

# Investigating the Strategic Impacts of Natural Gas on Transportation Fuel Diversity and Vehicle Flexibility

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Submitted to the Engineering Systems Division  
in partial fulfillment of the requirements for the degree

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## ABSTRACT

The near-total dependence of the U.S. transportation system on oil has been attributed to exposing consumers to price volatility, increasing the trade imbalance, weakening U.S. foreign policy options, and raising climate change concerns. As a matter of policy to mitigate these issues, the U.S. has promoted fuel diversification and vehicle fuel flexibility in the transportation sector as complementary strategies. However, the search for a fuel that replicates the features of oil has proven elusive to policy makers. With the technological innovation of horizontal hydraulic fracturing that has enabled low cost shale gas production, natural gas has a unique opportunity in potentially breaking the stalemate.

This thesis uses an exploratory approach to first identify the underlying factors that create challenges for scaling up alternative fuel and vehicle development. Second, it examines how consumers and policymakers, as two opposing sources of demand, influence and shape their development as well as directions for technological progress. Third, it develops a visual representation using natural gas as a case study to explore some of these issues and how they affect the potential pathways for using natural gas in light duty vehicle applications.

This thesis concludes that while there are no clear pathways forward for natural gas in light duty vehicle applications, the transportation sector's sensitivity to changes in fuel feedstock composition enables a number of opportunities for development rather than suppresses it. This thesis also finds that rather than searching for a single fungible alternative fuel, there may be more opportunities for accommodating new energy sources. However, how the transportation system responds and can adapt to them still remains an area for more research.

Thesis Supervisor: Professor John Heywood  
Professor of Mechanical Engineering, Sun Jae Professor, Emeritus



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# List of Acronyms

<b>ARPA-E</b>	Advanced Research Projects Agency-Energy
<b>DOE</b>	United States Department of Energy
<b>EIA</b>	Energy Information Administration
<b>IEA</b>	International Energy Agency
<b>KW</b>	Kilowatt
<b>KWh</b>	Kilowatt-hour
<b>MW</b>	Megawatt
<b>MWh</b>	Megawatt-hour
<b>NAS</b>	National Academies of Science
<b>NPC</b>	National Petroleum Council
<b>NRC</b>	National Research Council
<b>NREL</b>	National Renewable Energy Laboratory
<b>O&amp;M</b>	Operations and maintenance
<b>OEM</b>	Original equipment manufacturer
<b>RFS</b>	Renewable Fuels Standard



# Chapter 1

## Introduction

### 1.1 Problem Context

While a face may have once launched a thousand ships, this century's most heated and costly love affair is with oil. In the U.S., oil still dominates in one sector: transportation. In fact, the relationship between oil and transportation is mutually dependent: 71% of petroleum is consumed by the transportation sector and 94% of transportation relies on oil (EIA, 2011). There are many challenges attributed to this almost exclusive reliance and the current lack of fungibility in transportation fuels; for example it has been attributed to exposing consumers to price volatility, transferring wealth to oil-producing nations that increase the trade imbalance, diminishing the US foreign policy options, and raising climate change concerns (IEA, 2013). However, as a result of this mutual dependency, changes in the U.S. transportation fuel mix can potentially have dramatic reductions on the nation's oil consumption and address some of these policy issues.

The U.S. light-duty vehicle<sup>1</sup> fleet alone is responsible for roughly half of the U.S.' petroleum consumption and produces nearly 17% of its greenhouse gas emissions (EIA, 2011). Alternative vehicles and fuels are the flipside of these policy challenges with the promise to be cheaper in the long run, domestically produced, with potential environmental lifecycle benefits. However, until recently, fuel suppliers have struggled to produce and distribute an alternative fuel for light duty vehicle fleets that is as cost competitive and energy dense as petroleum-based fuels. This has created difficulties for vehicle manufacturers in producing alternative vehicles capable of meeting the high performance criteria set by conventional vehicles while remaining cost-competitive. Further, vehicle manufacturers argue that the lack of alternative refueling stations deters consumers from investing in alternative vehicles, while fuel suppliers argue that there is insufficient demand for alternative fuel to justify building refueling stations. From a policy perspective, this creates a "chicken and egg" problem for what infrastructure is needed first—increasing alternative fuel production and building fuel distribution infrastructure, or scaling up the numbers of manufactured alternative vehicles.

Policymakers have attempted to address this vicious cycle by proposing an "Open Fuel Standard" for vehicles to encourage alternative vehicle development as a means of stimulating fuel production and in parallel, issuing Renewable Fuel Standards to mandate production levels of certain alternative fuels [see Appendix B]. Notably, these are just two policy options that have been proposed among many others, but they have resulted in heated discussions. Those in favor argue that the "open fuel" aspect would enable greater fuel diversification, thereby challenging oil's stronghold over the

---

<sup>1</sup> Light duty vehicles are cars, SUVs, vans and pick-ups.

transportation sector through a market-based strategy, while also avoiding complaints that policymakers are “picking winners.” Those not in favor mainly object to the standard’s rather stringent and immediate timeline, deeming the open fuel standard to be a “low hanging fruit” policy, where only fuel and vehicle technologies that are currently economically viable are likely to be developed, to the detriment of developing advanced technologies that may prove superior.

Recent technological innovation of hydraulic fracturing further complicates the picture, enabling an enormous supply of shale gas at low cost in ways that could break this stalemate and have far reaching implications for U.S. energy policy. In fact, over the forty-year span of policy-driven alternative fuel and vehicle development, low cost natural gas has spurred a renewed interest in flexible fuel and electric vehicles as well as inspired new vehicle designs. Nonetheless, the potential pathways for natural gas still remain unclear, and given the significant uncertainty and need for fuel-vehicle infrastructure coordination, many studies have indicated that policymakers will continue to play an essential role in shaping their development.

However, policies that attempt to increase supply often are expensive to implement and can become an economic burden if they are not effective. These expenses often take the form of subsidies, tax credits, or other financial incentives. As demonstrated in the early years of alternative fuel and vehicle development where the federal government supported ethanol fuel, the ethanol industry received approximately \$5.68 billion in VEETC tax credits to the ethanol industry in 2010 alone, yet the industry was still unable to produce ethanol at a scale competitive with gasoline (EIA, 2011). Furthermore, not only was there a substantial financial cost associated with supporting ethanol, but it also created market distortions in which it was more profitable for farmers to convert corn—the primary feedstock in ethanol production—into ethanol fuel than to sell it as food as well as to burn acres of less profitable crops into land for growing corn.<sup>2</sup> Policies to help stimulate production of a fuel did rapidly scale up production, but inadvertently also created incentives to support fuel production at the expense of environmentally responsible land use, as well as potentially making corn into competing commodities as both food and a feedstock for ethanol fuel.

Beyond the financial aspects that can create immediate market distortions, policy signaling can also alter the pace of change and type of technology development. For instance, many have discussed the way that conceptually, the rationale behind supporting flexible vehicles capable of running on multiple fuels including gasoline or in a gasoline blend, reflects a certain pessimism or ambivalence about the pace of change. Moreover, it also indicates a desire to take advantage of the cheap alternative fuel opportunity, which some could argue was the same attitude that inspired technology and infrastructure to become optimized for petroleum<sup>3</sup> and resulted in both technology-infrastructure lock in and dependency on a fuel that has raises a number of policy issues.

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<sup>2</sup> Initially, most of the ethanol plants were farmer-owned, but by 2008 and 2009 an influx of non-farmer venture capital entered into the ethanol market (Urbanchuk, 2010).

<sup>3</sup> In the early development of vehicle technologies, electric vehicles competed with those powered by internal combustion engines. When petroleum became extremely cheap and vehicles were optimized for the fuel, and delivered high performance, electric vehicles could not longer effectively compete and fewer vehicle manufacturers produced them.



Given the issues created by technology and infrastructure inflexibility as well as what could be described as a fuel monopoly, policies that promote fuel diversification and vehicle flexibility seem to be a natural step. However, this could require regulatory coordination of fuel suppliers and vehicle manufacturers, and is still subject to uncertainty in consumer demand. Many studies focusing on scaling up alternative fuels and their respective vehicle technologies have indicated that each pathway faces different barriers to market entry requiring substantial assistance that the federal government is financially unable to provide to all of them (NPC, NRC, 2013). The focus of this thesis is to use natural gas as a case study to investigate the implementation realities of fuel diversification and vehicle flexibility and to identify potential ways in which policymakers could address the issues with fuel monopoly and system inflexibility that might align more naturally with consumer demand.

## **1.2 Research Questions**

As stated, given that the U.S. has promoted fuel diversification and vehicle fuel flexibility in the transportation sector as complementary strategies to reduce the sector's near-exclusive and relatively inflexible reliance on oil, the motivating questions are two-fold:

1. Given current vehicle technologies and infrastructure challenges as well as the potential of low cost unconventional natural gas, can a market-based solution like fuel diversification overcome the “chicken and egg” issues, or is it a supply-side strategy that treats a symptom rather than the underlying cause, namely low consumer demand?
2. Are there other policy strategies that can address the fuel monopoly and system inflexibility without requiring the federal government to coordinate or support all of the potential alternatives?

To address these questions, a series of exploratory questions are asked, which lend the structure of this thesis as well as help form the structure of a framework to aid policymakers in visualizing opportunities where flexibility and diversity can be advantageous. These exploratory questions are as follows:

1. What are the advantages and disadvantages of the current set of available alternative fuel and vehicle options? What are the major challenges and barriers to be overcome?
2. If fuel diversification and vehicle flexibility is a desired goal, how might industry respond and what are the possible vehicle technology options that could be advantageous?
3. Given the current options, how does one compare them?
4. If alternative fuels and vehicles are supplied, will consumers purchase them?
5. Based on the state of the industry and demand, does promoting fuel diversification and vehicle flexibility address the intended policy motivations to end the fuel monopoly and system inflexibility?

### **1.3 Thesis Roadmap**

Given the set of exploratory questions above, the thesis is organized into three parts.

Part I describes the state of alternative fuel and vehicle development from an industry perspective to address the first two questions. Following Chapter 1's introduction, Chapter 2 reviews the fuel pathways of currently available alternative fuels from production to consumption to identify their benefits and tradeoffs as well as identify other fuel pathways for natural gas. Chapter 3 provides a deeper analysis of the relationship between fuel characteristics, vehicle technology, and vehicle design as a way to characterize the uncertainty of technological progress.

Part II evaluates the demand for alternative fuels and vehicles from consumer and policy perspectives to address the third and fourth exploratory questions. Chapter 4 uses literature review of consumer demand as a way to assess whether fuel diversification and vehicle flexibility are desirable from a consumer perspective. Chapter 5 draws from historical policy trends to identify underlying policy motivations for alternative fuel and vehicle development that might help align them more naturally with consumer demand.

Part III combines the analyses of the supply and demand for alternative fuels and vehicles to evaluate their implication for policy makers, ability to meet policy goals, and identify potential policy strategies to address the final exploratory question. Chapter 6 uses natural gas as an example to explore different pathways, and Chapter 7 synthesizes the findings.

# Chapter 2

## Current Fuel Trends: Advantages, Disadvantages, and Infrastructure Challenges from Well to Wheels

### 2.1 Overview

As the predominant fuel for light duty vehicles, gasoline has a well-developed production and distribution infrastructure that is highly responsive to customer demand. It forms a kind of baseline for comparison with the infrastructure requirements for large-scale deployment of alternative fuels as well as for the alternative vehicle technologies they may require. The alternative fuels explored in this thesis predominantly focus on those that have received the most attention as of late—ethanol and compressed natural gas (“CNG”)—and briefly considers those that can be affected by and/or derived from natural gas, including methanol, butanol, natural gas to liquid (“GTL”) fuels, and electricity. The advantages and disadvantages of these fuels as viable alternatives to gasoline depend on a number of factors, particularly the extent to which they are compatible with existing production and distribution infrastructure, as well as with conventional vehicles.

This chapter summarizes the current fuel trends from the viewpoint of the fuel industry with particular emphasis on how natural gas might shift the viability of these fuels. Specifically, it outlines issues that may arise from fuel production capacity required to serve the light duty vehicle market as well as distribution systems to move alternative fuel products from refineries to retail refueling stations and to the vehicles that use them. Lastly, it identifies some emerging themes that could be useful in assessing the advantages and disadvantages of the alternative fuels.

### 2.2 Gasoline Supply and Infrastructure

As a point of reference for the size and scope of the U.S. gasoline market, U.S. demand for gasoline is currently over 370 million gallons per day and 134 billion gallons annually, 97% of which is domestically refined and distributed to over 160,000 gasoline retail stations across the country [Figure 1] (EIA, 2013). The U.S. gasoline market is a large, efficient, and mature industry that serves over 254.4 million registered passenger vehicles, 76% of which are light-duty vehicles (FHWA, 2013).

Gasoline, a refined product from crude oil, is made up of a mixture of medium to long hydrocarbon chains, most of which can be produced from crude oil by a relatively simple distillation process and the remaining through chemical refining. Since hydrocarbons all have different boiling points, they can be separated by heating and cooling them until they precipitate out as liquids. This distillation

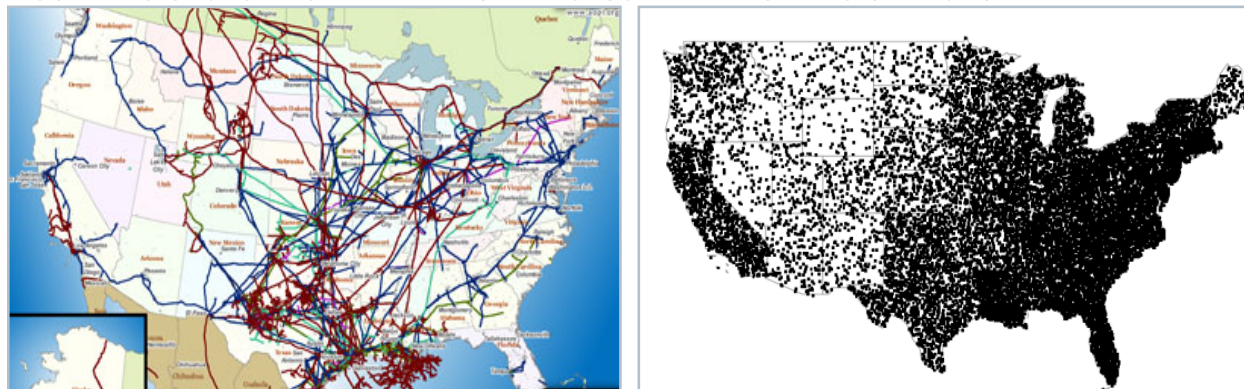
method produces about half the output of a barrel of crude oil. Chemical refining involves a process of “cracking” and “unification,” in which hydrocarbons are first broken apart into smaller components by chemical catalysts, then combined using another catalyst to form longer chains. Chemical refining outputs depend on demand, and most oil refineries are efficient at this process.

The U.S. resource base for crude oil<sup>4</sup> is quite limited, however; 45% of the petroleum (crude oil and petroleum products) consumed in 2011 was from net imports (EIA, 2013). As oil is a globally traded commodity, but geographically constrained, geopolitical risk has often been considered one of the major sources of uncertainty that can lead to supply shocks, which is one factor that contributes to oil’s price volatility. It is from this risk that has spurred exploration efforts into other sources of oil, mainly domestic, like shale oil, but also into those nearby, like Canada’s tar sands. However, these explorations often come with a high financial and environmental cost. It is important to note that domestic recovery of crude oil would not insulate the U.S. from oil price volatility, as it is globally traded and subject to global market demand and supply trends; however, it would enable the U.S. to reduce its oil imports.<sup>5</sup>

Since most crude oil is domestically refined, the U.S. petroleum processing and distribution infrastructure is well established, consisting of 55,000 miles of crude oil pipelines that feed 150 refineries [Figure 1]. As one of the many products from these refineries, gasoline is transported through another 95,000 miles of refined product pipelines and many local delivery trucks to the retail stations. This gasoline supply chain is depicted in Figure 2.

To effectively reduce oil consumption and compete with oil, alternative fuels, depending on how they are used—alone, blended, or as a secondary fuel—would have to be produced and distributed near current scales. However, each alternative fuel faces different well-to-wheel infrastructure challenges and costs.

**FIGURE 1 U.S. CRUDE OIL PIPELINES AND GASOLINE REFUELING STATIONS**

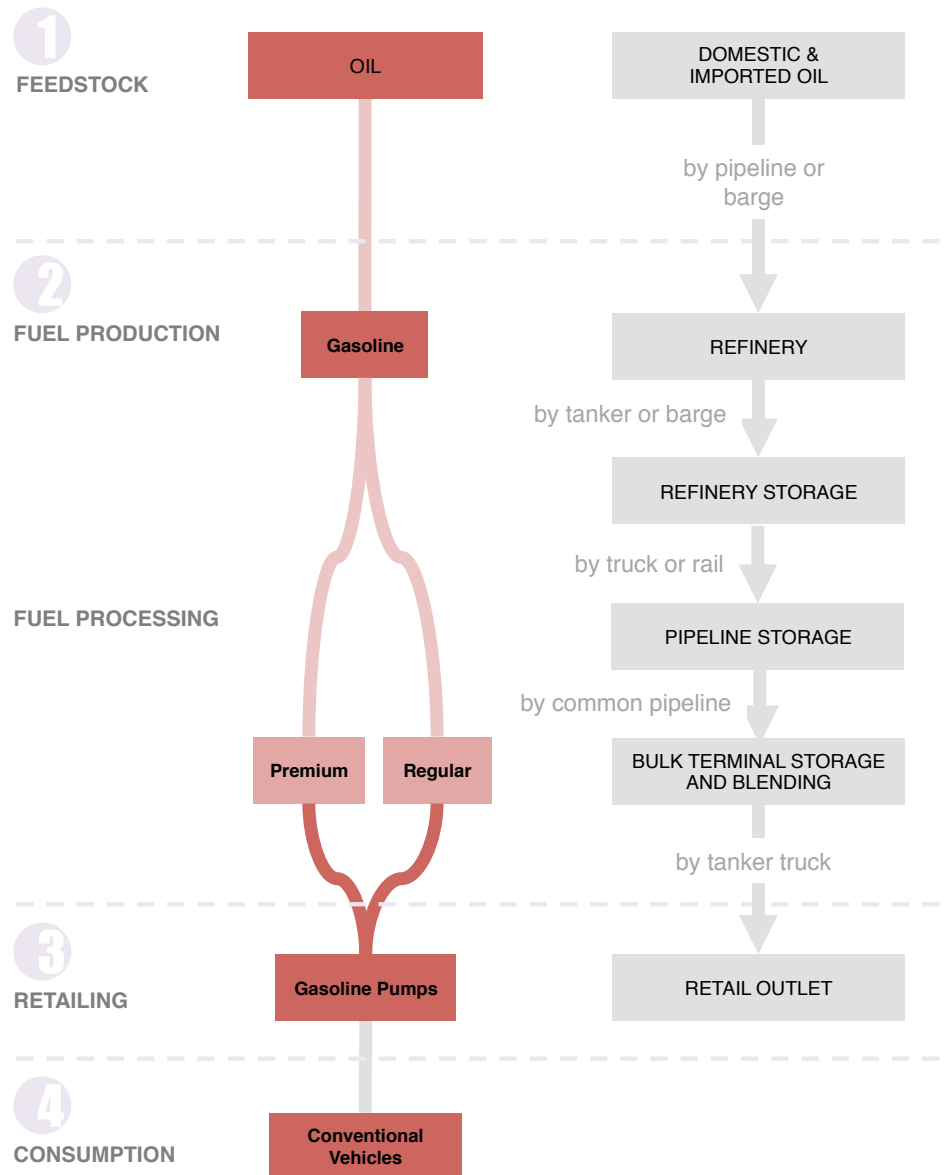


SOURCE: EIA, 2011.

<sup>4</sup> There are many different types of crude oil, which vary based on where they are produced and their quality; some have more impurities, which affects the refining process. These variations are generally reflected in the costs of these types of crude oil. For the purposes of the thesis, however, crude oil is used in an aggregated way.

<sup>5</sup> The top 5 countries the U.S. imports from have consistently been Canada, Saudi Arabia, Mexico, Venezuela, and Nigeria. In 2011, Canada supplied 35% of the imports or 2.2 billion barrels, Saudi Arabia 19%, Mexico 18%, Venezuela 15%, and Nigeria 13%.

**FIGURE 2 GASOLINE PATHWAY AND SUPPLY CHAIN**



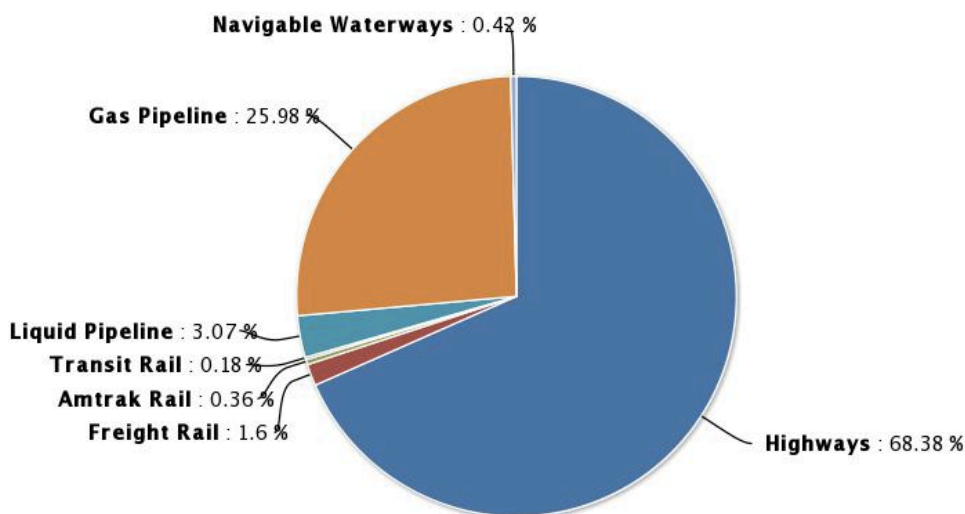
NOTE: PATHWAY CONNECTORS REPRESENT THE TRANSPORT MECHANISM FOR THE FUEL. FOR THIS THESIS, OIL IS ASSOCIATED WITH THE COLOR RED. SINCE PARTS OF THE TRANSPORT MECHANISM REQUIRE TRUCK OR BARGE, WHICH UTILIZES OIL PRODUCTS, THESE PATHWAYS ARE ALSO HIGHLIGHTED IN RED. THE COLOR INTENSITY REFLECTS THE DEGREE TO WHICH OIL HAS A ROLE IN THAT PATHWAY.

SOURCE: EIA, 2013. DATA AVAILABLE AT [HTTP://WWW.EIA.GOV/TODAYINENERGY/DETAIL.CFM?ID=9811](http://www.eia.gov/todayinenergy/detail.cfm?id=9811).

## 2.3 Fuel Characteristics that Impact Infrastructure Development

As noted earlier, gasoline production and distribution infrastructure involves storage facilities, pipelines, and tankers. It is important to keep in mind that the U.S. has many ways of transporting products [Figure 3], but pipelines are still the most efficient method and have the fewest emissions (AFDC, 2013).

FIGURE 3 MILES OF U.S. TRANSPORTATION INFRASTRUCTURE



SOURCE: AFDC, 2013. AVAILABLE AT [HTTP://WWW.AFDC.ENERGY.GOV/DATA/TAB/ALL/DATA\\_SET/10335](http://www.afdc.energy.gov/data/tab/all/data_set/10335).

A fuel that can be easily integrated into the gasoline infrastructure, or utilizes another part of the U.S. transportation infrastructure, would be more advantageous from a cost-perspective than one that requires a specialized one to be built. While fuel production requires considerable infrastructure development, typically, the only fuel properties considered relevant for infrastructure compatibility are those that relate to their storage and transport, which are listed below. Fuel production depends on the fuel source, which generally dictates the location and size of the fuel refineries, as well as operation.

- **Physical state** is how the matter is represented at a given temperature and pressure, which can be a solid, liquid, gas, or plasma.<sup>6</sup>
- **Hygroscopicity** is the ability of a substance to attract and hold water molecules from the surrounding environment. As water at low pH levels tends to corrode metal, hygroscopic materials require more preventative ways to avoid contact with water.

As gasoline is a mixture of hydrocarbon chains, it behaves as a hydrophobic liquid at room temperature. This allows it to be easily transported through steel pipelines, which over long distances is the most efficient delivery method, and can be stored in steel tanks for long periods of time without corroding them or absorbing their impurities. To be compatible with this infrastructure,

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<sup>6</sup> Electricity is an exception.

an alternative fuel would also have to be a hydrophobic liquid, or at least a liquid that does not corrode metal. For easier comparison, the properties relevant to fuel distribution infrastructure are summarized below in Table 1 for each of the alternative fuels.

**TABLE 1 FUEL CHARACTERISTICS RELEVANT TO INFRASTRUCTURE DEVELOPMENT**

	Gasoline	CNG	Ethanol	Methanol	Butanol	GTL
<b>Chemical Structure</b>	C <sub>4</sub> to C <sub>12</sub>	CH <sub>4</sub> (83-99%) C <sub>2</sub> H <sub>6</sub> (1-13%)	CH <sub>3</sub> CH <sub>2</sub> OH	CH <sub>3</sub> OH	C <sub>4</sub> H <sub>9</sub> OH	C <sub>4</sub> to C <sub>12</sub>
<b>Main Fuel Source</b>	Crude Oil	Underground reserves or shale beds	Corn, grains, agricultural waste (cellulose)	Natural gas, coal, or woody biomass	Corn, biomass, cellulose, yeast	Natural gas
<b>Physical State</b>	Liquid	Compressed Gas	Liquid	Liquid	Liquid	Liquid
<b>Hygroscopic</b>	No	No	Yes	Yes	No	No

SOURCE: AFDC, 2011.

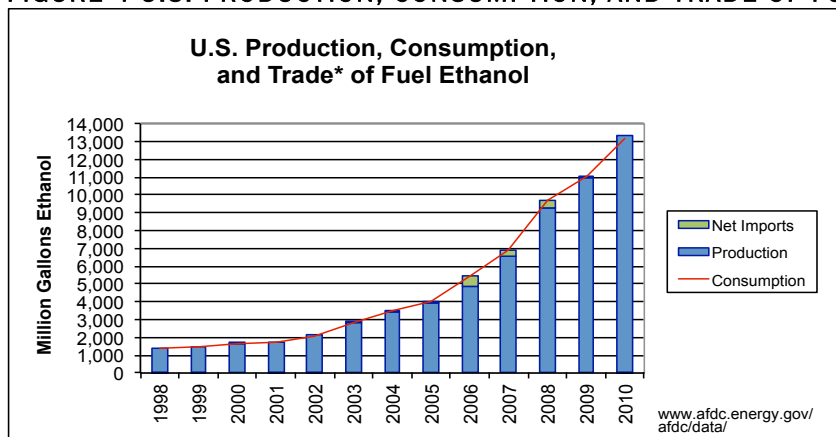
As shown in Table 1, of the currently available alternative fuels considered for light duty vehicle use, only butanol and GTLs could be distributed through the gasoline infrastructure.<sup>7</sup> Although butanol is an alcohol, which usually attracts water, its longer hydrocarbon chain allows it to exhibit more hydrophobic characteristics than ethanol and methanol, which do not have them and are consequently more hygroscopic. Due to their corrosive tendencies, ethanol and methanol require special lubricants as well as tanks and pipelines dedicated to storing and delivering them. As a gas, CNG cannot be transported through the gasoline infrastructure, but does not need to as it can be distributed through the network of pipelines of its primary feedstock—natural gas. Electricity, which was not included in the table as its production and distribution infrastructure is well established, will be discussed later in this chapter.

## 2.4 Ethanol Development

Since ethanol is incompatible with current infrastructure, its supply chain had to be developed and scaled up. It was first promoted as a renewable alternative fuel in 1998, which jumpstarted the industry, and since then the U.S. appetite for ethanol has grown rapidly [Figure 4]. In 2010, U.S. demand for ethanol was 13.2 billion gallons, most of which was from domestic production.

<sup>7</sup> Both of these, however, are not considered strong contenders as alternative fuels due to strict EPA standards and concerns about their potential GHG emissions. This will be discussed in further detail in section 4 of this chapter.

**FIGURE 4 U.S. PRODUCTION, CONSUMPTION, AND TRADE OF FUEL ETHANOL**



SOURCE: AFDC, 2012. AVAILABLE AT [HTTP://WWW.AFDC.ENERGY.GOV/AFDC/DATA/](http://www.afdc.energy.gov/afdc/data/).

### 2.4.1 Ethanol Production Infrastructure

Ethanol is primarily produced from corn; according to the EIA, ethanol production in 2011 was about 14 billion gallons, of which only 67.4 million gallons, or 0.47%, were from non-corn feedstock materials, including brewery/beverage waste, milo/wheat starch, waste sugars, wood waste, cheese whey, potato waste, and sugarcane gallons (EIA, Annual Energy Review, 2011). Whether ethanol is produced from corn or another feedstock material, or even imported, depends on the cost of the feedstock materials and the cost to process them. As the cheapest feedstock with reasonable processing costs, corn remains to be the dominant feedstock in U.S. ethanol production [Table 2].

It is worth noting that feedstock costs, and not processing costs, are the more critical determinant in ethanol production; while this can keep production costs low, it makes the industry highly susceptible to risks that affect feedstock supply. For instance, in 2006 Brazil had the lowest overall production costs when it used sugar cane as a feedstock on a cost equivalent basis, allowing it to be largest ethanol supplier; when U.S. demand exceeded what the domestic industry was able to supply, it had to import the remaining from Brazil [Figure 4, Table 2]. However, with laxer trade restrictions in the U.S. and sugar supply shortages in Brazil, which resulted in higher sugar prices, the U.S. surpassed Brazil in becoming the world's largest ethanol exporter in 2011 (EIA, 2011). While it is not surprising that the combination of these two factors allowed the U.S. to move ahead of Brazil, it highlights the dangers in being reliant on a dominant feedstock. That said, these feedstocks appear to not be entirely dissimilar in cost, which could reduce the risks associated with a dominant feedstock, though the cost dissimilarities depend on how much feedstock is needed to produce a comparable amount of energy.



