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**THE EFFECTS OF USING NATURAL GAS IN LIGHT-DUTY VEHICLE
FLEET OF THE UNITED STATES ON ITS ENERGY DEPENDENCY AND
GREENHOUSE GAS EMISSIONS**

by

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Old Dominion University in Partial Fulfillment of the
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May 2016

Approved by:

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ABSTRACT

THE EFFECTS OF USING NATURAL GAS IN LIGHT-DUTY VEHICLE FLEET OF THE UNITED STATES ON ITS ENERGY DEPENDENCY AND GREENHOUSE GAS EMISSIONS

Nurullah Ayyılmaz
Old Dominion University, 2016
Director: Dr. Jesse T. Richman

Shale boom has changed the track of discussions on the future of the U.S. energy politics. A new opportunity emerged to meet domestic demand of the U.S. by using secure sources. Transportation accounts for a quarter of energy consumption in the U.S. Increasing the share of natural gas in the transport sector bolsters the U.S. energy security because of shifting from insecure sources (imported oil) to secure sources (shale gas reserves). Using natural gas instead of oil in light-duty vehicles (LDVs) contributes to the efforts of decreasing dependence on insecure sources and also decreases anthropogenic greenhouse gas (GHG) emissions caused by this segment of the transport sector. Natural gas vehicles (NGVs) have the conversion advantage compared to other alternative fuel vehicles; current LDVs can be converted to natural gas-fueled vehicles. Different than the other alternative fuel vehicle types, there is no need to wait to renew the current LDV fleet. This aspect of NGVs makes it possible for natural gas to provide a solution in the short to middle term. This study examines the extent to which using the abundant shale gas reserves of the U.S. as a fuel for the U.S. LDV fleet can contribute towards decreasing both its energy dependency and anthropogenic GHG emissions by using a system dynamics model and simulating it under four different scenarios.

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This thesis is dedicated to my father.

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My committee members were very helpful during my research. I am grateful to have them in my committee. Dr. Steve A. Yetiv's suggestion catalyzed me to focus on this important research question. I enjoyed studying the transport sector and its place in energy consumption, which has the potential of spreading to developing countries with an emerging middle-income class. Comments and recommendations of Dr. Mecit Cetin, the director of Transportation Research Institute at Old Dominion University, incited me to study the literature of a different discipline and to see different aspects on alternative fuel vehicles.

I am also indebted to the faculty of GPIS, my GPIS classmates, and Turkish friends at Old Dominion University, who have not only motivated and encouraged me to overcome this process but also shared their constructive criticisms, helped to refine some parts of the thesis, and read an entire early draft of this study.

Most importantly, the love and support of my immediate family encouraged me throughout this endeavor as well as throughout my life. None of this would be possible without their spiritual support, love, and encouragement.

NOMENCLATURE

APERC	Asia Pacific Energy Research Center
b/d	Barrel per day
bbl	Blue barrel (equivalent to 42 gallon of oil)
BEV	Battery Electric Vehicle
BTL	Biomass to liquid
CNG	Compressed Natural Gas
CNGV	Compressed Natural Gas Vehicle
CO ₂	Carbon Dioxide
CTL	Coal to liquid
FCEV	Fuel-Cell Electric Vehicle
FCHEV	Fuel-Cell Hybrid Electric Vehicle
GGE	Gasoline Gallon Equivalent
GHG	Greenhouse Gas
GWP	Global Warming Potential
HDV	High-Duty Vehicle
ICE	Internal Combustion Engine
IEA	International Energy Agency
IOC	International Oil Company
Km/h	Kilometer per hour
LDV	Light-Duty Vehicle
Mcf	Thousand cubic feet

mmBtu	Million British Thermal Unit
Mph	Mile per hour
NOC	National Oil Company
NGV	Natural Gas Vehicle
OECD	Organization for Economic Co-operation and Development
PHEV	Plug-in Hybrid Electric Vehicle
Tcf	Trillion cubic feet
U.S. DoE	United States Department of Energy
U.S. DoT	United States Department of Transportation
U.S. EIA	United States Energy Information Administration
U.S. EPA	United States Environment Protection Agency
VMT	Vehicle Miles Traveled
WTW	Well to Wheel

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CHAPTER I

INTRODUCTION

“For decades, Americans have been talking about how do we decrease our dependence on foreign oil... Now, a great place to start is with natural gas... Think about an America where more cars and trucks are running on domestic natural gas than on foreign oil...”

Barack Obama (26 January 2012)

Shale boom has changed the energy security understanding of the United States in the last decade. While the U.S. was projected to be increasingly “addicted to oil” before the shale boom, its vast reserves of shale oil and shale gas have decreased its energy dependency at an important rate. The U.S. is projected to be a net exporter of natural gas in 2017 and meet some amount of its domestic demand for oil with domestic oil resources thanks to the shale boom. These developments are important for the U.S. as the largest energy consumer until recently.

The U.S. has two main problems related to its energy consumption. First, it is dependent on foreign energy resources. Politicians talk about energy independency since the OPEC oil crisis in the 1970s. Yet, there has not been a significant development to solve this problem until the shale boom. Second, climate change effects force all countries to take measures against global warming. The U.S. has the potential of leading the solution of this problem as the global superpower. To be able to lead others, it should put its own house in order. This dilemma forces the U.S. to take action against climate change at the domestic level. The shale boom provides solutions for both of these problems.

The recently discovered shale oil and shale gas reserves can change the way energy is

used in the U.S. Instead of only replacing imported energy from foreign energy resources with domestic ones, it can help to switch to more reliable and cleaner energy sources. In this regard, shale gas provides important opportunities for the U.S. energy consumption. As a cleaner source of energy compared to oil, it can be used as a bridge fuel and be beneficial to replace oil consumption. Until more reliable energy sources become widely usable, it might help to some extent to switch towards these more reliable sources.

Transportation is one of the sectors that is heavily reliant on oil in the U.S. and can be replaced with alternative sources of energy. As a widely populated country, the U.S. consumes almost a quarter of its energy in the transport sector. Some prominent alternatives that can be used in transportation have been FCEVs, PHEVs, BEVs, and CNGVs. The automobile market started to be dominated by BEVs among all other available alternative fuel vehicles since they provide a long-term solution with the advantage of their batteries that can be charged with electricity generated from various sources. In the long run, it is a good way of getting rid of oil consumption in the transport sector. However, it cannot help in the short to middle term because of two chief reasons. First, the battery technology hinders its use by many people. It is expensive, does not sustain a large mileage, and requires a long time to charge. Although many commuters do not drive long distances in the U.S., they are concerned about these problems associated with the battery technology in BEVs. Second, it needs to replace the whole U.S. LDV fleet, which currently has an average lifetime of 11 years. If all new LDVs sold in the U.S. are BEVs, it will take 11 years to replace the vehicles that use gasoline and diesel. Given that its battery technology will need some more time to be saturated because any change in the battery requires a long time to test this change, it will take much more than 11 years to provide a solution for the U.S. transport sector.

Natural gas has the potential to provide a solution for the U.S. transport sector in the short to middle term. CNG is the form of natural gas that has a very high pressure and is used as a fuel for LDVs. The current gasoline- and diesel-fueled LDV fleet of the U.S. can be converted to CNGVs in a very short time. It can create an aggressive change in the whole U.S. LDV fleet at an important rate in a year if the political action is taken. There is no range anxiety for CNGVs. Conversely, it almost doubles a gasoline- or diesel-fueled vehicle's range because the converted vehicle becomes a bi-fuel vehicle and can be used both on CNG and on gasoline/diesel.

Literature Review

The extant literature in alternative fuel vehicle's place in the energy politics mostly focuses on two aspects of energy consumption as this master's thesis does; energy dependency and lifecycle GHG emissions. Kromer, Bandivadekar, and Evans¹ stress the importance of the transport sector to reduce GHG emission and energy consumption. Their study suggests improving near-term vehicle technologies, emphasizing low-carbon biofuels, de-carbonizing the electric grid, and reducing travel demand. Similarly, Kyle and Kim² examine the role of the transport sector with a focus on LDVs. They analyze five different vehicle technology scenarios: a reference ICE vehicle scenario, an advanced ICE vehicle scenario, and three alternative fuel vehicle scenarios for natural gas, hydrogen, and electricity. In their alternative fuel vehicle scenarios, all LDVs are assumed to switch to selected alternative fuel. The findings indicate that electric and hydrogen vehicles are better compared to advanced ICE vehicles and natural gas

¹ Kromer, Bandivadekar, and Evans, "Long-Term Greenhouse Gas Emission and Petroleum Reduction Goals."

² Kyle and Kim, "Long-Term Implications of Alternative Light-Duty Vehicle Technologies for Global Greenhouse Gas Emissions and Primary Energy Demands."

vehicles in the long term (by 2095). Offer et al³ consider a similar scenario for BEVs, FCEVs, and HEVs to find out their lifecycle vehicle costs with a 2030 projection. They find that FCHEVs will be the cheapest from the perspective of lifecycle vehicle costs in 2030. Bandivadekar et al⁴ emphasize the importance of demand reduction rather than promoting specific vehicle technologies and alternative fuels to reduce GHG emissions and energy use in transportation. Anderson et al⁵ examine what the effects of increased ethanol use might be in the U.S. energy independence. In a more comprehensive manner, McCollum and Yang⁶ consider a scenario with a 2050 projection. They investigate the potential to cut GHG emissions caused by the U.S. transport sector 50-80% below from 1990 levels by 2050. Their scenarios consist of some elements like increased efficiency, lower-carbon fuels, and travel demand management. They conclude that there is no “silver bullet” strategy for an aggressive reduction in GHG emissions, instead, a mixture of all strategies should be implemented. Their study is also important to conclude that LDVs offer the greatest potential for GHG emission reductions. Some other studies⁷ focus on the world’s leading energy consumer country, China, in order to see the effects of alternative fuel vehicle use on energy demand and GHG emissions.

Studies that focus on natural gas usage in the transport sector mostly focus on country cases. Von Rosenstiel, Heuermann, and Hüsigg⁸ focus on Germany to explore why the introduction of NGVs has failed in that country. Their answer is that the coordination failure in

³ Offer et al., “Comparative Analysis of Battery Electric, Hydrogen Fuel Cell and Hybrid Vehicles in a Future Sustainable Road Transport System.”

⁴ Bandivadekar et al., “Reducing the Fuel Use and Greenhouse Gas Emissions of the US Vehicle Fleet.”

⁵ Anderson et al., “Implications of the Energy Independence and Security Act of 2007 for the US Light-Duty Vehicle Fleet.”

⁶ McCollum and Yang, “Achieving Deep Reductions in US Transport Greenhouse Gas Emissions.”

⁷ Ou et al., “Life-Cycle Analysis on Energy Consumption and GHG Emission Intensities of Alternative Vehicle Fuels in China”; Ou, Zhang, and Chang, “Scenario Analysis on Alternative Fuel/vehicle for China’s Future Road Transport.”

⁸ von Rosenstiel, Heuermann, and Hüsigg, “Why Has the Introduction of Natural Gas Vehicles Failed in Germany?”

complementary markets, a monopoly of service stations at motorways, imperfect information, and bounded rationality of consumers have been the chief reasons of failure of NGVs in Germany. Wang et al⁹ look at the Chinese case to see how effective NGV policies are in China. They find that relatively low natural gas prices are the key to promoting NGV development. They suggest that middle-income and medium-sized cities are more appropriate for developing NGVs in China. Khan and Yasmin¹⁰ discuss how CNGVs have been successful in Pakistan and recommend some policy changes for further development in CNGVs. In their article, Khan, Yasmin, and Shakoor¹¹ discuss the viability of natural gas as a transportation fuel in the global scale. The indicators they use in their study are economic, emission performance, and safety aspect. Their results show that CNG has advantages over diesel and gasoline in respect to considerable emission and cost reductions.

There are also studies that focus on using natural gas in the U.S. transportation system. Spearrin and Triolo¹² examine what the role of natural gas might be in the U.S. with a modeling of over 40-year time horizon. They find that the current market penetration of natural gas both as HDV and LDV fuel is suboptimal. In a short policy brief, Mallapragada and Agrawal¹³ discuss the impact of using natural gas in the U.S. LDV fleet on the U.S. energy security. Similar to the argument of this research, they suggest using it as a transition solution until alternative renewable energy sources are developed in the long term. Kragha¹⁴ emphasizes the benefit of natural gas usage in transportation for the U.S. case in her study. Her findings indicate that

⁹ Wang et al., “Development of Natural Gas Vehicles in China.”

¹⁰ Khan and Yasmin, “Development of Natural Gas as a Vehicular Fuel in Pakistan.”

¹¹ Khan, Yasmin, and Shakoor, “Technical Overview of Compressed Natural Gas (CNG) as a Transportation Fuel.”

¹² Spearrin and Triolo, “Natural Gas-Based Transportation in the USA.”

¹³ Mallapragada and Agrawal, “Role of Natural Gas in America’s Energy Future.”

¹⁴ Kragha, “Economic Implications of Natural Gas Vehicle Technology in U.S. Private Automobile Transportation.”

NGVs will help to reduce GHG emissions, emission-based policies will help to stimulate the penetration of NGVs, and increased natural gas usage will lead to a decrease in oil imports. In a report that was prepared for the U.S. Department of Energy, Rood Werpy et al.¹⁵ examine an aggressive future market penetration of CNG-fueled HDVs and off-road vehicles and find that it will reduce U.S. daily oil consumption by 8% by 2030 with a 36% market penetration rate.

To sum up, the extant literature mostly focuses on the effects of alternative fuel vehicles on the GHG emissions reduction and energy independence. Some studies analyze these effects in the case of NGVs. This study contributes to the literature by focusing solely on the U.S. LDV fleet and simulating the case with a system dynamics model to see what the impacts of CNG usage in LDVs might be in the short to middle term with a projection of 2050.

The Synopsis of the Study

The argument of this master's thesis is that using the shale boom opportunity in the U.S. in its largest segment of the transportation sector, LDV fleet, provides benefits for the U.S. energy independence and the efforts of reducing GHG emissions. It will do so by substituting petroleum products for unconventional natural gas by converting the current gasoline- and diesel-fueled LDVs to CNGVs. The advantage of its ability to convert vehicles immediately makes CNGVs the best alternative fuel vehicle in the short to middle term as it can use the current LDV fleet in this paradigm shift. Most of the other alternative fuel vehicles require replacing the current fleet, which means even all new LDVs are sold as a type of alternative fuel vehicle. It will take the time equal to the average lifetime of the current LDVs to switch to this

¹⁵ Rood Werpy et al., "Natural Gas Vehicles."

alternative fuel. As will be elaborated in Chapter 4, BEVs are the best alternative fuel vehicles in the long term in many aspects. These include them having the cheapest price for a unit of energy, emitting the least lifecycle GHG emissions, and having an opportunity to generate their fuel from many sources. Even using natural gas in BEVs is much more efficient and emits much fewer GHG emissions compared to CNGVs. However, the current battery technology is the factor that needs to be developed more in order to make them widely available. And as mentioned above, even if all new LDVs are sold as BEVs, it will take the time equal to the average lifetime of LDVs to replace the current U.S. LDV fleet. This period of time is currently around 11 years.

This study uses a system dynamics model to answer the aforementioned research question. The system dynamics model is simulated under four different scenarios including one indicates no-conversion case. Some factors such as the GGE price of CNG, gallon price of gasoline, cost of CNG conversion, the number of CNG fueling stations, and incentivizing CNG conversion make these scenarios different from each other. The simulations are created based on different values given to these variables.

The study starts with an analysis of the U.S. energy security in Chapter 2. It lays out what the shale boom has changed about the U.S. energy security by discussing it in four parts; its availability from indigenous resources, the accessibility to the current energy resources, the acceptability of them by the public and environmental standards, and affordability in the market. It compares oil and natural gas according to these four criteria to see whether natural gas is advantageous compared to oil for the U.S. Chapter 3 discusses the share of the transport sector in the U.S. energy consumption and anthropogenic GHG emissions. It also lists the ways of reducing energy consumption and GHG emissions caused by LDVs in the U.S. Chapter 4 examines what role shale gas can play in the U.S. LDV fleet. It discusses the reasons natural gas

usage in transportation brings benefits in the short to middle term and why BEVs as the most prominent alternative fuel vehicle type, cannot provide the expected benefits in the short to middle term. Chapter 5 designs a system dynamics model to see what the impact of natural gas usage in LDVs in the U.S. can be on different variables including GHG emissions, the amount of natural gas used by the LDV fleet, and the amount of oil used by the LDV fleet by 2050. It gives the simulation results according to four different scenarios, including one scenario of no-conversion case.

CHAPTER II

RETHINKING THE U.S. ENERGY SECURITY AFTER THE U.S. SHALE BOOM

Introduction

The U.S. shale boom is a tectonic shift in global energy politics. The U.S., as an important consumer of petroleum products in the world since it consumes 20% of the total world consumption, was projected to be dependent on foreign energy resources for its energy consumption before its shale boom. Today, it is expected to be more self-sufficient.

This chapter aims to redefine the U.S. energy security after the shale boom by comparing the contribution of oil and natural gas to the U.S. energy security. There are three reasons why this chapter will compare only these two energy sources. First, the U.S. shale boom will cause an increase in oil and natural gas production in the U.S. It is estimated to contribute to the production in an important rate. Second, these two fossil fuels are two leading energy sources, accounting for 63% of the whole U.S. energy consumption in 2014. The current situation indicates that the U.S. is more reliant on these two energy sources much more than others. Third, this research focuses on shifting an important amount of energy consumption in a segment of transportation from oil to natural gas. Therefore, discussing their comparative advantages against each other will provide a big picture of how energy secure the U.S. is with these sources. Doing so will also help to explain the extent to which the U.S. will be more advantageous by shifting towards using more natural gas.

This chapter will first discuss different energy security definitions, then redefine the U.S. energy security after the shale boom, using the most comprehensive energy security definition. APERC's 4A's will be used to assess the U.S. energy security after its shale boom.

