pipeline distribution. Widespread deployment of natural gas vehicles will require investment in additional production and distribution capacity, which is not quantified here.
  - **Hydrogen.** Assumes centralized production via steam methane reforming (SMR); Investment estimate based on $500–$1,500/kg-daily installed capacity for centralized SMR (see Chapter Fifteen, "Hydrogen"). Investment estimates do not include investments required for feedstock natural gas production and distribution to SMR facility. If surplus industrial-grade hydrogen is available, the total investment needed in new SMR hydrogen production capacity may be lower. However, some investment will be needed to produce high-purity hydrogen for FCEV applications.
  - **Electricity.** Transportation sector electricity prices (from AEO2010) used in the quantitative analysis are assumed to include levelized capital recovery cost for electricity generation, transmission and distribution. Widespread deployment of electric vehicles will require investment in additional generation, transmission, and distribution capacity, which is not quantified here.
  - **Biofuels.** Based on $64,000–$112,000 $/daily barrel installed capacity for biofuel production by pyrolysis (see Chapter Twelve, "Biofuels").
  - **LNG.** Based on LNG liquefaction plant investments at ~$30,000/daily-diesel-energy-equivalent-barrel installed capacity (see Chapter Fourteen, "Natural Gas"). Range of fixed investment for liquefaction, assuming 50–80% utilization. Does not include investment required for natural gas production or distribution to the liquefaction facility.
- Dispensing Investment:
  - **CNG.** Range of dispensing investments correspond to dedicated CNG stations (lower) versus modular CNG island (higher). Dedicated CNG stations at $2.5 million per station, dispensing 1 million gallons gasoline equivalent per year of CNG (~$38,000/daily-gasoline-energy-equivalent-barrel capacity). Dedicated CNG stations assume $1 million for land and $1.5 million for fixed installed equipment. Modular island costs of $400,000 dispensing 250 gallons gasoline equivalent/day (~$67,000/daily-gasoline-energy-equivalent-barrel capacity).

	Lower Bound	Upper Bound
Near Term (2015)	$1.53 million ($1.5 million fixed equipment/$30,000 land) for 250 kg/day installed capacity	$2.03 million ($2 million fixed equipment/$30,000 land) for 180 kg/day installed capacity
Long Term (2050)	$2.58 million ($2.5 million fixed equipment/$80,000 land) for 1,000 kg/day installed capacity	$3.08 million ($3 million fixed equipment/$80,000 land) for 750 kg/day installed capacity

Table 5B-1. *Range of Hydrogen Dispensing Infrastructure Investment*

- **Hydrogen.** Assumes truck distribution with fixed trailer investment of $500,000 per trailer with capacity of 400 kg/day. Lower end of dispensing investment based on average lower bound investment estimate for 2015–2050, high end of dispensing investment based on average upper bound investment for 2015–2050. Stations assume dispensed volume is 85% of max installed capacity. Investment estimates for dispensing are as shown in Table 5B-1.
- **Electricity.** Assumes no additional investment for electricity distribution; range of dispensing investment based on average dispensing infrastructure estimates for 2015–2050 for PHEV10, PHEV40, and BEV100 (levelized infrastructure estimates range 60 to 80 cents per gallon gasoline equivalent). The infrastructure estimates are strongly dependent on charger density assumptions, which are uncertain at this point of time.
- **Biofuels.** Assumes incremental investment of ~$10 billion to distribute additional 30 billion gallons per year of ethanol, at $0.47/ethanol-gallon-year investment in distribution (based on RFS2 regulatory impact analysis); dispensing infrastructure estimate of $10–30 billion to modify 33–100% of existing dispensers to handle E10+ ethanol blends
- **LNG.** Assumes truck distribution with variable costs only; dispensing infrastructure investment ($10–20 billion) based on building dedicated LNG stations at $1.75 million per station of 3.5 million diesel equivalent gallons per year dispensed capacity. Range based on utilization of 50–100%.