**TABLE 2 ETHANOL PRODUCTION COSTS FROM VARIOUS U.S. FEEDSTOCK MATERIALS**

Cost Item	U.S. Corn wet milling	U.S. Corn dry milling	U.S. Sugar cane	U.S. Sugar beets	U.S. Molasses 3/	U.S. Raw sugar 3/	U.S. Refined sugar 3/	Brazil Sugar Cane 4/	E.U. Sugar Beets 4/
Feedstock costs 2/	0.40	0.53	1.48	1.58	0.91	3.12	3.61	0.30	0.97
Processing costs	0.63	0.52	0.92	0.77	0.36	0.36	0.36	0.51	1.92
Total cost	1.03	1.05	2.40	2.35	1.27	3.48	3.97	0.81	2.89

1/ Excludes capital costs.

2/ Feedstock costs for U.S. corn wet and dry milling are net feedstock costs; feedstock costs for U.S. sugarcane and sugar beets are gross feedstock costs.

3/ Excludes transportation costs.

4/ Average of published estimates.

SOURCE: U.S. DEPARTMENT OF AGRICULTURE, "THE ECONOMIC FEASIBILITY OF ETHANOL PRODUCTION FROM SUGAR IN THE UNITED STATES," JULY 2006.

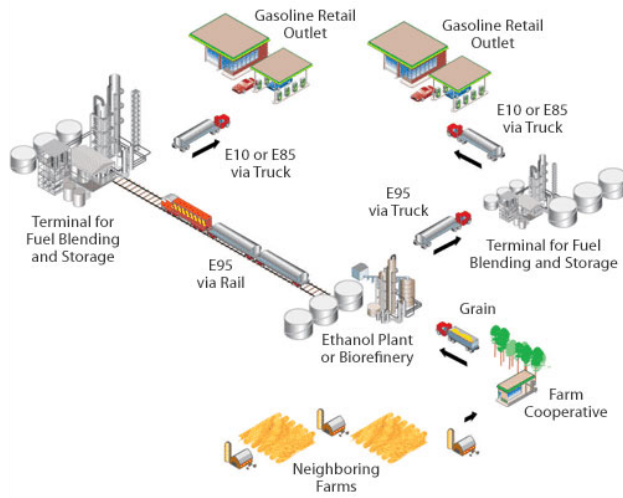
## 2.4.2 Ethanol Transport Infrastructure

Due to its high oxygen content and solvent properties, ethanol is corrosive and tends to absorb water and impurities when transported through pipelines, which currently only distributes less than 10% of fuel ethanol. As illustrated in Figure 5, ethanol production is generally transported by rail or truck from production facilities to gasoline storage terminals, where it is blended with gasoline into two formulations: E10 and E85. E10 consists of 10% ethanol and the remaining 90% is gasoline, while E85 is 85% ethanol and 15% gasoline. The EPA allows conventional vehicles to operate up to E15, above which it damages the vehicle, and allows flexible fuel vehicles<sup>8</sup> to operate up to a maximum of E85. Both of these blending quantities have been highly disputed; some studies by automobile trade groups argue that E10 is the maximum limit for conventional vehicles and flexible ("flex") fuel vehicle manufacturers note that both vehicles are tested with E100 and still perform the same (GreenWire, 2013).<sup>9</sup>

<sup>8</sup> "Flexible fuel vehicles" now is a term specifically used to describe vehicles capable of running on ethanol and gasoline blends up to E85.

<sup>9</sup> The EPA recently tested and approved E15 for use in vehicles from model years 2001 and newer. However, "GreenWire" reported on Jan 29, 2013 that a study conducted by the Coordinating Research Council (CRC) found gasoline with 15% ethanol by volume (E15) damages critical fuel components in an automobile fuel system of several car models—the 2007 Nissan Altima, 2001 Chevrolet Cavalier, 2004 Ford Focus, 2003 Nissan Maxima and 2004 Ford Ranger. Based on this result, the American Petroleum Institute argued that the testing on E15 by EPA and DOE was not correct and that the Renewable Fuel Standard should be repealed. Biofuel groups questioned the study, noting that the CRC study did not actually drive the cars, but instead tested the car components individually. Fuel America, a coalition of biofuels supporters, also noted that according to the CRC researchers, the testing included an 'aggressive' E15 blend that included more water and acid than what consumers would use in their cars.

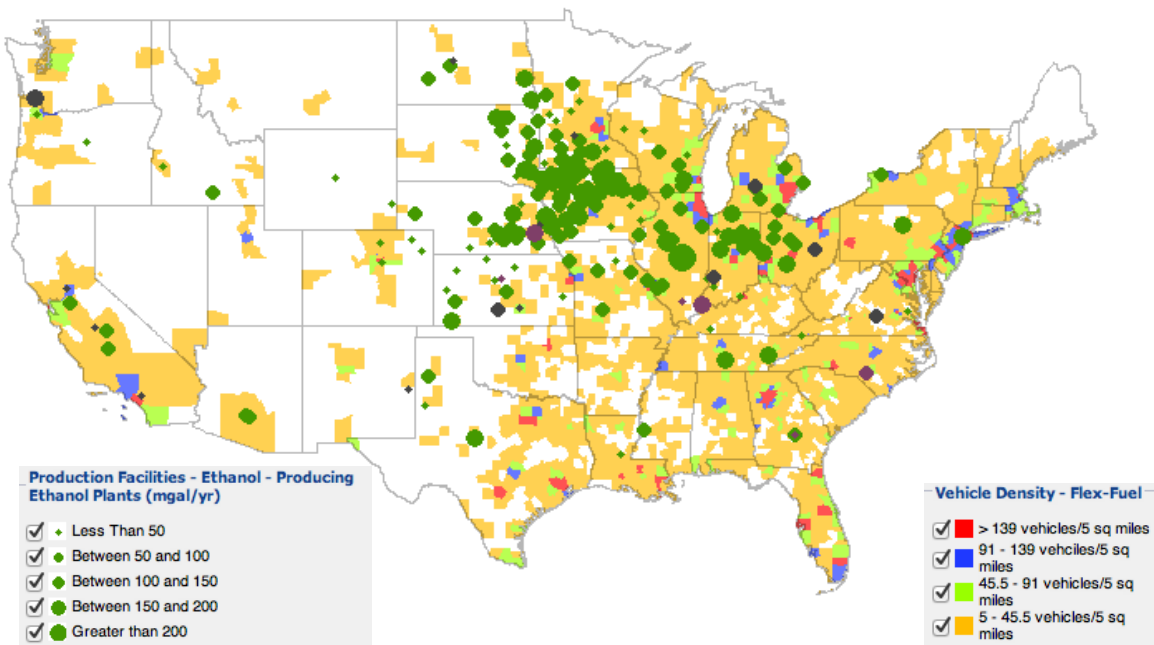
**FIGURE 5 SCHEMATIC OF U.S. RAIL AND TRUCK ETHANOL DISTRIBUTION SYSTEM**



SOURCE: AFDC, 2012. AVAILABLE AT [HTTP://WWW.AFDC.ENERGY.GOV/AFDC/FUELS/ETHANOL\\_PRODUCTION.HTML](http://www.afdc.energy.gov/afdc/fuels/ethanol_production.html).

Since fuel consumption is concentrated on the coastal regions, whereas most U.S. ethanol plants are concentrated in the Midwest, ethanol has to be transported over fairly long distances. The population of flex-fuel vehicles, while more concentrated in the Midwest, also exhibits a greater population density along the coasts [Figure 6]. As demand for ethanol fuel has grown steadily and is expected to continue—driven primarily by the Renewable Fuel Standards, which mandate increasing levels of ethanol production each year—dedicated ethanol pipelines have been considered a more reasonable investment. The Central Florida Pipeline Project is currently being built, and POET and Magellan Midstream Partners have proposed to construct a new dedicated ethanol pipeline connecting the Midwest and Northeastern states [Figure 7]. Nonetheless, to meet the RFS targets, ethanol production is expected to shift to new feedstocks, namely, non-corn starch advanced biofuel feedstocks and cellulose, which could expand the geographic distribution of ethanol production to the Southeast, Mid-Atlantic, and Northwestern states, which have seen dramatic growth in wood and wood waste feedstocks (Urbanchuk, John, 2010).

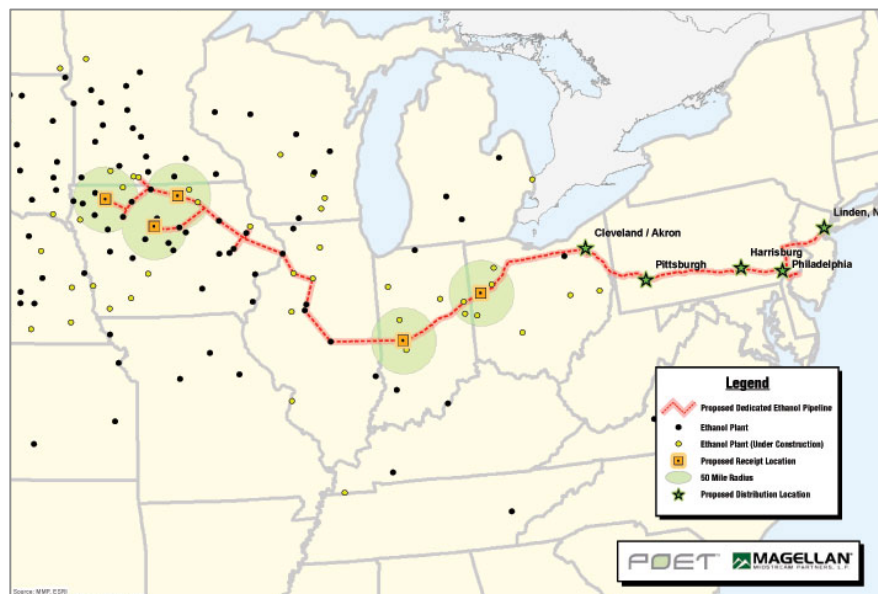
**FIGURE 6 U.S. ETHANOL PRODUCTION FACILITIES AND AREAS OF FLEX-FUEL VEHICLES**



NOTE: SHADED AREAS ON THE MAP DENOTE THE DENSITY OF REGISTRATIONS OF FLEX-FUEL VEHICLES.

SOURCE: NATIONAL RENEWABLE ENERGY LABORATORY, 2009-2012, AVAILABLE AT [HTTP://MAPS.NREL.GOV/TRANSATLAS](http://maps.nrel.gov/transatlas).

**FIGURE 7 PROPOSED DEDICATED ETHANOL PIPELINE**

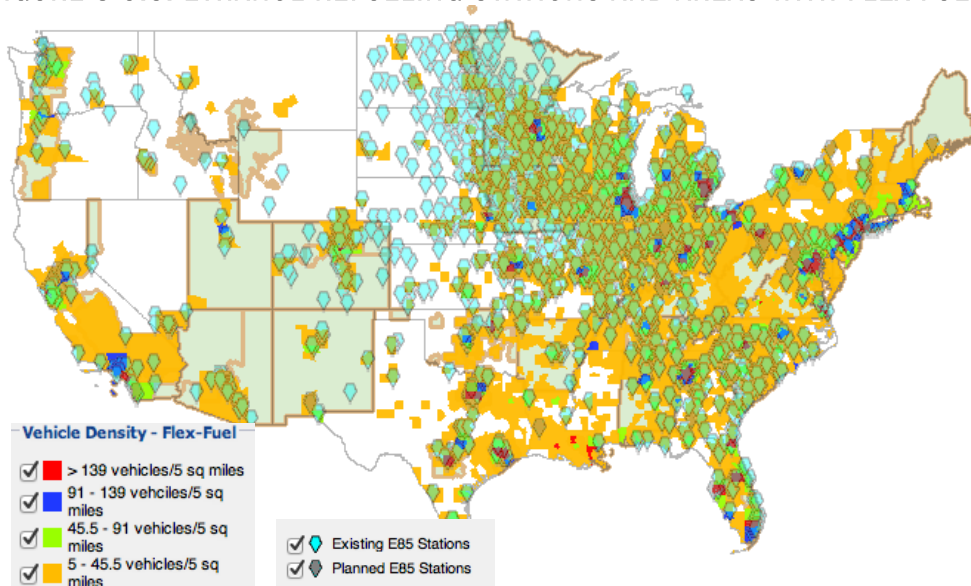


SOURCE: AFDC, 2012. AVAILABLE AT [HTTP://WWW.AFDC.ENERGY.GOV/AFDC/FUELS/ETHANOL\\_PRODUCTION.HTML](http://www.afdc.energy.gov/afdc/fuels/ethanol_production.html).

### 2.4.3 Ethanol Fueling Infrastructure

Currently, there are 2,498 ethanol (E85) refueling stations in the U.S., which are primarily located in areas where flex-fuel vehicles are distributed [Figure 8]. According to the AFDC and a 2008 NREL report, U.S. gasoline stations generally only have an average of 3.3 tanks. To provide E85 fueling capability, a gasoline station could either add an additional tank or convert an existing tank. A new tank costs on average \$71,735 (median \$59,153), while converting an existing tank costs an average of \$21,031 (median \$11,237) [Table 3].

**FIGURE 8 U.S. ETHANOL REFUELING STATIONS AND AREAS WITH FLEX-FUEL VEHICLES**



SOURCE: NATIONAL RENEWABLE ENERGY LABORATORY, 2009-2012. AVAILABLE AT [HTTP://MAPS.NREL.GOV/TRANSATLAS](http://maps.nrel.gov/transatlas).

**TABLE 3 COST OF ADDING E85 FUELING CAPABILITY TO EXISTING GASOLINE STATIONS**

Scenario	Cost	Source*	Description	Major Variables Affecting Cost
New tank, new or retrofit dispenser(s)	Mean: \$71,735 Median: \$59,153	NREL Survey	Includes new storage tank, pump, dispenser(s), piping, wiring, excavation, and concrete work	Dispenser needs, excavation, concrete work, sell backs, canopy, tank size, location, labor price, regulations
	\$50,000–\$200,000	NACS		
	\$50,000–\$70,000	DOT, EPA, DOE		
	>\$50,000	NEVC		
	<\$62,407	DAI		
Convert existing tank, new or retrofit dispenser(s)	Mean: \$21,031 Median: \$11,237	NREL Survey	Tank cleaning, replace non-compatible components in piping and dispensers	Dispenser needs, number of non-compatible components, location, labor price, regulations
	\$19,000–\$30,000	DAI		
	\$5,000–\$30,000	DOT, EPA, DOE		
	\$2,500–\$25,000	NEVC		

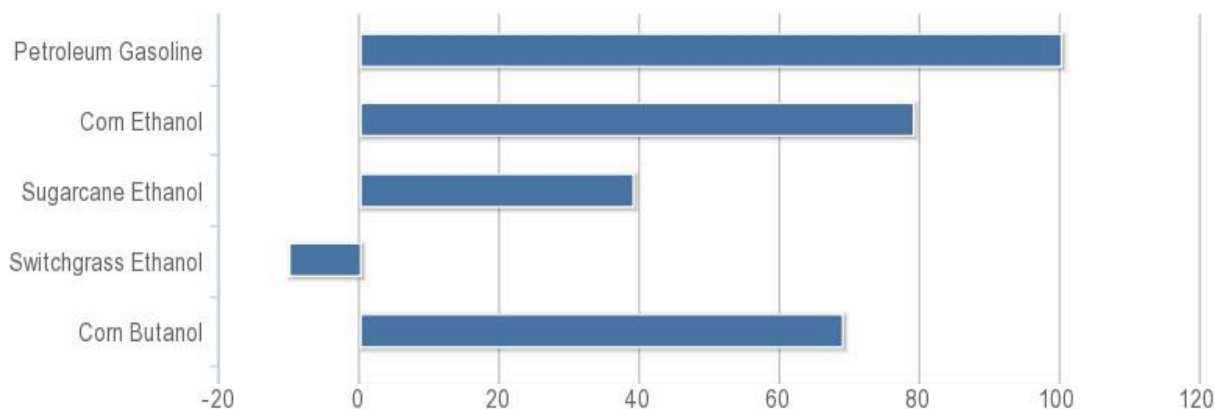
NOTE: NREL ESTIMATES ARE BASED ON INVOICES AND COST ESTIMATES PROVIDED BY GRANT ADMINISTRATORS, STATION OWNERS AND PROJECT MANAGERS FOR 120 E85 FUELING STATIONS, OF WHICH 84 WERE NEW TANK INSTALLATIONS AND 36 WERE CONVERSIONS OF EXISTING TANKS. THE RANGE OF COSTS FOR A NEW TANK WAS BETWEEN \$7,559 TO \$247,600 AND FOR CONVERSION OF AN EXISTING TANK OF \$1,736 TO \$68,00. NREL NOTES THAT THE LOWEST-COST TANK CONVERSIONS MAY HAVE TAKEN SHORTCUTS AND “ARE NOT RECOMMENDED BECAUSE OF CONCERNS ABOUT SAFETY AND MATERIALS.”

SOURCE: AFDC, MARCH 2008. AVAILABLE AT [HTTP://WWW.AFDC.ENERGY.GOV/AFDC/PDFS/42390.PDF](http://www.afdc.energy.gov/afdc/pdfs/42390.pdf).

#### 2.4.4 Ethanol Environmental Impact

While ethanol is considered a renewable fuel and perceived as being carbon neutral, its lifecycle impact has been shown to be far from carbon neutral when factoring in land usage. In fact, each feedstock for ethanol produces different environmental impacts [Figure 9]. Notably, corn ethanol, the predominant feedstock, offers modest GHG emissions reduction, but switchgrass ethanol produces negative emissions; according to the EIA, this is due to a net sequestration of carbon into the soil and biomass (EIA, 2013).

**FIGURE 9 U.S. LIFECYCLE GREENHOUSE GAS EMISSIONS OF BIOFUELS**



NOTE: GHG EMISSIONS ARE DENOTED AS A PERCENTAGE OF THOSE OF THE PETROLEUM THEY REPLACE.

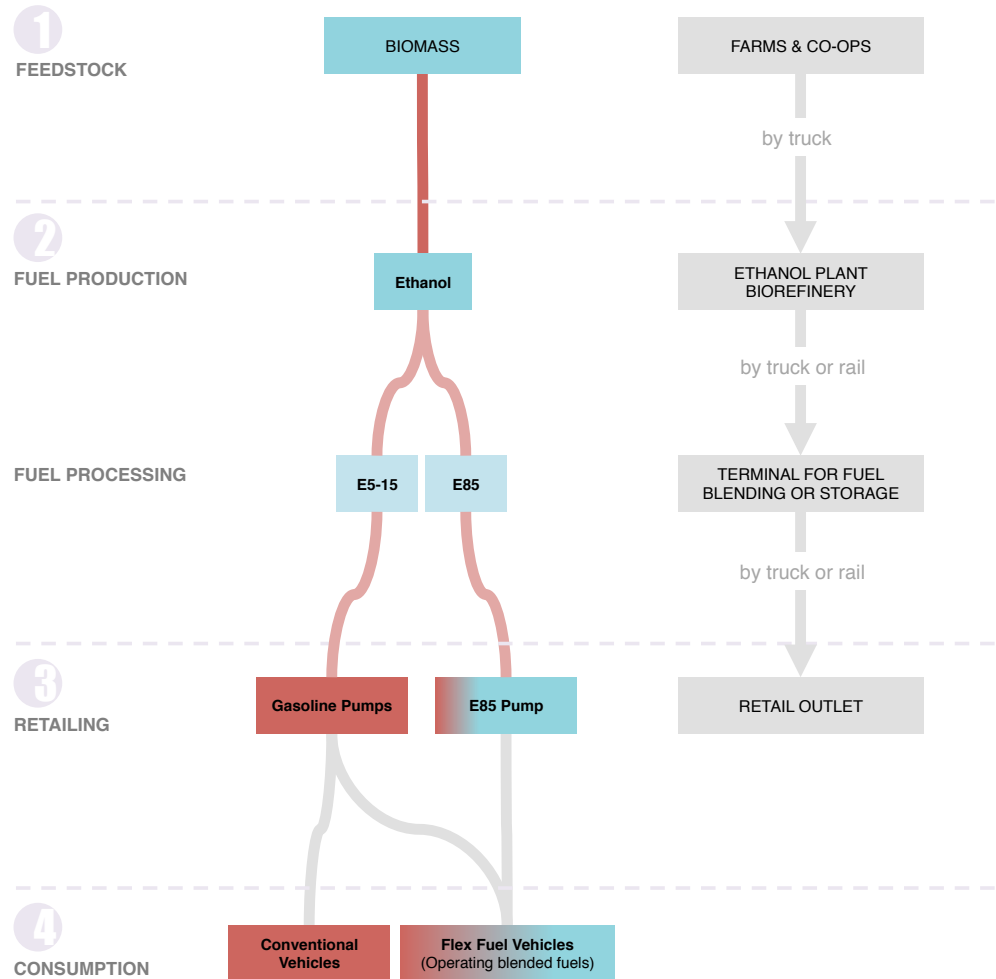
SOURCE: EIA, 2013. AVAILABLE AT [HTTP://WWW.AFDC.ENERGY.GOV/DATA/TAB/FUELS-INFRASTRUCTURE/DATA\\_SET/10328](http://www.afdc.energy.gov/data/tab/fuels-infrastructure/data_set/10328).

#### 2.4.5 Ethanol Summary

As a growing but not yet mature industry, ethanol still faces difficulties in scaling up production, as well as high distribution costs, though these may be reduced over time if feedstock sources increase or dedicated pipelines are built. The pathway for ethanol production to consumption and relationship to the supply chain is shown in Figure 10. Notably, because ethanol's production is concentrated in the Midwest and has to be transported by rail or truck, there are additional costs incurred from its use and does indicate a continued reliance on oil.

From an infrastructure and political standpoint, the primary advantage ethanol has over gasoline as a transportation fuel is that it is domestically grown and could be produced from a number of feedstocks. However, because only blended ethanol can be presently used in vehicles, and distributing ethanol relies on trucks and rail, there remains an inherent dependency on gasoline or petroleum-based fuels, which questions what material impact ethanol can actually have. Further, there are still financial and environmental tradeoffs associated with using each type of ethanol's feedstocks, which require study and review; since reducing greenhouse gas emissions has been added to the policy agenda, these are important considerations in promoting ethanol and alternative fuels.

**FIGURE 10 ETHANOL FUEL PATHWAY AND SUPPLY CHAIN**



NOTE: THE FUEL PATHWAY, WHICH CONNECTS THE FUEL PRODUCTION TO CONSUMPTION, IS THE LEFT DIAGRAM, AND ITS SUPPLY CHAIN IS ON THE RIGHT. COLOR CODING IS A CONTINUATION FROM EARLIER PATHWAY FOR GASOLINE (BUT BIOMASS WILL BE DENOTED AS BLUE), TO SHOW THE EXTENT TO WHICH THESE ARE RELATED. AGAIN, THE CONNECTORS BETWEEN (1) THROUGH (3) REPRESENT TRANSPORT AND DISTRIBUTION INFRASTRUCTURE, WHILE THE CONNECTOR BETWEEN (3) AND (4) SHOWS HOW THE FUEL RELATES TO THE VEHICLE.

## 2.5 CNG Development

In the U.S., interest in CNG has been growing steadily, due to recent discoveries of large domestic sources of unconventional natural gas from shale rock and technological innovations that have made it easier and cheaper to recover. This breakthrough resulted in a significant price drop in natural gas, from \$8.39 per thousand cubic feet (“mcf”)<sup>10</sup> down to \$3.47, which compared to oil at \$100/barrel<sup>11</sup>, is significantly cheaper (EIA, 2013). Because natural gas is distributed along an extensive pipeline infrastructure, CNG is capable of reaching a very large segment of the light duty vehicle market, which is a strong motivation for using it in transportation. However, in the U.S.

<sup>10</sup> Conversion factors for natural gas are included in Appendix A.

<sup>11</sup> This is often used as a benchmark for comparison, though recent prices for oil have been around \$96/barrel.

natural gas is used predominantly in power generation (30%), industrial sectors (34%), and residential heating (33%).<sup>12</sup> Only 3% of natural gas has been used in the transportation sector, and one of the large sources of uncertainty is whether there is enough of low cost natural gas feedstock to also supply the transportation sector.<sup>13</sup>

### **2.5.1 CNG Feedstock Supply**

In 2011, natural gas supply and demand reached record levels, with 23 trillion cubic feet (tcf) of domestic dry gas production and total consumption of 24.4 tcf (EIA Annual Energy Review, 2011). The average wellhead price was \$3.95 per thousand cubic feet (mcf), and the natural gas price at citygate locations was the lowest (in inflation-adjusted terms) in a decade (EIA Annual Energy Review, 2011). This low price is mostly attributed to the technological improvements in natural gas recovery from unconventional sources, namely, shale rock; prior to which natural gas was recovered from the same reservoirs as oil, as they were often found together, and was priced based on oil contracts and consequently strongly correlated with oil prices (MIT Natural Gas Study, 2011). With an expanded resource base, the price of natural gas more closely correlates with the fundamentals of its recovery process.

The U.S. natural gas resource base has been estimated to be at about 2,100 tcf, including gas from shale rock (“shale gas”) and Alaska natural gas, and at current production rates, this corresponds to about 90 years of natural gas supply (MITEI Natural Gas Study, 2011). The potential supply base of shale gas is very large, and may not yet be fully characterized.<sup>14</sup> The MIT Natural Gas Study estimated that a considerable portion of the shale resource base could be produced economically at prices between \$4/mcf and \$8/mcf. If current oil prices remain high at \$100/barrel, these natural gas prices would still remain cheaper.

The current supply outlook suggests that domestic natural gas resources could support a significant alternative fuels infrastructure, either in the form of CNG or through conversion to another fuel. For example, it was estimated that operating 50% of the current light-duty vehicle fleet on CNG would increase current natural gas demand by about one-third (Koonin, 2012). However, this could change if other competing uses develop, including LNG exports. It is also worth noting that the same technological process that enabled the supply of natural gas has also been used to extract oil from shale rock (“shale oil”), which could create a downward pressure on the need for new fuels.

### **2.5.2 CNG Fuel Production**

When recovered from conventional reservoirs, raw natural gas is composed primarily of 70-90% methane, 0-20% ethane, and a mixture of other gases and undergoes a simple process to refine it

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<sup>12</sup> The reliance of these sectors on natural gas in 2010 is 19% for electric power generation, 41% for industrial processes, and 76% for residential and commercial purposes. This chart is in Appendix B.

<sup>13</sup> A sustained low cost supply of natural gas is critical, as at prices above \$8/mcf, using natural gas was not as economically attractive.

<sup>14</sup> Further, there are other biological sources of natural gas, including those released during waste decomposition, though these are considered fairly small reserves compared to shale resource base.

down to specific gases and remove impurities [Table 4]. This often occurs at the natural gas plants before it is delivered through transmission and distribution pipelines. At this stage, it can undergo additional transformations into other fuels or in preparation for industrial feedstock purposes, compressed into CNG, or also be cooled down to -260°F, where it becomes liquefied natural gas (“LNG”) and can be transported or shipped in cryogenic tanks. The fact that natural gas is a gas at room temperature and as a liquid must be kept at extremely cold temperatures, has made it a commodity that is generally more expensive to transport by truck or barge, and is one of the contributing reasons why natural gas is primarily traded in regional markets, and not globally.<sup>15</sup>

**TABLE 4 TYPICAL COMPOSITION OF NATURAL GAS**

Compound	Chemical Structure	Percentage
Methane	CH <sub>4</sub>	70-90%
Ethane	C <sub>2</sub> H <sub>6</sub>	0-20%
Propane	C <sub>3</sub> H <sub>8</sub>	
Butane	C <sub>4</sub> H <sub>10</sub>	
Carbon Dioxide	CO <sub>2</sub>	0-8%
Oxygen	O <sub>2</sub>	0-0.2%
Nitrogen	N <sub>2</sub>	0-5%
Hydrogen sulphide	H <sub>2</sub> S	0-5%
Rare gases	A, He, Ne, Xe	trace

SOURCE: [HTTP://WWW.NATURALGAS.ORG/OVERVIEW/BACKGROUND.ASP](http://www.naturalgas.org/overview/background.asp)

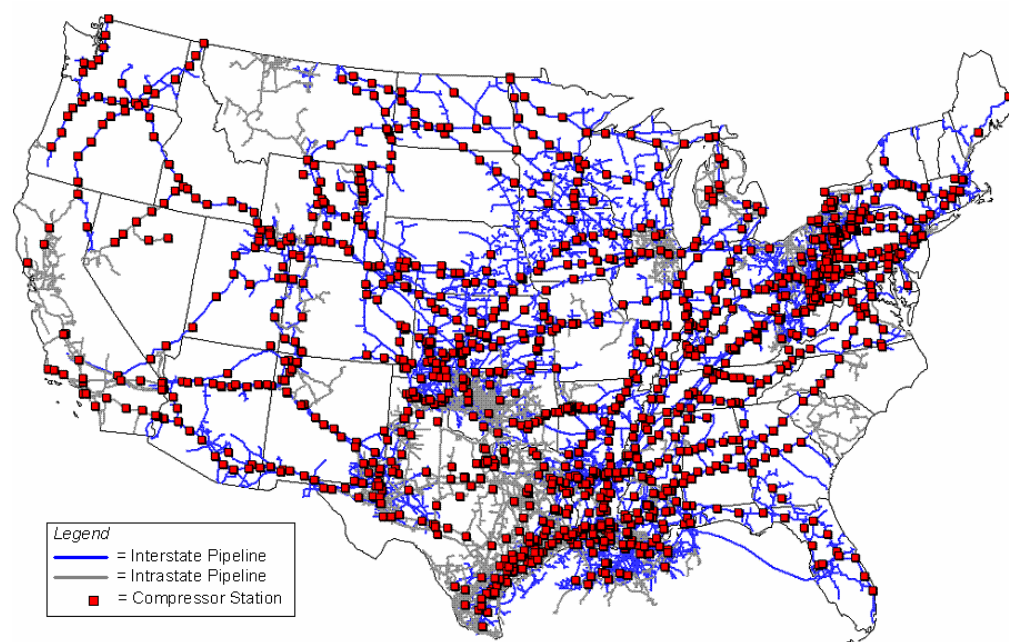
### 2.5.3 CNG Transport Infrastructure

The U.S. has a robust and mature system of natural gas interstate and intrastate pipelines, which consist of 300,000 miles of transmission pipelines [Figure 21] and 1.9 million miles of distribution lines (Koonin, 2012). Changes in the geographical pattern of natural gas production (e.g. increased production from the Marcellus gas shale region) as well as changes in the geographical pattern of demand for natural gas [Figure 12], likely will require additions to the pipeline system. However, the processes for planning, regulatory approvals and financing of new natural gas pipeline infrastructure are well-established and not likely to pose a barrier to increased use of natural gas in alternative fuel vehicles (Koonin, 2012).