Discussion of Energy Security Definitions

Energy security is a buzzword in energy politics literature. Although it is widely used, there is not a commonly accepted definition. The usual definition of energy security for the developed world is “simply the availability of sufficient supplies at affordable prices”¹ while in developing countries the main concern is based on how the change in energy prices affects their balance of payments². The vast majority of the studies define it for their specific purposes, depending on some factors like energy type and region that the study examines. For instance, two studies that examine the European natural gas supply security and the U.S. oil security might have two very different energy security definitions. Another reason for differing definitions is that the concept has transformed over time. Some factors like political conflict, unexpected natural disasters, and energy-related terrorism concerns are accepted within the definition of energy security. Climate change concerns are another factor that did not exist in the former definitions, but started to be a part of the definition in the latest ones. This chapter reviews how the concept of energy security has transformed over time and picks one definition that covers all current aspects of the term in a parsimonious way. It does this to find out to the extent to which the U.S. shale boom has transformed the understanding of its energy security.

The first discussion of energy security began with Winston Churchill’s decision to use oil in the Royal Navy instead of coal. His decision was criticized because it was felt that it was dangerous to depend on Persia. Churchill’s response to these critics has become the very first rule of the energy security: diversification. In the parliament of July 1913 he said, “On no one

¹ Yergin, “Ensuring Energy Security,” 70.

² Ibid., 71.

quality, on no one process, on no one country, on no one route, and on no one field must we dependent”.³

The primary question of energy security occurred after the 1973 Arab Oil Embargo: how could the developed world handle energy supply disruptions? Oil importer countries realized that they needed to find ways to handle disruptions of oil supply from producer countries after the Arab oil suppliers cut supplies to show their commodity’s power. “Energy independence” discussions came to the scene with this embargo. The U.S. president Richard Nixon pledged to provide energy self-sufficiency for the U.S. so that the country would have its energy independence by the end of the 1970s. In his address to the nation on November 7, 1973, President Nixon said:

Now, even before war broke out in the Middle East, these prospective shortages were the subject of intensive discussions among members of my Administration, leaders of the Congress, Governors, mayors, and other groups. From these discussions has emerged a broad agreement that we, as a nation, must now set upon a new course. In the short run, this course means that we must use less energy--that means less heat, less electricity, less gasoline. In the long run, it means that we must develop new sources of energy which will give us the capacity to meet our needs without relying on any foreign nation.⁴

Overall, Nixon’s speech indicates that he meant self-sufficiency with energy independence. However, the definition of energy security is beyond self-sufficiency today.

In 1974, the club of developed countries of the world, the OECD, founded the IEA in the wake of the 1973 oil crisis. Although its primary goal is to bolster the energy security of its members, the IEA also works with other countries such as China, India, and Russia. The most

³ Yergin, *The Quest*, 265.

⁴ Peters and Woolley, “Richard Nixon: Address to the Nation About Policies To Deal With the Energy Shortages.”

important role of the IEA for energy security is that it requires its members to hold at least 90 days of their daily net imports of the previous year, which is like a 90-day insurance for oil-importing countries in case of an oil supply disruption⁵. One of the main missions of the IEA is to coordinate the sharing of these oil reserves among the member countries. Its roles have developed over time and are currently defined in four main areas: energy security, economic development, environmental awareness, and engagement worldwide⁶. As one of its four focus areas, the IEA adopts the classical definition of energy security: “uninterrupted availability of energy sources at an affordable price”⁷.

In academic studies, the term is mostly considered as the security of energy supply. One of the very early studies on energy security, put forward by Lubell in 1961, uses ‘security of supply’ instead of ‘energy security’, which is widely used in contemporary studies to refer to the same concept. He evaluates the political implications of shifting from coal to oil in West Europe and points out the threats of depending on the Persian Gulf for oil demand⁸. Bohi and Toman take energy security in the context of economics in their book. They define energy security as “the loss of economic welfare that may occur as a result of a change in the price or availability of energy”⁹. The common point of these two studies is considering energy security as a problem of continuous supply of energy.

Increasing demand from the developing world and the peak oil discussions, which have been considered as a risk for energy supply security, caused the re-emergence of energy security discussions. These had declined in the late 1980s and in the 1990s after stabilizing oil prices and

⁵ The International Energy Agency, “Energy Supply Security 2014,” 22.

⁶ The International Energy Agency, “IEA - What We Do.”

⁷ The International Energy Agency, “IEA - Energy Security.”

⁸ Lubell, “Security of Supply and Energy Policy in Western Europe.”

⁹ Bohi and Toman, *The Economics of Energy Security*.

lessening the political embargo threat. China and India are the leading countries that have an increasing trend in energy consumption. China's breaking point in liquid fuels consumption was in September 2013 when China's net imports of petroleum and other liquid fuels exceeded the U.S. and made the country the largest net importer of oil in the world¹⁰. Although China's energy demand is expected to increase slowly until 2040, the rest of the world with the exception of the OECD countries is estimated to have an almost 70% increase in its energy demand by 2040¹¹. Even though the OECD countries are expected to maintain their demand level, they will have to compete against an enormously increasing demand from the developing countries. In other words, their energy supply security will be more at risk than today.

Peak oil discussions are another major part of increasing energy supply security risk. Michael Klare¹² argues that "resource depletion" will make it inevitable to face the end of fossil fuels because of increasing demand. Since fossil fuels are non-renewable and finite resources, they will end despite the discovery of new reserves. He uses the data that show that most of the biggest oil fields have peaked in their annual output more than two decades ago¹³. But Yergin reminds us that the peak oil discussions have been there for a long time and defenders of peak oil had to postpone the projected date of peak each time when their projected date came without any "peak"¹⁴. The content of this study confirms Yergin's views because its main argument is based on an unprojected discovery of an energy source. A decade ago, the U.S. was projected to meet its natural gas demand with imports. But fracturing technology and horizontal drilling made the

¹⁰ U.S. Energy Information Administration, "China Is Now the World's Largest Net Importer of Petroleum and Other Liquid Fuels."

¹¹ U.S. Energy Information Administration, "WEO 2014 - Presentation to the Press."

¹² Klare, *The Race for What's Left*.

¹³ *Ibid.*, 32.

¹⁴ Yergin, *The Quest*, 227–240.

shale gas resources available, which are considered as unavailable a decade ago. These technological developments contributed to postponing the date of “peak oil” one more time for the U.S. case.

It is true that the world will run out of finite resources sometime in the future if the demand keeps increasing. But the efforts at shifting towards renewables and less-carbon energy types indicate that the world will quit using oil before the energy resources run out. This supports a quote of a former Saudi Arabian oil minister that was expressed almost three decades ago: “The stone age did not end for lack of stone, and the Oil Age will end long before the world runs out of oil”¹⁵. Nuttall and Manz’s study¹⁶, in which they consider a scenario that climate change effects impact the world far earlier than expected, supports former Saudi Arabian oil minister’s quote. They argue that, in the case of a closer impact of climate change than its expected time, the peak in demand for fossil fuels will occur before the peak in supply since countries will make more efforts to shift towards clean energy alternatives. The key to shift clean energy sources is having an earlier alarm of climate change effects in their study.

Some studies take energy security as an instance of security like, military security, economic security, and human security. Therefore, they address the same questions asked to frame other security fields. Cherp and Jewell¹⁷ argue that Baldwin’s security definition, “low probability of damage to acquired values”¹⁸, can be applied to energy security. Therefore, they address Baldwin’s three questions of security to the energy security concept: security for whom, for which values, from what threats. Similarly, von Hippel et al.¹⁹ suggest three security

¹⁵ “The End of the Oil Age.”

¹⁶ Nuttall and Manz, “A New Energy Security Paradigm for the Twenty-First Century.”

¹⁷ Cherp and Jewell, “The Concept of Energy Security.”

¹⁸ Baldwin, “The Concept of Security.”

¹⁹ von Hippel et al., “Energy Security and Sustainability in Northeast Asia.”

questions in order to frame energy security: what to protect, what risks to be protected from, and how to protect. The only difference between these two approaches is while Cherp and Jewell are raising ‘security for which values?’ question, von Hippel et al. ask the ‘how to protect’ question as their third questions.

The discussions on energy security that are examined until this point are mostly based on energy supply security. But does energy security solely mean energy supply security? As mentioned above both in Yergin’s definition and the IEA’s definition that are accepted as the classical definition of energy security, the common ground for the definition is “the availability of sufficient supplies at affordable prices”²⁰. Defining the term in its historical context gives a definition that has supply security at its core. Over time, the concerns about energy usage have gone beyond the supply. Aforestated some studies approach energy security from a security perspective and consider it as a security issue. Most importantly, there is an additional dimension, which covers the term on a higher level than the national level. While it has mostly been considered on national level until recently, adding an environment dimension has raised the discussions to the global level.

Studies that review various energy security definitions indicate that there is an increase in the inclusion of environment into definitions. Ang et al.’s review study²¹, which covers 104 energy security-related studies published between 2001 and 2014, finds that the environment was included as a dimension of definition in 31 out of 83 studies that have energy security definition. There is a 37% increase from the first half (2001 to 2007) to the second half (2008 to 2014) of their time period in the proportion of definitions that add the environment as a dimension in the

²⁰ Yergin, “Ensuring Energy Security,” 70.

²¹ Ang, Choong, and Ng, “Energy Security.”

definition.

Von Hippel et al.²² argue that energy security is beyond the current understanding of the term as well as considering it as a security issue. They acknowledge that national energy policies, associated solely with energy supply security, face some challenges such as the need to protect the environment, risks associated with technological development and deployment, managing the demand-side of energy planning, concerns associated with social-cultural factors raised against energy policies, and emerging intersections of energy security and military security in some points like the international politics of plutonium fuel cycle development.

In his study on the U.S. shale boom, Yetiv²³ covers new dimensions of energy security in his oil security definition. His simple definition consists of three aspects: achieving reasonable oil prices, securing oil supply from severe disruptions, and negative consequences of oil consumption. The third aspect takes the definition beyond the classical definitions and adds some negative effects of oil usage like pollution, global terrorism, and domestic or international conflicts.

Rethinking the U.S. Energy Security According to 4 A's of Energy Security

One of the most recent definitions of energy security, widely discussed in the literature and this study will benefit from, was introduced by APERC in 2007. APERC lists 4 A's of energy security in its definition: availability, accessibility, affordability, and acceptability. It offers three fundamental elements for energy security: physical energy security, economic

²² von Hippel et al., "Energy Security and Sustainability in Northeast Asia."

²³ Yetiv, *Myths of the Oil Boom*.

energy security, and environmental sustainability²⁴. Their well-known 4 A's can be categorized as availability and accessibility within physical energy security, affordability within economic energy security and acceptability within environmental sustainability.

The following part of this chapter will further explain what it is meant with 4 A's and place the U.S. shale gas boom case in the context of U.S. energy security according to the APERC's 4 A's of energy security definition. The effects of the recent discoveries of unconventional natural gas and oil resources will be elaborated by examining the case from the perspective of availability, accessibility, acceptability, and affordability of energy sources by comparing two energy types. These two energy types will be two major fossil fuels: oil and natural gas. Oil is significant because it is the most consumed U.S. energy source. Natural gas is important to compare against oil because a significant amount has been accessible after the U.S. shale gas boom and it is the most feasible energy source for switching from oil to cleaner energy sources. While acknowledging that renewable energy sources are a much better option in many respects for U.S. energy security, these will be excluded from this study. This is because the focus of this chapter is the effects of the U.S. shale boom on the U.S. energy security.

Availability

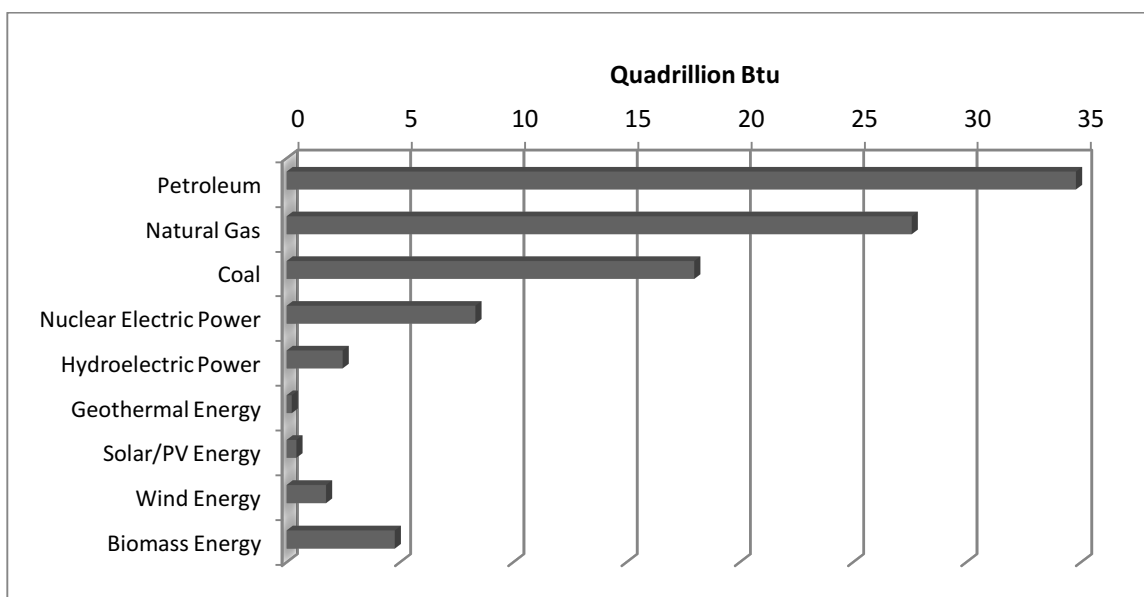
Energy security depends in part on the domestic availability of consumed energy sources. Availability refers to geological availability and simply means enough supply from domestic resources. In this section, the availability of oil and natural gas will be compared to assess whether it is advantageous to shift towards natural gas. Reserve to production (R/P) ratio will be

²⁴ Asia Pacific Energy Research Centre, *A Quest for Energy Security in the 21st Century*, 6.

used to measure how many years each energy source is projected to be available for energy supply.

Oil is the most consumed energy source in the U.S. as it has been in all other modern economies for decades. This makes its availability vital for many consumer countries. In 2014, the U.S. consumed 34.88 quadrillion Btu equivalent petroleum products, which was 35% of overall U.S. energy consumption²⁵. Chart 1 illustrates that it has the largest proportion among all energy sources. Together with natural gas and coal, all fossil fuels met the 81.6% of all U.S. energy consumption in 2014²⁶.

Chart 1: U.S. Primary Energy Consumption by Source in 2014



Source: Created by the author with the data drawn from the U.S. Energy Information Administration, 2015²⁷

While coal is widely distributed in the world, petroleum and natural gas resources are

²⁵ U.S. Energy Information Administration, “Monthly Energy Review December 2015,” 7.

²⁶ Ibid.

²⁷ Ibid.

clustered in some regions. The Persian Gulf is the biggest source of petroleum products. Accordingly, the countries in this region are the largest oil suppliers for many developed countries. Although the case is not valid for the U.S. since it imports the largest amount from its neighboring countries, the Persian Gulf countries are still an important source for the U.S. energy consumption.

There is a change in the oil self-sufficiency of the U.S. Once it was an important importer country of oil products. After the shale boom however, it has been projected to be a swing-producer of oil. This means that it has the ability to increase or decrease global oil prices by cutting or increasing production²⁸. According to the U.S. EIA projections, U.S. crude oil production will reach 10,002 thousand b/d in 2017.²⁹ This is slightly higher than Saudi Arabia's crude oil production in 2013, which was 9,637 thousand b/d.³⁰ The production volume will remain around 10,000 thousand b/d until 2025, the last year of the report's projected timeframe.

The U.S. is estimated to have 222,592 million barrels of crude oil resources.³¹ 36,520 million barrels of these resources are proved crude oil reserves as of 2013.³² If the production remains around 10,000 thousand b/d after 2025, as it is projected for years from 2017 to 2025 by the U.S. EIA, reserves will be produced 61 years with the current total technically recoverable crude oil amount³³. In other words, the U.S. will be able to produce the same amount of crude oil until 2074. On the other hand, the proven crude oil reserves of Saudi Arabia, the largest daily producer of crude oil, are 265,789 million barrels.³⁴ Venezuela has the largest amount of proven

²⁸ See Yetiv, *Myths of the Oil Boom*.

²⁹ U.S. Energy Information Administration, "U.S. Crude Oil Production to 2025."

³⁰ OPEC, "OPEC Annual Statistical Bulletin 2014," 8.

³¹ U.S. Energy Information Administration, "Technically Recoverable Shale Oil and Shale Gas Resources," 8.

³² U.S. Energy Information Administration, "U.S. Crude Oil and Natural Gas Proved Reserves, 2013," 25.

³³ It is calculated by dividing U.S. proven crude oil reserves into projected daily production and 365.4 to get the number of years. $(222,592,000,000/10,000,000/365.4=60.92)$

³⁴ OPEC, "OPEC Annual Statistical Bulletin 2014," 8.

crude oil reserves with 298,350 million barrels, although its production is 2,789 b/d.³⁵ It means that even if the U.S. exceeds the production amount of the largest producer of crude oil, Saudi Arabia, its resources will run out earlier than Saudi Arabia and Venezuela if they do not increase their daily production in an important rate.

The consumption of petroleum and other liquids in the U.S. was 18.96 million b/d in 2013³⁶. If the U.S. produces almost 10 million b/d, it will need foreign sources for almost half of its daily consumption. Therefore, continuing to use the same amount of oil will not help the U.S. from the availability perspective since the U.S. will still be dependent on the foreign supply of oil for half of its consumption.

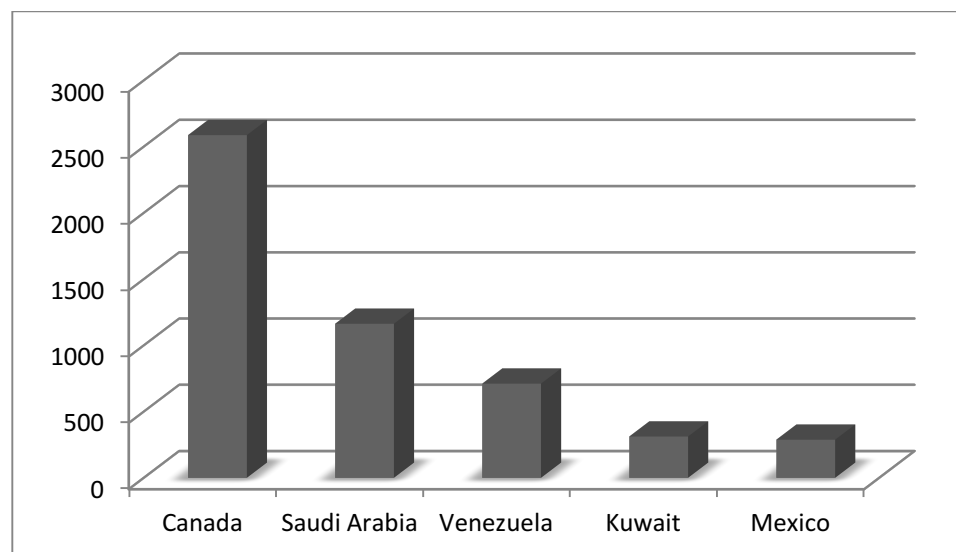
In the list of foreign suppliers of oil to the U.S. illustrated in Chart 2, Canada comes first with 2,586 thousand b/d in 2014. This is contrary to the common wisdom that the U.S. imports most of its oil from the Persian Gulf countries, mainly Saudi Arabia. Saudi Arabia is the second-largest net exporter of oil to the U.S. with a number slightly less than half of Canada's supply, 1,162 thousand b/d.³⁷

³⁵ Ibid.