APPENDIX 5C:
ALTERNATIVE FUEL PATHWAY INFRASTRUCTURE COST ASSUMPTIONS

BIOFUELS

Dispensing Infrastructure investment ~$10 billion:

- Investment required to upgrade dispensers at retail facilities to handle ethanol-gasoline blends up to E85.

Distribution Infrastructure:

- Ethanol infrastructure upstream of service station (terminal, rail, etc.) to reach RFS2 volumes (incremental 19 billion gallons per year) is $9 billion, which translates to $0.47/gallon/year of ethanol distributed.
- Assume total distribution infrastructure investment ($ billion) is ethanol volume (billions of gallons per year) x $0.47/gallon/year.
- Diesel biofuels assumed to have same or lower cost as ethanol.

References

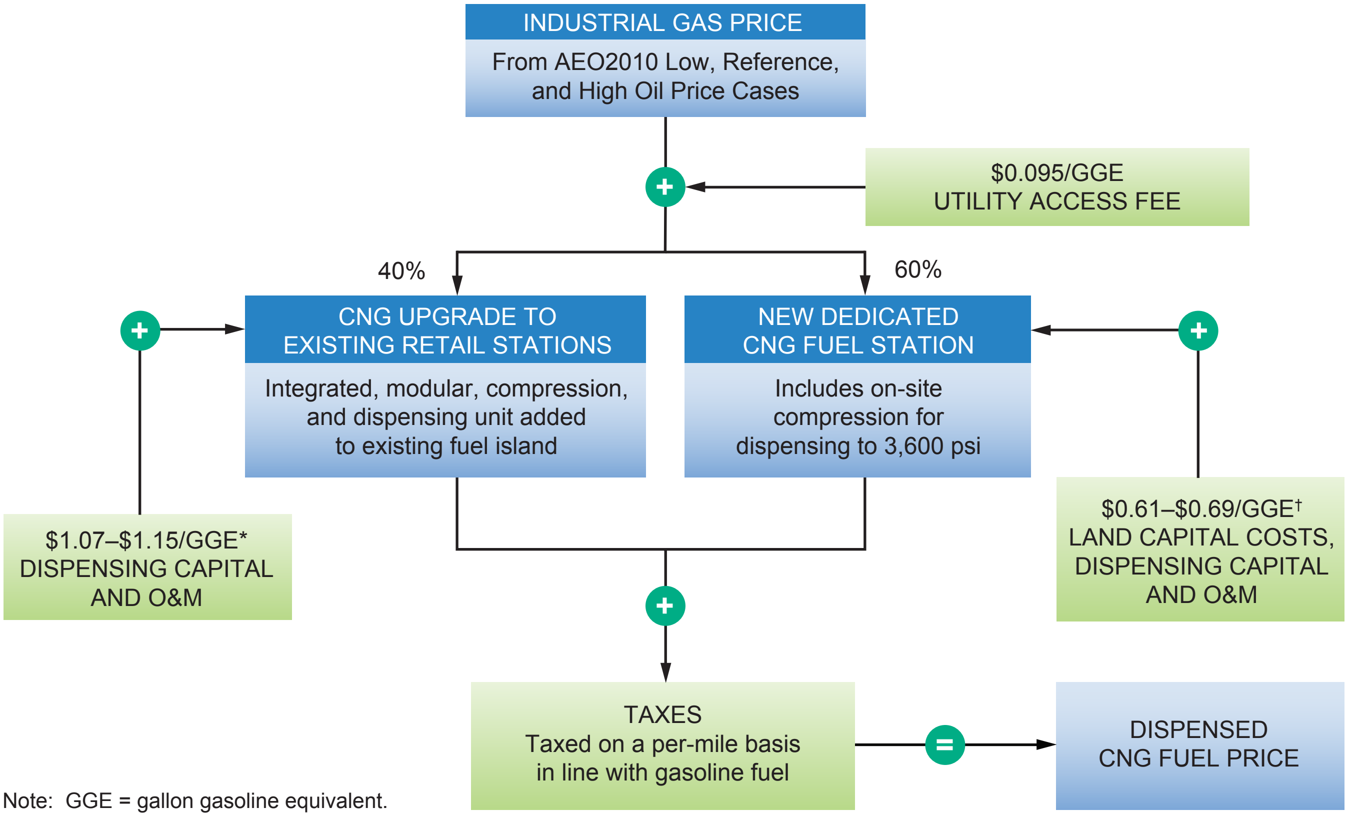
1. E85 and Blender Pumps: A Resource Guide to Ethanol Infrastructure, USDA, Clean Fuels Foundation and Nebraska Ethanol Board (2011).
2. Challenges Remain Before E15 Usage is Widespread, National Association of Convenience Stores, 2011, http://www.nacsonline.com/NACS/Resources/campaigns/GasPrices_2011/Pages/ChallengesRemainBeforeE15UsageIsWidespread.aspx.
3. API RFS2 Comments, Attachment 4: E85 Retail Fueling Cost Study, American Petroleum Institute, 2009.
4. Draft Regulatory Impact Analysis: Changes to Renewable Fuel Standard Program, Section 4.2.1.1.6, United States Environmental Protection Agency, March 2009.