<sup>15</sup> However, recent developments in storing natural gas has made it easier to transport natural gas over long distances, which have invited discussions of a potential global natural gas market (EnerSea, 2013).



FIGURE 11 U.S. NATURAL GAS PIPELINES AND COMPRESSOR STATIONS



SOURCE: EIA, 2013.

FIGURE 12 U.S. NATURAL GAS SHALE PLAYS



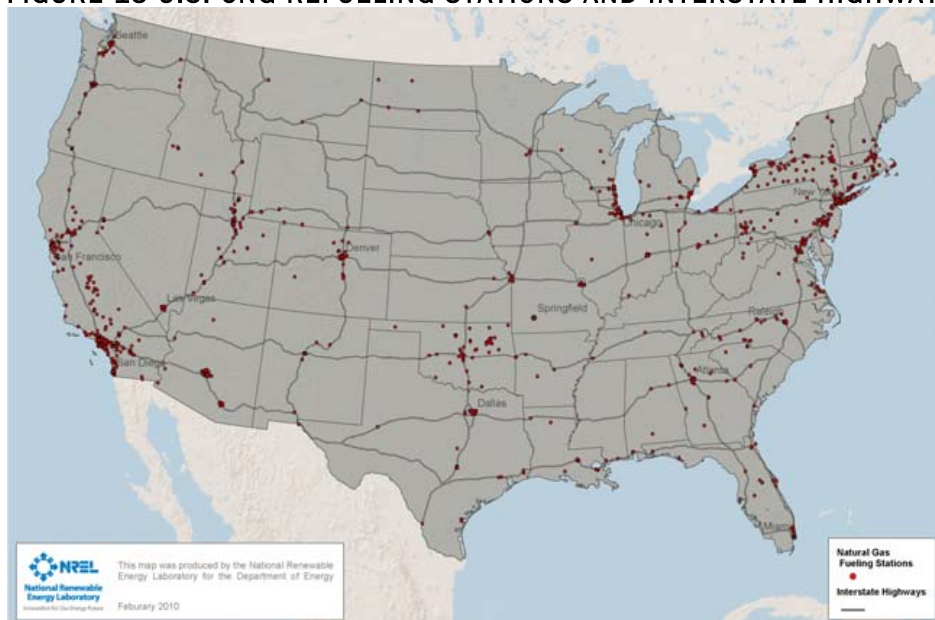
SOURCE: EIA, 2013.

## 2.5.4 CNG Fueling Infrastructure

The current fueling infrastructure for CNG has evolved around the two principal sources of vehicle demand: heavy-duty trucks in long-haul interstate transport and inner city fleets mainly of trucks and buses, but also with taxis. As a result, the current CNG fueling infrastructure is limited and

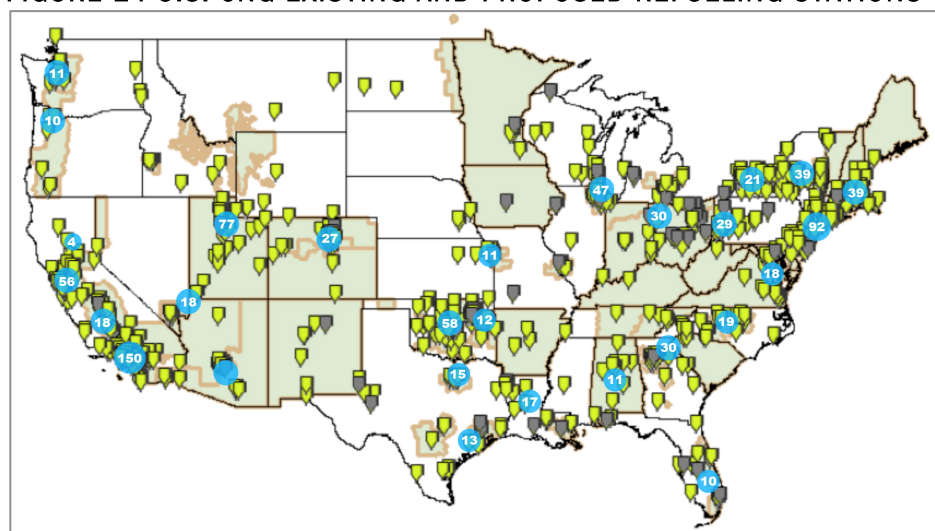
concentrated along the interstate highway system, not quite equipped to serve the broader non-fleet light duty market [Figure 13]. In fact, out of 1,190 CNG refueling stations in the U.S., only 578 of these are public (AFDC, 2013). However, the Clean Cities program under the Department of Energy's Office of Energy Efficiency and Renewable Energy has been working to promote expanding this network to support the broader light duty vehicle market (Clean Cities, 2013). Current proposals to expand the CNG refueling infrastructure are illustrated in Figure 14.

**FIGURE 13 U.S. CNG REFUELING STATIONS AND INTERSTATE HIGHWAYS**



SOURCE: NATIONAL RENEWABLE ENERGY LABORATORY, FEBRUARY 2010.

**FIGURE 14 U.S. CNG EXISTING AND PROPOSED REFUELING STATIONS**

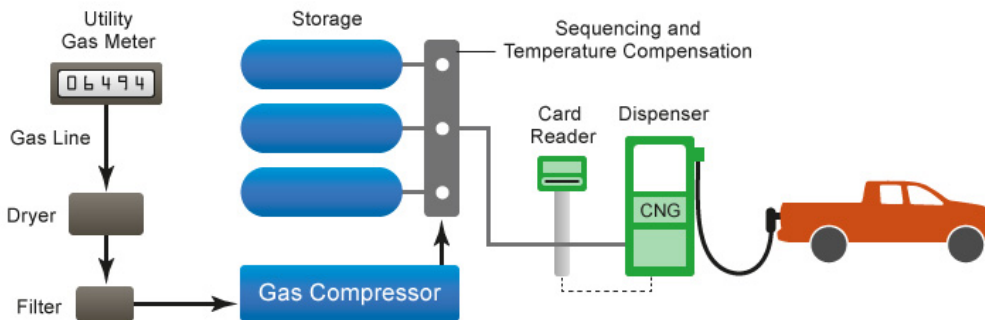


SOURCE: AFDC, APRIL 2012 AND NATIONAL RENEWABLE ENERGY LABORATORY, 2012. AVAILABLE AT [HTTP://MAPS.NREL.GOV/TRANSATLAS](http://maps.nrel.gov/transatlantis).

For vehicles operating on CNG, refueling requires a high-pressurized compressor station for natural gas and special nozzles to ensure a tight seal during the refueling process. Earlier refueling station designs used nozzles that required training to use, but recent nozzle designs more closely resemble those used to pump gasoline. There are two types of CNG refueling stations: fast-fill and time-fill. The principal difference between the two is the size of storage tanks and gas compressors, which determines, as their names suggest, the speed in which they can refuel a vehicle.

Fast-fill stations are capable of refueling a 20 gallon-equivalent tank in approximately 4-5 minutes, which is comparable to gasoline refueling times—an essential characteristic for non-fleet light duty vehicles [Figure 15]. Though CNG is usually pressurized and used at 3500 pounds per square inch (“psi”), the fast-fill stations are often pressurized to 4000 psi due to potential losses over time and require large storage capacity of CNG. The equipment for fast-fill stations is about the size of a parking space (AFDC, 2013). According to the AFDC, 75% of the refueling stations in the U.S. are fast-fill, of which more than half are public stations (AFDC, 2013).

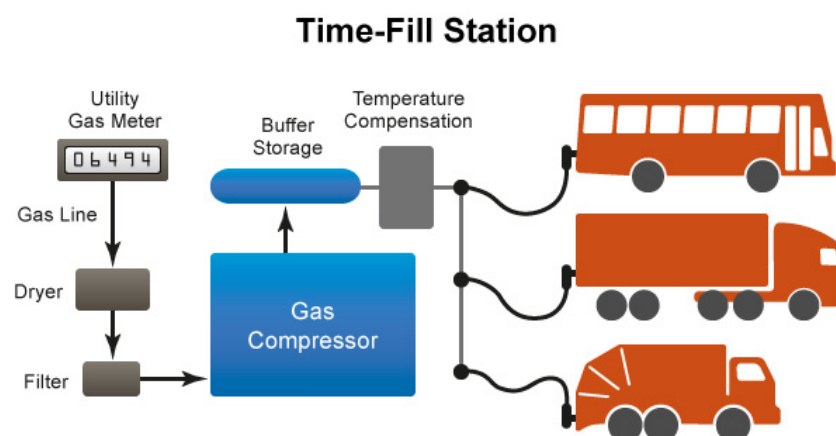
**FIGURE 15 ILLUSTRATION OF A CNG FAST-FILL FUELING STATION**  
**Fast-Fill Station**



SOURCE: COMPRESSED NATURAL GAS FUELING STATIONS, ALTERNATIVE FUEL DATA CENTER  
[HTTP://WWW.AFDC.ENERGY.GOV/FUELS/NATURAL\\_GAS\\_CNG\\_STATIONS.HTML#FASTFILL](http://www.afdc.energy.gov/fuels/natural_gas_cng_stations.html#fastfill).

By comparison, time-fill stations can take anywhere between several minutes to several hours to fill a vehicle and are designed for fleets, which are often centrally refueled and can deal with the longer fill times [Figure 16]. Time-fill stations typically have a relatively small amount of buffering storage, but are directly linked to the compressor; consequently, refueling times are linked to compressor throughput, and vary depending on the number of vehicles, compressor size and the amount of buffer storage. One advantage of time-fill is that the user can choose the time to refuel vehicles, and since electricity needed for running the compressor can cost less at off-peak hours, refueling at night might be more cost effective (AFDC, 2013).

**FIGURE 16 ILLUSTRATION OF A CNG TIME-FILL FUELING STATION**



SOURCE: COMPRESSED NATURAL GAS FUELING STATIONS, ALTERNATIVE FUEL DATA CENTER  
[HTTP://WWW.AFDC.ENERGY.GOV/FUELS/NATURAL\\_GAS\\_CNG\\_STATIONS.HTML#FASTFILL](http://www.afdc.energy.gov/fuels/natural_gas_cng_stations.html#fastfill)

The cost for CNG refueling stations depends upon the size of stations and the types of natural gases (CNG, LNG or both) that the stations offer. Whether a station is a fast-fill or a time-fill station also affects the cost. According to a 2010 report by U.S. DOE Pacific Northwest National Laboratory, a CNG refueling station can cost from \$400,000 to \$2 million [Table 5].

**TABLE 5 COST FOR CNG REFUELING STATIONS**

CNG Refueling Station Size	Maximum Capacity	Maximum Capacity (GGE Equivalent)	Estimated Cost
Small	< 500 scfm	4.0 gge/min	\$400,000
Medium	500-2000 scfm	4.0-15.8 gge/min	\$600,000
Large	> 2000 scfm	>15.8 gge/min	\$1,700,000

NOTE: "SCFM" IS STANDARD CUBIC FEET PER MINUTE, WHICH IS A MEASURE OF FLOW FOR NATURAL GAS.

SOURCE: U.S. DEPARTMENT OF ENERGY, PACIFIC NORTHWEST NATIONAL LABORATORY, "ISSUES AFFECTING ADOPTION OF NATURAL GAS FUEL IN LIGHT AND HEAVY-DUTY VEHICLES," PNNL-19745, SEPTEMBER 2010.

Given the high installation costs for CNG refueling stations and reluctance of refueling station owners in adding them, companies have offered an at-home re-fueling solution to deliver CNG. For a period of time, Honda, while producing and selling the CNG Accord GX, a vehicle that only runs on CNG<sup>16</sup>, it also marketed a home CNG refueling appliance called Phill, through a separate company. The appliance is now being marketed by the Italian Company BRC Gas Equipment and retails at about \$4,500. Depending on the customer's residential gas rate, installation costs, operating and maintenance costs, the resulting CNG cost is roughly \$3 to \$5 per gasoline gallon equivalent. While the advantage of refueling at home was a slight draw, Phill was a relatively low pressure (0.5 psi) CNG refueling system, which required about 8 hours to fill a CNG tank. However, the Department of

<sup>16</sup> A dedicated vehicle is one that runs only on that particular fuel. Another type of CNG vehicle is one that is bi-fuel, which refers to its ability to run on two fuels—gasoline and CNG.

Energy, through ARPA-E, recently awarded grants for developing low cost home refueling systems, which could significantly impact the demand for CNG vehicles.

Apart from home refueling options, the second development that emerged from the lack of refueling infrastructure was the development of CNG bi-fuel vehicles, which are capable of operating on both CNG and gasoline, though not simultaneously. There are advantages and disadvantages to these vehicles in terms of performance, range, and fuel economy, which will be described in further detail in Chapter 3. However, as bi-fuel vehicles have fewer refueling requirements than dedicated CNG vehicles, they not only minimize the impact of needing expensive public CNG fueling infrastructure, but also may make home-refueling options a more attractive business opportunity.

### **2.5.5 CNG Environmental Impact**

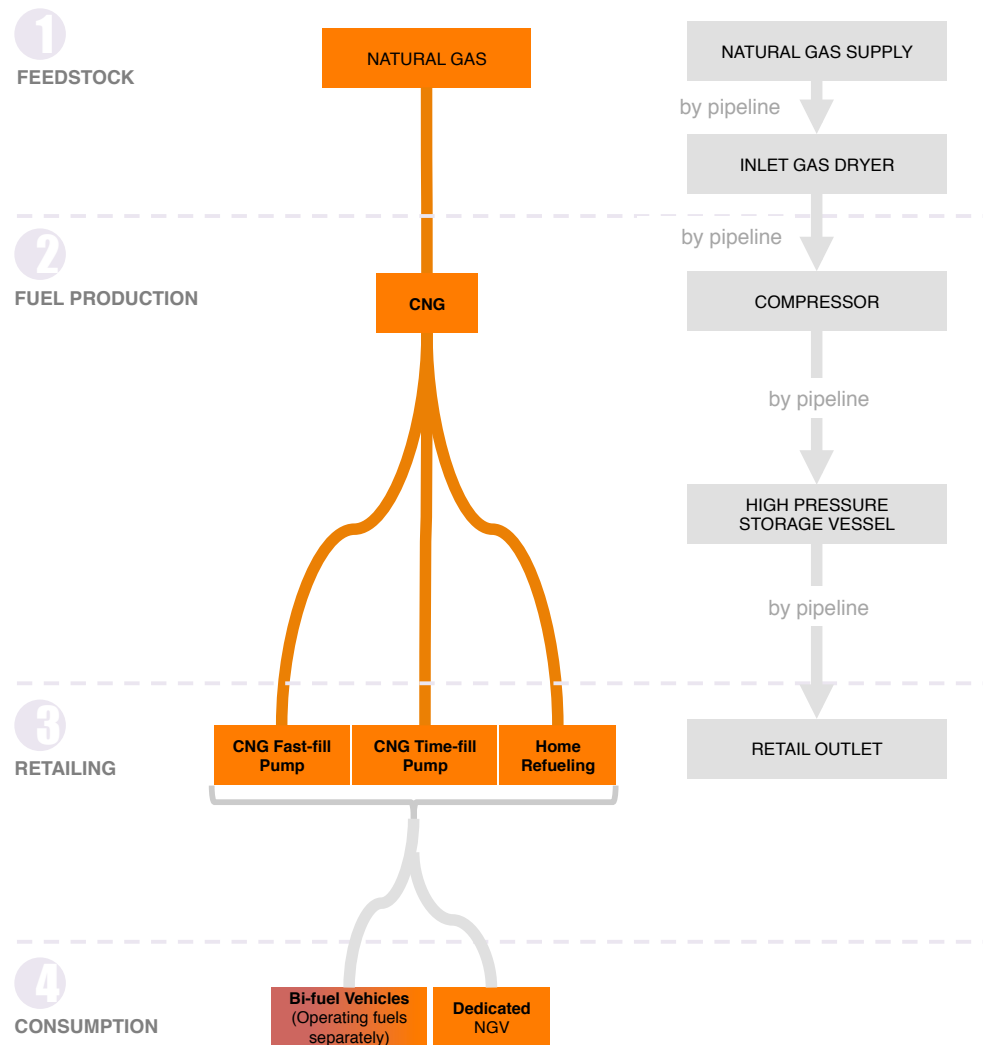
Compared to gasoline, CNG is a cleaner burning fuel, producing 20-45% fewer smog-producing pollutants, but only 5-9% fewer greenhouse gas (“GHG”) emissions on a well-to-wheels basis (DOE EERE Fuel Economy, 2013). Most of the GHG emissions are produced during natural gas recovery, primarily from methane leakages. Methane is considered a more potent GHG, trapping more radiation than CO<sub>2</sub>, though its half life is shorter (12 years). Pound for pound, the comparative impact of methane on climate change is over 20 times greater than CO<sub>2</sub> over a 100-year period (EPA, 2013). For perspective, of the methane emissions produced each year, natural gas and petroleum produces 30%, the remaining is from other sources. However, over 60% of methane emissions is due to human related activities (industry, agriculture, waste management, etc.).

### **2.5.6 CNG Summary**

Compared to ethanol, CNG has fewer setbacks in terms of its infrastructure development. Of its challenges, limited public refueling options are key, though there are opportunities to circumvent them through home refueling. The pathway for CNG from production to consumption as it relates to its supply chain is in Figure 17.

Like ethanol, CNG has the advantage of being primarily domestically produced, 94% in fact, and through recent technological developments can be produced more abundantly. Though natural gas prices can exhibit seasonality trends, it is partly a result of its other primary use in industrial heating, which is seasonal; unlike ethanol feedstocks, it is not as susceptible to climate-related supply shocks as are agricultural products. These immediate advantages have well-positioned CNG as a transportation fuel from a policy and industry perspective, though it still remains unclear whether or not it will also eventually be subject to global market uncertainty and risks, as well as whether the methane leakages and other environmental risks associated with natural gas can be resolved.

**FIGURE 17 CNG FUEL PATHWAY AND SUPPLY CHAIN**



NOTE: AGAIN, COLOR CODING IS CONTINUED FROM BEFORE, THOUGH NATURAL GAS IS DENOTED AS ORANGE. CONNECTORS STILL REPRESENT THE TRANSPORT MECHANISM.

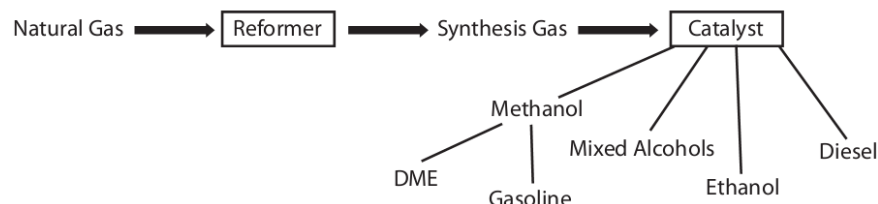
SOURCE FOR SUPPLY CHAIN: EIA, 2007. DATA AVAILABLE AT [HTTP://WWW.EIA.GOV/PUB/OIL\\_GAS/NATURAL\\_GAS/ANALYSIS\\_PUBLICATIONS/NGPIPELINE/TRANSPATH\\_FIG.HTML](http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/ngpipeline/transpath_fig.html).



## 2.6 Development of Other Natural Gas-Based Fuels

As noted earlier, natural gas can be converted into a number of different products. For fuels, some of these include methanol, natural gas to liquids (“GTLs”), and as electricity [Figure 18]. Given the affordable natural gas opportunity described earlier, interest in these fuels has been renewed.

**FIGURE 18 CONVERSION OF NATURAL GAS TO ALTERNATIVE FUELS**



SOURCE: MITEI, 2011, “THE FUTURE OF NATURAL GAS: AN MIT INTERDISCIPLINARY STUDY, 2011

### 2.6.1 Methanol

Converting natural gas to methanol is a relatively easy conversion compared to the production of other natural gas-derived fuels and given its advantage over CNG as a liquid fuel, methanol is sometimes considered a possible contender. However, very limited amounts are used for light duty vehicles due to current regulatory mandates and certification requirements that favor the use of ethanol over methanol. Further, the U.S. is currently a net importer of methanol, as there are very few domestic methanol conversion facilities currently in the U.S. While there is considerable global experience in large-scale natural gas to methanol conversion, it is mostly used as a feedstock for chemical production. With abundant domestic resources of natural gas, the U.S. could potentially become a large producer of methanol, but this would require new large-scale production facilities.

Methanol can be produced from several feedstock materials, including natural gas, coal and biomass. However it is generally produced overseas and shipped through ocean tankers, usually by Methanex, a world leader in methanol production. As a corrosive liquid, methanol would still face the same infrastructure and distribution challenges as ethanol. As a hazardous chemical, refueling with methanol would require methanol-compatible, liners, new dispensers, and filters to ensure health and fire safety. Underground storage tanks have been estimated to cost approximately \$50,000 (Bromberg et al., 2010).

In 2009, the U.S. demand for methanol was 1.85 billion gallons, of which 86% was imported from the Caribbean and South America and 90% was used for chemicals production (Bromberg et al., 2010). The remaining was produced domestically, the bulk of which is produced by four facilities. Together, these four produced a total of 329 million gallons [Table 6].

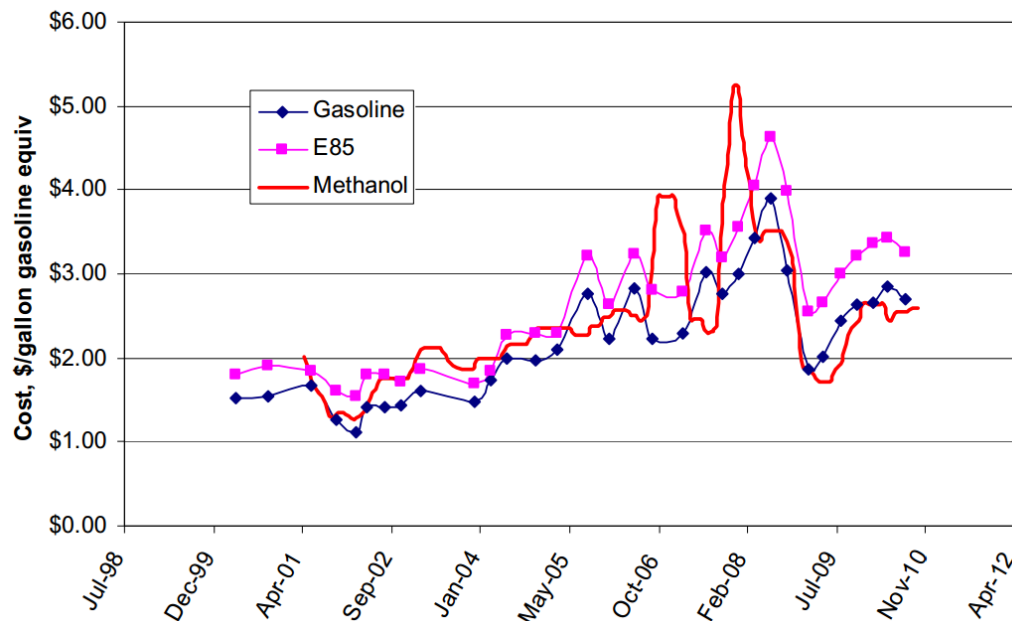
**TABLE 6 2009 U.S. METHANOL PRODUCTION (MILLIONS OF GALLONS)**

Methanol Facility	Production	Feedstock
Eastman Chemical (Kingsport, TN)	71	Coal
La Porte Methanol (Lyondell, DeerPark, TX)	203	Natural gas
CF Industries (Woodward, OK)	40	Natural gas
Praxair (Geismar, LA)	15	Natural gas

SOURCE: L. BROMBERG AND W.K. CHENG, "METHANOL AS AN ALTERNATIVE TRANSPORTATION FUEL IN THE US: OPTIONS FOR SUSTAINABLE AND/OR ENERGY-SECURE TRANSPORTATION", SLOAN AUTOMOTIVE LABORATORY, MASSACHUSETTS INSTITUTE OF TECHNOLOGY, NOVEMBER 2010.

According to Methanex, imported methanol has closely tracked gasoline prices over the period from 2005 to 2010 on an energy-equivalent basis, which could suggest that fuel price volatility would be unavoidable [Figure 19]. The contract cost of methanol in January 2012 was \$2.70 per gallon gasoline equivalent, while the spot price for gasoline was \$2.82/gal for New York Harbor conventional gasoline and \$2.77/gal for U.S. Gulf Coast conventional gasoline. While construction of state of the art methanol plants in the U.S. could provide methanol at a significantly lower cost than gasoline, it is unclear if it would still exhibit the same coupling effect as imported methanol and as E85 has also shown.

**FIGURE 19 NORMALIZED COSTS OF LIQUID FUELS AT THE GAS STATION**



NOTE: COSTS OF METHANOL AT THE STATION ARE ESTIMATES.

SOURCE: L. BROMBERG AND W.K. CHENG, "METHANOL AS AN ALTERNATIVE TRANSPORTATION FUEL IN THE US: OPTIONS FOR SUSTAINABLE AND/OR ENERGY-SECURE TRANSPORTATION" MASSACHUSETTS INSTITUTE OF TECHNOLOGY, 2010.



In summary, while methanol has the natural gas cost advantage, a significant investment in production facilities and distribution networks would be required for methanol to serve as a transportation fuel. That said, however, methanol is an intermediary step in one of the conversion processes for converting natural gas into gasoline, or GTL, which will be discussed in the next section.

### 2.6.2 GTL<sup>17</sup>

Since the early 1980s, the process of converting natural gas to gasoline or diesel has been practiced commercially. There are two methods by which this conversion takes place: first natural gas undergoes a thermochemical conversion to a mixture of carbon monoxide and hydrogen (“synthesis gas” or “syn gas”). Then it either undergoes a Fischer-Tropsch (“FT”) process to catalytically convert it into a broad range of paraffinic hydrocarbons, which can be converted to gasoline, or it is converted into methanol, which is then converted into gasoline (“MTG”). Mobil Corporation pioneered the MTG effort for nearly 10 years in the 1980s, producing gasoline from natural gas in a facility in New Zealand (NRC, 2013). Many companies including Shell, Sasol, and Chevron continue to use the Fischer-Tropsch process, though neither these facilities nor future planned ones are based in the U.S. (NRC, 2013).

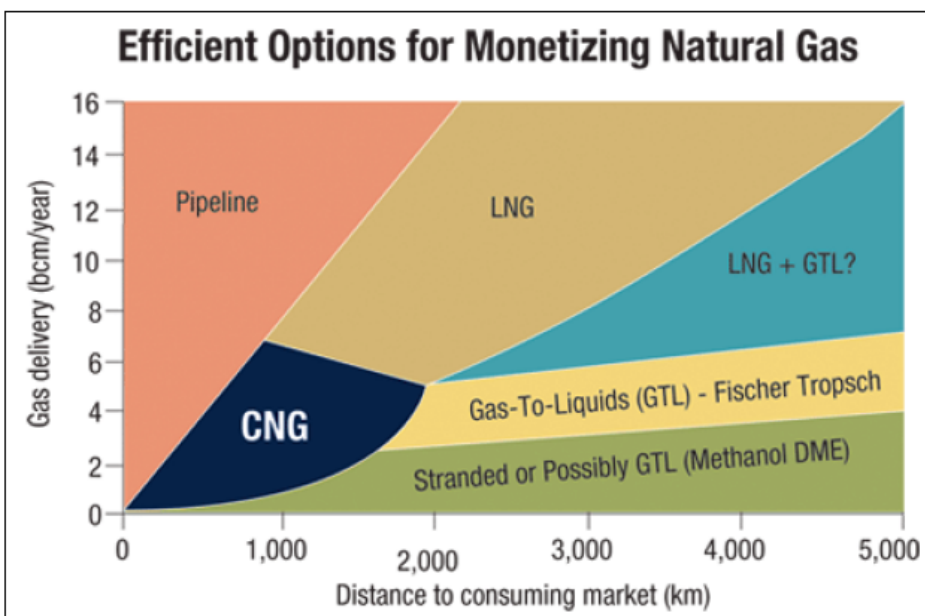
Production of gasoline or diesel through the FT process can also utilize a number of other feedstocks, including coal (“CTL”). However natural gas requires fewer complicated processing steps as it arrives to the facility in a purer form than coal, which often contains sulfur compounds (NRC, 2013). The costs for the facilities reflect some of these differences, though GTL plants, which were developed later after CTL plants, to some extent benefited from the learning curve of their predecessors. Given that natural gas is also a cleaner burning fuel compared to coal, GTL plants do not necessarily require carbon capture and sequestration (“CCS”).

However, because GTL facilities are primarily overseas, the investment opportunity for GTL facilities depends on the tradeoff in the cost of transporting the product overseas versus building a facility in the U.S. and delivering the product through a pipeline [Figure 20]. Put another way, from looking at the long-term oil supply curve, if oil prices continue to remain high, the opportunity for GTLs to enter as a substitute could become a more realistic possibility [Figure 21].

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<sup>17</sup> While GTL may be a confusing term for what is otherwise gasoline (or diesel), this term has been widely adopted to signify the differences in feedstocks (crude oil vs. another feedstock). As coal can also be similarly converted to gasoline from the same process, this fuel is called CTL. Collectively, GTLs and CTLs can be called XTLs. Another name for gasoline GTL is gasoil.