³⁶ U.S. Energy Information Administration, "Annual Energy Outlook 2015."

³⁷ U.S. Energy Information Administration, "Net Imports of Oil into the U.S. by Country."

Chart 2: U.S. Net Imports of Total Crude Oil and Products by Country in 2014 (thousand b/d)



Source: Created by the author with the data drawn from the U.S. Energy Information Administration, 2015³⁸

The data until here indicate that the U.S. domestic oil production is expected to meet domestic consumption for almost 61 years with some amount of imports. When it is taken into account that the U.S. oil production will be increasing, the U.S. oil consumption is projected to be at the same level from 2013 through 2040³⁹ and the U.S. total consumption of petroleum and other liquids was 19,050 thousand b/d in 2014⁴⁰. The U.S. will need to import approximately 1.7 million b/d less after 2018. This indicates that it may choose to not import any oil from the Persian Gulf in near term. Although it provides energy supply security for the U.S. to some extent since it will have the option of importing from more reliable suppliers, it does not make the U.S. energy independent. Projections on the production of crude oil reserves show the U.S. will not be self-sufficient in oil consumption even though it has an important amount of crude oil

³⁸ Ibid.

³⁹ U.S. Energy Information Administration, "Annual Energy Outlook 2015," 15.

⁴⁰ U.S. Energy Information Administration, "How Much Oil Is Consumed in the United States? - FAQ."

resources.

As for natural gas, the U.S. has a significant advantage. As Chart 1 illustrates above, natural gas accounts for 28.0% of all U.S. energy consumption in 2014. It comes right after petroleum products with a difference of 7.3%. Natural gas production in the U.S. increased by 44%⁴¹ from 2005 to 2014 while the natural gas consumption increased 21.8%⁴² in the same time interval. The production increased faster than the consumption. The difference in these growth rates caused a decrease in net imports of natural gas.

Natural gas consumption is increasingly based on domestic resources, meaning increasing independence in consumption. While domestic production increases at an important rate, net imports decrease significantly. After peaking in 2007 in all years from 1970 to 2014 for which years statistical data of natural gas imports and exports are available, net imports of natural gas are decreasing every year. Total net imports of natural gas decreased 68.8% from 2007 to 2014⁴³. While there is a 62.8% decrease in pipeline natural gas imports, which comes solely from Canada, liquefied form of natural gas decreased 94.0% from 2007 through 2014.⁴⁴ It means that the U.S. prefers one reliable supplier, Canada instead of diversifying suppliers. Until the end of 2014, the U.S. could not succeed in its quest to be self-sufficient in natural gas consumption.

Future projections of natural gas indicate that there will be 73% increase in shale gas production in the lower 48 states of the U.S. from 11.3 Tcf in 2013 to 19.6 Tcf in 2040⁴⁵. This increase is expected to contribute as a 45% increase in total U.S. dry natural gas production,

⁴¹ U.S. Energy Information Administration, "U.S. Natural Gas Marketed Production."

⁴² U.S. Energy Information Administration, "U.S. Natural Gas Total Consumption."

⁴³ U.S. Energy Information Administration, "U.S. Natural Gas Imports by Country."

⁴⁴ Ibid.; U.S. Energy Information Administration, "U.S. Natural Gas Exports and Re-Exports by Country," -.

⁴⁵ U.S. Energy Information Administration, "Annual Energy Outlook 2015," 20.

from 24.4 Tcf in 2013 to 35.5 Tcf in 2040⁴⁶. Import and export projections foresee that the U.S. net imports of natural gas will convert into net exports in 2017 after which net exports will be increasing every year until the end of the projection, 2040 in all four cases: low oil price, reference, high oil price, and high oil and gas resource cases. Net exports are expected to be mainly driven by LNG exports to overseas. After LNG exports reach their highest level in 2030, the projected growth slows down but still continues increasing steadily. The U.S. is expected to reach the highest volume of net exports of natural gas with 5.6 Tcf in 2040. While it still goes on relying on Canada as a reliable pipeline natural gas supplier until 2040, the projected volume of imported natural gas decreases. Another net importer of natural gas, Mexico becomes an important market for the U.S. with growing from 0.7 Tcf in 2013 to 3.0 Tcf in 2040 in the reference case of the Annual Energy Outlook 2015.⁴⁷

Total technically recoverable dry natural gas resources of the U.S. are estimated to be 2,266 Tcf as of January 1, 2012.⁴⁸ This data includes all proved and unproved reserves of natural gas. Proved reserves consisted of 354 Tcf (16% of total) in 2013 with setting a new record.⁴⁹ As stated above, projections on natural gas production foresee a 45% increase from 24.4 Tcf in 2013 to 35.5 Tcf in 2040, meaning a 1.4% increase per annum.⁵⁰ If the production keeps increasing at the same rate, the aggregate total production will be pretty close to the total technically recoverable dry natural gas resources of the U.S. by the end of 2072. In other words, the U.S. will be self-sufficient in natural gas until 2072 and also a net exporter after 2017.

In sum, the U.S. has an important advantage in the availability of both the most

⁴⁶ Ibid.

⁴⁷ Ibid., 21–22.

⁴⁸ U.S. Energy Information Administration, “Oil and Gas Supply Module,” 115.

⁴⁹ U.S. Energy Information Administration, “U.S. Crude Oil and Natural Gas Proved Reserves, 2013,” 10.

⁵⁰ U.S. Energy Information Administration, “Annual Energy Outlook 2015,” 20.

consumed energy source, crude oil and the energy source that this study focuses on, natural gas. Shale boom contribute to the U.S. energy independence in a significant way. The latest data on total technically recoverable resources of crude oil and natural gas indicate that crude oil can be produced until 2074 while it is 2072 for natural gas. However, an important point is that the oil consumption gives us an insight that the U.S. will still be dependent on foreign oil resources even having a significant amount of crude oil resources. It is expected that the U.S. will import almost the same amount of oil production from abroad. In other words, domestic oil resources will meet half of oil consumption. For the natural gas case, the U.S. is expected to be a net exporter of natural gas after 2017. It means the U.S. will be completely independent in its natural gas consumption until 2072. To sum up, the availability perspective tells the U.S. is in a better position in natural gas consumption until 2072.

Accessibility

Accessibility of available resources is another important dimension of physical energy security. APERC uses “challenge” word to define it, mentioning difficulties to reach current energy resources⁵¹. Reaching existing resources may be challenging because of various reasons. For instance, shale oil and shale gas resources were inaccessible before the developments in hydraulic fracturing. Fracturing is an instance of technology challenge of accessibility. APERC admits other accessibility challenges as well. These include geopolitical factors, geographical constraints, workforce constraints, development of pipeline network systems, and safety constraints⁵². Those challenges are mainly for fossil fuel resources. Renewable energy types have

⁵¹ Asia Pacific Energy Research Centre, *A Quest for Energy Security in the 21st Century*, 19.

⁵² *Ibid.*, 19–23.

different main challenges. APERC lists them as financial subsidization, policy push and market pull, and technology transfer from other developed economies⁵³. For the sake of parsimony, this study does not include accessibility challenges of renewable energy types. It only evaluates the challenges of oil and natural gas. It also excludes workforce constraints and safety constraints since their challenges do not differ too much for these two energy types.

The most important challenge was accessing the available fossil fuel resources. An important amount of U.S. natural resources was inaccessible because of technical difficulties a decade ago. Three technological developments contributed to the U.S. access: seismic imaging, horizontal drilling, and hydraulic fracturing. Developments in seismic imaging technology helped energy companies to discover energy-rich fields. Better estimation of energy-rich fields helped them to make investments in the right place. Horizontal drilling technology made it possible to drill fossil fuel resources which are laid down parallel to the ground. Formerly, it was not possible to reach them due to having only vertical drilling technology. Last, hydraulic fracturing made it possible to fracture underground rocks, which have fossil fuels inside or under them. Water is used to get fossil fuels of these rocks to the ground. Shale boom had its name from these underground rocks. These three technological developments have reduced accessibility constraints for the U.S.

Geopolitical factors are one of the most important accessibility problems for the world but not necessarily for the U.S. Oil is unevenly distributed in the world. Some regions have much more oil than others. The Middle East is the leading source of oil with 47.7% of the global oil reserves. South and Central America follows the Middle East with 19.4% thanks to the oil

⁵³ Ibid., 24–25.

reserves of Venezuela which holds 17.5% of the world's oil reserves.⁵⁴ Geopolitical distribution of oil is for NOCs and against IOCs. According to Ernst & Young's *Global Oil and Gas Reserves Study*, half of the top 20 oil companies listed according to their proven oil reserves are NOCs. Their share of oil reserves is 56% while IOCs have 44% of proven oil reserves of the top 20 oil companies.⁵⁵

NOCs and IOCs' operation purposes have some differences although both have a main aim of extracting oil. IOCs focus on returns and profit margins when making a decision on investments while NOCs may have some other agendas such as national energy independence, social effects of oil extraction, economic and environmental sustainability of their proven reserves. While IOCs are hungry for new oil reserves, NOCs need the technology mostly developed by IOCs.⁵⁶ IOCs do not cause a threat to the continuity of oil supplies for importer countries, as private companies' main concern is profitability. They are not likely to cut supplies in order to punish some importers as practiced in oil crisis in the 1970s by NOCs.

The U.S. does not have state-owned companies in the energy sector as a free-market-driven economy. Private companies operate all oil fields in the country and import necessary amount of energy or export surplus of production. Oil and natural gas reserves of the leading supplier country of the U.S., Canada, are also operated by privately-held companies. 51.3% of total U.S. oil imports are supplied by Canada. Almost all other suppliers' energy reserves are run by NOCs, which take another half of the total oil imports of the U.S.⁵⁷ Considering increasing independence of the U.S., it can be safely concluded that the U.S. does not have a serious threat

⁵⁴ BP, "BP Statistical Review of World Energy 2015," 6.

⁵⁵ Ernst & Young, "Global Oil and Gas Reserves Study 2014," 23–26.

⁵⁶ Asia Pacific Energy Research Centre, *A Quest for Energy Security in the 21st Century*, 19.

⁵⁷ U.S. Energy Information Administration, "Net Imports of Oil into the U.S. by Country."

in geopolitical availability of oil since as a rational actor it would prefer not keeping less reliable suppliers which are NOCs in this case.

As for natural gas, geopolitical factors have not had global effects until recently. There were regional natural gas markets connected by pipelines. This situation has kept security threats related to natural gas on a regional level. Importer countries have been dependent on exporter countries since natural gas requires a pipeline construction. Natural gas sale agreements have been long term agreements, at around 30 years. With an increasing number of liquefaction and de-liquefaction facilities around the world, natural gas is also becoming a global commodity like oil. The U.S. does not have a serious geopolitical threat to its supplies because it imports only 10.05% of its total natural gas consumption as of 2014.⁵⁸ The U.S. is strengthening its advantageous position in natural gas. It had an important advantage after the shale boom. As mentioned in availability section, the U.S. is projected to shift from the buyer position to the seller position of natural gas with positive values in net exports after 2017. There will not be any threat coming from foreign suppliers of natural gas for the U.S. indicating that there is no geopolitical threat in the foreseeable future.

Although the U.S. is not expected to have serious geopolitical accessibility barriers to reach the vast majority of its resources, there are some geopolitical limitations of extraction for some of its reserves. They are mostly based on weaknesses of international law in determining maritime boundaries. Geopolitical accessibility of some offshore oil and gas resources have still been discussed. The Arctic Region is the most discussed offshore resource of the U.S. that currently has geopolitical limitations. This is because outside of the U.S., it is being contested by

⁵⁸ Net imports of natural gas in 2014 were divided by total consumption of natural gas in the U.S. in 2014. (26,818,618 / 2,695,378 = 10.05%)

other countries such as Russia, Canada, and Denmark. According to a report of the U.S. Geological Survey, the Arctic region holds 13% of the world's undiscovered conventional oil resources (90 billion barrels) and 30% of its undiscovered conventional natural gas resources (1,668,658 billion cubic feet)⁵⁹. These reserves are getting accessible once ices melt in the Arctic. When they become completely accessible, the resources of this region will play an important role in both oil and natural gas production in the world.

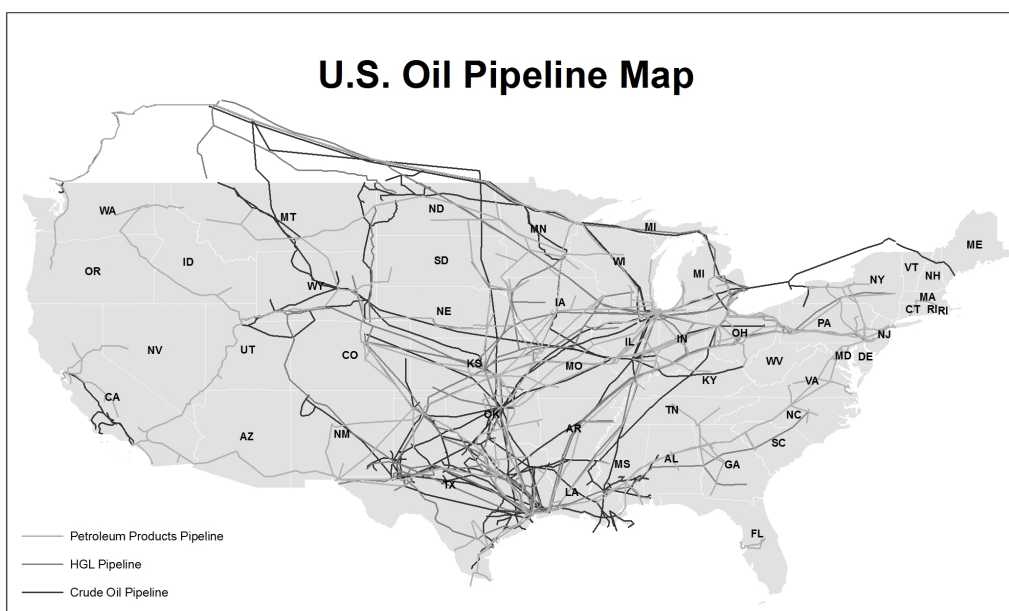
The debates on the Arctic Region started with a Russian submarine's operation to put a Russian flag in the deep ocean in the Arctic in 2007.⁶⁰ Since then, debates of territorial ownership are still continuing as each country claims it has the right to have territory in this region and extract fossil fuel resources. Once the ices melt, 13% of the world's conventional oil reserves and 30% of the world's conventional natural gas reserves will be available for producers. The amount that the U.S. will have at the end of debates will show how much of these reserves will be accessible for it to produce and so contribute to its energy security.

As for pipeline network, both oil and natural gas have widely distributed pipeline network systems in the U.S. But, since almost all natural gas is distributed via pipeline, it has an advantageous position compared to oil. Having households and industrial companies as its end-users makes natural gas much more easily accessible. Figure 1 and Figure 2 indicate that natural gas' pipeline web is densely distributed in many regions of the U.S. while the oil pipeline network has a sparse distribution throughout the lower 48 states. Both oil and natural gas pipelines are clustered in some states like Oklahoma, Texas, and Louisiana since these states are either the source or import center of energy sources.

⁵⁹ Bird et al., "Circum-Arctic Resource Appraisal."

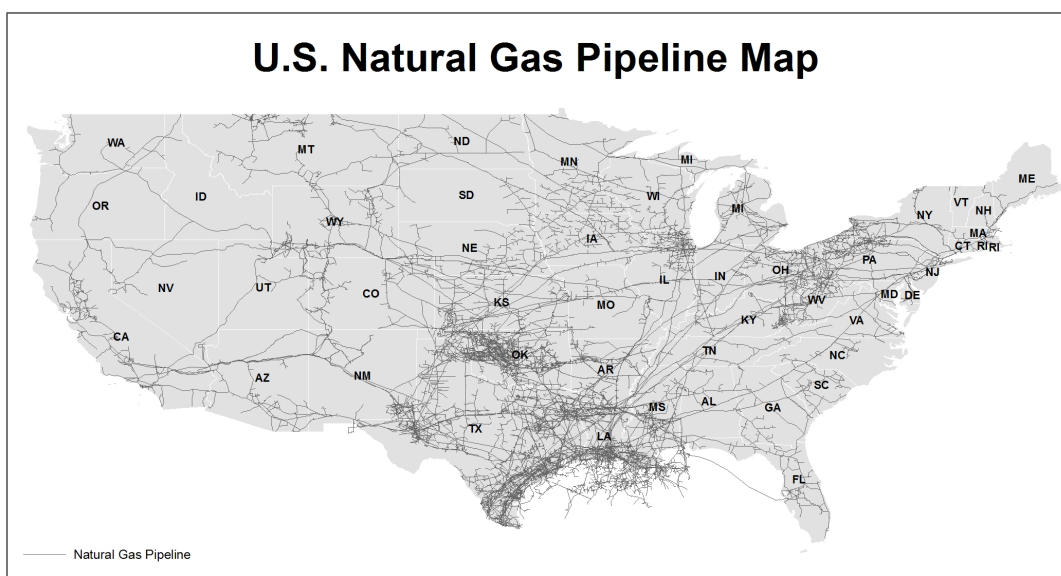
⁶⁰ Chivers, "Russians Plant Flag on the Arctic Seabed."