COMPRESSED NATURAL GAS

For details on natural gas infrastructure inputs and references, refer to Chapter Fourteen of this study, "Natural Gas." Figure 5C-1 shows fuel cost buildup for dispensed compressed natural gas.

LIQUEFIED NATURAL GAS

Figure 5C-2 shows fuel cost buildup for dispensed liquefied natural gas.



Note: GGE = gallon gasoline equivalent.

* Assumes a per-station dispensing capacity of 90,000 gallons of gasoline equivalent per year, requiring a capital investment of $400,000 for installation of modular island dispensing infrastructure at each station, and variable operating and maintenance costs (including compression costs) of $0.58 per gallon of gasoline equivalent dispensed.

† Assumes a per-station dispensing capacity of 1 million gallons of gasoline equivalent per year, requiring a capital investment of $1.5 million for CNG compression and dispensing (at 3,600 psi) infrastructure, land costs of $1 million per station, and variable operating and maintenance costs (including compression costs) of $0.34 per gallon of gasoline equivalent dispensed.

Figure 5C-1. *Compressed Natural Gas Dispensed Fuel Cost Buildup*

HYDROGEN

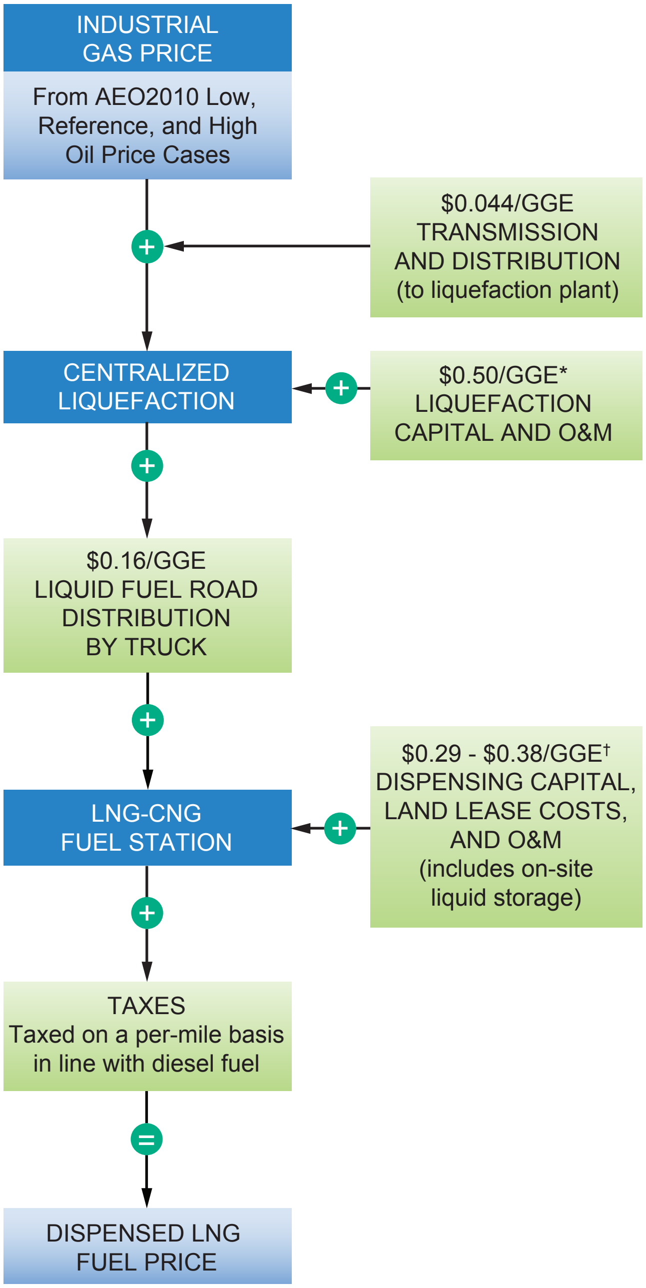
For details on hydrogen infrastructure inputs and references, refer to Chapter Fifteen of this study, “Hydrogen.” Figure 5C-3 shows fuel cost buildup for dispensed hydrogen.