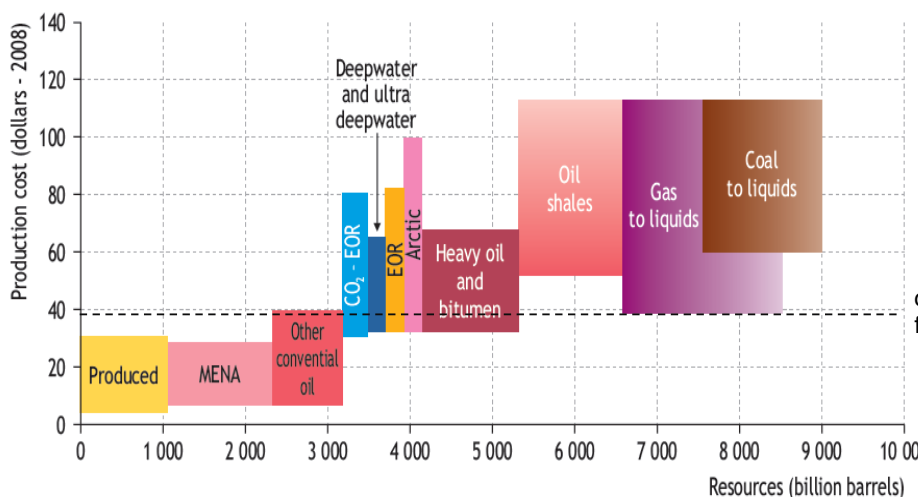
**FIGURE 20 PRODUCTION VOLUME VERSUS DISTANCE TO MARKET FOR VARIOUS GAS TECHNOLOGIES**



NOTE: BCM = BILLION CUBIC METERS, WHICH TRANSLATES INTO 35.3 BILLION CUBIC FEET, 36 TRILLION BTUS, OR 6.29 MILLION BARRELS OF OIL EQUIVALENT [APPENDIX A].

SOURCE: MARONGIU-PORCU ET AL., 2008. [HTTP://XGAS.US/IMAGES/SPE\\_115310\\_MOSCOW\\_08\\_FINAL.PDF](http://xgas.us/images/spe_115310_MOSCOW_08_FINAL.PDF).

**FIGURE 21 LONG TERM OIL SUPPLY COST CURVE**



Note: The curve shows the availability of oil resources as a function of the estimated production cost. Cost associated with CO<sub>2</sub> emissions is not included. There is also a significant uncertainty on oil shales production cost as the technology is not yet commercial. MENA is the Middle East and North Africa. The shading and overlapping of the gas-to-liquids and coal-to-liquids segments indicates the range of uncertainty surrounding the size of these resources, with 2.4 trillion shown as a best estimate of the likely total potential for the two combined.

SOURCE: IEA WORLD ENERGY OUTLOOK, 2008.

### 2.6.3 Electricity

Natural gas currently comprises 30% of the nation's power generation, which alone consumes 40% of the nation's primary energy sources, most of which is from coal. As natural gas remains a fairly cheap feedstock relative to its competitors, it has the potential to displace the less efficient coal plants, which could also reduce greenhouse gas emissions.

However, though electricity has a well-established production, transmission, and distribution network, not only would it have to be expanded to support electric vehicle fleets, but also a number of regulatory issues would have to be resolved. For instance, unlike the other fuels discussed in this paper, who builds and pays for charging infrastructure—public, utilities, or EV users—is less clear, and regulating the price for charging vehicles at residences or central stations would have to be well-defined. Further, municipalities, state public utility commissions, and the federal government even may have to be involved in detailed matters like vehicle maintenance; to do this would require more detailed vehicle studies in order to understand their operation, especially since electric vehicles generally come in two varieties (battery electric and plug-in hybrid electric) and can be charged anywhere.

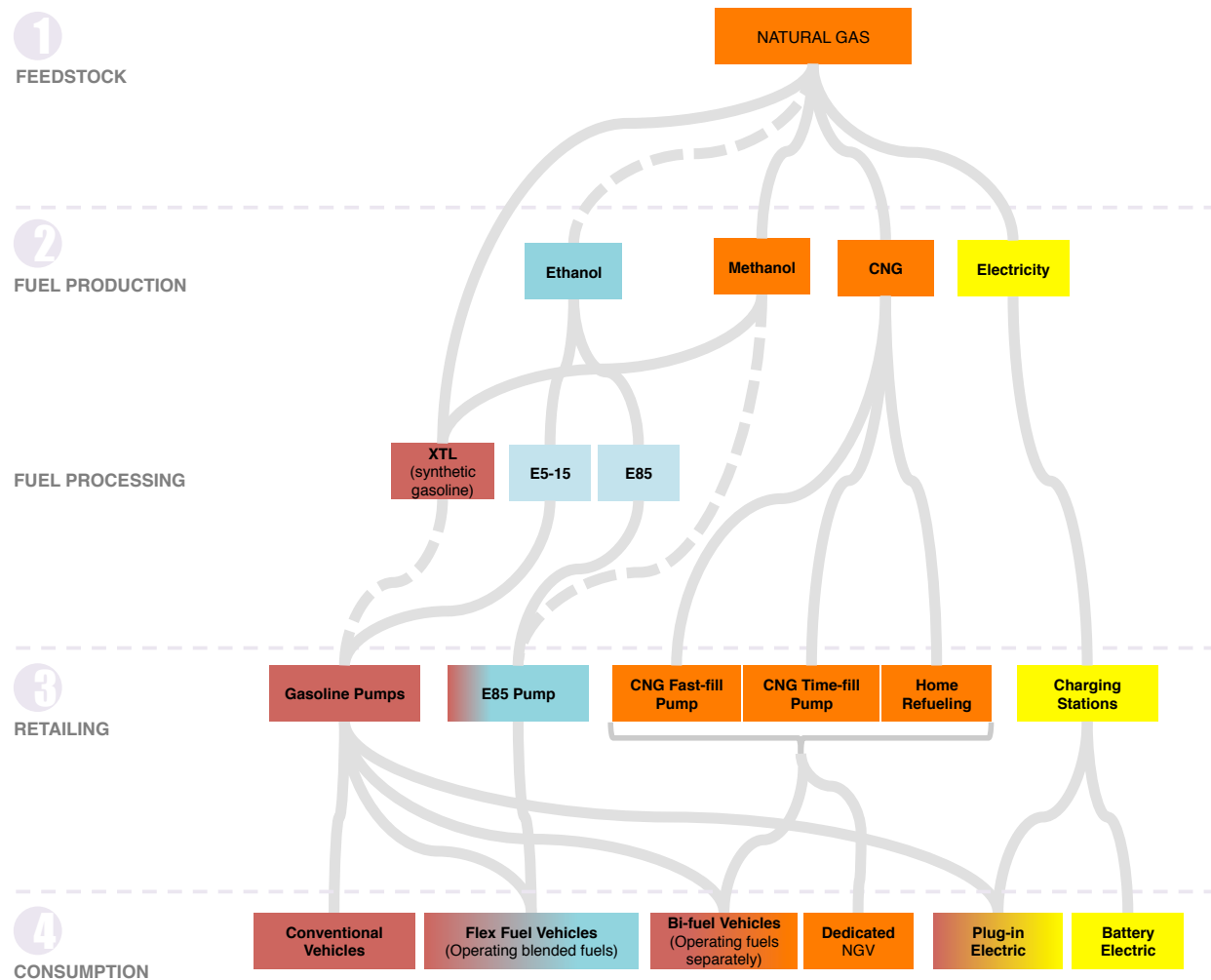
### 2.6.4 Ethanol

While natural gas can also be converted to fuel-grade ethanol, which has been demonstrated by a company called Celanese, producers have argued that the Renewable Fuel Standard creates a roadblock preventing fossil-fuel derived ethanol to be produced; as the mandates for ethanol refineries to produce biomass-derived ethanol calls for supplies that exceed current demand, the opportunity for other producers to enter is reduced. However, given the similar agricultural risks biofuel ethanol often shares, a case could potentially be made for natural gas ethanol, assuming its seasonality effects do not augment those with biofuel ethanol.

### 2.6.5 Summary

As shown, there are a number of different pathways for natural gas to be used, namely, methanol, GTLs, electricity, and ethanol [Figure 22]. However, despite the fact that natural gas can be a useful feedstock for producing these fuels, each fuel still has various tradeoffs and drawbacks that do not necessarily break their stalemate, apart from one—GTL. The opportunity for GTL production is improved by higher oil prices and low natural gas prices, which if sustained, could justify their investment. However, as many of these facilities are located overseas, it is unclear whether or not the investments would remain overseas, or be developed in the U.S. While there is considerable uncertainty in GTL development, the abundance of low cost unconventional natural gas does still make this a relatively appealing option. As methanol can be an intermediate step for GTLs, another consideration is the intermediate scaling up of the small methanol industry in the U.S. to expand beyond products for chemical conversion.

FIGURE 22 PATHWAYS FOR NATURAL GAS FUELS



NOTE: THESE PATHWAYS MERELY REPRESENT THE CONNECTIONS BETWEEN FUEL SOURCE, PRODUCTION, PROCESSING, RETAILING, AND CONSUMPTION; THOUGH THESE PATHWAYS ARE DEPICTED EQUALLY, THEY ARE NOT ALL THE SAME IN TERMS OF COSTS, GEOGRAPHIC DISTRIBUTION, ETC.

DOTTED LINES IN THE DIAGRAM INDICATE EITHER POSSIBLE PATHWAYS THAT HAVE NOT YET BEEN EXPLORED OR HAVE NOT BEEN DEMONSTRATED SUFFICIENTLY IN THE U.S.

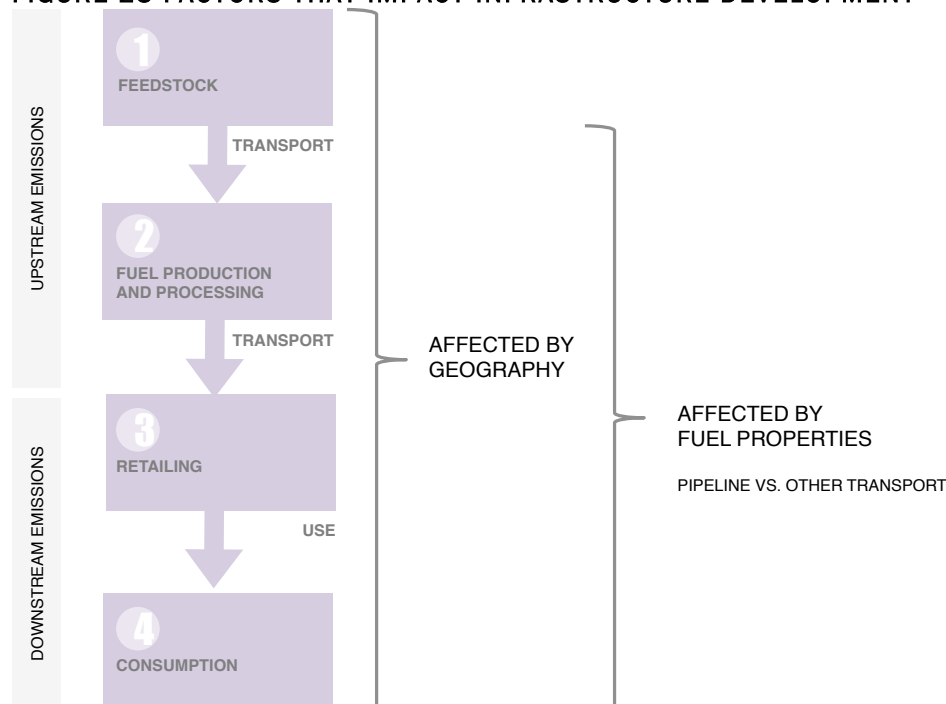
## 2.7 Considerations for Alternative Fuels Development

As noted above, the predominant fuels still have some considerable challenges to overcome. However, a few important themes emerge, which can be one way of evaluating the advantages and disadvantages of these alternative fuels in comparison to gasoline:

- **Geography matters.** Whether this increases the possibility of geopolitical risk or creates difficulties in transporting the fuel, geography is an important consideration for both feedstock selection and infrastructure development, as it can create tradeoffs between building a new production facility and incurring higher transport costs.
- **Fuel properties matter.** These affect the ways in which the fuels are transported. Corrosive materials like ethanol have to be stored in special tanks, for instance, and materials that only become a liquid at extremely cold temperatures like LNG have to be kept in cryogenic tanks.
- **Fuel feedstock composition matters.** The more dominant the feedstock is in the fuel production, the more it can influence the fuel supply; as demonstrated with ethanol, its supply is highly sensitive to changes in its feedstocks and as it is produced from agricultural products, typically experiences the same risks that agriculture products face.

Where along the fuel pathway these factors matter is illustrated in Figure 23. As reducing GHG emissions is on the policy agenda, emissions are another key component; upstream emissions are generally considered easier to regulate than downstream ones, which tend to be more distributed.

FIGURE 23 FACTORS THAT IMPACT INFRASTRUCTURE DEVELOPMENT



# Chapter 3

## Technological Progress and the Impact of Fuel Diversification on Vehicle Design

### 3.1 Overview

Though there are number of infrastructural issues that make comparing the advantages and tradeoffs between fuels difficult, vehicle technologies and design offer some clarity but can also create further complications. One of the motivating arguments for policies that promote fuel diversification and the alternative technologies that support them is the case that the issues with oil were created by inflexible demand in the short-term (Minsk, 2009); in other words, it was created by inflexible vehicles and/or the lack of other vehicle options.

This chapter summarizes the potential vehicle-fuel trends from a vehicle manufacturers viewpoint as a way to characterize how fuel uncertainty affects vehicle design and how it can also be incorporated into vehicle design. Specifically, it outlines the fuel characteristics and properties that affect vehicle design, explores some current vehicle designs that accommodate multiple fuels and their cost constraints, and the implications they have on the broader discussion of fuel diversification and vehicle flexibility. Some of the overarching messages that emerge are the following:

- Generally, the more divergent the properties of the alternative fuel are from gasoline's, the more vehicle design changes are required. While certain properties are more important for fungibility with the mainstream vehicle technology, others require specific vehicle modifications. Depending on how many components have to be changed, these characteristics can increase the cost to manufacture the vehicle.
- With current vehicle technology, multiple fuel operation generally results in performance reductions, with the exception of blending small amounts of ethanol with gasoline.
- Industry tends towards incremental changes as the cost of research and development ("R&D") increases and the opportunity cost in developing alternative vehicles increases.

### 3.2 Fuel Characteristics that Impact Conventional Vehicle Design and Performance

While the fuel properties that affect transport and storage determine infrastructure development, they become even more relevant in vehicle design, performance, and maintenance. The majority of

gasoline-powered light duty vehicles on the road use internal combustion engines, specifically spark-ignition engines, as they are simple, robust, and deliver high performance. The engines themselves are capable of operating on many fuels, but differ in how the fuel is delivered, mixed with air, ignited, etc. These factors that alter how the fuel is delivered comprise the components of the fuel processing system, which is where most of the alternative vehicles begin to depart from conventional vehicle design. Generally, the more divergent the fuel is from gasoline, the more modifications it requires to the fuel processing system and the more likely the vehicle requires a form of operation optimized for that particular fuel. These aspects can also affect the overall vehicle design.

Four of the characteristics that are critical for compatibility with conventional vehicles are the following:

1. **Fuel volatility** is the tendency of a substance to vaporize. A fuel with excessive or too high volatility can result in the car failing to start. In the case of excess volatility, what is known as “vapor lock” can occur where, due to insufficient fuel, combustion fails to occur because the liquid fuel has changed to a gaseous state in the fuel lines. A fuel with too low volatility has the opposite effect: insufficient fuel vaporization. Weather can intensify these effects. Fuel volatility is also a consideration in evaluating evaporative emissions.
2. **Heat of vaporization** is the energy required to transform a given quantity of a substance from a liquid into a gas at a given pressure (usually atmospheric). A fuel with a high latent heat of vaporization can create engine difficulties in cold conditions, namely, a cold start, as a significant amount of energy is needed to vaporize the substance. With direct-injection spark-ignition engines, fuel evaporation within the cylinder cools the air, generally benefiting engine operation.
3. **Energy density** of a fuel is its specific energy, or the energy per unit mass. The higher the energy density, the more energy may be stored or transported for the same amount of volume, which has implications on fuel consumption of an vehicle and its range.
4. **Research Octane Number (RON)** determines the “anti-knock” quality or resistance to spontaneous fuel and air mixture ignition. Generally, a fuel with a higher octane rating is less prone to knocking (91 RON, regular gasoline, has moderate knock resistance; 98 RON, premium, has higher knock resistance; ethanol at 109 RON, higher still knock resistance), which can improve fuel economy, torque and power.

For purposes of easier comparison, the fuel properties and attributes for the alternative fuels compared to gasoline are summarized in Table 7.

**TABLE 7 FUEL PROPERTIES AND ATTRIBUTES**

	Gasoline	CNG	Ethanol	Methanol	Butanol
<b>Hygroscopic</b>	No	No	Yes	Yes	No
<b>Fuel Volatility</b>	More volatile		Less volatile	Less volatile	Volatile
<b>Heat of Vaporization</b>	0.36 MJ/kg		0.92 MJ/kg	1.2 MJ/kg	.43 MJ/kg
<b>Research Octane Number (RON)</b>	91-99	130	108.7	108.6	98-105
<b>Energy Density</b>	32 MJ/L		19.6 MJ/L	16 MJ/L	29.2 MJ/L
<b>Energy Contained in Various Alternative Fuels as Compared to One Gallon of Gasoline</b>	100%	5.66 pounds or 126.67 cu. ft. of CNG has 100% of the energy of one gallon of gasoline. <sup>13</sup>	1 gallon of E85 has 77% of the energy of one gallon of gasoline. <sup>18</sup>	1 gallon of methanol has 49% of the energy of one gallon of gasoline.	
<b>Air-Fuel Ratio<sup>19</sup></b>	14.6	14.2	9.0	6.4	11.1

SOURCE: AFDC, 2006-2011 AND NREL, 2011

From this table, what becomes apparent is that gasoline, and by extension GTL, remains to be the highest energy density fuel, though CNG and butanol are close. Ethanol and methanol are not as energy rich, which mean more fuel is consumed in using them, in terms of driving, this could increase the frequency of refueling the vehicle.

Based on their volatilities, ethanol and methanol require more heat to vaporize, which means they are less likely to spontaneously pre-ignite and experience engine knock, but are more likely to suffer from cold starts in cold temperatures, particularly during winter. However, given that gasoline is more volatile and not as good at resisting knock, one can begin to see the complementarities in blending alcohol and gasoline (SAE High Octane Fuel Symposium, 2013). In fact, this has been one of the motivations for using small amounts of ethanol, 8% usually, with gasoline to suppress engine knock. Interestingly, though at higher concentrations ethanol's hygroscopic nature tends to damage vehicles, at smaller quantities these effects are lessened and allow ethanol's more advantageous qualities to be utilized. These potential areas of compatibility present one interesting opportunity for alternative fuels, and coincidentally also do not require as significant of a change to the system.

While the stoichiometric air-fuel ratio is provided in the table, differences in values reported in the table do not necessarily imply superiority. Methanol and ethanol operate at lower air-fuel ratios than gasoline, but the ratio for each is set at a level close to the stoichiometric ratio for that particular fuel in the engine, which means that almost all stoichiometric mixtures have equivalent energy content during the combustion process. Nonetheless, since air is a limiting factor and a fuel that occupies more space reduces the volume available for air, some alternative fuels result in a loss in engine power. Use of higher compression ratios can partially offset any power loss due to the fuels' overall lower mixture energy density.

<sup>18</sup> According to the AFDC, the ethanol content of E85 is usually lower than 85% for two reasons: 1) fuel ethanol contains 2-5% gasoline as a denaturant and 2) fuel ethanol content is lowered to 70% in the winter in cold climates to facilitate cold starts. When the actual composition of E85 is accounted for, the lower heating value of E85 varies from 82,970 Btu/gal to 89,650 Btu/gal, which is 72% to 77% the heat content of gasoline.

<sup>19</sup> Air-fuel ratio is the mass ratio of air to fuel present in an internal combustion engine.



### 3.3 Vehicle Designs to Optimize Fuels<sup>20</sup>

The types of light duty alternative fuel vehicles currently offered are often categorized based on the number of fuels they operate on [.

Table 8], however, the ways in which they operate these fuels can be quite different. The ones discussed in this chapter are those that have been demonstrated for CNG and ethanol fuels.

**TABLE 8 TYPES OF LIGHT DUTY ALTERNATIVE FUEL VEHICLES**

Conventional fuel vehicle	Any vehicle engineered and designed to be operated using gasoline or a gasoline blend containing ethanol (or methanol) that can be used in the vehicle without need for modifications.
Dedicated Mono-fuel alternative fuel vehicle	Any vehicle engineered and designed to be operated using a single source of alternative fuel. This category includes battery electric vehicles (“BEV”) and dedicated natural gas vehicles (“NGV”).
Bi-fuel vehicle	Any vehicle engineered and designed with two independent fuel systems, which can be operated on either of the two fuel processing systems separately, but not in combined operation simultaneously. This category includes gasoline/natural gas vehicles and plug-in hybrid electric vehicles (“PHEV”).
Flex-fuel vehicle (FFV)	Any vehicle engineered and designed to be operated on a single fuel processing system that can accommodate mixtures of varying quantities of two or more liquid fuels that are combusted together. This category includes vehicles that can operate on either gasoline or ethanol (E85), or conceivably, gasoline and methanol (M85). Also included are vehicles with two liquid fuel processing systems that can operate individually or simultaneously, employing up to three liquid fuels (tri-flex fuel vehicles). However, these are still in the R&D phase.

SOURCE: MITEI 2012 SYMPOSIUM.

#### 3.3.1 Conventional Gasoline Vehicles

Just as gasoline sets a kind of baseline for infrastructure development, gasoline-powered internal combustion engine vehicles (“ICEVs”), which constitute most on the road light duty vehicles—1.5 billion in the world, in fact—sets a high bar in terms of fuel economy, performance, and minimizing costs. Gasoline-powered ICEVs are fairly efficient at utilizing this fuel and are becoming increasingly more so. There are a number of avenues to improve mainstream technology and achieve higher efficiencies, namely, through downsizing engines and making them more efficient, reducing vehicle weight and drag, or adding lubricants to reduce the amount of energy lost as heat from friction. Vehicle manufacturers are also able to produce gasoline-powered ICEVs at low cost compared to other vehicle designs. These cost and efficiency benefits are in part due to the gains from moving

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<sup>20</sup> While battery electric vehicles would be considered in this category, they are not discussed in this thesis, as they still are not cost-competitive and face a number of regulatory issues.

down the learning curve but also because the materials used in their construction are cheaper and becoming lighter, which in turn contributes to better vehicle performance.

The fuel properties mentioned earlier are those that are most relevant to compatibility with this design, and most of the alternative vehicles on the market are variations of it, with the exception of electric vehicles.

### 3.3.2 CNG Dedicated Vehicles

In 2009, the U.S. had a total of about 245 million vehicles on the road, of which about 235 million were light duty cars, and only 4% were vehicles with either dedicated alternative fuels or flex fuel systems (Transportation Energy Data Book, 2011). Other than gasoline and diesel, the only significant dedicated mono-fuel vehicles are natural gas vehicles (“NGVs”) that predominantly run on CNG. Globally, however, this picture is quite different; there are roughly 15 million NGVs worldwide, and many of these bi-fuel vehicles, though this is primarily due to vehicle retrofits and not Original Equipment Manufacturer (“OEM”) models.

Since these vehicles have a high cost premium of \$6000, the deployment of dedicated NGVs in the U.S. has largely been driven by government policy. For instance, purchases of dedicated natural gas vehicles are eligible for federal tax credits<sup>21</sup> (Natural Gas Vehicle Association, 2013). Many dedicated NGVs were also purchased by state governments and alternative fuel provider fleets to comply with the requirements of the Energy Policy Act of 1992.

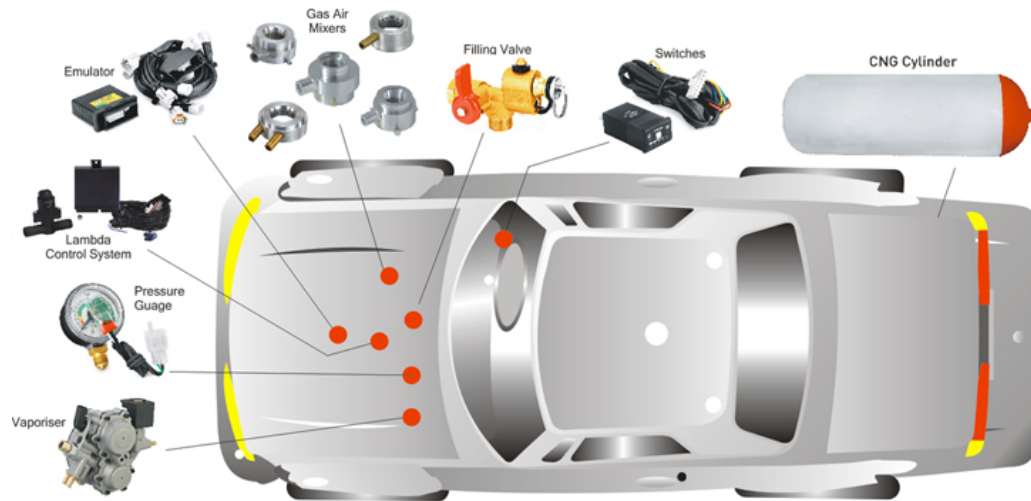
While currently Honda is the only OEM in the U.S. that offers a dedicated CNG passenger vehicle, most NGVs in the U.S., are aftermarket conversions of gasoline vehicles by small volume manufacturers. However, because of EPA certification requirements established under the Clean Air Act, many of these retrofits are concentrated in specific models. A small volume manufacturer must obtain EPA certification for each make and model to be converted, and the cost of obtaining an EPA certification has been estimated to cost as much as \$200,000 per vehicle make and model (NGVA, 2013). Amortizing the cost over the number of vehicles converted to operate as NGVs; it is estimated that a certified conversion by a small vehicle manufacturer costs an additional \$10,000 compared to the price of a comparable gasoline-powered vehicle.

Figure 24 illustrates the modifications required to enable a spark-ignition, gasoline-fueled vehicle to operate on natural gas, which are all changes to the fuel processing system, not the engine. The hardware modifications are designed to deliver comparable vehicle performance, though have considerably less range with CNG due to the weight and limitations of CNG storage tanks. Because CNG has a higher octane rating than gasoline, engine controls could be optimized for greater performance and fuel economy. However, to maximize performance potential, the engine cylinder compression ratio would need to be increased, which is typically not performed for engines originally manufactured for gasoline operation; increasing the compression ratio to improve fuel economy with CNG could prevent acceptable gasoline operation, due to potential issues with engine knock.

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<sup>21</sup> Bi-fuel vehicles are not.

**FIGURE 24 MODIFICATIONS FOR CNG DEDICATED VEHICLES**



SOURCE: [HTTP://WWW.MIJOAUTOGAS.CO.IN/CNG-MIXER-SYSTEM-LAMBDA-CONTROL-STYSTEM.HTM](http://www.mijoautogas.co.in/CNG-MIXER-SYSTEM-LAMBDA-CONTROL-STYSTEM.HTM).

### **3.4 Vehicle Designs for Accommodating Multiple Fuels<sup>22</sup>**

While there are a number of different types of possible configurations, there are currently none that are capable of running on E85, CNG, and gasoline. Rather, the vehicles that are currently on the market instead try to maximize a pairing of them, E85 and gasoline or CNG and gasoline. This is mainly a response to issues with dedicated vehicles, which create “range anxiety” or the “walk home” issue.

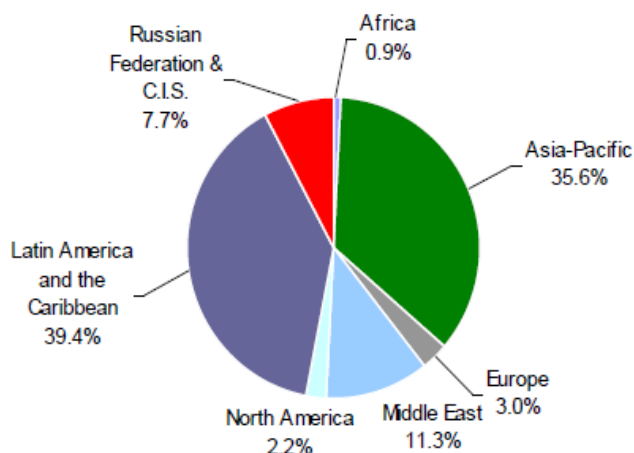
#### **3.4.1 Bi-fuel Vehicles**

The most common type of bi-fuel vehicle is one that can operate on either gasoline or compressed natural gas (CNG). Currently, bi-fuel vehicles are primarily in other countries rather than the U.S. It is estimated that there are more than 15 million vehicles worldwide that can operate on natural gas, the majority of which are bi-fuel (AFDC, 2013). The geographical distribution of natural gas capable vehicles is predominantly in developing countries in Latin America, Asia Pacific, and to some extent, the Middle East [Figure 25].

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<sup>22</sup> PHEVs would be considered here, but are not included in this thesis.

FIGURE 25 GLOBAL DISTRIBUTION OF MONO-FUEL AND BI-FUEL NGVS (2010)



SOURCE: J. SEISLER, CLEAN FUELS CONSULTING WORKING PAPER TO TIAx ON "INTERNATIONAL PERSPECTIVE NGV MARKET ANALYSIS: LIGHT- AND MEDIUM-DUTY VEHICLE OWNERSHIP AND PRODUCTION," APRIL 2011.

Bi-fuel vehicles still operate with a conventional spark-ignition engine, but the primary difference between bi-fuel and dedicated operation is that instead of having one fuel processing system (e.g. fuel regulator, injector, engine management, manual switch), there are now essentially two; because CNG and gasoline cannot be blended, they cannot be combusted simultaneously and have to be stored in separate tanks. This results in vehicle design changes to accommodate two tanks, which compromises trunk space. The added tank weight also reduces vehicle range. An engine control system that allows switching between fuels is an additional requirement for bi-fuel vehicles, which modifies engine settings to optimize engine performance for either fuel.

Overall, CNG bi-fuel vehicles are similar to dedicated gasoline mono-fuel vehicles with regard to power, acceleration, and cruising speed. However, because of the slightly lower energy density of CNG relative to gasoline, and the additional weight associated with the CNG fuel tank, CNG bi-fuel vehicles have a shorter driving range, lower fuel economy, and less cargo capacity. Consumer perspectives on these trade-offs are discussed in the next chapter.