Figure 1: U.S. Oil Pipeline Map



Source: Created by the author with using shapefile data from the EIA⁶¹ and the U.S. Census Bureau⁶²

Figure 2: U.S. Interstate and Intrastate Natural Gas Pipeline Map



Source: Created by the author with using shapefile data from the EIA⁶³ and the U.S. Census Bureau⁶⁴

In conclusion, technological developments in horizontal drilling, hydraulic fracturing,

and seismic imaging made an important amount of fossil fuel resources accessible in the U.S. which were once thought inaccessible. These technological developments can be considered as a milestone for overcoming accessibility challenges to U.S. energy security, resulting in increased forecasts of both oil and natural gas production. As for geopolitical accessibility challenges, the U.S. does not have a serious challenge for both energy sources. Most of the world is at risk because of relying on oil-importers whose energy resources are operated by NOCs. The fact that the U.S. imports almost half of its oil resources from Canada, where energy business is run by IOCs, and its oil dependency on foreign nations is expected to decrease over years, indicate that the U.S. will not have a serious geopolitical accessibility threat for oil. It is even more advantaged in natural gas as it currently imports only 10% of its domestic consumption and is expected to be a net exporter of the commodity after 2017. The pipeline network system also puts natural gas in an advantageous position compared to oil. Since it is an energy type that is distributed to its end-users via pipelines, it is in an advantageous position compared to oil in pipeline aspect. In short, the accessibility component of U.S. energy security suggests natural gas consumption.

Acceptability

APERC's definition of acceptability indicates solely environmental sustainability⁶⁵.

Another widely cited definition of 4 A's, which broadens APERC's definition covers societal

⁶¹ U.S. Energy Information Administration, "Layers Information for Interactive State Maps."

⁶² U.S. Census Bureau, "Cartographic Boundary Shapefiles - States."

⁶³ U.S. Energy Information Administration, "Layers Information for Interactive State Maps."

⁶⁴ U.S. Census Bureau, "Cartographic Boundary Shapefiles - States."

⁶⁵ Asia Pacific Energy Research Centre, *A Quest for Energy Security in the 21st Century*, 27–33.

acceptability as well⁶⁶. Since many studies in the literature prefer using this broadened definition, acceptability is generally regarded as including these two dimensions. Societal acceptability can be defined as how an energy type is welcomed by the society. The environmental aspect is easier to analyze than societal aspects since it entails quantitative findings with which different energy types can be compared. Environmental acceptability will include some other energy types and their values do not only represent the U.S. as being global impacts of energy consumption.

Societal acceptability of an energy type depends on its benefit, harm and perception in the society. Societal benefits include new job opportunities, development in the neighborhood of energy facilities while harmful sides might be some negative effects like environmental harm to the area around the energy facilities. For instance, people are concerned about contamination effects of hydraulic fracturing technology on drinking waters in the U.S. This contamination effect, if there is, is both a societal and an environmental harm of shale gas and shale oil technology. Such societal effects related to the environment will be elaborated more within environmental acceptability.

Perception is an important part of societal acceptance. If people perceive something as a threat to their life quality, they oppose it and become likely to participate in activism events to prevent it from happening. For instance, an Oscar-nominated documentary *Gasland*, which tells the stories of neighborhood members of shale oil and gas facilities that are affected by hydraulic fracturing, is an important factor in the U.S. public perception on hydraulic fracturing. According to a recent study, *Gasland* affected the public perception on hydraulic fracturing both at the national and local level. At the local level, people who are close to the hydraulic fracturing facilities are more likely to participate in activism events. At the national level, people became

⁶⁶ Kruyt et al., “Indicators for Energy Security.”

more interested in facts related to hydraulic fracturing after the documentary was released and nominated for an Oscar award⁶⁷.

The power of business coalitions and the position of energy companies in the U.S. economy are indicators that their effects on societal acceptability might be bigger in order to protect their profits. Sadly, there is not any study on the role of energy companies in the U.S. public diplomacy towards societal acceptability of energy sources. A study's findings indicate how business coalitions' efforts are effective in the U.S. to implement policies that will affect their profits negatively. The study focuses on environmental regulations that might decrease companies' profitability since these regulations require them to implement some environment-friendly energy policies⁶⁸. This study's findings signal that they might be working in the same way for the perception management towards societal acceptability of energy types. In that regard, U.S. oil companies might be supporting anti-shale gas campaigns and natural gas companies might be supporting pro-shale gas campaigns both in political and societal life and vice versa.

The lack of enough study in the field of societal acceptability of energy types and the difficulty of comparing these different energy sources' societal acceptability make it hard to find out which energy type is the more accepted one by the American society. Therefore, societal acceptability has no tangible conclusion for the comparison of oil and natural gas.

Environmental concerns make up the other half of acceptability. Energy types have different harmful outcomes for the environment. Contamination of air, contamination of underground water resources, and contamination of soil are some important parts of these

⁶⁷ Vasi et al., "'No Fracking Way!' Documentary Film, Discursive Opportunity, and Local Opposition against Hydraulic Fracturing in the United States, 2010 to 2013."

⁶⁸ Meckling, "The Globalization of Carbon Trading."

harmful effects. In environmental studies, the most prominent harmful effect is air contamination, which is studied under the topic of climate change. This part will firstly compare GHG emission outputs of shale gas, natural gas, oil, and coal and then discuss some other environmental concerns regarding shale gas. It aims to provide a better picture of different energy types in the context of environmental sustainability.

The most important factor in environmental concerns is air contamination. It is measured according to GHG emission values of different energy types. There are six main GHGs that mostly contribute to the pollution. The list according to the abundance in the atmosphere is as follows: water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3) and chlorofluorocarbons (CFCs)⁶⁹.

There are various methods of calculating the GHG emission values of energy sources. Some studies calculate it according to the outputs that occur in the process of combustion such as powering a vehicle to travel or generating electricity from the fuel. This method does not give the actual results since fuels cause significant amounts of GHG emissions in other processes as well as in production. To be able to see the complete picture of GHG outputs, this study will not only look at GHG emissions occurred by the combustion of fuel. Instead, it will look at the whole process of production, which is called life-cycle GHG emissions or global warming potential. It includes all GHG emissions from the beginning, which is the extraction of energy source, until the end, the usage of it by the end user. For instance, 3.6% to 7.9% of the major component of natural gas CH_4 escapes to the atmosphere in the production phase. The global warming potential of CH_4 is far greater than CO_2 , which is estimated to be 28 to 36 times of

⁶⁹ U.S. Environmental Protection Agency, “Greenhouse Gas Overview.”

global warming potential of CO₂ over 100 years⁷⁰. Therefore, gas flare devices are used in the production sites to prevent natural gas from escaping to the atmosphere⁷¹. They convert methane to CO₂ by flaring since CO₂ has less GHG emission value. With the exception of the combustion phase of the natural gas life-cycle analysis, the key parameters can be listed as: CH₄ emissions from well completion and workovers (venting), liquid unloadings (venting), well equipment (leakage and venting), processing (leakage and venting), and transmission and distribution (leakage and venting), and CO₂ emissions from well equipment (CO₂ from flaring and venting) and processing (CO₂ from venting)⁷².

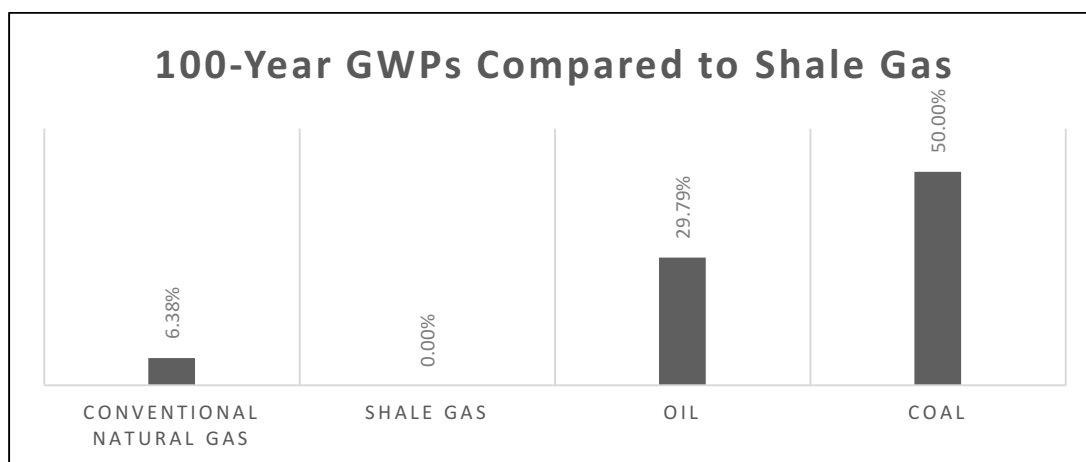
As for GWP, Burnham et al.⁷³ use three different measures which vary according to their end-use; per-mega joule of fuel burned, per-kWh of electricity produced and per-kilometer driven for transportation services. Per-mega joule values of natural gas, shale gas, oil, and coal will be used to compare them in this chapter. Their study estimates GWPs in two time periods of 100 years and 20 years. This study will use 100-year values to understand their effects in the long run.

⁷⁰ U.S. Environmental Protection Agency, "Understanding Global Warming Potentials."

⁷¹ Howarth, Santoro, and Ingraffea, "Methane and the Greenhouse-Gas Footprint of Natural Gas from Shale Formations."

⁷² Burnham et al., "Life-Cycle Greenhouse Gas Emissions of Shale Gas, Natural Gas, Coal, and Petroleum," 621.

⁷³ Burnham et al., "Life-Cycle Greenhouse Gas Emissions of Shale Gas, Natural Gas, Coal, and Petroleum."

Chart 3: 100-year GWPs of Four Energy Types Compared to Shale Gas

Source: Compiled by the author with the data drawn from Burnham et. al's study ⁷⁴

Different studies have very different estimates for the same calculations. This study uses Burnham et al.'s findings which were generated in a well-known laboratory in emission measurements, which is Argonne National Laboratory. Their findings indicate that the GWP of three energy types compared to shale gas are as follows: conventional natural gas is 6% higher, oil is 30% higher, and coal is 50% higher than shale gas. As Chart 3 illustrates, shale gas is the most environmentally acceptable according to the lifetime GHG emissions.

Shale gas production is related to some other environmental concerns as well. Some of these concerns are local air pollution, water consumption in the production phase, water quality in the fracturing areas, induced seismicity, and some other community impacts⁷⁵. The most discussed one of these concerns has been the one that argues that hydraulic fracturing method causes contamination of water resources. There have been many scientific studies about this concern. Accordingly, many news pieces have covered the issue presenting the outcomes of

⁷⁴ Ibid.

⁷⁵ Clark et al., "Hydraulic Fracturing and Shale Gas Production."

these studies and public concerns. Some studies contend that hydraulic fracturing causes gas leaks into the underground water⁷⁶, while some others argue that there is no causal relationship between hydraulic fracturing and water contamination⁷⁷. Among those reports that say there is no causal relationship between the factors, EPA's report has been the latest one, which published as a draft copy after 4 years of study. The report says that EPA "did not find evidence that these mechanisms have led to widespread, systemic impacts on drinking water resources in the United States"⁷⁸. EPA's 4-year study looks like helped to conclude the discussions on whether hydraulic fracturing causes water contamination⁷⁹.

To sum up, this part of the study has compared mainly oil and shale gas from the acceptability perspective. Acceptability was regarded as societal and environmental acceptability. In regards to societal acceptability part, there is an opposition against shale gas mostly because of its local and global environmental impacts, which is mainly driven by some tools such as the documentary *Gasland* that have significant effect on public opinion. The environmental acceptability section examined the two most important environmental effects of shale gas: GHG emissions and water contamination. GWP measurements indicate shale gas has a better position compared to conventional natural gas, oil, and coal according to GHG emission measurements. EPA's landmark report indicates hydraulic fracturing does not cause widespread,

⁷⁶ Llewellyn et al., "Evaluating a Groundwater Supply Contamination Incident Attributed to Marcellus Shale Gas Development."

⁷⁷ Darrach et al., "Noble Gases Identify the Mechanisms of Fugitive Gas Contamination in Drinking-Water Wells Overlying the Marcellus and Barnett Shales"; Hammack et al., "An Evaluation of Fracture Growth and Gas/Fluid Migration as Horizontal Marcellus Shale Gas Wells Are Hydraulically Fractured in Greene County, Pennsylvania"; U.S. Environmental Protection Agency, "Assessment of the Potential Impacts of Hydraulic Fracturing for Oil and Gas on Drinking Water Resources (External Review Draft)."

⁷⁸ U.S. Environmental Protection Agency, "Assessment of the Potential Impacts of Hydraulic Fracturing for Oil and Gas on Drinking Water Resources (External Review Draft)," ES-23.

⁷⁹ The search in New York Times' archive showed that there has not been a news article in New York Times website focuses on the relationship between hydraulic fracturing and water contamination since the draft of EPA's study published on June 2015 till the date of this part of this study concluded on September 28, 2015.

systemic impacts on drinking water resources, which helped to end the discussion on this concern.

Affordability

The only economic element of APERC's energy security definition is affordability. It is about the ability to meet the economic cost of energy. This section will examine how affordable oil and natural gas are for the U.S. Looking at them from the economic perspective lays out two distinctions. First, their situation in the global trade is different. Natural gas has local market prices while oil has a unique global price since it is a globally traded commodity. Therefore, states might be able to affect natural gas prices while they cannot do the same for oil unless they are one of the major producers of oil. Second, North American natural gas consumers pay the lowest price among other regions, which makes it a cheaper substitute of oil for the North Americans.

Oil is a Global Commodity

Oil is a global commodity with a unique price in the entire world. A significant decrease in supply or a significant increase in demand of this commodity causes an increase in the price of oil on a global level. One of these possibilities is more predictable. The demand side increases incrementally with a foreseeable future projection. For instance, current projections show that by 2035, Asia-Pacific's energy demand will increase by over 67%.⁸⁰ Other countries that will face the challenges of rising Asian demand have enough time to implement policies to counter the

⁸⁰ Calculated over 2.1% annual increase between 2010 and 2035 from Doi and Asian Development Bank, *Energy Outlook for Asia and the Pacific*, X.

effects of increasing demand. On the other side of the coin, there is supply part of this global commodity, which plays the key role in short-term price changes. Short-term price changes are crucial for developed countries because they directly affect markets since oil is the main energy source for many industries. As discussed in the energy security section, the world has experienced the effects of supply disruptions in the OPEC oil crisis in the first half of the 1970s. Declining supply caused severe problems in many developed countries. It was quite unexpected by the developed world and the first power demonstration by the suppliers. OPEC countries showed to the developed countries that their supply of oil is very critical to their industry's stability.

In addition to aiming to increase the oil prices as in the OPEC oil crisis, major suppliers may also attempt to lower prices. For instance, Saudi Arabia, as swing producer of oil, did not cut production in the mid-2010s in order to “protect market share, which was threatened by a variety of developments, including the American oil boom, and possible overproduction of oil by other big oil producers.”⁸¹ Although increasing prices will be better in the short term for Saudi Arabia, its long term interests are better off with low oil prices for a few years. This is in order to prevent new oil producers from entering the market.

Like any other developed country, the U.S. has also been affected by the fluctuation in oil prices. High oil prices cause the same effect as would be in any developed country; increase the cost of production abruptly. Low prices have the reverse effect on industry; they decrease the production cost which is definitely a desirable outcome for developed countries. When we look at in detail, low oil prices have some other side effects in developed countries.

The IEA member countries have to keep at least 90-fold of their daily oil consumption.

⁸¹ Yetiv, *Myths of the Oil Boom*, 18.

This is like an insurance against the shock of increasing prices at least for 90 days. But they don't have any protection against decreasing oil prices in case it hurts some aspects of their economies. In the U.S. case, low oil's negative impacts may come from two roles of the U.S. in global oil market: a reemerging swing producer and being the second major consumer of oil in the world. Because of low prices, in the long run, people may tend to consume more oil. Shale companies may also oppose instituting smart regulations which aim at promoting the healthy production of shale in the U.S. Since these regulations will hurt their profitability more under low oil prices, the U.S. economy might lose some job opportunities as an oil producing country. A decrease in oil production, and change of OPEC's balancer role after decreasing its spare capacity that is used in times of price changes might lead a volatility in oil prices⁸².

Oil prices may fluctuate based on attitudes of major producers. They may increase prices in the near future once it starts hurting swing producers. The crucial point about this commodity is that no one country has power to act alone. It means even if the U.S. becomes self-sufficient with its increased level of oil production, it will not be able to unilaterally determine oil prices, neither in the world nor within its own borders.

Natural Gas is a Local Commodity

Due to its physical condition, natural gas has different characteristics in the world market compared to oil. The infeasibility of natural gas' transportation is an important distinction between these two commodities. Oil can be transported in ships because of being in liquid form whereas natural gas's gaseous nature makes it difficult to transport overseas. This feasibility

⁸² Bordoff, "The Promise and Peril of Cheap Oil."

concern made natural gas transported solely via pipelines in underground and under the sea. Oceans have been the major constraint for the shipment of this commodity, since they are not feasible for a pipeline transportation. Therefore, natural gas markets emerged as regional markets in three far away continents; OECD Europe, North America, and Japan/South Korea. Their source of natural gas has been Norway, Russia, and Algeria; Canada and Mexico; and Indonesia, Australia, Malaysia and the Middle East⁸³ with some changes over the last years due to some big developments such as U.S. shale boom. U.S. shale boom made the U.S. the leading source of natural gas in North America.

In recent years, some changes about the storage of natural gas made it global to some extent but not completely like oil. Liquefaction, which reduces the volume of natural gas by about 600 times and makes it more efficient to transport via ships was a milestone for the natural gas trade. Especially in the last decade, two major developments led the construction of many liquefaction and deliquefaction facilities around the world: Europe's policy towards diversifying energy sources to not to be dependent on Russian natural gas and profitable Asian markets under the high oil prices. As a result of these facility constructions, world LNG trade has peaked to 50% in the total natural gas trade in 2014⁸⁴ up from 35% in 2005⁸⁵. It is an important development in the way of making natural gas a global commodity but it is still far from the status of oil. The increase in the volume of global trade does not make it a global commodity since there is not a unique price in the world markets. For instance, the U.S. people paid almost one-fourth of what Japanese paid and half of what the British and Germans paid in 2014⁸⁶.

⁸³ Siliverstovs et al., "International Market Integration for Natural Gas?"

⁸⁴ BP, "BP Statistical Review of World Energy 2015," 29.