ELECTRICITY

For details on electricity infrastructure inputs and references, refer to Chapter Thirteen of this study, “Electric” (section “Inputs for Integrated Analysis”). Tables 5C-1 through 5C-5 show electricity infrastructure assumptions.

The levelized electric charging infrastructure costs (i.e., infrastructure $/gallon gasoline equivalent) in Appendix 5A are calculated as follows:

- Using charger density assumptions (i.e., number of various types of chargers required per vehicle) and Installed Charger Costs ($/type of charger) shown in the tables in this appendix, a weighted average cost of charging infrastructure per vehicle is calculated.
- The average miles traveled by the vehicle per year, utility factors (fraction of total miles on electricity), and vehicle efficiency (watt-hours/mile on electricity) is used to calculate total electricity consumption by the vehicle per year (gallon gasoline equivalent/year).
- The cost of charging infrastructure is levelized over the total electricity consumed by the vehicle over its economic life (20 years), assuming a 10% weighted average cost of capital.

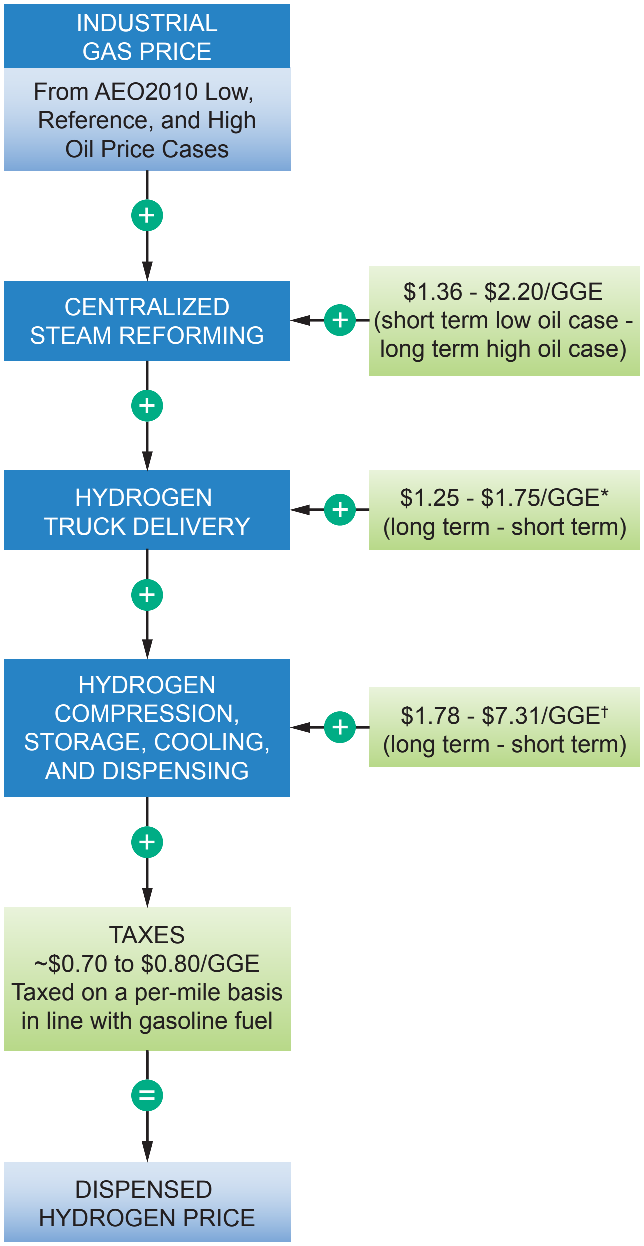


Note: GGE = gallon gasoline equivalent.

* Assumes per-plant LNG production capacity of 40.8 million gallons of gasoline equivalent per year requiring a capital investment of $70 million per liquefaction plant, and operating at 80% utilization with variable operating and maintenance costs of $0.25 per gallon of gasoline equivalent dispensed.

† Assumes a per-station LNG dispensing capacity of 3.9 million gallons of gasoline equivalent per year, requiring a capital investment of $1.75 million for LNG dispensing infrastructure and $300 thousand for CNG dispensing infrastructure at each station, and variable operating and maintenance costs (including land lease and on-site liquid storage expenses) of between $0.24 and $0.32 per gallon of gasoline equivalent dispensed.