The modifications to a gasoline vehicle for bi-fuel operation are shown in Figure 26, and are essentially the same as for a dedicated vehicle. The four basic types of CNG fuel tanks are illustrated in Table 9.<sup>23</sup> Each of the four meet the same performance and safety requirements, such as resistance to temperature extremes (-40°F to +185°F), multiple fills (pressure changes), cargo spillage, vibration, vehicle fires, corrosion, and collision. However, there are considerable differences in the choice of material, weight and cost. Weight is a critical parameter. For light duty vehicles, fuel consumption is reduced by 0.6 to 0.9 percent for every 3 percent increase in weight (Jackson, 2012). In addition, all of these changes come at a high cost, though to vehicle manufacturers is equivalent to those for dedicated CNG vehicles (MITEI 2012 Symposium).

<sup>23</sup> These tanks are also considered for dedicated CNG vehicles, but can be a more critical factor given that the added weight has a significant impact on fuel consumption.

**FIGURE 26 COMPONENTS TO CONVERT AND OPERATE CONVENTIONAL VEHICLES WITH CNG**



NOTE: ATTACHED TO THE FUEL TANK [1] IS THE REGULATOR [2], WHICH REDUCES TANK PRESSURE FROM 3600 PSI TO 125 PSI. FUEL IS THEN FED TO A PARALLEL FUEL RAIL [3] AND TO NEW, SECONDARY INJECTORS PLUGGED INTO AN ADAPTER [4]. A WIRING HARNESS [5] PLUGS INTO THE FACTORY ENGINE-CONTROL UNIT AND INTERCEPTS THROTTLE INFORMATION, SENDING IT TO A NEW FUELING COMPUTER [6], WHICH SLIGHTLY ALTERS THE DATA AND PASSES IT TO THE CNG INJECTORS [7] THROUGH A PARALLEL WIRING HARNESS [8].

SOURCE: [HTTP://WWW.POPULARMECHANICS.COM/CARS/HOW-TO/MAINTENANCE/SHOULD-YOU-CONVERT-YOUR-CAR-TO-NATURAL-GAS-2](http://www.popularmechanics.com/cars/how-to/maintenance/should-you-convert-your-car-to-natural-gas-2).

**TABLE 9 VARIOUS TYPES OF CNG FUEL TANKS**

Tank Design	Material	Cost	Weight
Type 1	All metal (aluminum or steel)	Least expensive	Heaviest
Type 2	Metal liner partially reinforced by composite wrap (glass or carbon fiber) around middle (“hoop wrapped”)	↓	↑
Type 3	Metal liner reinforced by composite wrap around entire tank (“full wrapped”)		
Type 4	Plastic gas-tight liner reinforced by composite wrap around entire tank (“full wrapped”)	Most expensive	Lightest

SOURCE: [HTTP://WWW.CLEANVEHICLE.ORG/TECHNOLOGY/CNGCYLINDERDESIGNANDSAFETY.PDF](http://www.cleanvehicle.org/technology/cngcylinderdesignandsafety.pdf).

There currently are no U.S. OEM bi-fuel vehicles and a relatively limited number of aftermarket conversions to bi-fuel operation exist. In contrast, the majority of natural gas fueled vehicles in other countries are bi-fuel vehicles that have been aftermarket conversions, motivated by market forces; low cost conversion kits and installations, fewer emissions controls, and no OEM certification

requirements produce relatively short payback periods (Jackson, 2012). However, with continued higher gasoline prices, Europe has moved steadily towards OEMs, which currently have at least 12 OEM bi-fuel vehicle models. As European OEMs expand their bi-fuel vehicle offerings, further market segmentation is taking place, where models have different gasoline and CNG tank sizes.<sup>24</sup>

### 3.4.2 Flex-Fuel Vehicles

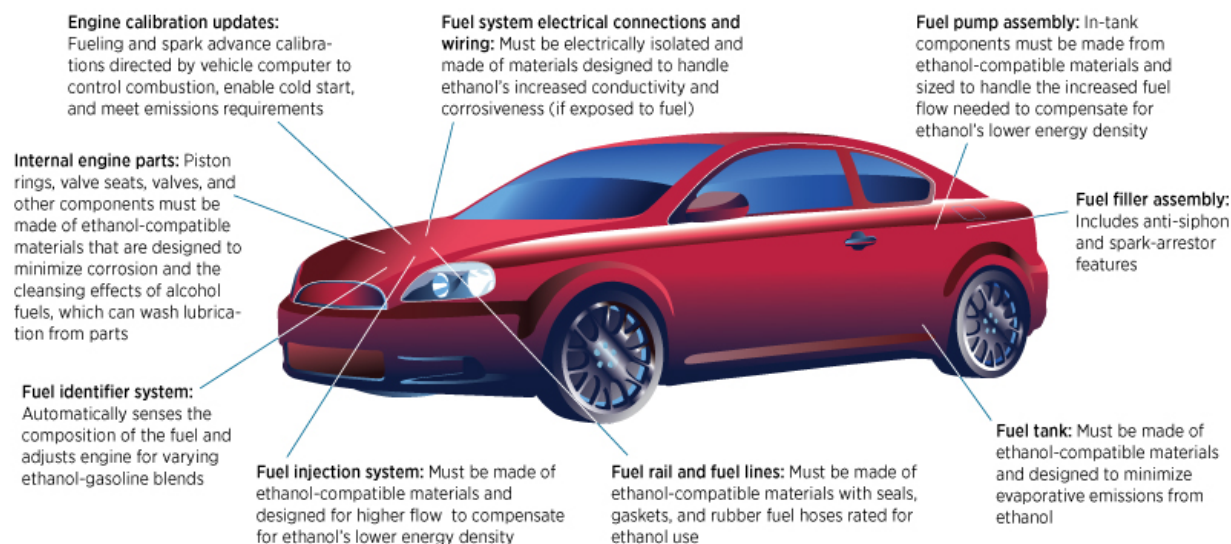
The U.S. currently has 9 million registered flex fuel vehicles on the road, representing about 4% of all light-duty vehicles. Conceptually, flex-fuel vehicles are vehicles that can operate with a mixture of more than one liquid fuel, however, current vehicles are capable of operating only on gasoline or blends up to E85, which effectively makes them “bi-flex fuel” in a way. Nonetheless, there have been discussions of other fuel blends, including a combination of gasoline, ethanol, methanol (“GEM”), which some have claimed that at varying blends can produce the same stoichiometric ratios as E85; this is still undergoing vehicle tests to see if these “tri-flex fuel” blends achieve the same performance criteria (Turner et al, 2012). Other explorations have considered separating the fuels into two tanks, but unlike traditional bi-fuel operation, simultaneous operation could be possible since conceivably these fuels can be blended; this arrangement has been referred to as a “dual fuel” operation in contrast to “bi-fuel,” which cannot use the fuels simultaneously.

Regardless of the physical arrangement, flex-fuel vehicles are designed to operate with much higher concentrations of alcohols, ethanol or methanol, in fuel mixtures than the 10% ethanol currently allowed in conventional vehicles. As noted earlier, alcohols fuels have several fuel properties—lower energy density, corrosive to metals, rubber and plastics, higher oxygen content—that differ from gasoline and drive the need for a more specialized technology. The modifications required to accommodate these fuels are illustrated in Figure 27; note, these are based on currently available bi-flex fuel operations. The cost to vehicle manufacturers has been estimated to be around \$300/vehicle.

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<sup>24</sup> The European Union currently classifies bi-fuel vehicles with gasoline tanks less than 15 liters as “mono-fuel,” even though these vehicles have bi-fuel capability (Jackson, 2013).

**FIGURE 27 FLEX FUEL VEHICLE MODIFICATIONS**



SOURCE: AFDC, 2013. AVAILABLE AT [HTTP://WWW.AFDC.ENERGY.GOV/VEHICLES/FLEXIBLE\\_FUEL.HTML](http://www.afdc.energy.gov/vehicles/flexible_fuel.html).

As noted in the diagram, all the aspects of the fuel processing system and fueling system that come in contact with alcohol have to be changed to ethanol-compatible and corrosion-resistant materials, such as stainless steel, or isolated from them with lubricants or other materials. In addition, fuel tanks have a larger capacity to compensate for the effects of ethanol's lower energy density, which results in higher fuel consumption and shorter driving range. Unlike bi-fuel operations which has a manual switch between the fuels, flex-fuel vehicles need a flex-fuel sensor, which monitors fuel composition and signals the powertrain control module to adjust engine operation (e.g. air-fuel ratio and ignition timing) accordingly. The commonly used sensor is an oxygen sensor, but the alternative is a dielectric sensor, which can measure electrical conductivity of the fuel. As alcohol can conduct electricity, higher conductivity generally is a good indicator of higher concentrations of alcohol in the fuel blend.

### 3.5 Value of Flexibility

Compared to conventional gasoline vehicles, flex fuel and bi-fuel vehicles highlight two very different interpretations of flexibility and user engagement. With bi-fuel vehicles, because there are two tanks but only one fuel is used at a time, effectively one of the fuels always serves as backup. While this would be an expensive price tag for essentially what is an extra tank and potential fuel cost savings, there are a few upsides: it could mean fewer refueling times overall and allows users more time to arbitrage the price differences between gasoline and CNG. The value of this kind of flexibility depends on the user attitude and his price sensitivity. Flex-fuel vehicles, in contrast, require users to immediately choose between gasoline and the alternative fuel, or E85, since most only have one tank. As a result, the value of flexibility with flex-fuel vehicles can be reduced simply to prices at the pump. The vehicle's ability to accommodate blends of gasoline and ethanol up to E85 might also



not be one that the user has any control over, as most of these fuels are blended before reaching the retail station.<sup>25</sup>

From a market perspective, vehicles with two tanks makes more sense for long distance trips and less so in urban areas where trips are short, and also would be more useful for the larger light duty vehicles (SUVs, pick up trucks, vans) where the tank size would not severely constrain the cargo space. Most bi-fuel vehicles that are currently offered in the U.S. reflect this trend. As flex fuel vehicles rely more on public refueling stations than do bi-fuel vehicles, which have the option of being refueled at home or less frequently, conceivably they would fare better as city cars. Through market segmentation strategies, these vehicles could circumvent some of the challenges they might face and also avoid having to compete with one another. Interestingly, however, flex fuel vehicles are typically offered as larger size class light duty vehicles, particularly SUVs and trucks, because they can maximize the value of the alternative fuels Corporate Average Fuel Economy (“CAFE”) credits in larger vehicles (MITEL, 2012).

From a policy perspective, vehicle flexibility poses an interesting take on enabling fuel diversification but also reinforcing gasoline’s status in the transportation fuel mix directly and indirectly through the CAFE standard loophole. While flexibility reflects ambivalence about the pace of technological change, it is also realistic in that gasoline is likely to remain part of the fuel mix. The perceived advantage of allowing consumers to essentially price arbitrage the differences between the fuels might also not have any material impact on reducing gasoline prices. E85 appears to be cheaper though on an energy equivalent basis is not, and also seems to track gasoline prices<sup>26</sup>; and because CNG bi-fuel vehicles allow users more time to price arbitrage, the feedback gained from their CNG use is delayed since users have a choice when to use the fuel.

### 3.6 Summary

Though ethanol, compressed natural gas, and their respective vehicle technologies have taken center stage in the alternative fuel and vehicle arena, in reality the scope and magnitude of possible fuels and technologies are fairly numerous, and many configurations have yet to be explored. However, of those that are currently available, there are distinct tradeoffs in dedicated CNG vehicles and bi-fuel vehicles; from a vehicle manufacturer’s perspective, these cost roughly the same to produce but serve very different purposes. Flexible fuel vehicles, in contrast, cost little to produce, but the challenges with scaling up ethanol infrastructure make it difficult to predict if it will remain a fuel that is blended with gasoline in small amounts to improve anti-knock resistance, or if it will have a larger role to play.

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<sup>25</sup> Though this might be a better option, as when dial-your-own options were briefly offered, they confused users. The other concern is that because ethanol is highly susceptible to weather conditions, users may not know which formulations will work better in their vehicles.

<sup>26</sup> This will be discussed in Chapter 4.



# Chapter 4

## Insights from Consumer Perspectives

### 4.1 Overview

While policymakers, trade organizations, and lobbyists can incentivize and encourage alternative fuel and vehicle adoption through many different avenues, when it comes to light duty vehicles, consumers ultimately decide their fate or success. This chapter explores the different attributes that factor into consumer preferences in vehicle purchasing decisions and the implications they have on the current alternative fuel and vehicle options.

### 4.2 Factors in Consumers' Preferences

To predict how consumers will react to new vehicles and fuels options in the market, two methods are generally used. The first is to conduct consumer surveys, which have generally shown that consumers across many countries including the U.S. consider vehicle price, safety, and power in their purchasing decisions (NRC, 2013). The second method is to develop economic models based on past consumer data of all the vehicles that have been purchased and deducing the prices they were willing to pay for various vehicle attributes. Both methods produce similar results, suggesting that consumers value vehicle price, safety, and power.

However, both methods have also received criticism for not being able to sufficiently describe or account for market trends like luxury or highly-priced cars and for using past data to predict consumer attitudes towards a technology that did not exist when it was collected. Choice models, which generally account for any aspect of a vehicle that consumers might value, attempt to show how customers choose pricier cars but are also limited. Nonetheless, literature<sup>27</sup> still indicates that consumers primarily valued the following attributes:

1. Vehicle performance
2. Vehicle functionality and design
3. Fuel Efficiency and Cost competitiveness
4. Backward-compatibility
5. Ease of Refueling
6. Safety

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<sup>27</sup> This is based on several large reports, including but not limited to the National Petroleum Council (NPC) Study on transportation fuels and National Academy of Sciences and National Research Council reports, as well as from the 2012 MITEI Symposium and white papers solicited for the symposium.

### 4.3 Comparisons of Currently Available Alternatives

Based on the attributes consumers generally value when making purchasing decisions, Table 10 summarizes the differences between bi-fuel and flex fuel vehicles. Dedicated vehicles were not included as these are essentially the same as bi-fuel vehicles, with some slight variations.

**TABLE 10 COMPARISON OF VEHICLES BASED ON ATTRIBUTES CONSUMERS VALUE**

Attributes Consumers Value	Bi-fuel CNG Vehicle	Flex-fuel Vehicle
Vehicle performance	<ul style="list-style-type: none"> <li>• Comparable to gasoline vehicle; less prone to knocking</li> <li>• Lower fuel economy due to fuel tank weight and size</li> </ul>	<ul style="list-style-type: none"> <li>• Comparable to gasoline vehicle, with appropriate engine modifications</li> <li>• Lower fuel economy on volumetric basis, but not necessarily on an energy basis</li> </ul>
Vehicle Functionality	<ul style="list-style-type: none"> <li>• Trunk space reduced due to larger tank</li> </ul>	<ul style="list-style-type: none"> <li>• Potentially no compromises in vehicle design</li> </ul>
Cost competitiveness	<ul style="list-style-type: none"> <li>• Vehicle cost premium</li> <li>• Fuel savings*</li> </ul>	<ul style="list-style-type: none"> <li>• Fuel cost premium</li> </ul>
Ease of Refueling	<ul style="list-style-type: none"> <li>• Proximity to CNG refueling stations unclear</li> <li>• Time required for refueling (e.g. high-speed filling systems of 4-5 minutes)</li> <li>• Possibility of home refueling (e.g. Phill home compressor systems )</li> </ul>	<ul style="list-style-type: none"> <li>• Availability of alternative fuel stations</li> <li>• No change in fueling process (same as conventional vehicle)</li> </ul>
Safety	<ul style="list-style-type: none"> <li>• Concerns with pressurized gas</li> </ul>	<ul style="list-style-type: none"> <li>• Toxicity concerns</li> </ul>

NOTE: \* THESE SAVINGS WOULD BE REDUCED IF REFUELED WITH A PHILL HOME COMPRESSOR SYSTEM. DEPENDING ON THE CUSTOMER'S RESIDENTIAL GAS RATE, INSTALLATION COSTS, OPERATING AND MAINTENANCE COSTS, THE RESULTING COST OF CNG COULD BE \$3 TO \$5 PER GASOLINE GALLON EQUIVALENT.

SOURCE: MITEI 2012 SYMPOSIUM

#### 4.3.1 Vehicle Performance & Functionality

Given the current alternative vehicle technologies, both bi-fuel and flex-fuel vehicles, were considered to be well optimized to deliver equivalent vehicle performance relative to conventional gasoline powered light duty vehicle; since the octane ratings of CNG and ethanol exceed that of gasoline, their higher vehicle performance compensates for their lower energy densities. Interestingly, while this is an important attribute in consumer acceptance, it did not appear to be a significant differentiator among the various alternative vehicle and fuel options.

The conditions in which these vehicles are driven, however, can create differences in vehicle functionality. For instances, ethanol's higher heat of vaporization could have more issues with cold start capability, and though flex fuel vehicles are capable of using up to E85, during the winter sometimes the threshold is E70. As for the large tanks required for CNG vehicles, while these would

not pose an issue for larger vehicles, SUVs, light pick-up trucks, with more cargo space, these could produce problems for smaller cars to operate on it.

#### 4.3.2 Fuel Efficiency and Cost Competitiveness

Cost competitiveness is a key determinant of consumer behavior, and in many global case studies, can be the most important attribute in consumer behavior. Many of these studies note that most consumers opt for the least expensive fuel even if the price difference with the second least expensive fuel is very small (Kramer, 2012). The challenge with alternative fuel and vehicle technologies is that it not only requires a conversion factor to compare them across different units, but also involves performing a comparison on fuel cost savings; when consumers choose to buy a vehicle that has a cost premium and higher maintenance costs compared to conventional vehicles, this cost has to be justified in some way—the easiest and most widely advertised reason is through fuel cost savings. However, these fuel cost savings are a function of vehicle usage patterns, retail fuel prices, fuel efficiency, and other details that can quickly become more complicated and are hard to predict.<sup>28</sup> Since bi-fuel and flex-fuel vehicles may not be as attractive in other ways—less trunk space, fewer refueling stations, longer refueling times, performance uncertainties, safety concerns—consumers will continue to prefer conventional gasoline-only vehicles if there is no way to take advantage of the fuel cost savings fully. However, in the event that there is the possibility of fuel price arbitrage or a measure of insurance against price volatility, then bi-fuel and flex-fuel vehicles would be the vehicle designs to enable this.

Cost competitiveness can be analyzed in several ways. One approach is to estimate the undiscounted payback time by comparing the initial cost premium to annual fuel cost savings. Another approach is to compare actual monthly cash flows, which is possible in cases where the purchase price is largely financed. For vehicles with multiple fuel capabilities, both approaches require consideration of the alternative fuel's consumption pattern relative to the likely proportion of continued gasoline use. While the value of a bi-fuel or flex-fuel vehicle as a hedge against gasoline price volatility as an option value or insurance policy<sup>29</sup> is possible, it is difficult to predict whether consumers see it this way or will use the vehicles this way.

Bi-fuel vehicles are most amenable to payback analysis because they have significant vehicle price premiums but offer the most fuel cost savings. As natural gas prices have become largely decoupled<sup>30</sup> from oil prices from the surge in shale gas production, these prices have remained significantly lower than gasoline prices, on an energy-equivalent basis [Figure 28]. However, an analysis of CNG conversions in other countries shows that periods of strong CNG vehicle market

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<sup>28</sup> While there are quick methods to performing fuel cost savings analyses, it can still be difficult to characterize price uncertainties.

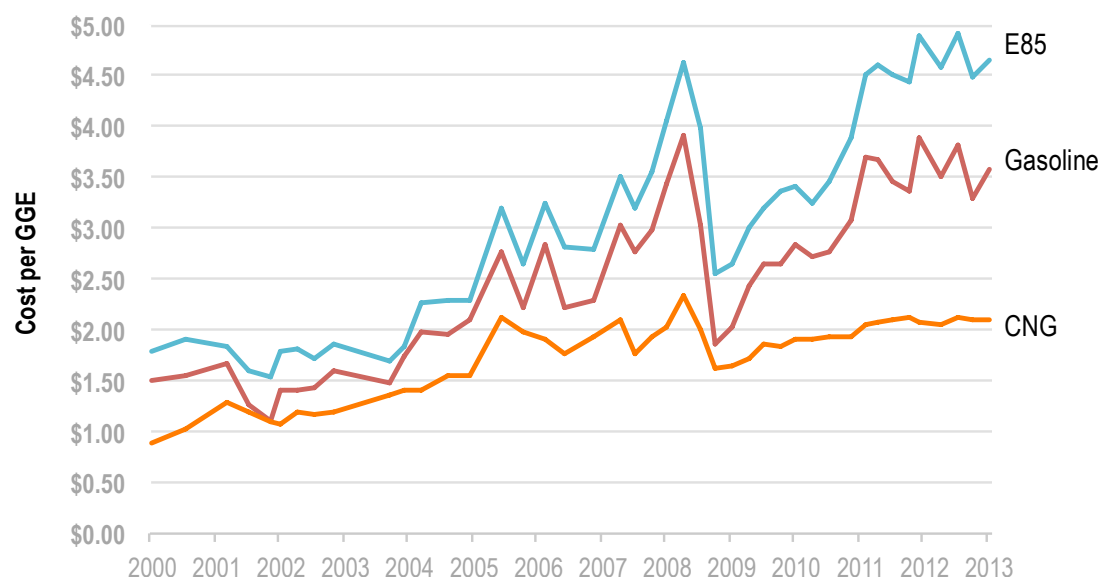
<sup>29</sup> As an option, the value of a vehicle capable of operating two different fuels increases with uncertainty, specifically, fuel price volatility. Alternatively, an insurance policy is valuable for those who desire to use an alternative fuel but are not confident in finding close refueling stations, or for the buyer who does not want to be forced to change his behavior.

<sup>30</sup> Decoupling is a term that refers to the recent occurrence in which natural gas prices have strongly deviated from oil prices. Prior to horizontal hydraulic fracturing, natural gas prices were based on oil contracts and therefore tracked oil prices. Now, natural gas prices more strongly reflect the natural gas recovery fundamentals and are considered “decoupled” from oil.

penetration occurred when the payback period was less than 3 years (Yeh, 2011). For light duty vehicles, meeting this condition requires a combination of a price spread of \$1.50 per GGE, vehicles in high mileage service (35,000 miles per year) and an initial cost premium of less than \$5,000 (MITEI Natural Gas Study, 2011).

Assessing cost competitiveness of flex-fuel vehicles is easier compared to bi-fuel vehicles, as flex-fuel vehicles have a much smaller cost premium, though there are no fuel cost savings [Figure 28]. In fact, on an energy equivalent basis, these are more expensive [Table 11]. The advantages that do occur in the market are typically those due to effects of federal and state financial incentives, including CAFE and RFS standards. Nonetheless, this could eventually change if gasoline prices continue to increase.

**FIGURE 28 U.S. AVERAGE RETAIL FUEL PRICES<sup>31</sup>**



SOURCE: AFDC, 2013. DATA AVAILABLE AT [HTTP://WWW.AFDC.ENERGY.GOV/FUELS/PRICES.HTML](http://www.afdc.energy.gov/fuels/prices.html).

**TABLE 11 U.S. NATIONAL AVERAGE PRICES (3/29 - 4/12/2013)**

Fuel	Price	Price in GGEs	Conversion Factor
Gasoline	\$3.59/gallon		
Ethanol (E85)	\$3.30/gallon	\$4.65/GGE	1.41 gallon of ethanol is 1 gasoline gallon equivalent
Natural Gas (CNG)	\$2.10/GGE		126.67 cubic feet is 1 gasoline gallon equivalent

SOURCE: AFDC, 2013. DATA AVAILABLE AT [HTTP://WWW.AFDC.ENERGY.GOV/FUELS/PRICES.HTML](http://www.afdc.energy.gov/fuels/prices.html).

<sup>31</sup> GGE = gasoline gallon equivalent, which is a unit of measure that is the amount of alternative fuel it takes to equal the energy content of one liquid gallon of gasoline.

### 4.3.3 Compatibility

Backwards compatibility in a vehicle refers to the capability of a vehicle to operate on conventional fuels as well as alternative fuels. Bi-fuel, flex-fuel, and hybrid vehicles share this advantage and could potentially attract consumers who value this particular kind of fuel flexibility. European models have varied models of these vehicles to emphasize the use of the alternative fuel and advertise the gasoline fuel as a backup. The value of this extra storage<sup>32</sup> has been compared to an insurance policy or an option. If there are few refueling stations or the price of gasoline remains significantly higher, there are cost advantages in switching between fuels. In case studies abroad where some of these vehicles are more widely used, particularly bi-fuel and flex-fuel vehicles, backwards compatibility—and more broadly, fuel flexibility—is a desirable vehicle attribute, particularly when gasoline prices are volatile and alternative fuel prices remain low, or when there is uncertainty in refueling availability.

### 4.3.4 Ease of Fueling

Ease of fueling includes several factors: availability of refueling stations, length of time to refuel, frequency of refueling, and operational safety of the refueling process. As described in Chapter 3, the gasoline refueling infrastructure is well-developed, and the alternative refueling stations are still in need of some more development [Table 12].

**TABLE 12 COMPARISON OF THE NUMBER OF REFUELING STATIONS IN THE U.S.**

	Gasoline	CNG	E85	Electric	Other
Total	160,000	1,190	2,648	7,495	3665
Public		578	2,339	5,866	

NOTE: REFUELING STATIONS AS OF APRIL 25, 2013. "OTHER" INCLUDES BIODIESEL, LPG, LNG, AND HYDROGEN.

SOURCE: AFDC, 2013.

The availability of CNG refueling stations does pose a challenge; although there are a large number of stations, they are currently located to conveniently serve centrally-fueled fleets and vehicles that travel primarily along the interstate highway system. Bi-fuel vehicles relieve this pressure of "range anxiety" or "walk home" factors by having the gasoline option. Further, because these vehicles do not force consumers to change their behavior, they are easier to accept. That said, CNG bi-fuel vehicles have a shorter range compare to gasoline vehicles, though are better than other multiple fuel alternative vehicles, which could mean more frequent refueling.

As liquid fuels, ethanol, methanol, GTL, and butanol would have comparable refueling times with gasoline, whereas CNG's compressing time depends on whether or not it is a fast-fill or time-fill station. Fast-fill refueling would result in comparable times, while time-fill and home refueling could take much longer, on the order of 4-8 hours. The convenience of a home-refueling option however does also help aid acceptance of the vehicle.

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<sup>32</sup> This storage only accommodates a specific fuel, and is consequently limited.

#### 4.3.5 Safety

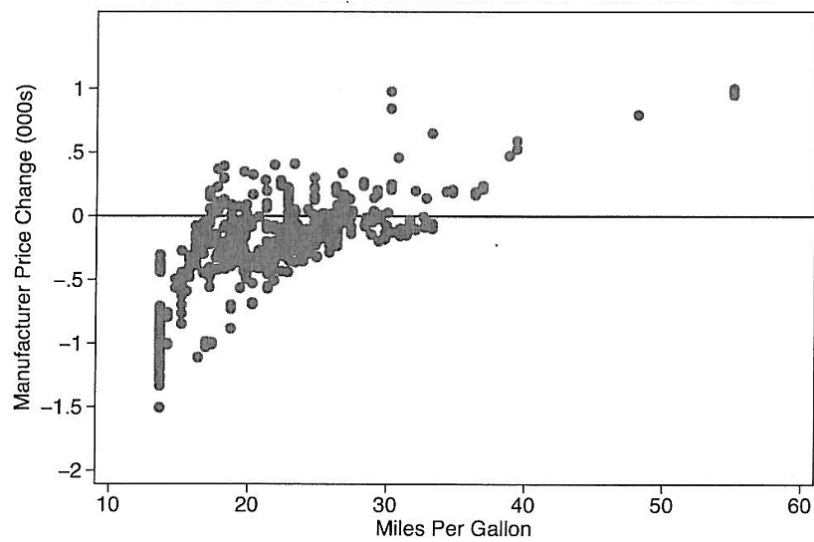
Safety issues associated with the use of alternative fuels also is a source of concern for consumers. Ethanol is toxic, though not as much as methanol. The risk associated with ingestion of methanol is higher than with gasoline; unlike gasoline, methanol does not cause vomiting if ingested, and can cause serious health effects at low levels of ingestion (Nichols, 2003). While there was not a single case of accidental poisoning by methanol reported in California in 1980s when it was first proposed as a fuel, there is some discussion that adding a bitterant could sufficiently deter consumers from ingesting it. Natural gas is non-toxic and normally odorless, but additives give it the distinct smell to detect leakages. In the event of a leakage, CNG is a flammable gas, but it disperses fairly rapidly as it is lighter than air. Its flammability range is considered fairly narrow, igniting only when air concentrations are between 5-15% (Murphy, 1994); below and above which the air-gas mixture is too lean or too rich to ignite, respectively.

#### 4.4 Implications of Consumer Preferences

The advantages and disadvantages between bi-fuel and flex-fuel vehicles become apparent when assessed on a cost-competitive basis. While flex-fuel vehicles are cheaper, they currently offer no fuel cost savings to give them any competitive advantage over conventional vehicles. Bi-fuel vehicles, in contrast, have a vehicle cost premium with potential fuel cost savings that could justify their upfront cost; however, the price differentials for this to happen are unclear. Because gasoline serves as a back up in bi-fuel vehicles, however, there is an additional value proposition associated with storage in that it could potentially serve as an option value or as an insurance policy. Despite the attempts to make the case for alternative vehicle technologies, these arguments are still insufficient when compared to conventional gasoline-powered vehicles.