⁸⁵ BP, "BP Statistical Review of World Energy 2006," 30.

⁸⁶ BP, "BP Statistical Review of World Energy 2015," 27.

Pricing shows clearly that even if it consisted half of global trade, liquefaction did not change its characteristic as regional commodity.

Except the normal conditions for price changes, there are some exogenous variables that affect prices in the short term. These variables include weather, inventories, hurricanes and other seasonal factors. Although many studies ignore the effects of these factors, Hartley et al.⁸⁷ and Brown and Yücel⁸⁸ find that they are affecting the natural gas prices in the short term. Even though they do not test these variables for oil price, they might be affecting oil prices as well to some extent. Due to global and regional market price differences between oil and natural gas, oil might be affected by these exogenous variables to a lesser extent, but they still have an effect. Hurricane Katrina, which caused severe destruction in one of major oil hubs of the U.S., affected the price of petroleum products in the U.S. in 2005.

To sum up, the comparison of natural gas and oil from the affordability perspective encourages preferring natural gas over oil in the U.S. The main reason is their difference as a global or regional commodity. Controlling the price of natural gas is much easier than controlling oil prices since the latter has a globally determined price. Second, natural gas is much cheaper than oil in the U.S. as a substitute fuel. The North American natural gas price is the lowest one in the world.

Conclusion

This chapter reviewed many different energy security definitions. The discussions of this term began in 1913 when Winston Churchill, then as the First Lord of the Admiralty, decided to

⁸⁷ Hartley, III, and Rosthal, "The Relationship of Natural Gas to Oil Prices."

⁸⁸ Brown and Yücel, "What Drives Natural Gas Prices?"

convert the battleships from coal to oil. His decision was criticized that it would make the country dependent on Persia. His speech, which indicates the diversification of supply from variety of sources, is the first to mention energy security. The salience of energy security term started with the first oil shock in 1973. When the Arab members of the OPEC declared an oil embargo, its results affected not only the developed countries but also all other countries because of global interdependence. One of the important outcomes of this first oil shock has been the foundation of the IEA by the OECD member countries. The major contribution of the IEA to the energy security of its members has been the 90-day insurance against oil supply disruptions.

Energy security is mostly used to refer energy supply continuity in political discourses. Initial definitions in academic studies have also adopted the same understanding. They first accepted it as the problem of continuous supply of energy. Peak oil discussions can be considered within this category since it is also related to the problem of continuous supply of energy. These discussions however, are inconclusive since the proponents of peak oil discussions need to postpone the peak date each time due to the developments in energy extraction technology or the developments in energy resources.

Overtime, the concept's definition in academic studies has widened. Some studies consider energy security as an instance of security like military security, human security, etc. They argue that the questions that are asked for other security issues should be directed to energy cases to define energy security. Some recent studies consider the environmental aspects of energy consumption within the energy security term. The trend of including environmental concerns into the definition is associated with the increase in global warming discussions. APERC's definition of 4 A's of energy security reflects one element of this broadened understanding of the definition. It suggests defining energy security according to four

perspectives: availability, accessibility, acceptability and affordability.

As for energy security, this chapter compared the most consumed energy type of the U.S., oil, with natural gas which has been a new opportunity for the U.S. after the shale boom. APERC's definition of 4 A's is used to evaluate oil and natural gas according to their availability, accessibility, acceptability and affordability.

Availability, which simply means geological availability of energy sources from domestic resources, shows that the current total technically recoverable crude oil will be enough for domestic production until 2074 given that the oil production will remain at around 10,000 thousand b/d until that time. Also the U.S. will still rely on foreign resources for almost half of its oil consumption and will have the ability to opt out importing oil from the Persian Gulf countries. Natural gas projections show that the U.S. will be self-sufficient in natural gas production after 2017, in which it is estimated to become a net exporter of natural gas, and the production will be able to continue until 2071.

Accessibility, which is simply defined as the challenges to reach available resources, is examined from the perspective of geopolitical factors, geographical constraints, and development of pipeline network systems. The technological developments in horizontal drilling, hydraulic fracturing, and seismic imaging, which are three important causes of the U.S. shale boom, helped to access oil and natural gas resources more. The geopolitical factors indicate that the U.S. will be in an advantageous position in oil since it will have the option of not relying on NOCs and it will be even more advantaged in natural gas since it will need all domestic consumption with domestic production. The pipeline network system also makes natural gas advantageous because it already has a wider distribution network than oil since it is transported to end-user via pipelines.

Acceptability has two dimensions; societal acceptability and environmental sustainability. The societal acceptability section concluded that it is not possible to measure societal acceptability easily since it does not entail quantitative values. A recent study showed that public perception is an important factor in societal acceptability of energy sources. The environmental sustainability section concluded that conventional natural gas has 6% higher, oil has 30% higher, and coal has 50% higher GWP than shale gas, compared using their life-cycle GHG emissions in a 100-year period.

Affordability is defined as the the ability to meet the economic cost of energy source. This section emphasized how prices are determined rather than comparing their current or projected prices. Price comparison makes natural gas better off because the same amount of energy can be produced with natural gas cheaper than oil in most sectors. The fact that oil is a global commodity and natural gas is a regional commodity is an important distinction in how their prices are determined. Depending on oil might cause unexpected outcomes for the U.S. since its price is mostly determined by swing producers while the U.S. can be a determiner of the North American regional price of natural gas since its price does not depend on total global production.

The comparison of oil and natural gas according to the 4 A's of energy security definition suggests using natural gas for the U.S. It will be better off switching to natural gas in many sectors. The next chapter will look at the place of transportation among many sectors in the U.S. oil consumption.

CHAPTER III
THE IMPACTS OF LDVS ON THE U.S. ENERGY CONSUMPTION AND GHG
EMISSIONS AND WAYS OF REDUCING THESE IMPACTS

Introduction

Transportation has a significant place in energy consumption and GHG emissions both in the world and in the U.S. As a widely populated country, the values for the U.S. are slightly higher than the world statistics in both GHG emissions and energy consumption. This chapter analyzes the share of transportation in GHG emissions and energy consumptions both at the global level and the U.S. domestic level. Then, it looks at the share of LDVs within the U.S. transport sector according to their energy consumption. Last, it lays out the ways of reducing oil consumption in the transport sector. It lists improving fuel efficiency, improving operation practices, reducing travel demand by car, and fuel switching as the ways of reducing oil consumption and emphasizes that they are not alternatives to each other. They can and should be implemented all together.

The Share of Oil Consumption within the Transport Sector's Energy Consumption and GHG Emissions

The U.S. will be better off reducing oil consumption and shifting towards natural gas when both of these energy sources are compared as elaborated in the previous chapter. Decreasing foreign oil dependence of the U.S. by decreasing its consumption will not only change the U.S. energy security but also will have implications at the global level for energy politics since oil is a globally-traded commodity. Oil's share in the transport sector has an

important place in the U.S. Therefore, any change in the transport sector's energy consumption will directly affect the total U.S. oil consumption. This section will look at the share of oil in total energy consumption and anthropogenic GHG emissions both at the global level and at the U.S. level.

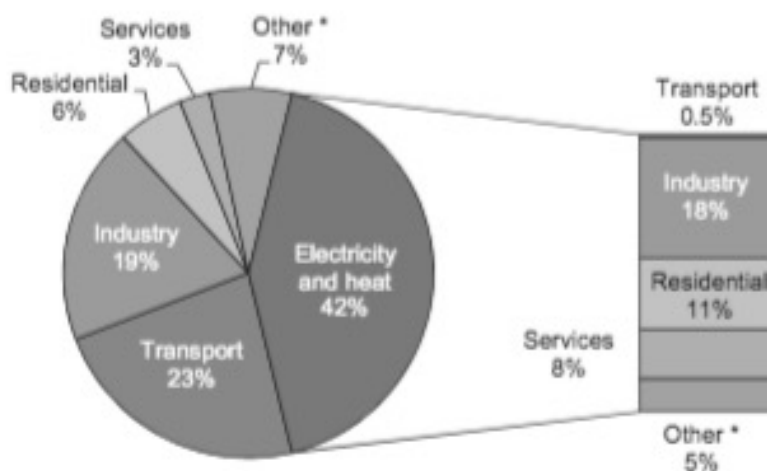
In the world, the highest share of oil consumption belongs to transport sector. In 2013, 63.8% of oil was demanded by the transport sector¹. Looking from another perspective, the transport sector's share was 19% of world total energy consumption in 2013 and 93% of this demand was met with oil.² Therefore, any global-level policy change in the transport sector will aim more than three-fifths of the oil consumption globally. Given that 60% of world's population is expected to live in urban areas by 2035, which is up from 50% today³, it is inevitable that people's transport demand will increase. This means a growing share of the transport sector in total world energy consumption and accordingly an increase in oil's consumption in the world if there is not a significant change to decrease transport sector's growth or oil's share.

¹ The International Energy Agency, "2015 Key World Energy Statistics," 33.

² Ibid., 37.

³ The International Energy Agency, "World Energy Outlook 2012," 348.

Figure 3: World CO₂ Emission by Sector in 2013



Source: International Energy Agency, 2015⁴

As parallel to transport sector's share in global energy consumption, it has a big share in anthropogenic GHG emissions. Energy consumption causes two-thirds of global GHG emission, and 90% comes from CO₂ emissions⁵. As illustrated in Figure 3, the transport sector accounts for 23% of total global CO₂ emissions in 2013. Almost all of it comes from oil consumption with an exception of 3% from natural gas and less than 1% from coal combustion⁶. In sum, oil's role as a transport fuel in total anthropogenic GHG emissions accounts for almost 13% of global GHG output. Shifting towards cleaner energy sources in transportation is able to change 13% of GHG emissions at the global level.

The U.S. has almost the same trend with the world in the share of transport sector in oil consumption. 70% of petroleum products were consumed in transportation in 2014⁷. Looking

⁴ The International Energy Agency, "CO₂ Emissions from Fuel Combustion," 10.

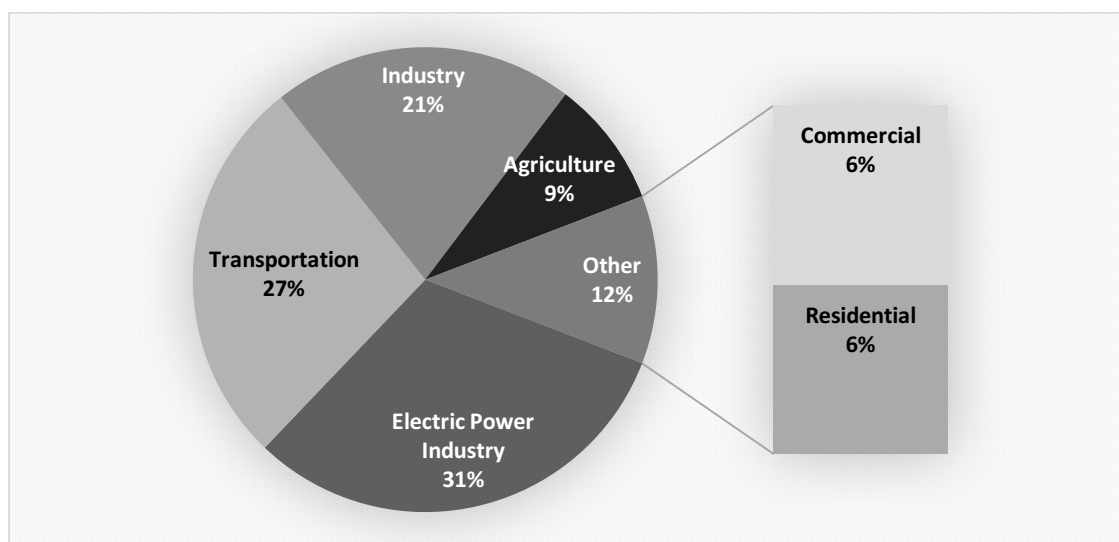
⁵ Ibid., 7.

⁶ Ibid., 127.

⁷ U.S. Energy Information Administration, "Monthly Energy Review December 2015," 64.

from the other perspective, 28% of the consumed energy belongs to the transport sector⁸ and 92% of the transport sector used oil as total primary energy source⁹ in 2014. It means that any policy change in transport sector will aim a quarter of energy consumption in the U.S. The EIA estimates that transportation's share will be slightly lower than today's value in 2040 after peaking in somewhere in the second half of the 2010s and then decreasing until somewhere between 2030 and 2035, then again having slightly increases until 2040¹⁰. The EIA argues that Corporate Average Fuel Economy (CAFE) standards and GHG emission standards are the main drivers of this slight decrease in the middle term.

Figure 4: U.S. Greenhouse Gas Emissions by Sectors



Source: Created by the author with the data drawn from the U.S. Environmental Protection Agency¹¹

GHG emissions caused by the transport sector in the U.S. is roughly a quarter of total

⁸ Ibid., 29.

⁹ Ibid., 37.

¹⁰ U.S. Energy Information Administration, "Annual Energy Outlook 2015," 10.

¹¹ U.S. Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks," ES-22.

GHG emissions, accordingly with the share of the transport sector in total energy consumption. As shown in Figure 4 above, the transport sector accounted for 27% of total GHG emissions in the U.S. in 2013¹². To the best of my knowledge, there is no publication that differentiates GHG emissions caused by the transport sector according to fuel types in the U.S. The share of petroleum products can be used to give a basic understanding of how much of this amount was created by oil. In 2014, 92% of the transport sector's energy demand was met with petroleum products¹³. Therefore, any policy change towards cleaner energy sources in the U.S. transport sector is able to eliminate roughly 25% of the total anthropogenic GHG emissions.

The most important takeaway from this section is that the transport sector is heavily dependent on oil products both at the global and U.S. national levels, with a percentage higher than 90% at both levels. Any policy change regarding transportation will directly affect oil consumption and anthropogenic GHG emissions. At the global level, policy changes in the transport sector will address 18% of total energy consumption while this percentage is 26% for the U.S. Its impact on GHG emissions will be the ability to lower 13% of anthropogenic GHG emissions in the world and a quarter of anthropogenic GHG emissions in the U.S. This shows how critical the transport sector is in energy politics, affecting an important amount of energy consumption and consequently, of anthropogenic GHG emissions in the global level. It plays even a more important role for U.S. energy consumption and anthropogenic GHG emissions.

The Share of Light-Duty Vehicles in U.S. Energy Consumption

The previous section showed the importance of transportation in the consumption of

¹² Ibid.

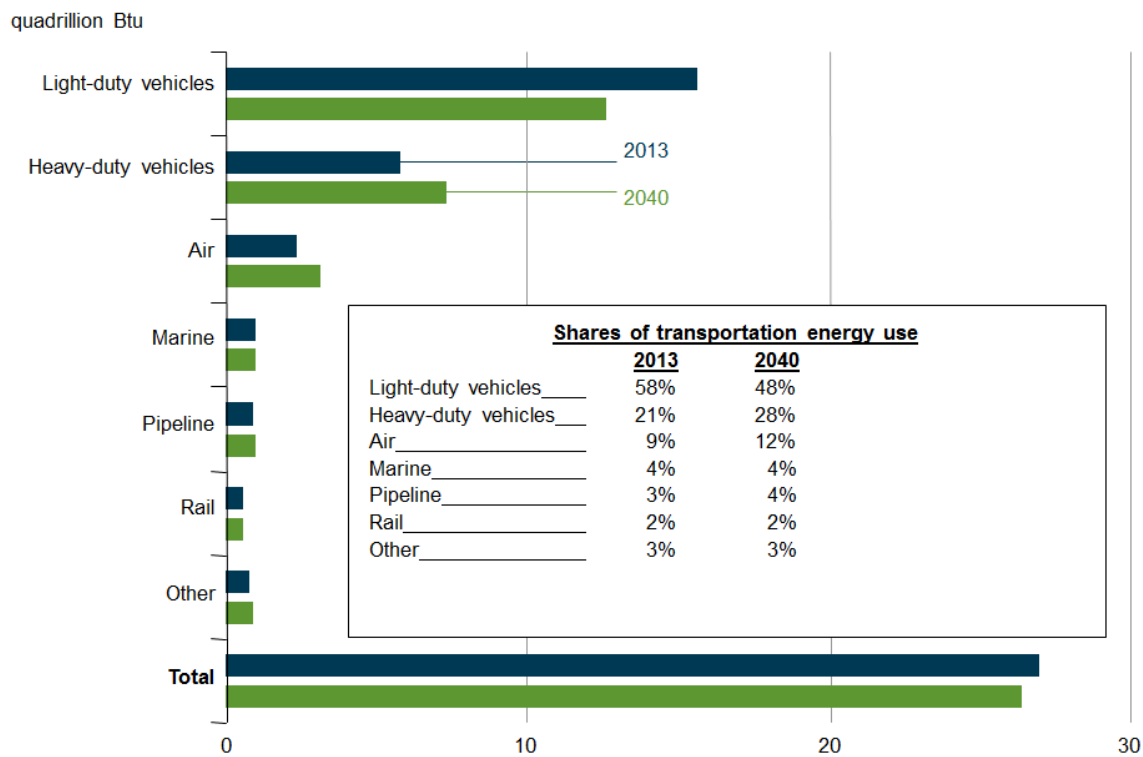
¹³ U.S. Energy Information Administration, "Monthly Energy Review December 2015," 37.

energy sources and the production of anthropogenic GHG emissions. The U.S. data compared to the world was presented. Transportation modes and their share in energy consumption will be elaborated in this section.

As a widely populated country, the highest energy consumption share within the transport sector of the U.S. belongs to individual commuters. LDVs, which are the vehicles whose gross vehicle weight rating (GVWR) is 8,500 pounds or less, account for 58% of energy consumption in the U.S. transport sector. The EIA projects a 10% decrease by 2040 in LDVs' share in the U.S. energy consumption¹⁴. Even factoring this 10% decrease, individual commuters' share within the transport sector's energy consumption still hold an important percentage. Considering the current share of LDVs in the transport sector, any change in the LDVs will have an impact on 58% of the transportation sector's energy consumption. In a broader picture, it will have an impact on 13% of the whole U.S. energy consumption.

¹⁴ U.S. Energy Information Administration, "Annual Energy Outlook 2015," 10.