Figure 5C-2. *Liquefied Natural Gas Dispensed Fuel Cost Buildup*



Note: GGE = gallon gasoline equivalent.

* Assumes a levelized fixed cost of hydrogen delivery of $0.34 per gallon of gasoline equivalent (assumes trucks deliver at full capacity of 400 kg/day over a 10 year life) and variable distribution costs of between $0.91 (in the long-term) and $1.41 (in the short-term) per gallon of gasoline equivalent.

† Assumes a per-station hydrogen dispensing capacity of between 55 thousand and 310 thousand gallons of gasoline equivalent per year (multi-fuel station scenario), requiring a capital investment of between $1.5 million (for stations with lower annual dispensing capacity) and $3 million (for stations with higher annual dispensing capacity), land costs of between $27 thousand and $82 thousand (i.e. between 600 and 1800 sf at $1 million per acre), and variable operating and maintenance costs of between $0.80 and $3.04 per gallon of gasoline equivalent.

Figure 5C-3. *Hydrogen Dispensed Fuel Cost Buildup*

	Residential						Workplace / Commercial					
	Home Charging Scenario			Ubiquitous Charging Scenario			Home Charging Scenario			Ubiquitous Charging Scenario		
	L1	L2	L3/DC	L1	L2	L3/DC	L1	L2	L3/DC	L1	L2	L3/DC
2010	1.00			1.00						0.27	0.07	
2015	1.00			1.00						0.27	0.07	
2020	1.00			1.00						0.27	0.07	
2025	1.00			1.00						0.27	0.07	
2030	1.00			1.00						0.27	0.07	
2035	1.00			1.00						0.27	0.07	
2040	1.00			1.00						0.27	0.07	
2045	1.00			1.00						0.27	0.07	
2050	1.00			1.00						0.27	0.07	

Note: L1 = Level 1 Charging (low power); L2 = Level 2 Charging (medium power); L3/DC = Direct Current Fast Charging (high power).