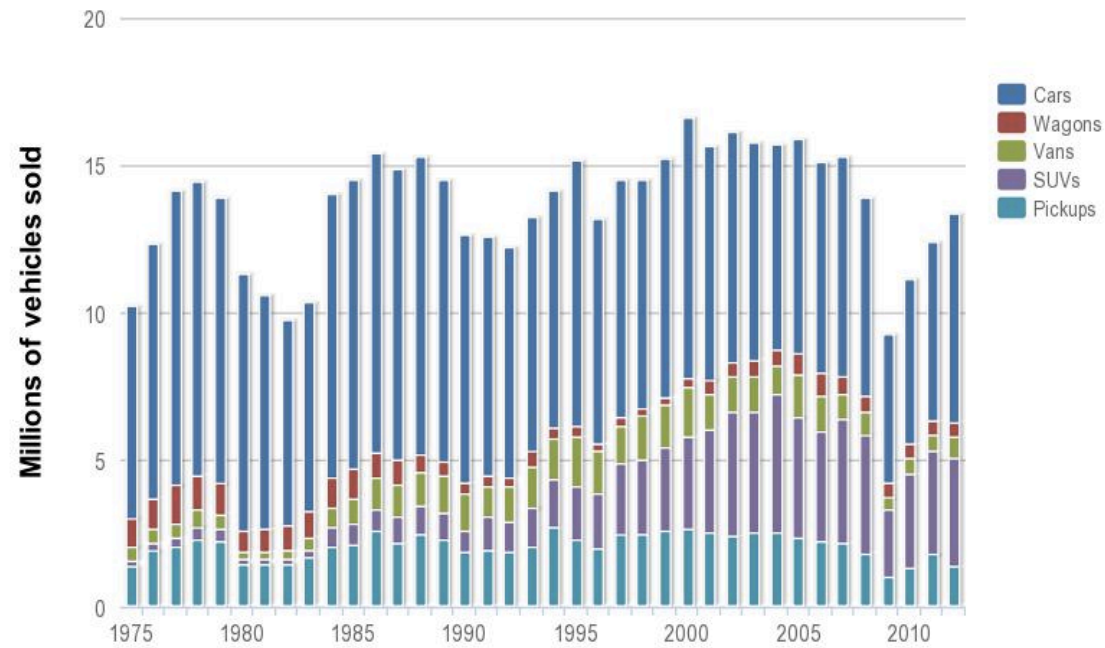
In fact, even conventional gasoline-powered vehicles face some flux in usage as changes in gasoline price can cause substitution effects. In the U.S., gasoline price fluctuates by season and by region, as well as by short-run changes in commodity prices. It was shown that when gasoline prices go up, people with multiple vehicles spend more time driving more fuel-efficient vehicles rather than less-efficient ones. Rather than reducing their total driving time, people tend to increase the use of high MPG vehicles instead. As shown in Figure 29, the \$1 increase in gasoline price (y-axis) correlates with a preference in higher MPG vehicles (x-axis). It is possible that alternative fuels can change this effect though, as one could interpret higher fuel economy as another way of lowering gasoline prices by essentially getting more mileage out of the dollar. Even though alternative vehicles MPG might be lower than conventional vehicles', it is possible that if the price is low enough, they could be treated as a substitute. However, this is also contingent upon that people are willing to buy the vehicle in the first place [Figure 30]. Interestingly, the number of SUVs sold seems to be growing, which, as established earlier, could be a possible opportunity for CNG bi-fuel vehicles.

FIGURE 29 THE EFFECT OF \$1 INCREASE IN THE GASOLINE PRICE



SOURCE: STEPHEN ANSOLABERE, SYMPOSIUM PRESENTATION, DRAWN FROM GRANGER AND MILLER.

FIGURE 30 LIGHT DUTY VEHICLES SOLD IN THE U.S.



SOURCE: AFDC, 2013. AVAILABLE AT [HTTP://WWW.AFDC.ENERGY.GOV/DATA/TAB/VEHICLES/DATA\\_SET/10314](http://www.afdc.energy.gov/data/tab/vehicles/data_set/10314).

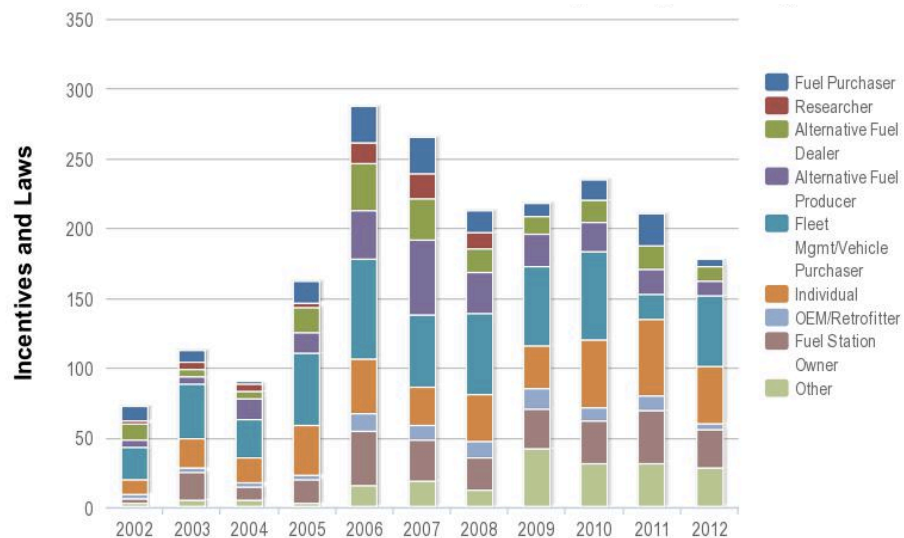
# Chapter 5

## Policy Considerations with Moving Targets and Changing Contexts

### 5.1 Overview

Over the forty-year span of alternative fuel and vehicle development, policymakers have used a number of different policy instruments (standard-setting and mandates, financial incentives, and R&D funding) to coax industry and consumers into internalizing the broader policy goals of reducing oil consumption and greenhouse gas emissions [Figure 31]. While industry has accepted this gauntlet readily, the range of products it has produced still have experienced low consumer reception, despite the growing number of incentives targeted to individuals.

**FIGURE 31 INCENTIVE AND LAW ADDITIONS BY TARGETED AGENT**



SOURCE: AFDC, 2013. AVAILABLE AT [HTTP://WWW.AFDC.ENERGY.GOV/DATA/TAB/LAWS-INCENTIVES/DATA\\_SET/10363](http://www.afdc.energy.gov/data/tab/laws-incentives/data_set/10363).

As established in Chapter 4, consumers are a critical determinant in alternative fuel and vehicle development. However, consumers often reduce a fuel's advantage primarily down to a price point and its reliability, and vehicles down to a set of performance and cost criteria. And in the event of rising gasoline prices, consumers simply switch to more fuel-efficient vehicles, as they are effectively cheaper per mile, without changing the number of miles they drive. What this suggests is that 1) consumers are willing to switch to more fuel efficient vehicles if there is a fuel cost savings advantage and switching does not require them to dramatically change their driving behavior, and 2)



that reducing greenhouse gas emissions and oil consumption are policy objectives that inherently are not aligned with consumer preferences. Also established in earlier chapters, alternative fuel and vehicle development in the light duty vehicle sector is unlikely to occur through a market-based solution without additional or continued policy direction and/or intervention.

Given this, policymakers have essentially two choices in aiding alternative fuel and vehicle development: find a way to engage consumers, or act like a consumer and recognize that they are another source of demand with the ability to affect change in the system. The danger with the latter, of course is in determining the limit of their willingness to pay to address the policy goals. However, thinking in this way can be a useful exercise, as the alternative fuel and vehicle development has already largely been aided by federal financial support, as well as been policy driven. Some of the questions it raises are the following:

- Is the slow growth and need for further federal aid just an expected part of the transition from an incumbent fuel and technology, or is it a validation for oil's reign as a transportation feedstock in light duty vehicle applications?
- Oil has served the transportation sector well, what exactly about oil is the problem?
- What is the final goal? If it is to reduce oil consumption and greenhouse gas emissions, how much oil reduction is enough? Is there a target reduction for greenhouse gas emissions?
- Are alternative fuels and vehicles actually necessary? And if so, which ones and how?
- How should policymakers get involved, if at all?

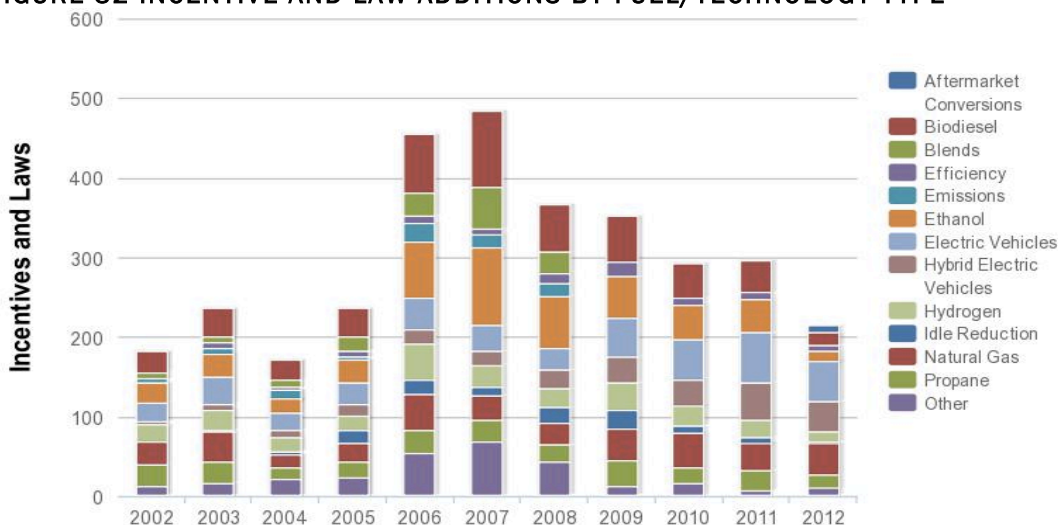
Depending on how one begins to investigate these motivations, whether it is from looking at historical trends or the problems that the U.S. oil dependency creates, each perspective produces a different story, much like a “choose your own adventure” book. The one consistent ending is that the motivations and targets have been changing. However, laying them side-by-side, a few interesting trends emerge, though it also becomes apparent that the disconnects also reflect knowledge gaps. This chapter first examines a few of these perspectives to tease out some of the underlying motivations, and second, draws some policy considerations from the insights on alternative fuel infrastructure development and vehicle adoption.

## **5.2 Learning From History**

Initially triggered by the economic pain felt from oil shocks, the U.S. government supported the ethanol industry as an alternative, but as land use issues emerged, began to call for other fuels and vehicles that were more environmentally sustainable, supporting electric vehicles and hydrogen fuel cells [Figure 32]. Once natural gas emerged as a potentially more affordable option, even more fuels and vehicles vied to displace oil [Figure 33, Figure 34]. In terms of historical trends, the story seems to suggest that even though the criteria for alternative fuels and vehicles have been continuously evolving to meet higher standards—primarily domestic produced, environmentally sustainable, and economically self-sustaining—the prospect of a more abundant alternative feedstock is what brought about a much more rapid change. This could suggest that the transportation system, though seemingly inflexible, can be highly sensitive and responsive to new fuel feedstocks. As consumers

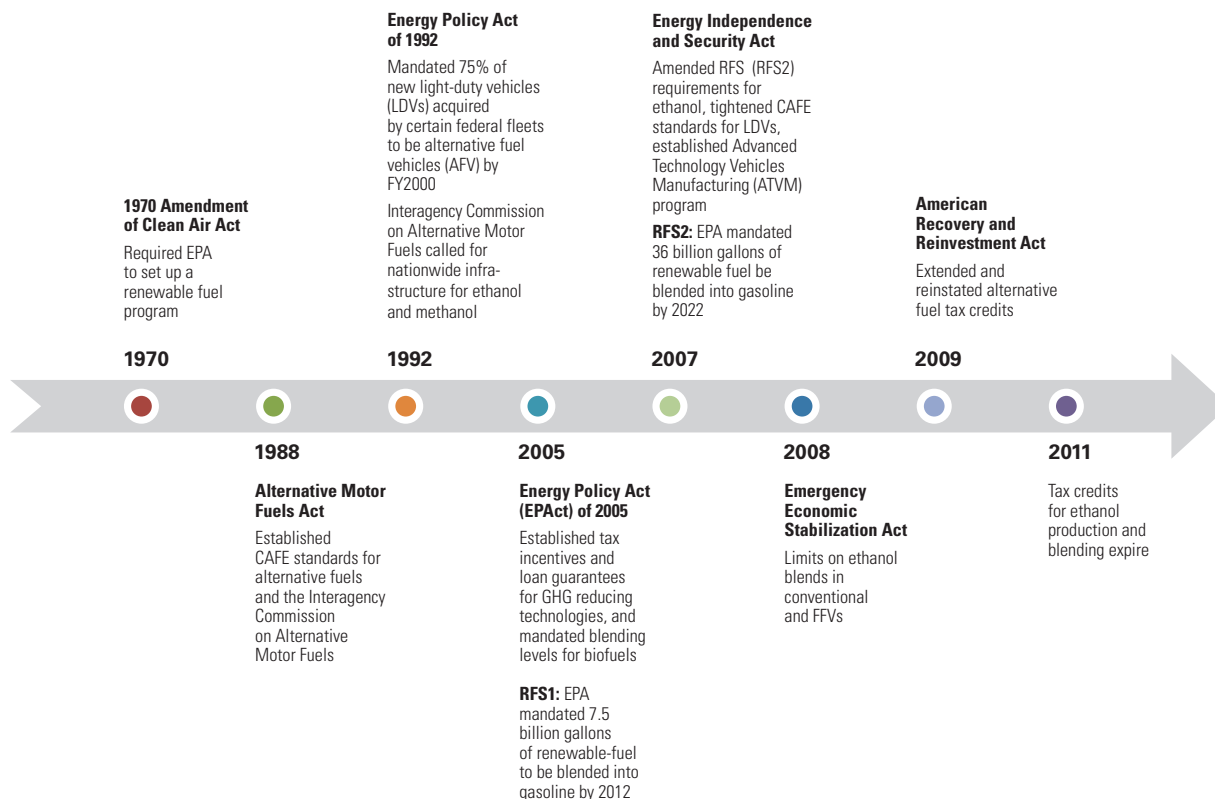
do not directly care about fuel feedstocks, as so much as it affects the fuel price, this could be an interesting opportunity for policymakers to affect change without relying on consumer acceptance.

**FIGURE 32 INCENTIVE AND LAW ADDITIONS BY FUEL/TECHNOLOGY TYPE**



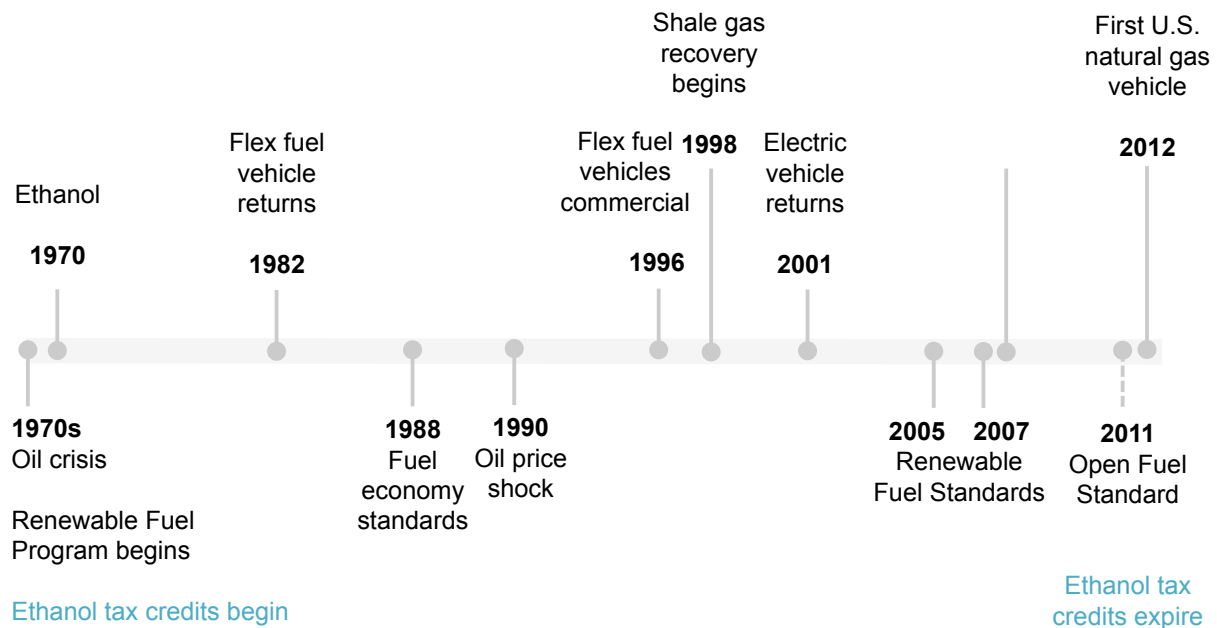
SOURCE: AFDC, 2013. AVAILABLE AT [HTTP://WWW.AFDC.ENERGY.GOV/DATA/TAB/LAWS-INCENTIVES/DATA\\_SET/10360](http://www.afdc.energy.gov/data/tab/laws-incentives/data_set/10360).

**FIGURE 33 TIMELINE OF FEDERAL ALTERNATIVE FUELS LEGISLATION**



SOURCE: MITEI 2012 SYMPOSIUM.

**FIGURE 34 TIMELINE OF FEDERAL ALTERNATIVE FUELS LEGISLATION AND TECHNOLOGY DEVELOPMENT**



### 5.3 Redefining the Oil Problem as Risks and Uncertainties

When revisiting the reasons why oil has received so much attention, it can be useful to see how changing contexts affect them and why might a new feedstock bring about such a growth in new technologies. Each of the positions and justifications for the energy and economic security, national security, and climate change issues that oil has been attributed with are briefly outlined below.

- Energy and Economic Security:** Although physical quantities of petroleum imports have decreased from a peak in 2005, the dollar value has increased. The U.S. spent \$335 billion on imported oil in 2011, an increase of 84% from 2005 (EIA Annual Energy Review, 2011). The U.S. oil import bill is estimated to account for over half of the net trade deficit (Koonin, 2012). As transportation is the largest user of petroleum, half of which light duty vehicles consume, reducing oil consumption in this sector could have a large impact.
- National Security:** Oil prices are set globally, but since 79% of global conventional oil reserves are controlled by the OPEC cartel, it can affect global prices through its control of production levels and leverage oil as a geopolitical strategic commodity. Since the U.S. has ties to some of these countries through oil imports—though currently 49% of U.S. petroleum imports are from the Western Hemisphere—the reliance on oil is perceived as limiting foreign policy options (Koonin, 2012).

- **Climate change:** Light duty gasoline-powered vehicles comprise nearly one-third of total net U.S. greenhouse gas emissions (Koonin, 2012), which suggests that it will be a part of climate policy.

A few developments have altered this picture: as global oil prices remain high, opportunities for unconventional sources of oil production have emerged, as well as for oil products derived from non-oil sources. The same technological innovation of horizontal hydraulic fracturing that has enabled domestic shale gas has also enabled domestic shale oil. Gas to liquids are capable of producing the same oil products, including gasoline and diesel, in a more competitive way. The impact of the first directly affects the U.S. supply of oil, in which shale oil is economical at current prices. The second development suggests that it would reduce the need for oil imports; however, how it would affect crude oil and gasoline prices is unclear.<sup>33</sup> Climate change seems to remain an unresolved issue and also adds irreducible uncertainty; as such, climate policies are likely to remain on the policy agenda, though more research and lifecycle assessments may be needed to apply them effectively.<sup>34</sup>

What this suggests is that the problem is not the commodity itself, but that because oil is globally traded and there are no international regulatory bodies to prevent the market from being dominated by a cartel, it experiences high geopolitical risks, which were exacerbated by the fact that oil is not produced domestically in sufficient quantities.<sup>35</sup> Interestingly, by identifying one particular problem with oil as geopolitical risk rather than as its effects on the economy and foreign policy, it becomes easier to see the opportunities for technology development to help address them, and how feedstocks play a significant role. Once again, these developments occur upstream of demand, which could be useful as a regulatory strategy.

## 5.4 Separating Issues with Fuel Feedstocks from Fuels

However, returning to the issue with GTLs, it is unclear how feedstock and fuel prices actually affect one another. Although association with its primary feedstock has vilified gasoline, it is simply a mixture of hydrocarbon chains that can be produced from many feedstocks. According to the EIA, 67% of the gasoline price is attributed to crude oil prices, 15% to refining, 7% to distribution and marketing, and 11% to taxes (EIA, 2013). If gasoline was produced from feedstocks other than crude oil, how would this affect its price? Would one see the impact of GTLs reflected in refining and distribution, or in crude oil prices [Figure 35]? Is GTL pricing strongly tied to the fundamentals in its fuel pathway, which currently involves tankers, and could therefore be expected to track crude oil? Depending on how these prices relate and adapt to another feedstock, can dramatically change policy strategies. For instance, if gasoline prices depend on feedstock prices and not simply on

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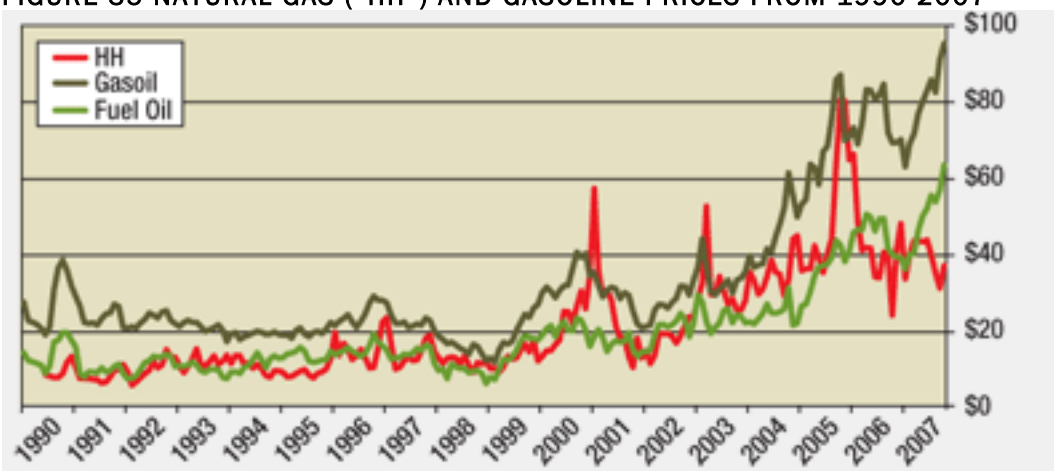
<sup>33</sup> Since oil is a globally traded commodity, reducing oil consumption will not insulate the U.S. from price volatility; however, as the U.S. relies less on oil, it will eventually be less impacted by it.

<sup>34</sup> A different climate strategy than the one used in the electric power sector may have to be used, as vehicle technologies can dampen the effectiveness of carbon pricing. For example, a carbon price of \$40 ton CO<sub>2</sub> could result in significant changes in energy use in the electric power sector, but it corresponds to only a \$0.35 per gallon increase in the price of gasoline, which consumers might not respond to (Koonin, 2012). However, carbon pricing may be effective when moved upstream of demand.

<sup>35</sup> To some extent, the fuel does not necessarily have to be produced domestically but imported from closer sources, as evidenced by the interest in Canadian tar sands.

crude oil prices, XTLs could be an attractive option to support as it also requires the fewest infrastructure changes. However, if XTLs are considered simply to be part of an oil supply curve, then perhaps they might not have any impact on gasoline prices, and alternative fuels may be a better strategy.

**FIGURE 35 NATURAL GAS (“HH”) AND GASOLINE PRICES FROM 1990-2007**



NOTE: GASOIL IS THE SAME AS GTL. THIS FIGURE ONLY SHOWS PRICES JUST BEFORE SHALE GAS EMERGED.

SOURCE: [HTTP://WWW.ENERGYTRIBUNE.COM/1028/DECOUPLING-OF-OIL-AND-GAS-PRICES#STHASH.MPUIPGV5.DPBS](http://www.energytribune.com/1028/DECOUPLING-OF-OIL-AND-GAS-PRICES#STHASH.MPUIPGV5.DPBS).

## 5.5 Technology Limitations Matter

Apart from potential policy considerations on the fuels side, the alternative vehicles pose an interesting dilemma. As demonstrated in Chapter 3, based on how vehicles are design and used, the perceived benefits of an alternative fuel can sometimes be negated. As shown in Chapter 4, if either the vehicle or fuel is not cost-competitive, consumers will not readily adopt them.

Alternative vehicles, as shown in Chapter 3, have primarily been developed in ways to help a new fuel gain traction in the market, offered either as a dedicated option or “flexible” option, which essentially only provides backwards-compatibility. There are dangers in this kind of one-directional vehicle development, as it suggests that the solution to the oil situation lies with a single fuel, when sometimes two can be better than one. For instance, the fact that in small amounts ethanol can improve gasoline’s performance in conventional vehicles is an interesting complementarity that offers a modest but useful way in which ethanol can play a role in the transportation sector within reason of its currently limited production capacity. Forcing infrastructure expansion as well as vehicle development through Renewable Fuel Standards and possible Open Fuel Standards, in contrast, could be expensive and not necessarily efficient.

## 5.6 Giving Consumers Too Many Choices

Introducing a number of different fuels and a variety of different vehicles to ask consumers to choose is unlikely to aid alternative fuel and vehicle development unless the options are meaningfully differentiated from mainstream fuels and vehicles.

While the idea of vehicle flexibility is an attractive one, as it theoretically can be a form of enabling fuel diversification, how it translates into vehicle operation can be very different. Thus far, it has only resulted in vehicles that still cannot compete with the performance and cost-competitiveness of conventional vehicles on the road and are valued only as an option or insurance policy. While it is conceivable that a vehicle could be designed such that flexibility is achieved without compromising some aspect of vehicle performance and is also relatively cost-competitive, again it is unclear how consumers would value this kind of flexibility. Perhaps the more interesting use of flexibility is not in making consumers decide, but in utilizing potential complementarities in currently existing fuels.

Another factor to consider is that in urbanized areas where consumers have other modes of transportation to choose from, the substitution effects can further reduce the likelihood of alternative fuel and vehicle adoption unless given some additional incentives. As a result of the changing system dynamics, the broad policy goals of reducing oil consumption and greenhouse gases can be complicated and vague. Adding alternative fuels and vehicles as more options further increases the complexity; with a greater number of ways to achieve these broad policy goals through improvements in mainstream technologies, it can become harder to rationalize and justify the cost of switching to a new energy source.

# Chapter 6

## A Natural Gas Example

### 6.1 Overview

As established in Chapters 2, there are a number of ways in which natural gas can enable options or make current options relatively more economically viable or circumvent some of the challenges with fuel infrastructure. Chapter 3 and 4 highlighted the challenges with developing new technologies that still meet consumer expectations without forcing them to change their behavior. Chapter 5 illustrated some of the issues policymakers often have to consider, particularly stakeholder mismatch, when considering various policy strategies to aid alternative fuel and vehicle adoption. Synthesizing these and drawing on natural gas' many potential pathways, this chapter explores them from these perspectives—consumer preferences to aid alternative fuel and vehicle adoption, minimizing infrastructure development, and reducing greenhouse gas emissions. Its impact on oil consumption is also briefly considered, but in relation to affecting transport.

Acknowledging that there is a considerable amount of uncertainty in the rate and directions of technological progress, as exemplified by the natural gas opportunity itself<sup>36</sup>, this example is merely demonstrative of how each pathway produces different tradeoffs and how comparing them can be a difficult task. It is also worthwhile to note that the assessments are based on currently available data from the EIA, several independent studies, and expert elicitation<sup>37</sup>; barring drastic future technological change and assuming that the opportunity for natural gas, which stems from the decoupling of oil and natural gas prices as well as their price differential, still remains. As technology improves and becomes more affordable, and as more studies on environmental impact are performed, the pathways presented in this chapter can change. The important takeaway is in illustrating the connections within the system and showing areas of overlap as well as gaps.

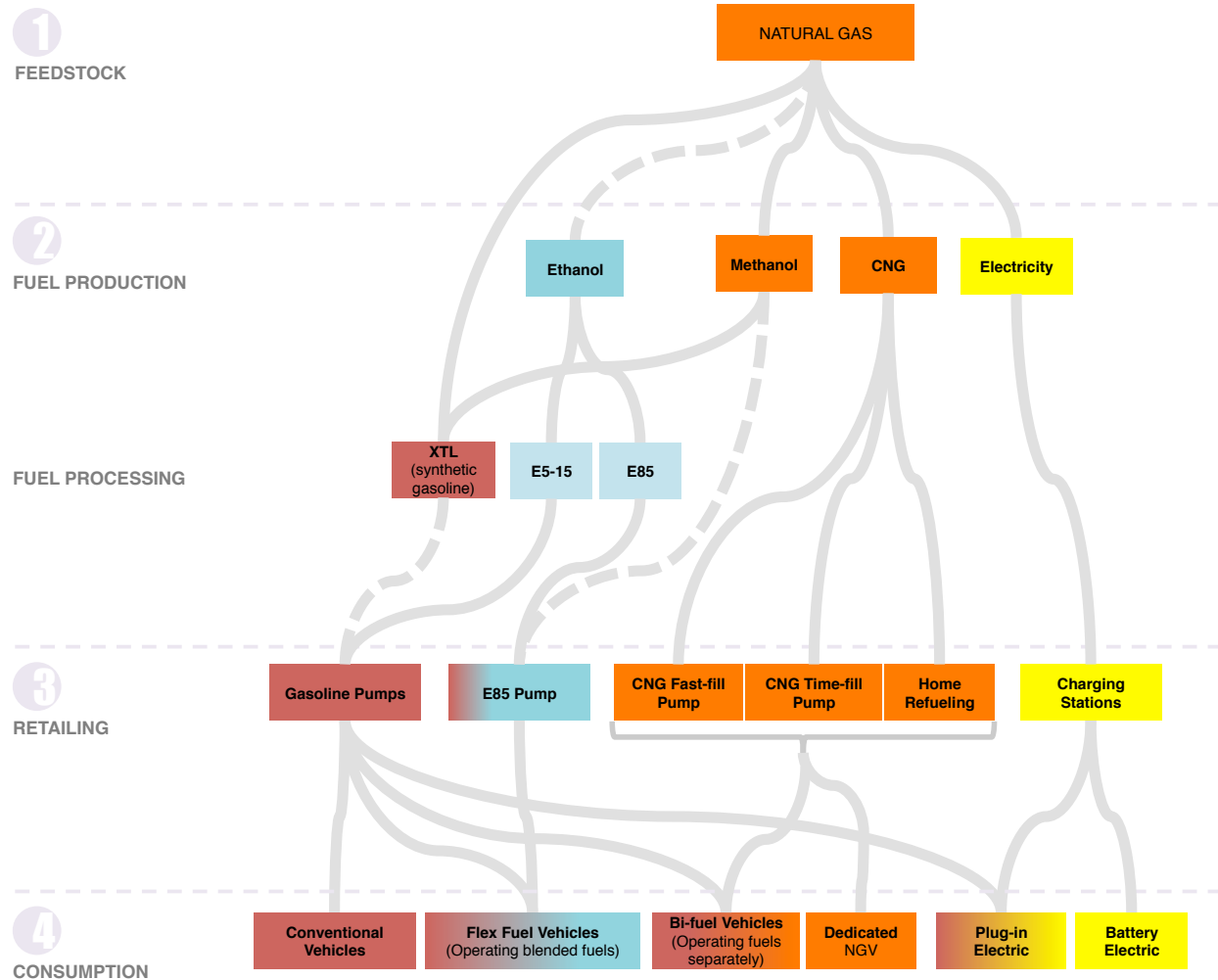
Figure 22 from Chapter 2, reproduced below, shows the current and potential pathways for natural gas fuels. The color coding in this diagram is the same as used previously, in that it shows the relationship between the primary fuel feedstocks, fuels, and vehicles. The fuel is colored according to the primary feedstock currently used in its production, with the exception of XTLs, which are denoted in red to show its equivalence with gasoline.