Figure 5: Energy Use in the Transport Sector by mode in the Reference case, 2013 and 2040 (projected)



Source: Annual Energy Outlook 2015¹⁵

In the U.S., over 90% of the transport sector consumes gasoline. Therefore, almost all of this 13% energy consumption of LDVs contributes to the U.S. oil consumption. The U.S. could choose to not import any amount of oil from the Persian Gulf (which made up 10% of oil consumption in 2014) and decrease another 3% of its oil import if the whole U.S. LDV fleet was using alternative fuels instead of oil products in 2014. Not using any gasoline-fueled LDV is definitely a utopic approach for such a huge U.S. LDV market. Whatever the outcome of the efforts of decreasing oil consumption becomes, either via shifting toward other fuel types or increasing fuel efficiency, it will decrease both U.S. foreign dependency in energy consumption

¹⁵ Ibid.

and anthropogenic GHG emissions.

Ways of Reducing Oil Consumption in the Transport Sector

Oil consumption in transportation can be reduced in various ways. The policy of improving fuel efficiency is one of these options, which should be implemented whether a country is energy secure or not. Improving operation practices of drivers also contributes to reducing energy consumption of LDVs. The third way of decreasing oil demand is simply reducing travel demand. If people do not drive as much as they do today, it will also contribute towards decreasing total consumption. The fourth way is fuel switching. Different than the first three ways, fuel switching has the ability to cut the whole oil consumption as it mostly replaces petroleum products with other fuel types.¹⁶ As will be elaborated in more detail below, flexible-fuel vehicles are excluded in this study because they mostly require using gasoline and another fuel's mixture rather than switching to another fuel. Also it is worth to mention that although this section aims to list ways of reducing oil consumption in the transport sector, the first three suggested measures are not limited to oil consumption. They provide ways for reducing any kind of fuels used in transport sector.

Improving Fuel Efficiency

Improving fuel efficiency via improving parts and technology in LDVs is a method of decreasing oil consumption, which should be supported in any case. It is mostly related to the

¹⁶ There are many ways of reducing oil consumption in transportation. This part of this study is structured according to the structure of suggestions of US Environmental Protection Agency on decreasing oil consumption in transportation. See U.S. Environmental Protection Agency, "Greenhouse Gas Overview."

production phase of vehicles although it also includes some other factors. Technologies related to the vehicle are improvements in engine system, in transmission system, and in overall vehicle such as its aerodynamic, weight, tires and auxiliary power systems like lights, heating, cooling, etc.¹⁷.

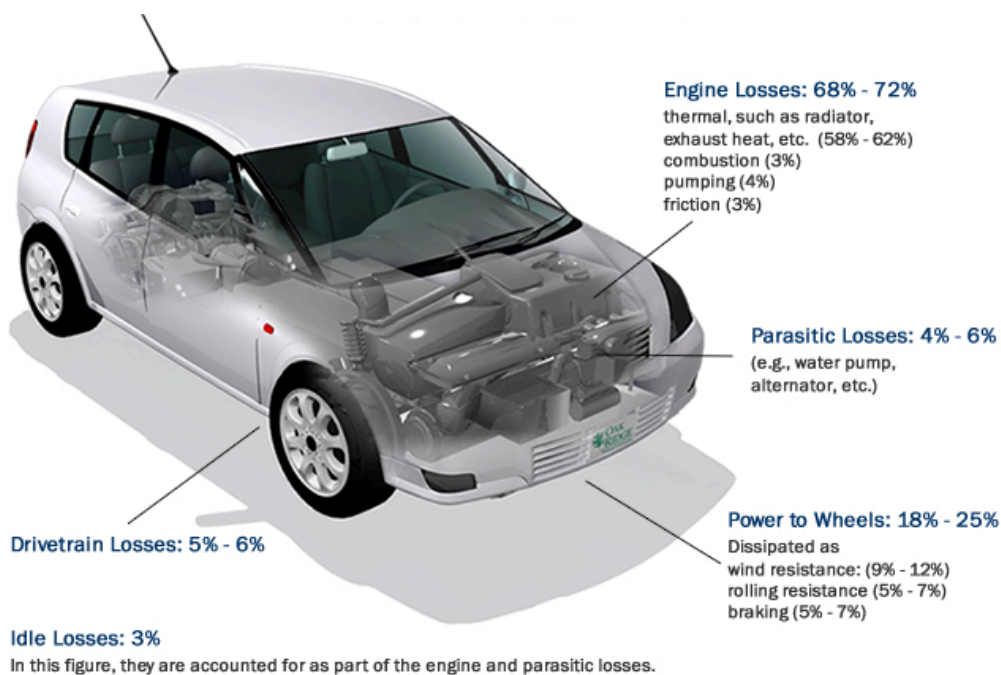
According to an IEA report¹⁸, vehicles consume only one-fifth of a gallon of gasoline to propel them. This means that there is a long way to go to improve fuel efficiency in the future. Although important successes have been achieved with strict energy consumption regulations, there is still room to further improve efficiency. The U.S. Department of Energy says that engine causes the highest loss in an LDV's energy consumption. The loss of energy caused by an ICE ranges from 68% to 82%. The primary reason is thermal, causing energy loss in the engine as heat. There are more losses after the engine generates an amount of power. The power generated from the one-fifth of fuel is lost when it reaches from engine to wheels. U.S. DoE estimates that this loss ranges from 18% to 25%. Aerodynamic drag, which has been one of the most important factors to determine a vehicle's design for years, is the largest source of this loss. The vehicle's rolling resistance, related with the tires, also cause energy loss on the way from power to wheels.¹⁹

¹⁷ The International Energy Agency, "Fuel Economy of Road Vehicles," 17.

¹⁸ The International Energy Agency, "Fuel Economy of Road Vehicles."

¹⁹ U.S. Department of Energy, "Where the Energy Goes: Gasoline Vehicles."

Figure 6: Major Energy Losses in an LDV



Source: The U.S. Department of Energy, Fuel Economy Website²⁰

Increasing energy efficiency 25% for gasoline (spark ignition) engines is estimated to cost around \$1,000 per vehicle. This estimate rises for diesel (compression ignition) engines since they are already more efficient than gasoline engines²¹. Another costly improvement is the enhancement of materials that increase the weight of the car. Instead of relying on steel because of safety and strength advantages, using some other materials such as aluminum, fiberglass, and carbon fiber may decrease the vehicle's weight and increase efficiency. This cost is estimated to be between \$1,200 and \$1,500 for 20% reduction in vehicle's weight and in turn to provide 10% fuel efficiency²².

²⁰ Ibid.

²¹ The International Energy Agency, "Fuel Economy of Road Vehicles," 18.

²² Ibid.

Improving Operation Practices

Operation practices are one of the factors that may consume more energy than the optimum consumption amount. Drivers are the key point to decrease operation-related energy consumption. But there are also some external factors such as city planning, intelligent transportation systems, road surface etc. This category includes anything that could help to save energy, ranging from driver's maintenance of the vehicle to the design of road infrastructures.

IEA evaluates some operating practices factors that may help to consume less energy in a 2012 report²³. According to the report, there are measures that should be taken before and during driving the vehicle. Before driving, drivers should be careful about the condition of their vehicles. For instance, they should get engine maintenance done regularly, make sure that tire pressure is adjusted, get tire alignment checked regularly, and not move unnecessary items in the car. During driving, average speed and driver behaviors are important to save energy. The optimum speed range is between 50 and 90 km/h (31 and 56 mph). While increasing or decreasing the speed out of this speed range consumes more energy than the optimum level, increasing speed over 120 km/h (75 mph) causes much more energy waste. Driver mistakes that cause energy-wasting include some factors like waiting for the engine to warm up before starting driving, rapid starts and stops, and not using cruise control in appropriate conditions.

External factors have many dimensions such as the condition of the road surface, real-time traveler information, adaptive signal control, arterial management programs, and city planning. These factors are all related to the management system of highways, traffic signals, meaning that they are out of drivers' ability to save energy. However, they are still related to the

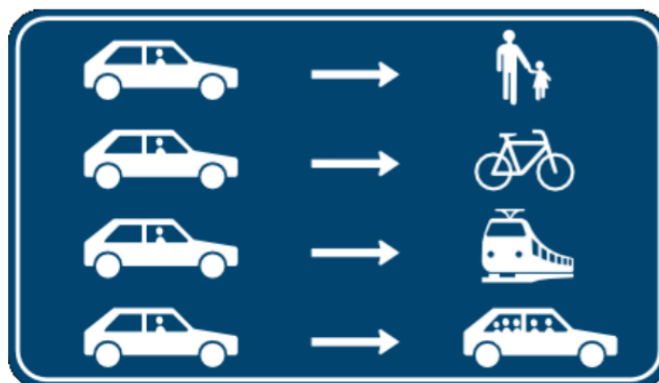
²³ Ibid., 31–34.

improving operation practices. A detailed list of these infrastructural factors can be reached from the U.S. Department of Transportation's website²⁴. Also the IEA provides the impact of speed and road surface on energy consumption in a report in 2012²⁵.

Reducing Travel Demand by Car

As one IEA presentation states, “[t]he most energy efficient trip is the one that is not performed”²⁶. Eliminating a potential demand for a trip is the primary measure that should be taken in order to decrease energy consumption.

Figure 7: Ways of Reducing Travel Demand



Source: IEA – Energy Technology Perspectives 2012²⁷

Figure 7 illustrates four basic ways of reducing travel demand: going somewhere by walking, by biking, by public transportation vehicles and car pooling instead of using a personal vehicle. These are the strategies that people should be incentivized to do. Various methods can

²⁴ U.S. Department of Transportation, “Intelligent Transportation Systems.”

²⁵ The International Energy Agency, “Fuel Economy of Road Vehicles,” 33.

²⁶ Körner, “Transport Sector: Trends, Indicators Energy Efficiency Measures,” 50.

²⁷ Ibid., 51.

be used to incentivize people to reduce travel demand. Pricing strategies towards driving are among the most effective ones to provide people with incentives to not use their personal vehicles if they are not really needed. Pricing might be implemented via charging drivers based on per mile of travel, determining insurance cost based on miles driven (pay-as-you-drive insurance) rather than a fixed cost, pricing roadway facilities in times of congestion, pricing entrance to a specific area, and implementing more taxes on transportation fuels (e.g. carbon tax)²⁸. U.S. DoE estimates the effect of pricing strategies on reducing energy consumption to be between 4% and 6.1% by 2030²⁹.

Improving transit options can provide important benefits. It may include investing new fixed-guideway urban transit, expand coverage of current bus systems, increasing time coverage of the current public transportation systems, and reducing fares. All of these improvements aim to incentivize public transportation in order to decrease individual driving. Other investment-related improvements may include increasing the number of sidewalks, pedestrian crossings, bicycle lanes, bicycle parking places, and educating people on how to use these systems in the most efficient way.

Parking management (supply of parking spaces, pricing, effective parking planning), worksite trip reduction/employee commute options, providing opportunity for distance working rather than traditional office environment (if applicable), flexible working hours, ridesharing and carsharing are some other options that have possibility to reduce travel demand of single-occupant vehicles³⁰.

City planning may also help to reduce travel demand. Eco-cities are important in the

²⁸ Porter et al., “Effects of Travel Reduction and Efficient Driving on Transportation,” 27–30.

²⁹ Ibid., 52.

³⁰ Porter et al., “Effects of Travel Reduction and Efficient Driving on Transportation.”

development process throughout the increasing urbanization process. The least developed countries are expected to have the highest urban proportion growth by 2050³¹. Urban proportion of the U.S. is projected to rise from 81% to 87% between 2014 and 2050³². The increase in urban proportion in the world is projected to be 12% from 54% to 66% in the same time frame³³. The increase in the U.S. urban proportion is not projected to be as high as many other countries but it can provide important benefits for decreasing energy demand in transportation if the urbanization process is managed well. In this regard, eco-cities, which aim to protect the environment with as low as zero-carbon level, provide an important efficiency solution in transportation. Eco-cities can help to decrease the demand for transportation in some areas involving “compact, mixed-use urban form, well-defined higher-density, human-oriented centres, priority to the development of superior public transport systems and conditions for non-motorized modes, with minimal road capacity increases, and protection of the city’s natural areas and food-producing capacity”³⁴. The means eco-cities helps to decrease transportation demand by increasing the ways illustrated in Figure 7.

Fuel Switching

Fuel switching in LDVs means using a different fuel type than conventional petroleum fuels (gasoline and diesel). In the Energy Policy Act of 1992, alternative fuels for fuel switching are defined as follows:

³¹ The urban proportion of the least developed countries is projected to rise from 31% to 49% between 2014 and 2050. See United Nations, “World Urbanization Prospects,” 20.

³² Ibid., 24.

³³ Ibid., 20.

³⁴ Kenworthy, “The Eco-City: Ten Key Transport and Planning Dimensions for Sustainable City Development.”

[1] Methanol, denatured ethanol, and other alcohols; [2] mixtures containing 85 percent or more ... by volume of methanol, denatured ethanol, and other alcohols with gasoline or other fuels; [3] natural gas; [4] liquefied petroleum gas; [5] hydrogen; [6] coal-derived liquid fuels; [7] fuels (other than alcohol) derived from biological materials; [8] electricity (including electricity from solar energy); [9] and any other fuel the Secretary determines, by rule, is substantially not petroleum and would yield substantial energy security benefits and substantial environmental benefits.³⁵

The type of vehicles that use alternative fuels may be flex-fuel vehicles, dedicated vehicles, and bi-fuel vehicles. Flex-fuel vehicles use the mixture of fuels, which are usually the blend of gasoline and ethanol or methanol. They have an ICE and one fuel tank. Both fuels are stored in one fuel tank and the vehicle uses the blend of these fuels. Dedicated vehicles operate on only one fuel. They also have one fuel tank. Bi-fuel vehicles use two different fuels as their operator energy. These vehicles have two fuel tanks different than dedicated and flex-fuel vehicles. They may run on either one of the fuel.

Hybrid electric vehicles are not a type of alternative fuel vehicles unless they can be charged directly from an electric outlet because they still run on conventional fossil fuels. Electric batteries of hybrid electric vehicles are usually used to increase energy efficiency rather than providing an alternative fuel. However, pure battery electric vehicles, plug-in hybrid electric vehicles, and fuel-cell vehicles are considered as alternative fuel vehicles. Although they have a battery like usual hybrid vehicles, they provide direct charging opportunity and are designed to have the capability to run only on electric battery rather than helping ICE in order to gain energy efficiency.

Alternative Fuels Data Center of the U.S. DoE currently features six different types of

³⁵ *The Energy Policy Act of 1992.*

alternative fuels:

- Biodiesel
- Electricity
- Ethanol,
- Hydrogen,
- Natural Gas
- Propane³⁶

Different than the first three ways of decreasing oil consumption, fuel switching completely eliminates oil consumption, replacing it with another type of energy. While decreasing oil consumption, it will increase another fuel's consumption. Therefore, this measure should be applied with a mixture of the first three in order to minimize total energy consumption caused by the transport sector.

Conclusion

This chapter examined the role of transportation both at the U.S. level and the global level. In the world, transportation accounts for 23% of GHG emissions while its share is 27% of the GHG emissions in the U.S. In energy consumption, the share of transportation was 19% in the world and 28% in the U.S. Both globally in the U.S., oil accounts for almost 93% of energy consumption in transportation, meaning that the transport sector heavily dependent on oil. Given these shares of oil in transportation in the world and in the U.S., any change regarding

³⁶ U.S. Department of Energy, "Alternative Fuels and Advanced Vehicles."

challenging oil's status quo in transportation will have a potential to affect 18% of energy consumption in the world and 26% of energy consumption in the U.S.

The world has a potential of growth in transportation because of rising urbanization while the U.S. demand for transportation is expected to stay almost at the same level. LDVs account for 58% of the transport sector's energy consumption in the U.S. The IEA projects a 10% decrease by 2040 in LDVs' share in the U.S. energy consumption. Even factoring this decrease, it still holds an important place in the U.S. energy consumption.

Oil consumption can be decreased mainly in four ways: improving fuel efficiency, improving operation practices of vehicles, reducing travel demand by car, and fuel switching. Although this study focuses on fuel switching option, implementing this strategy together with the first three strategies is important to achieving energy security benefits in the long term

CHAPTER IV

SHALE GAS AS A FUEL FOR LIGHT-DUTY VEHICLES

Introduction

Various alternative fuels are available to switch from oil in transportation. As discussed in the previous chapter, natural gas is one of six alternative fuels that are featured by the Alternative Fuels Data Center of the U.S. DoE. This chapter argues that it is the best available option in the short to middle term among other alternatives for many reasons. It compares natural gas vehicles with the most popular alternative fuel vehicles in the current market; electric vehicles. It weighs their advantages and disadvantages in order to find out what might be better in the short to middle term for the U.S. transport sector.

Using natural gas as an alternative fuel in the U.S. transport sector has many advantages compared to other substitute fuels. First of all, as elaborated in the second chapter, the superiority of natural gas for the U.S. energy security puts it in a better position for the U.S. transport sector. It is available, accessible, affordable and acceptable for the U.S. compared to oil in general energy security terms. The second important advantage is the convertibility advantage in a short period of time. Current ICE vehicles can be converted to natural gas vehicles by adding a CNG tank and some kits. There is no need to wait until the whole U.S. LDV fleet completes its lifetime and is replaced. Other alternative fuels lack this advantage; they require the replacement of the whole fleet in order to reach their saturation point in the market, which may take 20-30 years. The third advantage is that there is no “range anxiety” in converted natural gas vehicles, which is a weakness in most of the alternative fuel vehicle types. Converted natural gas vehicles have the ability to run both on natural gas and gasoline as they have two fuel tanks. This almost

doubles the vehicle's range. The last advantageous point about the natural gas vehicles is their safety. Contrary to common wisdom, natural gas tanks are not more dangerous compared to gasoline ones.

This chapter will also compare natural gas vehicles to battery electric vehicles as they are currently the most popular alternative fuel vehicles in the market. Acknowledging that they provide benefits in the long-term, they are not in an advantageous position until their technology is saturated. Most of their weaknesses arise from the battery technology. Firstly, current BEV batteries are very expensive. Their cost is almost half of the vehicle's production cost. There is a direct relationship between the battery cost and the vehicle price. Once the battery gets cheaper, BEVs will be available for more customers as their price will also get cheaper. The second point is the size and weight of the battery. Current batteries use lithium as the main material, which is heavy and takes significant space. The third disadvantage is related to the time needed for charging the battery. Even the best available BEVs in the market require at least one hour to charge the battery depending on the battery size, which is very long compared to other alternative fuels. All in all, the battery technology needs more innovation, which may take time. Adding LDV fleet replacement time, it may take at least 20-30 years until this battery technology is saturated and used in the market at an important rate.