Table 5C-1. *PHEV10 Charger Density Assumptions*

	Residential						Workplace / Commercial					
	Home Charging Scenario			Ubiquitous Charging Scenario			Home Charging Scenario			Ubiquitous Charging Scenario		
	L1	L2	L3/DC	L1	L2	L3/DC	L1	L2	L3/DC	L1	L2	L3/DC
2010	0.60	0.40		0.60	0.40					0.08	0.06	
2015	0.60	0.40		0.60	0.40					0.08	0.06	
2020	0.60	0.40		0.60	0.40					0.08	0.06	
2025	0.60	0.40		0.60	0.40					0.08	0.06	
2030	0.60	0.40		0.60	0.40					0.08	0.06	
2035	0.60	0.40		0.60	0.40					0.08	0.06	
2040	0.60	0.40		0.60	0.40					0.08	0.06	
2045	0.60	0.40		0.60	0.40					0.08	0.06	
2050	0.60	0.40		0.60	0.40					0.08	0.06	

Note: L1 = Level 1 Charging (low power); L2 = Level 2 Charging (medium power); L3/DC = Direct Current Fast Charging (high power).

Table 5C-2. *PHEV40 Charger Density Assumptions*

	Residential						Workplace / Commercial					
	Home Charging Scenario			Ubiquitous Charging Scenario			Home Charging Scenario			Ubiquitous Charging Scenario		
	L1	L2	L3/DC	L1	L2	L3/DC	L1	L2	L3/DC	L1	L2	L3/DC
2010	0.20	0.80		0.20	0.80				0.005	0.010	0.018	0.002
2015	0.20	0.80		0.20	0.80				0.005	0.010	0.018	0.002
2020	0.20	0.80		0.20	0.80				0.005	0.010	0.018	0.002
2025	0.20	0.80		0.20	0.80				0.005	0.010	0.018	0.002
2030	0.20	0.80		0.20	0.80				0.005	0.010	0.018	0.002
2035	0.20	0.80		0.20	0.80				0.005	0.010	0.018	0.002
2040	0.20	0.80		0.20	0.80				0.005	0.010	0.018	0.002
2045	0.20	0.80		0.20	0.80				0.005	0.010	0.018	0.002
2050	0.20	0.80		0.20	0.80				0.005	0.010	0.018	0.002

Note: L1 = Level 1 Charging (low power); L2 = Level 2 Charging (medium power); L3/DC = Direct Current Fast Charging (high power).

Table 5C-3. *BEV100 Charger Density Assumptions*

	Total Infrastructure Costs (Including Installation)					
	Residential			Workplace / Commercial		
	L1	L2	L3/DC	L1	L2	L3/DC
2010	800	2,700	59,300	1,600	9,000	59,300
2015	700	2,300	50,800	1,400	7,500	50,800
2020	600	2,000	44,500	1,200	6,100	44,500
2025	600	1,800	43,000	1,200	4,900	43,000
2030	500	1,600	41,600	1,100	4,800	41,600
2035	500	1,400	40,300	1,000	4,700	40,300
2040	400	1,200	39,000	900	4,600	39,000
2045	400	1,000	37,700	800	4,500	37,700
2050	300	800	36,600	700	4,400	36,600

Note: L1 = Level 1 Charging (low power); L2 = Level 2 Charging (medium power); L3/DC = Direct Current Fast Charging (high power).

Table 5C-4. *Electric Charger Cost Assumptions*

Utility Factor						Vehicle Efficiency in Watt-Hours/Mile		
PHEV10		PHEV40		BEV100		PHEV10	PHEV40	BEV100
Home	Ubiq	Home	Ubiq	Home	Ubiq	Average	Average	Average
27%	50%	65%	80%	100%	100%	307	293	255
27%	50%	65%	80%	100%	100%	307	293	255
27%	50%	65%	80%	100%	100%	298	286	254
27%	50%	65%	80%	100%	100%	299	287	250
27%	50%	65%	80%	100%	100%	298	285	247
27%	50%	65%	80%	100%	100%	297	284	246
27%	50%	65%	80%	100%	100%	297	283	245
27%	50%	65%	80%	100%	100%	297	282	244
27%	50%	65%	80%	100%	100%	296	281	244

Table 5C-5. *Utility Factors and Vehicle Efficiency (on Electricity)*