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<sup>36</sup> This refers to horizontal hydraulic fracturing to recover unconventional natural gas more cheaply.

<sup>37</sup> During the MITEI 2013 Symposium, experts from industry, academia, and policy were invited to provide insights on the challenges facing bi-fuel and tri-flex fuel vehicle development, as well as for alternative fuel and vehicle development more broadly.

## Pathways for Natural Gas [Chapter 2, Figure 22]





## 6.2 Possible Pathways

Conceivably, all of the possible pathways using natural gas as a feedstock will result in reduced oil consumption, but to what degree in light duty vehicle applications is unclear and depends on a number of factors. For a market-driven solution, the primary factor is that the alternative fuel remains cheaper than the oil-derived fuel; if not, consumers are unlikely to switch from the mainstream fuel unless given some other incentive. Other factors that determine the degree to which oil consumption is reduced, include the rate of adoption of alternative vehicles, driving behavior, and rate of fuel efficiency improvement in mainstream vehicles.

Assuming that the price differential between natural gas and oil are sustained, this example considers the potential pathways for using this energy source in light duty vehicle transportation based on consumer preferences, infrastructure requirements, and greenhouse gas emissions reductions. As a point of clarification, though ethanol is included as one of the potential fuels, its primary feedstock still is assumed to be corn and eventually other cellulosic materials; but supposing natural gas becomes another feedstock for ethanol, this example considers what effects it might have.<sup>38</sup>

### 6.2.1 Pathways Consumers Prefer

Most consumers can be described as being economically rational, in that they respond to price and given identical options will pick the cheaper of the two, and environmental pragmatists, who are willing to switch to an environmentally friendlier fuel so long as it does not force them to alter their behavior. Since the “chicken and egg” fuel infrastructure and vehicle development issues can be in part explained as a low-demand driven problem <sup>39</sup>, using consumer expectations of cost-competitiveness and reliability could be a useful starting place or guidepost. After all, the vehicle transportation system is a service industry that thrives on being responsive and adaptive to consumer needs.

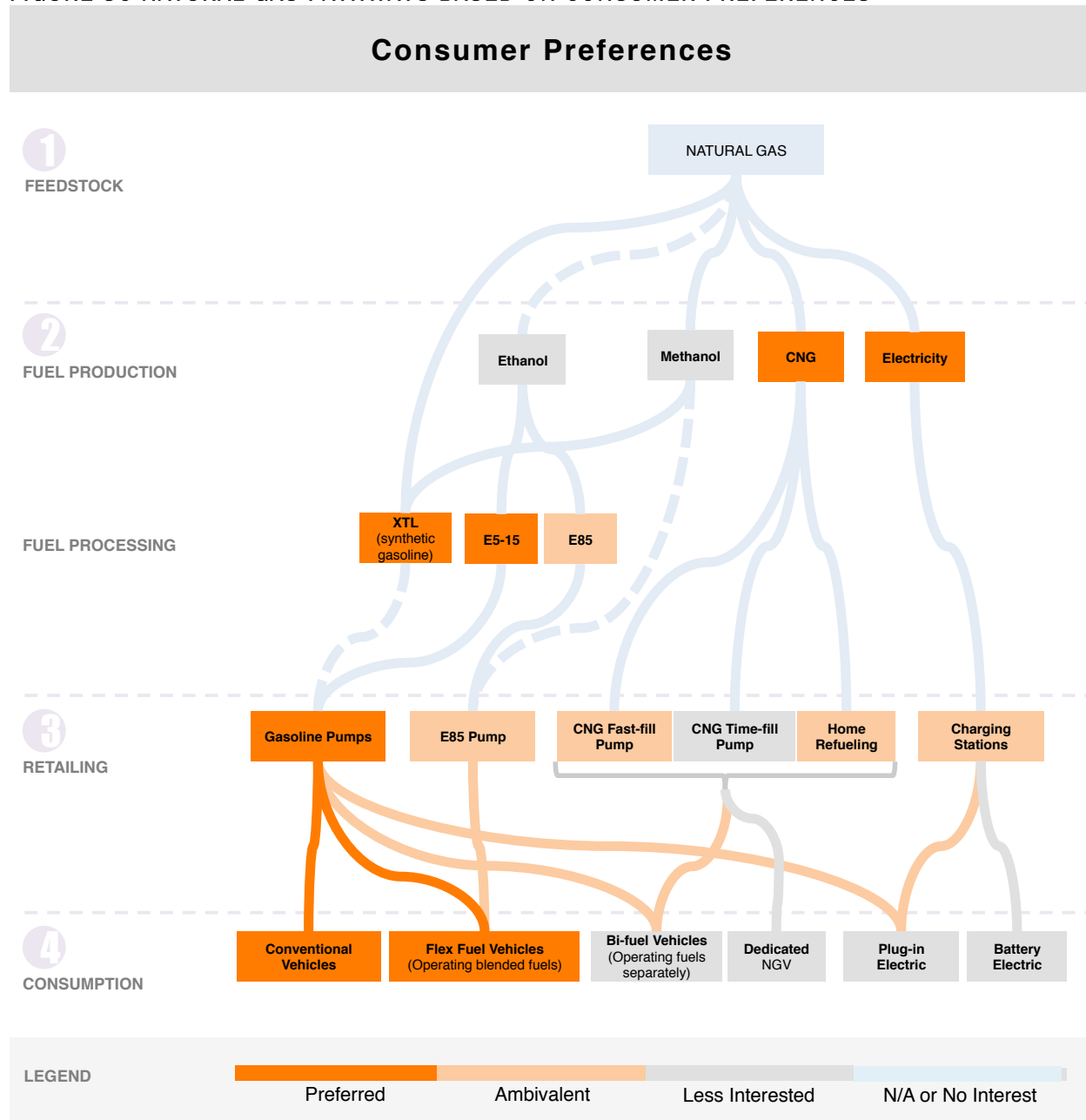
In observing the fuel pathways, it is important to recognize that consumers are connected only to the products and the refueling infrastructure, not the process in producing and delivering them, and generally only respond to changes in those aspects. As such, the options that result in the cheapest options or fewest changes to their general vehicle usage are highlighted in Figure 36.

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<sup>38</sup> This example does not consider time effects. Since it is unclear how using natural gas as an ethanol feedstock might change ethanol prices,

<sup>39</sup> Others could argue that this is merely an expected outcome and cost of transitioning to a potential new technology from a mainstream technology. This idea will be discussed further.

FIGURE 36 NATURAL GAS PATHWAYS BASED ON CONSUMER PREFERENCES



NOTE: CONNECTORS IN (1) AND (2) REPRESENT TRANSPORT AND DISTRIBUTION INFRASTRUCTURE, WHILE IN (3) CONNECTORS REPRESENT PREFERRED OPTIONS. GIVEN A CHOICE BETWEEN FILLING UP WITH GASOLINE OR E85, CONSUMER WOULD PREFER THE CHEAPER OR MORE ACCESIBLE OPTION, WHICH IS CURRENTLY GASOLINE. GIVEN A CHOICE BETWEEN BI-FUEL AND DEDICATED CNG VEHICLES, CONSUMERS ARE MORE LIKELY TO CHOOSE THE MORE FLEXIBLE VEHICLE UNLESS GIVEN MORE CERTAINTY THAT CNG PRICES WILL REMAIN CONSISTENTLY LOWER THAN GASOLINE AND THAT REFUELING INFRASTRUCTURE IS RELIABLE.

#### 6.2.1.1 Fuels<sup>40</sup>

Consumers prefer fuels that can result in a fuel cost savings by being cheaper than gasoline or can be used in conventional vehicles. Of the fuels, CNG and electricity would be preferred because they are likely to be cheaper than gasoline<sup>41</sup>. XTL or GTL, in this case, and E5-15 are preferred as they can both be employed in current conventional vehicles; in fact, since GTL would likely be sold as gasoline, consumers would not know the difference. Consumers also may not become aware of the degree to which gasoline blends are mixed with ethanol either unless there are separate pumps for E5-15 and E85; in the event that there is a separate pump for E5-15, consumers may be indifferent if the prices for gasoline and E5-15 are the same, or they would just pick the cheaper of the two. E85, on the other hand, could create some confusion for consumers, as it is currently more expensive on an energy-equivalent-basis compared to gasoline, but retails at a price that appears cheaper than gasoline. Whether natural gas as a feedstock would in fact impact this or not depends on how ethanol pricing is determined. Assuming that the consumer has a vehicle that is capable of running on E85, this could be a reason for them to choose E85 over gasoline, or if they are aware of the energy equivalence conversion, may only use E85 once it is actually cheaper than gasoline on an energy-equivalent basis. The other potential concern is that because E85 is less energy dense than gasoline, it could result in higher fuel consumption, which means more frequent refueling. As E100 and M100 are not likely to be offered as options, these will remain unselected.

#### 6.2.1.2 Refueling

When it comes to refueling their vehicles, consumers prefer comparable fill speeds as gasoline (4-5 minutes) and sufficient number of refueling stations. Based on these two criteria, gasoline pump refueling was the only option that satisfied both. While E85 offers comparable fill speeds, E85 refueling stations are limited in number; however, since flex-fuel vehicles allow users to use 100% gasoline, limited number of refueling stations would not be a concern. Of the CNG options, fast-fill pumps would be the preferred option, but still are few in number. Time-fill pumps are not preferable from a general standpoint, as they can take 4 to 8 hours to fill; however, in fleet operations, this could be less of an issue. Home refueling takes as long or longer than time-fill pumps, but are more acceptable as they can be refueled overnight in the convenience of or near one's own home.<sup>42</sup> Most public charging stations are similar to CNG time-fill stations in that vehicles take 4 to 8 hours to charge, though more companies have been developing faster charging stations.

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<sup>40</sup> In terms of fuel cost competitiveness, this is based on current prices. For ethanol, however, how natural gas would change its price is ambiguous. It is important to note that price changers are a critical factor in assessing the economic viability of these alternative fuels.

<sup>41</sup> The fact that their potential volatility is not attributed to oil shocks for geopolitical reasons like oil embargos, but are more likely instead subject to seasonality or other more fundamental sources of uncertainty, can also be an attractive aspect for those who have dedicated alternative vehicles.

<sup>42</sup> This would be a more palatable option for those who have a direct connection to a gas line, though for apartment complexes, this might not work.

### 6.2.1.3 Vehicles

Vehicle preference is similar to that for fuels, in which given similar options, consumers prefer a cheaper car that does not force them to change their behavior. As flex fuel vehicles can be competitive with conventional vehicles, these can be and often are indistinguishable for consumers. In contrast, bi-fuel CNG vehicles and dedicated CNG vehicles, which cost roughly the same to produce and conceivably have a similar price point, are still significantly more expensive than a similar gasoline-powered vehicle, and would not be preferred. However, given the lack of refueling stations, bi-fuel CNG vehicles would have a perceived advantage over dedicated models in that they would not force consumers to change their behavior, since they could still fuel their vehicles with gasoline. However, as bi-fuel vehicles carry an extra tank, they increase fuel consumption, requiring users to refuel more if they used CNG, which could lessen the potential fuel cost savings. Electric vehicles<sup>43</sup> are in a similar category as bi-fuel and dedicated CNG vehicles, but are at an even higher cost disadvantage due to expensive batteries. Nonetheless, vehicles that are capable of running on multiple fuels can have value similar to that of an option value or insurance policy, in which greater gasoline price volatility and insufficient number of CNG refueling stations can increase this value.

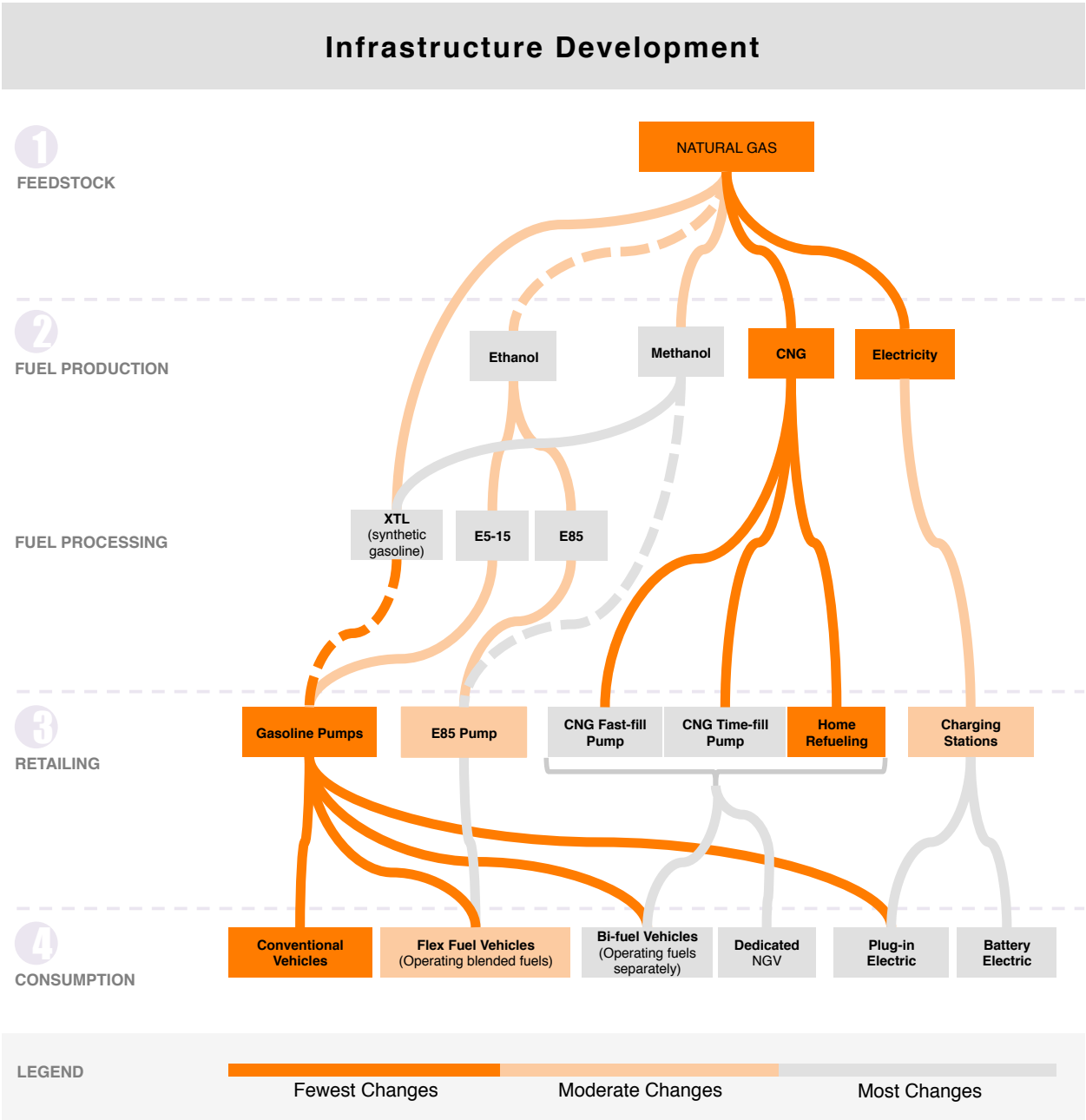
### 6.2.2 Pathways Minimizing Infrastructure Development

Earlier in Chapter 2, natural gas as a feedstock could reduce the costs of fuel production as well as some of the infrastructure needs. From this basis, the remaining infrastructure development required for these fuels was explored and summarized in Figure 37. Note that each box and connector represents an aspect of the infrastructure development, from fuel production and processing, to distribution, and to consumption.

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<sup>43</sup> Only plug-in hybrid and battery electric vehicles are considered electric vehicles; though hybrid electric vehicles are usually included in electric vehicle discussions, they were not considered here since they are fueled by gasoline.

FIGURE 37 NATURAL GAS PATHWAYS MINIMIZING INFRASTRUCTURE DEVELOPMENT



NOTE: CONNECTORS IN (1) AND (2) REPRESENT TRANSPORT AND DISTRIBUTION INFRASTRUCTURE, WHILE IN (3) CONNECTORS REPRESENT THE OPTION WITH THE FEWEST INFRASTRUCTURE CHANGES.

#### 6.2.2.1 Fuel Production

Natural gas and electricity production both have well-established infrastructures in place. As methanol and GTL production from natural gas do not take place in the U.S., these facilities would have to be built to support domestic production, granted that it is cheaper than shipping them from other locations. As for ethanol production, this pathway is blocked in part by the Renewable Fuel Standard, which makes it arguably not economical for natural gas to be converted to ethanol when there are already mandates for ethanol to be supplied by other feedstocks (Forbes, 2013). However, if this were a possible path, then ethanol to natural gas production facilities would have to be built or current ethanol production facilities would have to accommodate natural gas as a feedstock.<sup>44</sup>

#### 6.2.2.2 Transporting Fuel to Retail Market

CNG is primarily transported via distribution pipelines and could be easier to support scaled up CNG production compared to the other options. Similarly, GTLs could use the same transport system as gasoline, which is either by a common pipeline or by tanker truck. While electricity is delivered through an extensive transmission and distribution network, an expansion of the grid would still be required to support large-scale adoption of electric vehicles; as vehicles are likely to be charged around the same time, mainly at night or during business hours post or prior to morning and evening rush hour, this could overload the grid (MIT Electrification Symposium, 2010). As ethanol is primarily distributed via trucks and rail, natural gas derived ethanol would likely use the same transport structure unless dedicated pipelines become economically attractive. Methanol, as a similarly corrosive fuel, would likely also have to be transported by truck.

#### 6.2.2.3 Refueling Stations

Gasoline pumps and CNG home refueling options would create the fewest large infrastructure changes, as gasoline stations are well and highly distributed across the U.S., and CNG home refueling options would be used on an as-needed basis by the user. E85 pumps, as established earlier, can cost anywhere from an average of \$21,031, for a retrofit to an average of \$71,735 for a newly installed tank at gas stations. While E85 pumps are expensive to install, they are relatively more affordable compared to CNG pumps, which can cost anywhere from \$400,000 to \$1.7 million. Regarding electric vehicle, they can always be charged at home without requiring additional equipment, though this would be a long charge, the need for public charging stations would not be as high as public refueling stations would be for CNG vehicles.

#### 6.2.2.4 Vehicle Production

The cost to produce a flex fuel vehicle and conventional vehicle is approximately \$300/vehicle, and would not be difficult for vehicle manufacturers to produce. Bi-fuel vehicles and dedicated vehicles are differentiated by the fact that bi-fuel vehicles have an additional fuel processing system for the gasoline tank, but compared to flex fuel vehicles, would require more changes and generally cost

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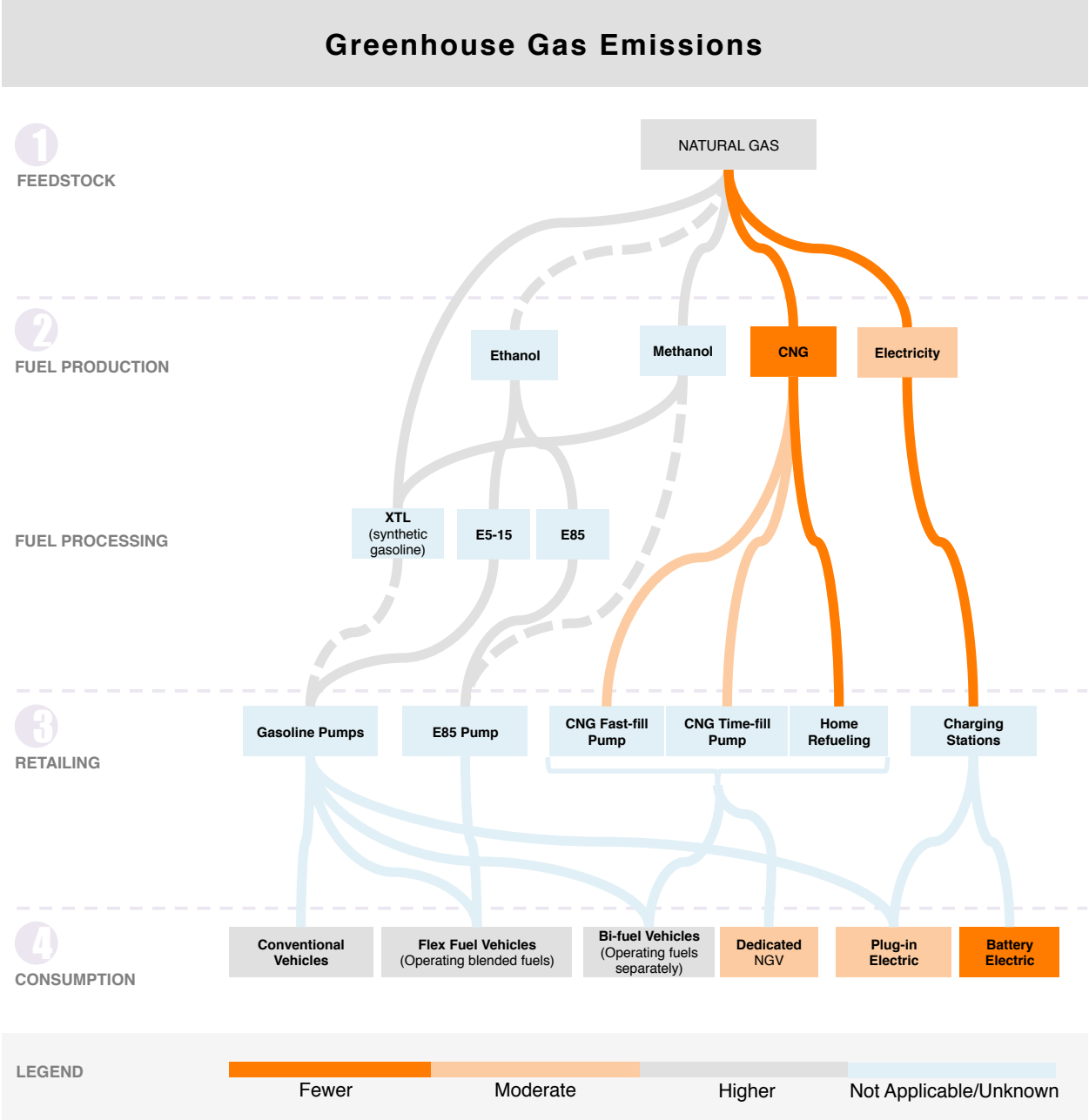
<sup>44</sup> Natural gas is currently used as a fuel in traditional ethanol plants to power conversion processes. This was included as a contributing factor in ethanol's lifecycle emissions studies (Wang et al., 2007).

more than \$5000/vehicle to produce. The primary cost constraint in electric vehicle production are the batteries, which cost \$500/kWh and are thus still considered expensive (NRC, 2013).

### **6.2.3 Pathways Reducing Greenhouse Gas Emissions**

Most studies produce lifecycle assessments of the fuels from well-to-wheels, where electricity on average produces fewer emissions than the other fuels (AFDC, 2013). However, this could change depending on the mix of electricity sources in that particular area; electricity generated mostly from coal has a higher carbon footprint than one with fewer greenhouse gas emissions, like wind (AFDC, 2013). Figure 38 attempts to show where along the fuel lifecycle produces the highest emissions, as a way of helping to identify opportunities for reducing or controlling emissions.

FIGURE 38 NATURAL GAS PATHWAYS THAT REDUCE GREENHOUSE GAS EMISSIONS





### 6.2.3.1 Upstream Emissions

Upstream emissions are those that are produced during fuel and vehicle production. As natural gas and CNG are transported through pipelines, they are tightly sealed to prevent leakages, which generally result in few emissions. In the case of methanol and GTL, since these are currently imported, this involves barges and trucks that would produce emissions; however, if this was done domestically, this could potentially offset some of the emissions from transporting them. Again, as ethanol from natural gas has encountered roadblocks in scaling up production, the emissions produced from them are uncertain, though their transport would most likely still produce emissions from shipping. Natural gas recovery itself, however, still produces the highest emissions relative to other aspects of its fuel pathways, and depending on climate policy, can be an important factor in how likely and to what extent it will be used as a feedstock.<sup>45</sup>

### 6.2.3.2 Downstream Emissions

Downstream emissions are those that are produced during fuel and vehicle use, which broadly include evaporative and tailpipe emissions. Evaporative emissions occur during the refueling process, depending on the fuel volatility; as a very volatile liquid, gasoline evaporates to release various organic compounds into the air, some of which contributes to air pollution. Blending with ethanol reduces the overall fuel volatility. Tailpipe emissions are part of the exhaust produced from combusting the fuel. When combusted, natural gas produces roughly 20% less CO<sub>2</sub> than gasoline. It is unclear how flex fuel vehicles compare. Electric cars running only electricity have zero tailpipe emissions (AFDC, 2013).

## 6.3 The Big Picture

From observing these different perspectives, it is easy to understand why alternative fuel and vehicle development can be a difficult and enormous undertaking, and it comes as no surprise that so many different policy strategies have been attempted. Whether it is looking at all of these perspectives together [Figure 39] or overlaying them [Figure 40], one message is clear: there is no straightforward path for natural gas in light duty vehicle applications. However, there is a silver lining—where the paths disconnect are opportunities, some of which can be brought about naturally by market forces and others through some more coaxing by employing certain policy levers.

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<sup>45</sup> Climate policy often incorporates some aspect that internalizes the cost of emissions, which are generally easier to apply upstream than downstream. This often results in increases in production costs of the fuel or vehicle, which can be reflected in higher prices. For feedstocks, these changes could make it less attractive relative to others.