Viable Alternatives of Gasoline in the Transport Sector

The previous chapter's last section discussed the alternative fuels in general. This part will examine how viable these alternative fuel vehicles are in the future and will give the rationale behind selecting CNG-fueled LDVs and BEVs to discuss in the rest of this chapter.

Consumers prefer the vehicle that uses the cheapest fuel type given that all other

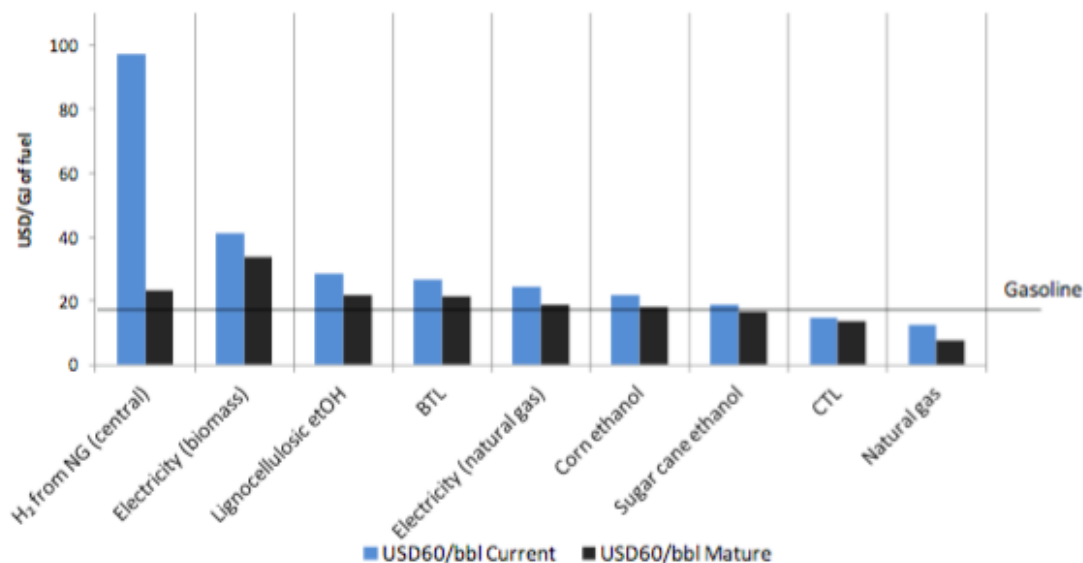
specifications of the vehicle are the same. An IEA report, *Production Costs of Alternative Transportation Fuels*, examines the cost-effectiveness of alternative fuels in different scenarios of oil prices and technology maturity levels¹. As for oil prices, the report uses USD 60 per bbl and USD 150 per bbl of oil, which is a reasonable price in a long-run projection. As for the maturity levels, it uses Current Technology Scenario and Mature Technology Scenario. In the Current Technology Scenario, “fuel production costs are estimated for today’s market environment ... in which emerging technologies have not fully benefited from economies of scale or know-how.”² The Mature Technology Scenario assumes “a fully mature supply chain exists independently for each fuel”³.

¹ Cazzola et al., “Production Costs of Alternative Transportation Fuels.”

² Ibid., 7.

³ Ibid.

Chart 4: Cost of Fuel for Current Technology Scenario versus Mature Technology Scenario for USD 60 per bbl



Source: Cazzola et al, Production Costs of Alternative Transportation Fuels⁴

Chart 4 shows the competitiveness of alternative fuels in the case of oil prices of USD 60 per bbl. This is the lowest case scenario of the IEA report, meaning that it is more difficult for alternative fuels to be competitive against oil products. The horizontal line is the competitiveness level. According to this chart, natural gas is the cheapest alternative fuel in both Current Technology Scenario and Mature Technology Scenario in USD 60 per bbl case. In the mature scenario, its cost decreases around 40 percent and becomes even more competitive compared to other alternatives.

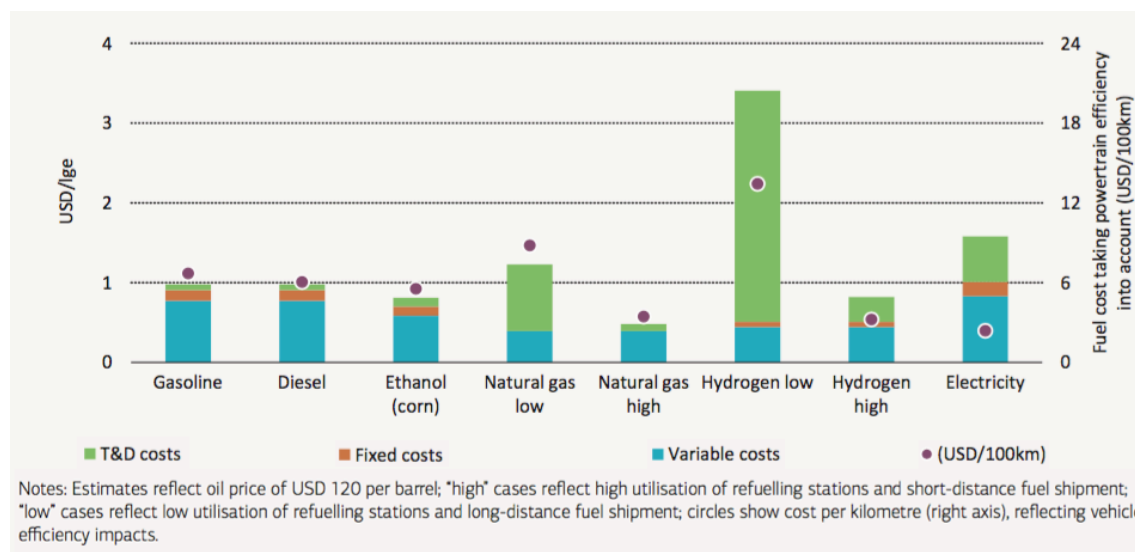
However, Chart 4 does not provide a long-term perspective. Another IEA report, *Energy Technology Perspective 2012*, examines the fuels costs in 2050 with the oil price of USD 120 per bbl⁵. It factors in transportation and distribution costs (T&D costs), fixed costs, and variable

⁴ Ibid.

⁵ The International Energy Agency, "Energy Technology Perspective 2012," 422–455.

costs in the calculation.

Chart 5: Fuel costs in 2050 for selected fuel pathways, per unit of energy and distance travelled



Source: The IEA, Energy Technology Perspective 2012⁶

The chart presents estimations for high and low cases, which reflect “high utilization of refueling stations and short-distance fuel shipment” and “low utilization of refueling stations and long-distance fuel shipment” respectively⁷. Natural gas is estimated to be less competitive in low utilization case in 2050. However, once its utilization level increases, it becomes the most cost-effective fuel according to its aggregate cost. Yet, its total cost as a transport fuel is slightly higher than electricity- and hydrogen-fueled vehicles in the long-term estimations as its usage in transportation causes more energy losses compared to electricity- and hydrogen-fueled vehicles. Even considering this fact however, there is not a wide gap between their costs as a transportation fuel in 2050. The difference in cost levels in Chart 4 and Chart 5 indicates that

⁶ Ibid., 437.

⁷ Ibid.

electricity and hydrogen will be a cheaper fuel sometime close to 2050. This supports this study's argument that natural gas will be the cheapest in the short-to-middle term.

The rest of this chapter will compare the CNG-fueled vehicles with BEVs. The reason for choosing BEVs is that they started to dominate alternative fuel vehicle market in the last couple of years. Increasing production rate of BEVs indicates that CNG-fueled vehicles will need to compete against the BEVs in the short to middle term. Hence, the following two sections evaluate the feasibility of CNG-fueled vehicles and BEVs in the short to middle term.

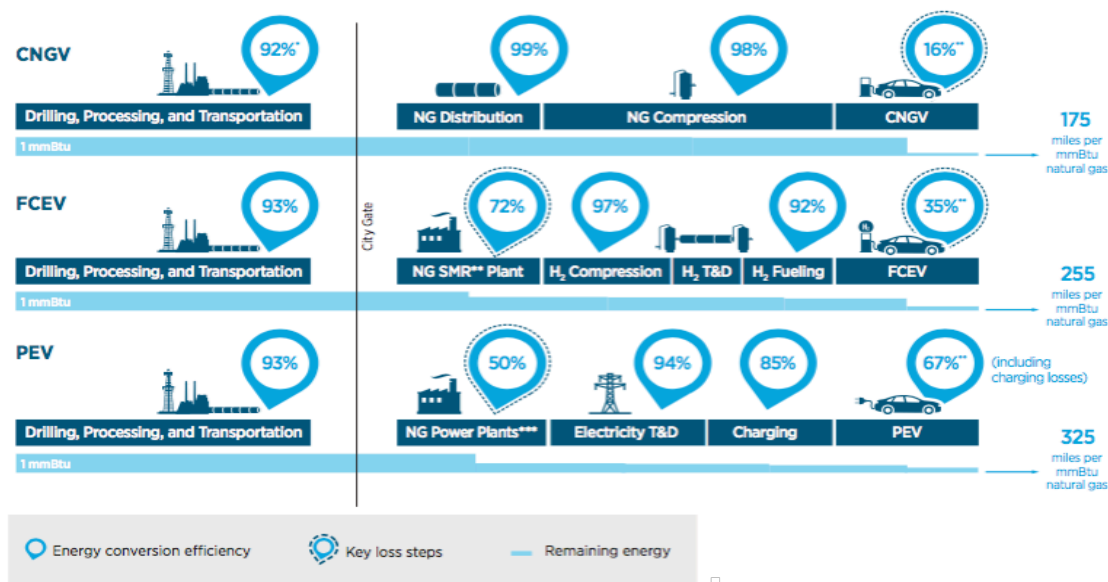
Comparing Using Natural Gas in Three Different Alternative Fuel Vehicle Technologies: CNGV, FCEV, and BEV

Natural gas can be used primarily in three different alternative fuel vehicle technologies. The first option is using it directly as natural gas by compressing or liquefying it. This type of alternative fuel vehicles uses ICE, which is the engine system of conventional gasoline-fueled vehicles. The second option is getting hydrogen from natural gas and using it in FCEVs. The third option is generating electricity from natural gas and using it in EVs⁸.

As illustrated in Figure 8, CNG-fueled ICE vehicles have the greatest losses among three alternative fuel vehicle technologies. The greatest loss of a CNGV occurs during the combustion stage. Using it in an ICE causes 84% fuel loss in the consumption process after the CNGV is fueled with CNG.

⁸ U.S. Department of Energy, "Using Natural Gas for Vehicles: Comparing Three Technologies."

Figure 8: Lifecycle Efficiency of Natural Gas in Three Different Alternative Fuel Vehicle Technologies



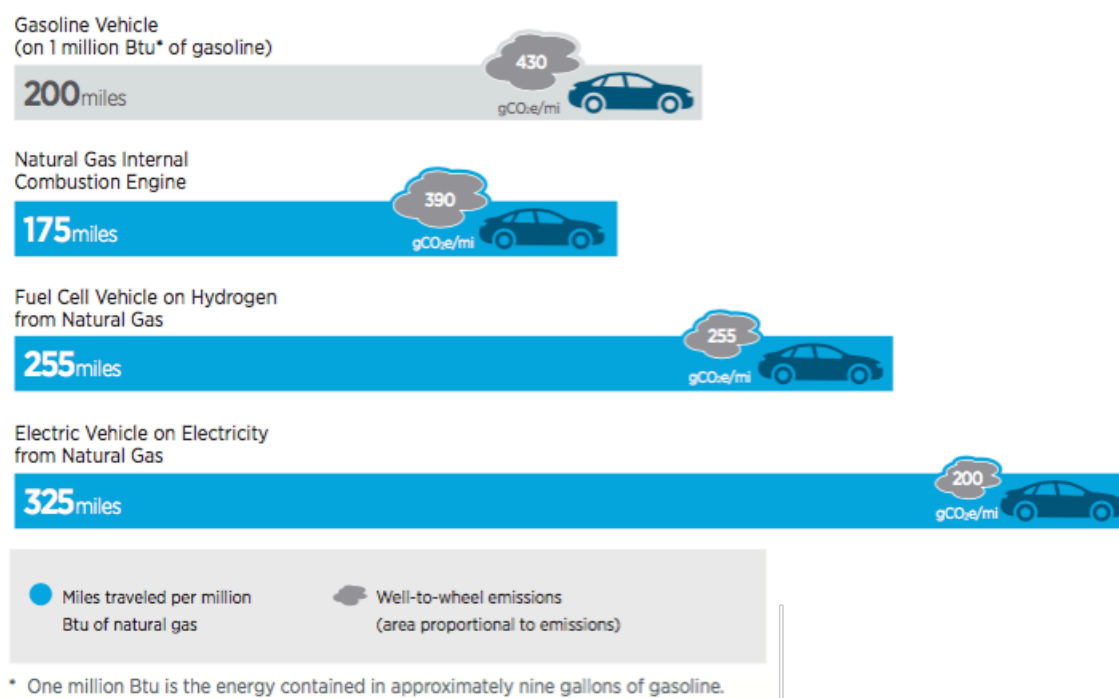
Source: U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, 2015⁹

FCEVs lose an important amount of energy during electricity generation from hydrogen in the vehicle. They lose 65% of energy in this process. The loss of an EV is the least among these three technologies. The most important loss occurs in the process of electricity generation from natural gas, which is around 50%.

The same unit of energy, a mmBtu of natural gas, results in different ranges after these energy losses in the three alternative fuel technologies. A CNG-fueled vehicle that uses ICE can be driven 175 miles with compressing a mmBtu-equivalent of natural gas. An FCEV's range can approximately be 225 miles with the same unit of energy while this number is 325 miles for an EV. These numbers indicate that using natural gas in EVs via generating electricity provides the most efficient solution in its lifecycle efficiency rather than using it directly in CNGVs.

⁹ Ibid., 2.

Figure 9: Lifecycle Efficiency and GHG Emissions of Three Different Alternative Fuel Vehicle Technologies



Source: U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, 2015¹⁰

WTW GHG emissions comparison suggest that natural gas should not be used as a direct fuel in transportation. Lifetime GHG emissions give the same order as the lifetime efficiency of these three alternative fuel vehicle technologies: EVs are the best, FCEVs are moderate, and CNGVs are the worst option compared to each other. Per mile GHG calculations are 390 grams of CO₂ equivalent per mile, 260 grams of CO₂ equivalent per mile, and 200 grams of CO₂ equivalent respectively for CNGVs, FCEVs, and EVs.

Lifetime efficiency and GHG emissions suggest using natural gas in transportation via electricity generation instead of using it directly as fuel. However, as will be discussed below,

¹⁰ Ibid., 4.

some level of technology maturity is needed for EVs to have a battery technology that is mature and cheap enough to use it widely. As Figure 9 shows, it is still a viable option compared to gasoline vehicles in lifetime GHG emissions. Also, as Chart 4 indicates, it is currently the cheapest way of using it as a fuel. Therefore, its ability to convert the current U.S. fleet in a short time rather than waiting current vehicles to be replaced by new technologies makes CNGVs still a good option in the short to middle term. One should compare CNGVs with gasoline-fueled vehicles in the short to middle term rather than comparing with FCEVs or EVs.

The Best Short- to Middle-Term Solution for the U.S. Transport Sector: Compressed Natural Gas Vehicles

Superiority of Shale Gas for the U.S. Case

The effects of the shale boom in the U.S. energy security were elaborated in the second chapter. Its effects are examined from the perspective of 4 A's definition of energy security: availability, accessibility, affordability, and acceptability. This section will evaluate the superiority of shale gas, not from a general perspective for the U.S. energy security, but as a transportation fuel.

Availability

As discussed above between pages 17 and 24, an important amount of unconventional natural gas resources were discovered in the U.S. Natural gas production rose by 44.0% from 2005 to 2014, higher than consumption rate of 21.8% in the same period. Higher increase in production indicates less dependency on foreign resources in natural gas consumption. The U.S.

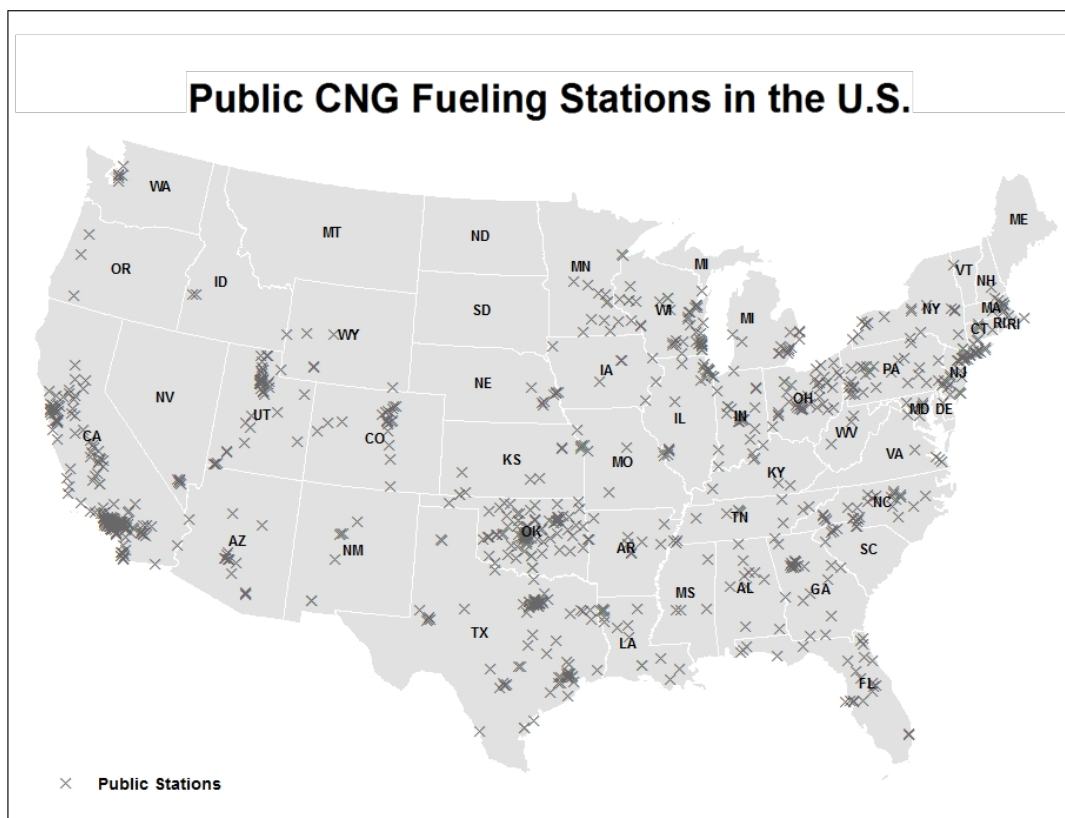
is expected to be self-sufficient in natural gas consumption by 2017. Middle-term projections foresee that the U.S. natural gas production will increase 45% from 2013 to 2040, indicating a 1.4% increase per annum. If the increase rate continues at this level, the total technically recoverable dry natural gas resources will last until 2072 in the U.S. All these numbers indicate that the U.S. will not have an availability problem in natural gas in the short to middle term if it chooses to use natural gas widely as an alternative fuel.