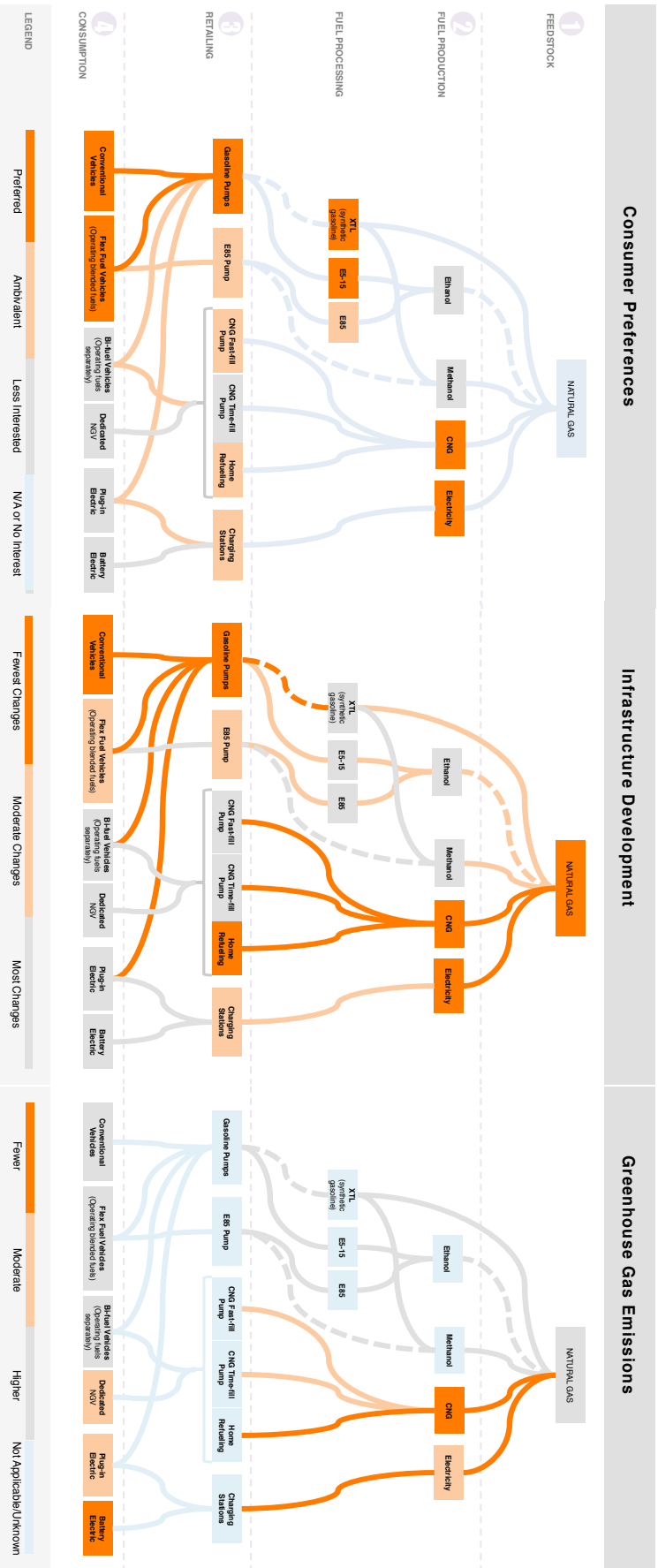
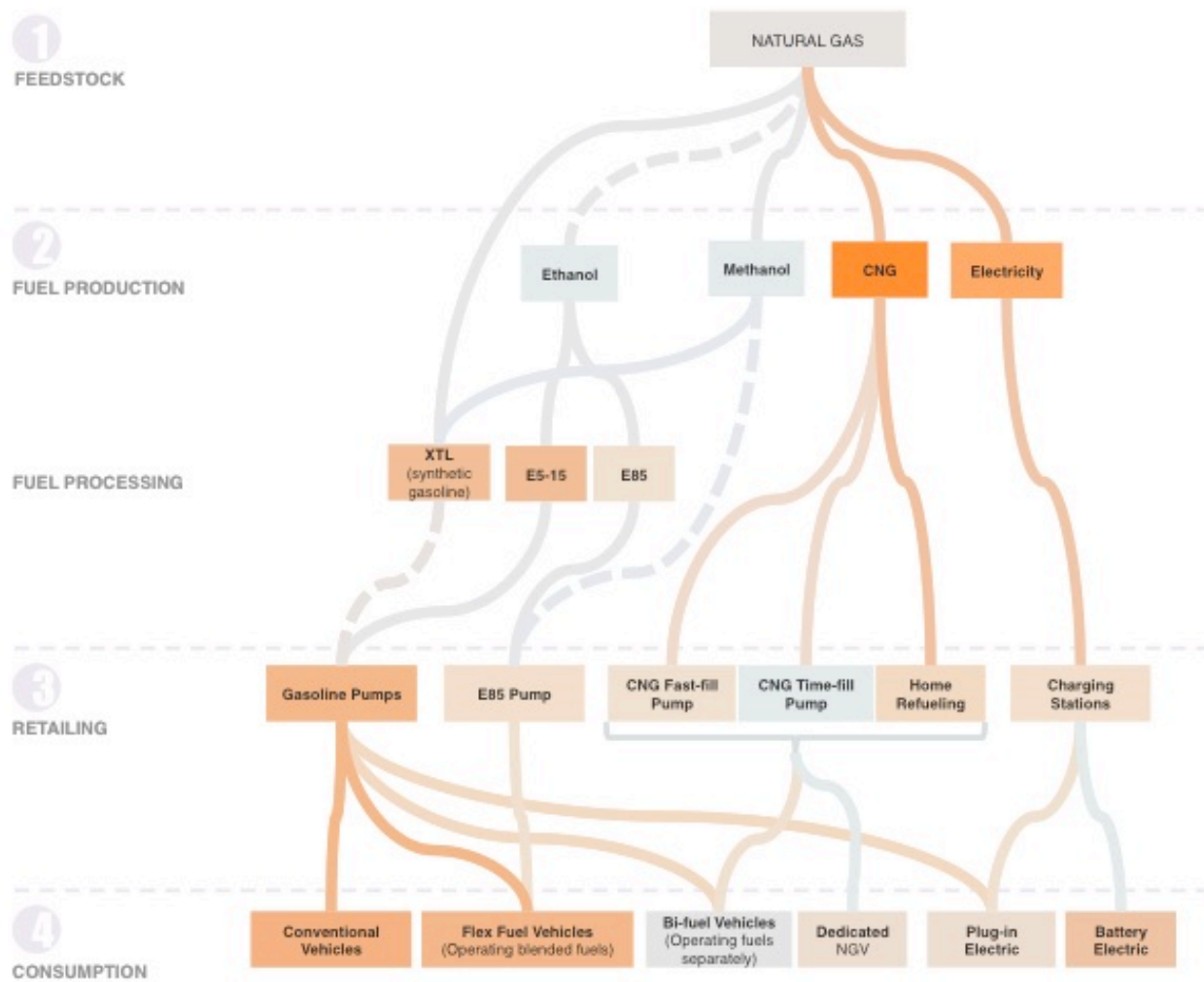


FIGURE 39  
NATURAL GAS  
PATHWAYS  
COMPARISON

FIGURE 40 NATURAL GAS PATHWAYS SYNTHESIZED



NOTE: THIS IS NOT INTENDED TO BE A ROBUST ANALYSIS, BUT MERELY TO DEMONSTRATE HOW THERE IS A DISCREPANCY BETWEEN WHICH ALTERNATIVE FUELS AND VEHICLES MIGHT FARE BETTER IN A LIGHT DUTY VEHICLE MARKET.

### 6.3.1 Opportunities for Vehicle Design

One of the interesting observations from this example is that if reducing GHG emissions is at the top of the policy agenda and if alternative and conventional vehicles are not differentiated in a market segmenting way, bi-fuel vehicle designs can be at a disadvantage. There are a few possible takeaways from this observation: first, that fuel cost savings is expected as a way to incentivize a commitment to switching fuels, not to encourage indecision. Second, though disadvantaged when compared to all other alternative vehicle designs, bi-fuel capability could potentially still be useful if there was a way to better optimize the core technology (fuels, fuel processing system, powertrain) to achieve higher performance, reduce overall vehicle costs, or use some kind of market segmentation strategy that could justify its higher price tag. Plug-in hybrids, in contrast to CNG-gasoline bi-fuel vehicles, reflect a better compatibility of the two fuels.

### 6.3.2 Opportunities for Fuels and Fuel Feedstocks

As another observation, the fact that there are no clear paths also helps demonstrate the flaw in placing too much emphasis on one particular feedstock and expecting that its use for a particular vehicle application can bring about the desired policy transformations in reducing oil consumption and by extension, greenhouse gas emissions. Further, shale natural gas only represents one way of obtaining methane, which can actually be produced from a variety of other sources, but are currently still too expensive at a large scale (Han et al, 2011).

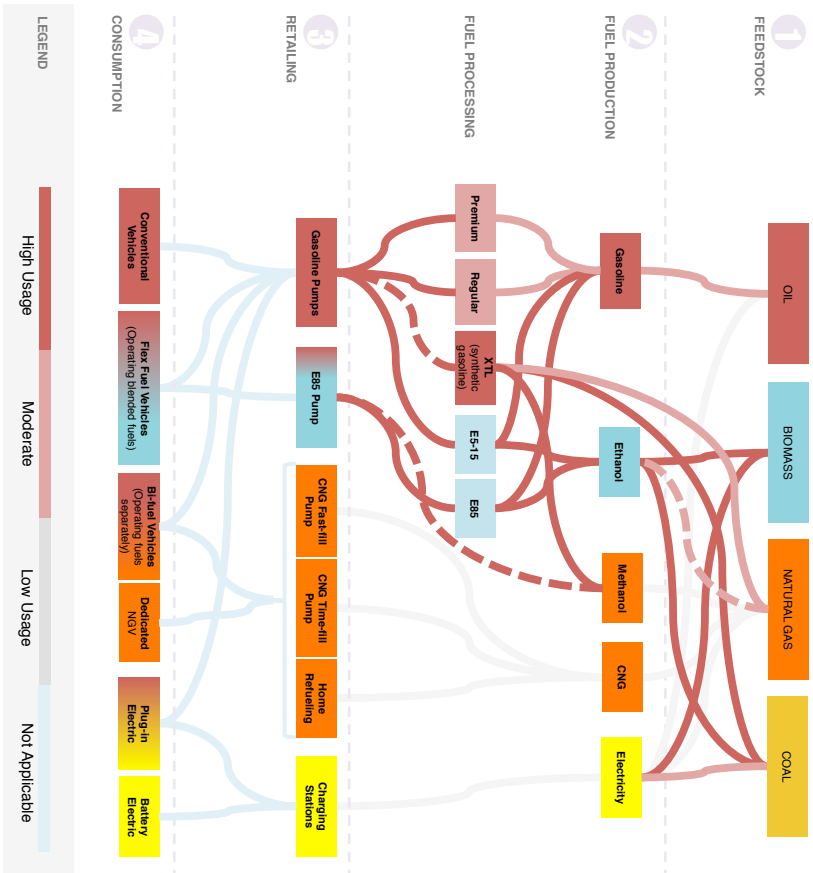
Stepping back, while affecting change in light duty vehicle applications can be an attractive area given its large petroleum consumption and carbon footprint, there are other aspects of the fuel pathways that also consume oil and emit greenhouse gases. For instance, for certain feedstocks and fuels, transporting and distributing them often involve trucks and tankers.<sup>46</sup> There are two takeaways from this: first, that when evaluating the costs and benefits for fuels and fuel feedstocks, determining how reliant they are on oil in their transport can be a relevant factor. Second, as trucks and tankers are typically centrally fueled, it could create an opportunity for adapting natural gas or potentially other feedstocks for these medium and heavy-duty vehicle applications, which require fewer large and distributed infrastructure changes that would be needed to serve the light duty vehicle market [Figure 41].

Nonetheless, more research is needed to better understand how the transportation system would respond and adapt to new energy sources, fuels, vehicles, or other technologies that are potential “game changers.”

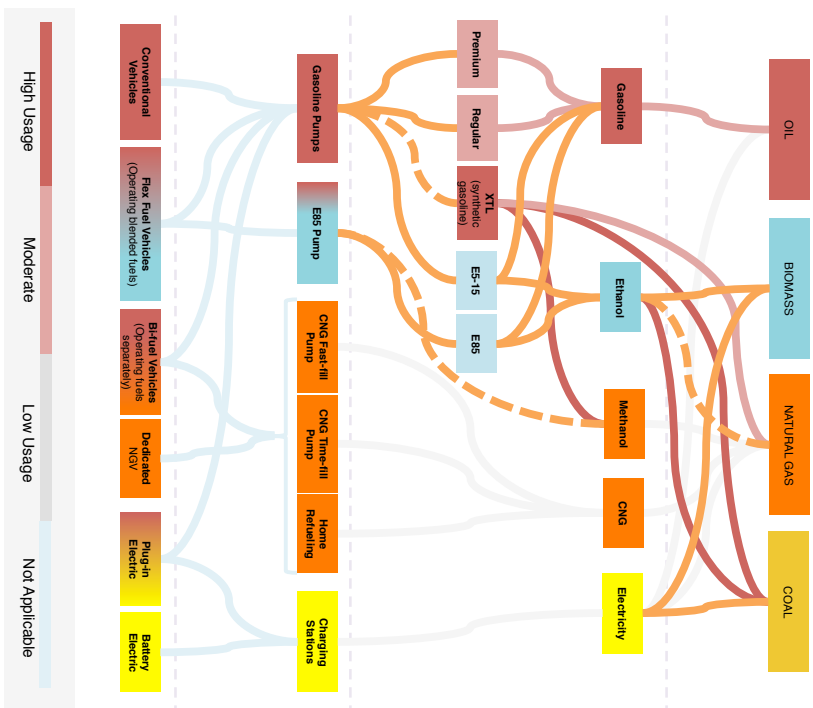
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<sup>46</sup> These typically run on diesel fuel and not gasoline, but are still predominantly petroleum-derived fuels. Biodiesel, which is made from biomass, can be used in diesel engines without modification (AFDC, 2013).

## OIL USED IN FUEL TRANSPORT



## POTENTIAL OIL DISPLACED IN FUEL TRANSPORT



**FIGURE 41 OIL CONSUMPTION AND POTENTIAL DISPLACEMENT IN FUEL TRANSPORT**

NOTE: WHILE THIS SCHEMATIC DOES NOT MAKE THE GEOGRAPHIC CONSIDERATIONS APPARENT, IT EMPHASIZES THE RELATIONSHIPS BETWEEN CURRENTLY AVAILABLE FUELS AND VEHICLES AS A WHOLE. ALSO NOT INCLUDED ARE THE TIME EFFECTS

# Chapter 7

## Conclusions

Given the infrastructure realities and uncertainties, as well as the potential coordination efforts required between fuel infrastructure development, vehicle manufacturers, and incentivizing consumers, encouraging alternative fuel and vehicle development can be an enormous undertaking. It is no surprise then that though vehicles capable of running on non-oil based fuels have been tried for years, many of those have failed and of those that have experienced global success, namely, E85 in Brazil and CNG in India, only succeeded from a direct policy push.<sup>47</sup> Those that were non-federally funded were cars retrofitted to run on cheaper fuels,<sup>48</sup> which the U.S. EPA now severely curbs until potential environmental issues with them are better understood and can be more reliably regulated.

The recent push for alternative fuels and vehicles in the U.S. has similarly been driven by policymakers trying to achieve larger policy objectives; however, it has been slow in part due to evolving motivations and shifting policy strategies. While the fuel and vehicle industries have been eager to explore new options, the expectations placed on what these alternative fuels and vehicles can deliver are continuously increasing, while the market conditions have remained fairly unchanged.

This creates two competing directions for technological progress: to improve mainstream technology or to transition to new energy sources. These competing directions can create tensions in the system—as mainstream technology improves, it sets a higher baseline that tends to augment the challenges for scaling up a new technology. Coupled with the greater uncertainties they generate, these challenges can increase the opportunity cost of developing alternative fuels and vehicles. Depending on which policy levers are used to incentivize R&D or aid some other aspect of technology or infrastructure development, these competing directions become more evident and raise more questions on whether accommodating a new energy source is worthwhile, or if strategies for improving efficiency are enough.

Given the current technologies, there are no clear answers. And as demonstrated with the natural gas example, there are no straightforward paths for alternative fuel and vehicle development. However, there are a number of lessons from recent alternative fuel and vehicle demonstrations that provide insights into how the transportation sector could more naturally align with policy goals of reducing oil consumption and greenhouse gas emissions. While fuel diversity may be one avenue to

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<sup>47</sup> Ethanol in Brazil, for instance, was part of the Brazilian government's aggressive plan in the mid-late 70s to promote ethanol as a direct response to the oil shocks (Barros, 2010); India's switch to natural gas was actively pushed forward to address air quality and pollution in Delhi (Fehrenbacher, 2011).

<sup>48</sup> For instance, coal was once used as a fuel for automobiles during World War II. Due to gasoline rationing imposed by the Vichy government, cars in France were retrofitted to run on coal. (Fox News, 2013).

curb oil consumption, vehicle technology can limit the scale to which the fuels are used and fuel feedstocks can affect their reliability and cost-competitiveness. Whether it is to promote fuel diversity, fuel feedstock diversity, or vehicle flexibility, by stepping back and viewing the options as a whole, one can see that pursuing individual fuel pathways from production to consumption can be a limiting and prohibitive strategy; the fact that they are interconnected, in contrast, allows for new solutions to emerge.

Though some of the disconnects in the pathways can be resolved naturally by market forces, others may still need the help of certain policy levers. The critical issues for policymakers to consider is that in weighing the advantages and disadvantages between the alternative fuels and vehicles, it is important to recognize that the transportation system is highly sensitive to changes in the fuel feedstock composition, and that its development and costs depend on geography and fuel fungibility. Secondly, while vehicle technologies can be designed to accommodate multiple fuels, those that take advantage of potential fuel compatibilities or produce higher performance when the core technology is optimized for the fuel may be better adapted to increasing fuel choices; depending on which designs emerge can also determine the degree to which the alternative fuels need to be scaled. Thirdly, since consumers ultimately determine the success of alternative fuels and vehicles and generally base it on a perceived fuel cost savings and vehicle cost-competitiveness when presented with undifferentiated choices, understanding the dynamics between fuel feedstock and fuel pricing could be another important area for research.

While oil has served as the dominant fuel feedstock for light duty vehicles and replacing it is appealing, the desire to find an ideal substitute that replicates its properties without the associated geopolitical risks is problematic and restrictive; realistically, many fuels can coexist and policymakers have a number of considerations in determining where and how deeply to get involved.





# Appendix A: Glossary of Terms

## Vehicle Classes

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### Class One: 6,000 lbs. or less



### Class Two: 6,001 to 10,000 lbs.



### Class Three: 10,001 to 14,000 lbs.



### Class Four: 14,001 to 16,000 lbs.



### Class Five: 16,001 to 19,500 lbs.



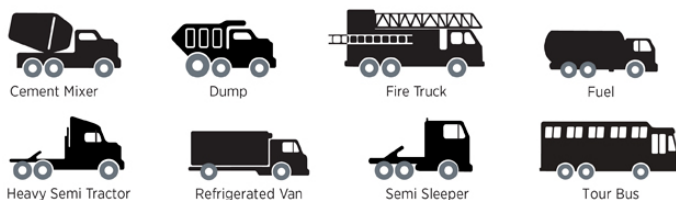
### Class Six: 19,501 to 26,000 lbs.



### Class Seven: 26,001 to 33,000 lbs.



### Class Eight: 33,001 lbs. & over



## Vehicle Terms

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SOURCE: EIA ANNUAL ENERGY OUTLOOK, 2012.

**Light-duty vehicle:** An on-road vehicle with a gross vehicle weight rating equal to or less than 8,500 pounds. Automobiles, motorcycles, minivans, SUVs and other small pickups fall into this category.

**Medium-duty vehicle:** An on-road vehicle with a gross vehicle weight rating between 8,501 and 26,000 pounds. Some larger cargo vans, pickup trucks and maintenance trucks fall into this category.

**Heavy-duty vehicle:** An on-road vehicle with a gross vehicle weight rating equal to or greater than 26,001 pounds. Transit buses and large delivery trucks fall into this category.

**Dedicated or mono-fuel vehicle:** Any vehicle engineered and designed to be operated using a single fuel.

**Conventional gasoline vehicle:** Vehicles that run on conventional gasoline fuel.

**CNG-dedicated vehicle:** Vehicles that run on only CNG.

**Bi-fuel vehicle:** A vehicle that is capable of operating on and switching between two fuels—generally gasoline or diesel and an alternative fuel—that are stored in separate tanks. A bi-fuel vehicle engine runs on one fuel at a time and the fuels are not mixed. E.g. CNG/gasoline.

**Flex-fuel vehicle (flexible-fuel vehicle):** Vehicles that are designed to run on more than one fuel, usually gasoline blended with ethanol (E85). The most common flex-fuel vehicles in the world use ethanol as its alternative fuel source. Unlike bi-fuel vehicles, flex-fuel vehicles store two fuels in the same tank.

**Dual-fuel vehicles:** A type of a Flex-fuel vehicle in which there are two independent fuel systems that can operate on both fuels simultaneously or on one fuel alone.

**Plug-in hybrid electric vehicles (PHEV):** Vehicles that use battery power for driving some distance, until a minimum level of battery power is reached, at which point they operate on a mixture of battery and internal combustion power. Plug-in hybrids also can be engineered to run in a “blended mode,” where an onboard computer determines the most efficient use of the battery and internal combustion power. The batteries can be recharged from the grid by plugging a power cord into an electrical outlet.

**Battery electric vehicles (BEV):** Vehicles that use batteries to store the electrical energy that powers the motor.

## Fuel Terms

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**Conventional (traditional) fuel:** Fuels that are petroleum-based. (E.g. gasoline and diesel)

**Alternative fuel:** Any fuel materials that are not conventional fuels. Alternative fuels for transportation include methanol, denatured ethanol, compressed or liquefied natural gas, liquefied petroleum gas (propane), hydrogen, coal-derived liquid fuels, cellulosic biofuel, and electricity.<sup>1</sup>

**Ethanol blend fuel:** A mixture of liquid ethanol and gasoline in various ratios. “E” numbers describe the percentage of ethanol fuel in the mixture by volume. For example E15 is 15% anhydrous ethanol and 85% gasoline by volume.

**Methanol blend fuel:** A mixture of liquid methanol and gasoline in various ratios. “M” numbers describe the percentage of ethanol fuel in the mixture by volume.

**XTL:** Any alternative liquid fuel produced from conversion of a solid or gaseous feedstock. This includes, Coal-to-Liquids (CTL), Gas-to-Liquids (GTL), and Coal/Biomass-to-Liquids (CBTL).

## Natural Gas Acronyms

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SOURCE: TRILLIUM USA, 2013

**Btu:** British Thermal Unit corresponds to the amount of energy required to raise the temperature of one pound mass of water by 1 °F.

**DGE:** Diesel Gallon Equivalent corresponds to the amount of CNG containing the same energy content as one gallon of diesel. Ultra-low sulfur diesel has slightly less energy than traditional diesel, so 1.35 therms per DGE is commonly cited conversion rate.

**GGE:** Gasoline Gallon Equivalent corresponds to the amount of CNG containing the same energy content as one gallon of gasoline. The typical conversion rate is 1.25 therms per GGE.

**Inlet or Suction Pressure:** Both inlet and suction pressure refer to the incoming pipeline gas pressure that supplies the CNG station. Inlet pressure is one of the main factors that determine the overall flow rate of a CNG station.

**LNG:** Liquefied Natural Gas is natural gas that has been cooled to -260 degrees Fahrenheit and then condensed into a colorless, odorless, non-corrosive and non-toxic liquid. LNG is characterized as a cryogenic liquid.

**Methane (CH<sub>4</sub>):** Is commonly known as natural gas, is an abundant, colorless gas that burns efficiently without many byproducts. As methane is naturally odorless, it has a distinctive odor added as a safety measure.

**MMBtu:** One Million Btu.

**PSI:** Pounds per Square Inch refers to pressure measured with respect to atmosphere pressure. Pressure gauges are adjusted to read zero at the surrounding atmospheric pressure.

**SCF:** Standard Cubic Foot contains approximately 1,000 BTU.

**SCFM:** Standard Cubic Feet per Minute is the standard measurement for the flow rate of gas. A CNG station with a flow rate of 125 SCFM equates to 1 GGE per minute.

**Therm:** Is 100,000 British thermal units (Btu). A common measure of gas as sold by utilities.

## Natural Gas Conversion Factors

SOURCE: IOWA STATE UNIVERSITY, 2008. AVAILABLE AT  
[HTTPS://WWW.EXTENSION.IASTATE.EDU/AGDM/WHOLEFARM/HTML/C6-89.HTML](https://www.extension.iastate.edu/agdm/wholefarm/html/C6-89.html).

1 cubic foot natural gas (NG) – wet	=	1,109 Btu
1 cubic foot – dry	=	1,027 Btu
1 cubic foot – dry	=	1,087 kilojoules
1 cubic foot – compressed	=	960 Btu
1 pound	=	20,551 Btu
1 gallon – liquid	=	90,800 Btu – higher heating value
1 gallon – liquid	=	87,600 Btu – lower heating value
1 million cubic feet	=	1,027 million Btu
1 metric ton liquefied natural gas (LNG)	=	48,700 cubic feet of natural gas
1 billion cubic meters NG	=	35.3 billion cubic feet NG
1 billion cubic meters NG	=	.90 million metric tons oil equivalent
1 billion cubic meters NG	=	.73 million metric tons LNG
1 billion cubic meters NG	=	36 trillion Btus
1 billion cubic meters NG	=	6.29 million barrels of oil equivalent
1 billion cubic feet NG	=	.028 billion cubic meters NG
1 billion cubic feet NG	=	.026 million metric tons oil equivalent
1 billion cubic feet NG	=	.021 million metric LNG
1 billion cubic feet NG	=	1.03 trillion Btus
1 billion cubic feet NG	=	.18 million barrels oil equivalent
1 million metric tons LNG	=	1.38 billion cubic meters NG
1 million metric tons LNG	=	48.7 billion cubic feet NG
1 million metric tons LNG	=	1.23 million metric tons oil equivalent
1 million metric tons LNG	=	52 trillion Btus
1 million metric tons LNG	=	8.68 million barrels oil equivalent
1 million metric tons oil equivalent	=	1.111 billion cubic meters NG
1 million metric tons oil equivalent	=	39.2 billion cubic feet NG
1 million metric tons oil equivalent	=	.805 million tons LNG

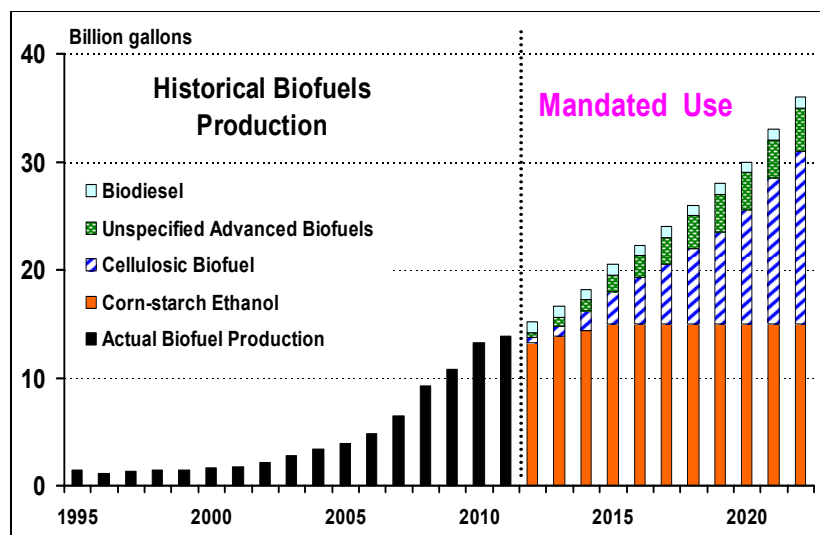
1 million metric tons oil equivalent	=	40.4 trillion Btus
1 million metric tons oil equivalent	=	7.33 million barrels oil equivalent
1 million barrels oil equivalent	=	.16 billion cubic meters NG
1 million barrels oil equivalent	=	5.61 billion cubic feet NG
1 million barrels oil equivalent	=	.14 million tons oil equivalent
1 million barrels oil equivalent	=	.12 million metric tons of LNG
1 million barrels oil equivalent	=	5.8 trillion Btus
1 trillion Btus	=	.028 billion cubic meters NG
1 trillion Btus	=	.98 billion cubic feet NG
1 trillion Btus	=	.025 million metric tons oil equivalent
1 trillion Btus	=	.2 million metric tons LNG
1 trillion Btus	=	.17 million barrels oil equivalent
1 short ton	=	53,682.56 cubic feet
1 long ton	=	60,124.467 cubic feet
1 cubic foot	=	.028317 cubic meters
1 cubic meter – dry	=	36,409 Btu
1 cubic meter – dry	=	38.140 megajoules
1 cubic meter	=	35.314 cubic feet

# Appendix B: Federal Legislation

## Renewable Fuel Standard

The purpose of the Renewable Fuel Standard is to help develop the U.S. biofuels sector and increase the role of renewable fuels in the national transportation fuel supply. The EPA is responsible for establishing and implementing the RFS, which mandates a minimum volume of biofuels, including cellulosic, biomass-based diesel, and advanced biofuels to be used, and bases its standards on projections from the EIA. The first RFS (RFS1), which was issued in 2007, established compliance standards for fuel suppliers, including a tracking system with credit verification and trading and waiver provisions for small refineries. After the Energy Independence and Security Act of 2007, the EPA expanded the Renewable Fuel Standard (RFS2) in 2010 to require the annual use of 9 billion gallons of biofuels in 2008 and 36 billion gallons annually by 2022, of which no more than 15 billion gallons could be ethanol from corn starch, and no less than 16 billion could be from cellulosic biofuels. In addition, each qualifying biofuel would be required to achieve a minimum threshold of lifecycle GHG emission reductions, with some exceptions for existing facilities, as well as be produced from renewable biomass feedstocks<sup>49</sup>, subject to certain land use restrictions.

The schedule by which biofuel producers would be required to meet the standard is shown below.



SOURCE: CONGRESSIONAL RESEARCH SERVICE, JANUARY 2012. AVAILABLE AT [HTTP://WWW.NATIONALAGLAWCENTER.ORG/ASSETS/CRS/R40155.PDF](http://www.nationalaglawcenter.org/assets/crs/R40155.pdf).

<sup>49</sup> There are five categories of feedstocks: 1) crop residues (e.g. corn stover, wheat straw, rice straw, citrus residue), 2) forest material (e.g. eligible forest thinings and solid residue from forest product production), 3) secondary annual crops planted on existing cropland (e.g. winter cover crops), 4) separated food and yard waste (e.g. biogenic waste from food processing), and 5) perennial grasses (e.g. switchgrass and miscanthus).

The RFS has generated considerable debate, particularly on its requirement to incorporate direct and indirect land use in its GHG emissions assessment. Some environmental and academic groups argue that under these considerations, corn ethanol could not meet the GHG emissions requirement under RFS2. However, in a 2010 report, the EPA confirmed that based on existing technology, ethanol and biobutanol produced from corn starch, as well as biodiesel from various feedstocks, would all still comply with the RFS2 standards. Notably, plant facilities that existed or commenced construction prior to December 19, 2007 are exempt from the RFS2 lifecycle GHG emissions requirement.

**EISA-MANDATED REDUCTIONS IN LIFECYCLE GHG EMISSIONS BY BIOFUEL CATEGORY  
(PERCENT REDUCTIONS FROM 2005 BASELINE FOR GASOLINE OR DIESEL FUEL)**

<b>Biofuels category</b>	<b>Threshold reduction</b>
Renewable fuel <sup>a</sup>	20%
Advanced biofuels	50%
Biomass-based diesel	50%
Cellulosic biofuel	60%

SOURCE: CONGRESSIONAL RESEARCH SERVICE, JANUARY 2012. AVAILABLE AT [HTTP://WWW.NATIONALAGLAWCENTER.ORG/ASSETS/CRS/R40155.PDF](http://www.nationalaglawcenter.org/assets/CRS/R40155.PDF).

## The Open Fuel Standard

An open fuel standard is a broad-based mandate that requires original equipment manufacturers (“OEMs”) to manufacture vehicles capable of operating on a variety of fuels and fuel mixtures without the need for aftermarket adjustments. Requiring vehicle flexibility on OEM vehicles is intended to help facilitate consumer acceptance as well as ensure that they meet all applicable environmental emissions standards and certifications.

The Open Fuel Standard Act of 2011 provides one possible blueprint for an Open Fuel Standard. As proposed, the proposed legislation would require each OEM to manufacture a minimum proportion of vehicles meeting the standard, on a mandated schedule of:

- 50% qualified vehicles in model year 2014;
- 80% qualified vehicles in model year 2016; and
- 95% qualified vehicles in model year 2017 and each subsequent year.

The legislation defines a “qualified vehicle” broadly to include:

- A vehicle that operates solely on natural gas, hydrogen, or biodiesel;
- A flex-fuel vehicle capable of operating on gasoline, E85 and M85;
- A plug-in electric drive vehicle; or
- A vehicle propelled solely by fuel cell or by a technology other than an internal combustion engine.



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