Accessibility

The accessibility perspective also provides valuable benefits if natural gas is used as a fuel in the U.S. Two points are important to evaluate the accessibility of natural gas as a transportation fuel: distribution of fuel within the country and distribution of CNG fueling stations. Different than many other alternative fuels, natural gas has an advantage in accessibility. It can be fueled from a house by using a compression kit if the house has natural gas pipe system. With the exception of electricity, other alternative fuels lack this accessibility advantage.

Natural gas pipeline infrastructure is the first accessibility indicator. Figure 2 above showed the natural gas pipeline system of the lower 48 states on page 29. It is already accessible in many states with the current pipeline infrastructure. The natural gas pipeline network is distributed across the whole country, clustering in some hubs in Oklahoma, Texas, Louisiana. In a high utilization case, this pipeline network is expected to rise and become even more accessible throughout the country.

Figure 10: Map of Public CNG Fueling Stations in the U.S.



Source: Created by the author with the data drawn from the Alternative Fuel Data Center¹¹ and the U.S. Census Bureau¹²

The second point related to natural gas' accessibility as a transportation fuel is how widely its fueling stations are distributed throughout the country. The number of public CNG fueling stations is 904 as of February 2016¹³. The highest number of stations belongs to electricity with 12,306 charging stations and 30,908 charging outlets while ethanol follows it with 2,807 stations in the U.S.¹⁴

¹¹ U.S. Department of Energy, "AFDC- Data Downloads."

¹² U.S. Census Bureau, "Cartographic Boundary Shapefiles - States."

¹³ U.S. Department of Energy, "Alternative Fueling Station Locator."

¹⁴ Ibid.

Table 1: Number of Public Alternative Fuel Stations in the U.S.

Alternative Fuel Type	Number of Stations
Electric Stations	12,306
Electric Charging Outlet	30,908
Ethanol (E85)	2,807
Liquefied Petroleum Gas (Propane)	1,536
Compressed Natural Gas	904
Biodiesel (B20 and above)	228
Liquefied Natural Gas	76
Hydrogen	21

Source: Compiled by the author with the data drawn from the U.S. Department of Energy Website¹⁵

The number of public CNG fueling stations is not at the desired level if it is planned to be used widely in LDVs. Definitely, demand is the crucial point for the rise in the number of stations. Once it is incentivized, CNG fueling stations will be more in the free market system as a result of growing demand.

As illustrated in Table 2, Smith and Gonzales estimate that the cost of a medium-to-large fast-fill public station may range between \$550,000 and \$1,800,000.¹⁶

¹⁵ Ibid.

¹⁶ Smith and Gonzales, "Costs Associated With Compressed Natural Gas Vehicle Fueling Infrastructure," 10–12.

Table 2: Costs of Different Types of CNG Fueling Stations

Size	Type	Cost Range	Fueling Capacity	Total Capacity
Basic Time-Fill	Time-Fill	\$5,500 – \$6,500	One LDV 5 gge/night	5–10 gge/day
	Time-Fill	\$9,000 – \$10,000	Two LDVs 5 gge/night	
Starter Station	Fast-Fill	\$45,000 – \$75,000	Four LDVs 10 gge/day	20–40 gge/day
	Time-Fill	\$35,000 – \$50,000	Two Trucks 20 gge/night	
Small Station	Fast-Fill	\$400,000 – \$600,000	15-25 LDVs 7 gge/day	100–200 gge/day
	Time-Fill	\$250,000 – \$500,000	15-20 LDVs 7 gge/night	
Medium Station	Fast-Fill	\$700,000 – \$900,000	50-80 LDVs 10 gge/day	500–800 gge/day
	Time-Fill	\$550,000 – \$850,000	75-80 LDVs 7 gge/night	
Large Station	Fast-Fill	\$1,200,000 – \$1,800,000		1,500–2,000 gge/day

Source: Created by the author with the data drawn from the Smith and Gonzales's Report¹⁷

The main difference between time-fill and fast-fill stations is their storage capacity and the size of the compressor used in the fueling station. Fast-fill stations are more appropriate as public stations since many LDVs and other types of vehicles may arrive randomly and want to fill up quickly. The filling time in a fast-fill station is almost the same as fueling the tank with gasoline. In time-fill stations, vehicles are filled directly from the compressor over a long period

¹⁷ Ibid.

of time, while fast-fill stations store compressed natural gas in storage tanks and fill from there.¹⁸

Home fueling advantage is another accessibility superiority of natural gas. The CNGVs use the natural gas that is used in houses for heating. The only difference between the residential natural gas and CNG is their pressure. The pressure of the residential natural gas is lower than 0.5 psi while a CNGV requires it to be between 3000 and 3600 psi¹⁹. A disadvantage of the residential natural gas is its price. As it includes residential distribution fee, its price may be higher than commercial natural gas²⁰.

To sum up, natural gas has an accessibility advantage as it is already distributed via pipelines throughout the country while its fuel stations are not at the desired level compared to other alternative fuel vehicle fueling stations. The number of public CNG fueling stations should be increased. In the free market system of the U.S., the number will increase as the demand for fueling stations increase. Therefore, starting with incentivizing CNGVs is a good point to make CNG more accessible.

Affordability

Chart 4 and Chart 5 showed how competitive natural gas compared to other alternative fuel types. This trend is expected to continue until 2050 with some changes in using hydrogen and electricity vehicle's fuel cost in transportation. Although almost at the same level as the cost of natural gas, the fuel costs of electricity- and hydrogen-fueled vehicles are expected to be slightly cheaper than natural gas.

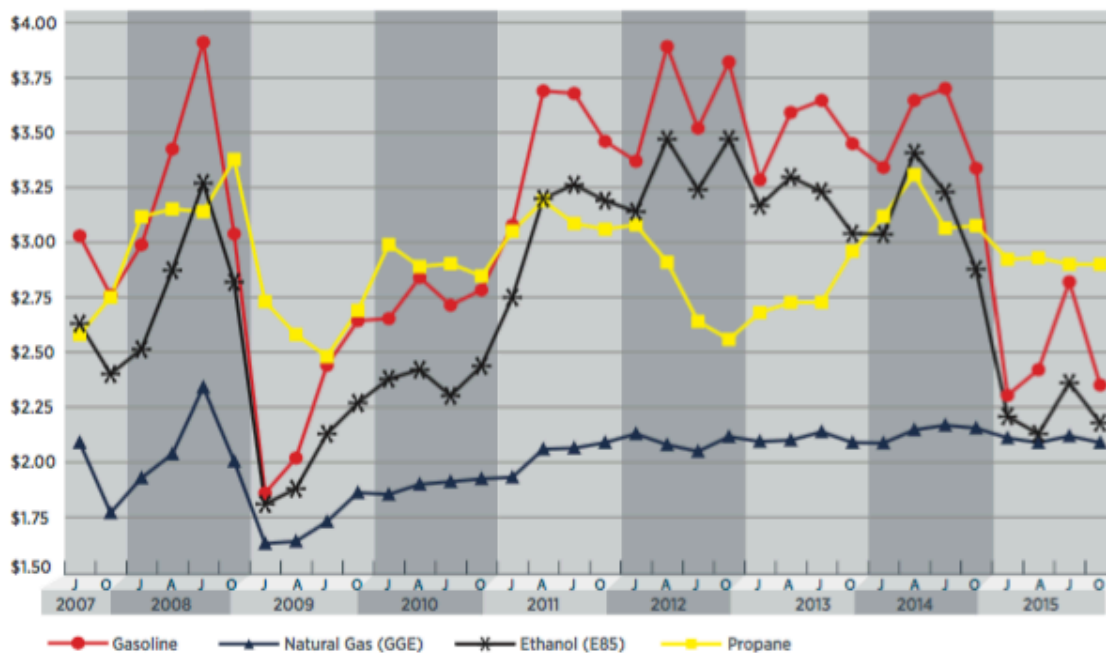
¹⁸ U.S. Department of Energy, "Compressed Natural Gas Fueling Stations."

¹⁹ Whyatt, "Issues Affecting Adoption of Natural Gas Fuel in Light- and Heavy-Duty Vehicles," 2.4–2.5.

²⁰ Ibid., 2.5–2.6.

As this study aims to see the effects of replacing natural gas with gasoline in LDVs in the U.S., the comparison of a gallon of gasoline and GGE of CNG is important to understand how affordable natural gas is as a transportation fuel.

Chart 6: GGE Prices of Gasoline, CNG, Ethanol, and Propane in the U.S. from 2008 to 2016



Source: Clean Cities Alternative Fuel Prices Report²¹

Chart 6 shows national average prices of four fuel types from the mid-2007 to the end of 2015. CNG prices, measured in the same unit as the others, has been the cheapest among four fuel types. In high gasoline price cases, CNG becomes more competitive. For instance, in the second half of 2008 and between 2011 and 2014, gasoline prices have been around \$3.50, while a GGE of CNG was around \$2.00 for the same period. In some states, this price range is even

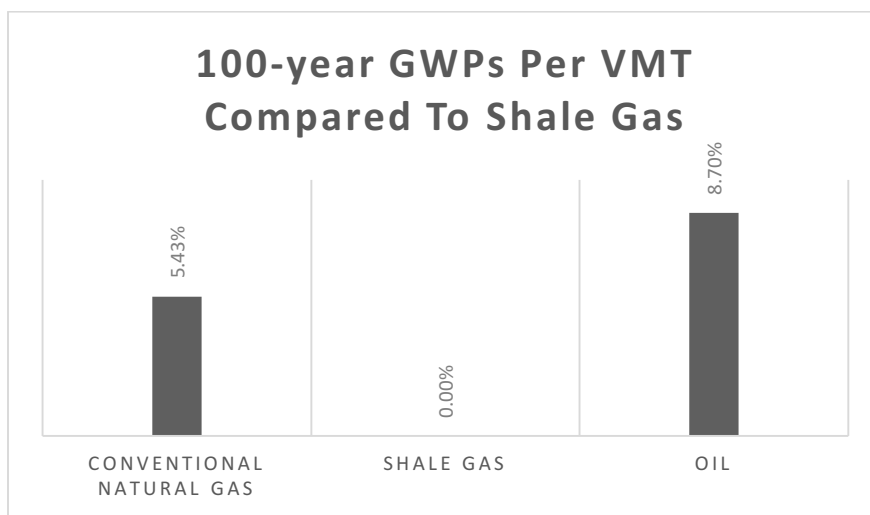
²¹ Bourbon, "Clean Cities Alternative Fuel Price Report," 22.

higher, making CNG more competitive compared to gasoline. A state-based price analysis might provide a more detailed understanding of the affordability comparison. However, this study does not focus on regional dynamics, rather it examines country-level data.

Acceptability

Acceptability, as mentioned on page 30 in detail, deals with both a fuel's environmental impact and societal impact. As for environmental impact, the most important measure of natural gas as transport fuel is its long-term impact on global warming. 100-year GWP provides data on the long-term climate change impacts of fossil fuels.

Chart 7: 100-year GWPs of Conventional Natural Gas, Shale Gas, and Oil per VMT



Source: Compiled by the author with the data drawn from Burnham et. al's study²²

Chart 7 provides 100-year GWP of natural gas compared to oil. The GWP of shale gas is less than the GWP of conventional natural gas. Hence, the chart treats them separately. Based on

²² Burnham et al., "Life-Cycle Greenhouse Gas Emissions of Shale Gas, Natural Gas, Coal, and Petroleum."

shale gas's GWP in transportation, using CNG compiled from conventional natural gas has 5.4% more GWP, while gasoline compiled from oil has 8.7% more GWP.

Societal impact is difficult to measure as it is intangible. As mentioned in the previous sections, some concerns are shared regarding the extraction of shale gas. These concerns are the societal effects related to the thoughts of contamination of air and drinking water in nearby areas of where it is extracted. The negative impacts of CNG are the same as its general negative impacts.

The positive impacts of using CNG in transportation can also be the same as the general positive effects of using domestic natural gas resources as well as some other impacts. For instance, the fact that it will support domestic resource utilization and decrease dependence on foreign energy resources might be a good point to use to increase its societal acceptability. Some natural gas lobby groups advertise this aspect of CNGVs but their voice is not so strong to create a big change in societal acceptability. Incentivizing CNG usage at the state level might bring important benefits for its societal acceptability.

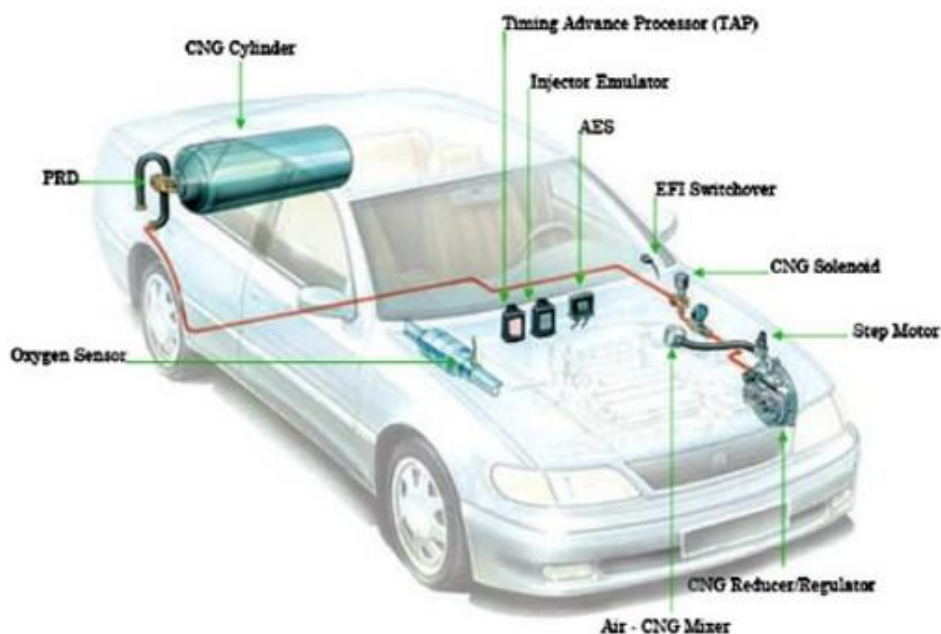
One of the impacts of natural gas, addressed by President Obama in the State of the Union Address in 2014, is the local jobs that the natural gas industry will create. Related to CNG, he urges the Congress to “help by putting people to work building fueling stations that shift more cars and trucks from foreign oil to American natural gas”²³. This suggestion is to some extent affected by the surge in oil prices after the State of the Union Address in January 2014. There is still however, an untapped potential in this area for the Congress. An action towards this aim can be taken in case of high oil prices.

²³ The White House, “President Barack Obama’s State of the Union Address 2014.”

Convertibility Advantage of the Whole U.S. Fleet in A Short Time

Gasoline- and diesel-fueled vehicles have convertibility advantage. Some automobile companies sell dedicated NGVs that use only natural gas as fuel. However, natural gas equipment can also be installed in most of the vehicles as an aftermarket installation. OEM gasoline- and diesel-fueled vehicles are appropriate for installing natural gas equipment. As Figure 11 shows, there are some parts that need to be installed in a vehicle to be able to make it run on CNG. After installation, the vehicle becomes a bi-fuel vehicle and run both on its OEM fuel and on CNG.

Figure 11: Installed Parts of an Aftermarket Converted Bi-Fuel Vehicle



Source: Energy Supply Association of Australia, 2014²⁴

The conversion process does not take away any function of the vehicle, instead, it adds a

²⁴ Energy Supply Association of Australia, "Developing a Market for Natural Gas Vehicles in Australia."

new one. The most important added function is the ability to drive the vehicle on CNG whenever the driver wants to switch to it.

There are controversies about the engine performance when the vehicle runs on CNG after the conversion. Some academic and commercial sources argue that the vehicle performance stays the same and runs the same as how it runs on gasoline²⁵. Some arguments say that the vehicle's engine performance decreases a little when it runs on CNG compared to its performance on gasoline. For instance, American Honda sells both dedicated CNG and dedicated gasoline models for Honda Civic in the U.S. The company lists engine performance metrics of these two models differently. The dedicated CNG model's engine performance is a little bit less than the dedicated gasoline type. Table 3 shows differences as listed in American Honda's website.

²⁵ "NGVi - Frequently Asked Questions"; Semin, "A Technical Review of Compressed Natural Gas as an Alternative Fuel for Internal Combustion Engines."

Table 3: Comparison of Performance-Related Specifications of 2015 Honda Civic GX and 2015 Honda Civic LX

	2015 Honda Civic GX (Dedicated CNG Vehicle)	2015 Honda Civic LX (Dedicated Gasoline Vehicle)
Displacement (cc)	1798	1798
Compression Ratio	12.7 : 1	10.6 : 1
Horsepower @ rpm (SAE net)	110 @ 6500	143 @ 6500
Torque (lb-ft @ rpm, SAE net)	106 @ 4300	129 @ 4300
MPG for 5-speed Automatic Transmission (City / Highway / Combined)	27 / 38 / 31	30 / 39 / 33
	2015 Honda Civic GX (Dedicated CNG Vehicle)	2015 Honda Civic LX (Dedicated Gasoline Vehicle)
Fuel Capacity	8.03 GGE @ 3600 psi	13.2 gal

Source: American Honda Website for 2015 Honda Civic GX²⁶ and 2015 Honda Civic LX²⁷ Models

The installation of these parts to the vehicle takes the same amount of time as the vehicle's other services. In many cases, consumers have their vehicles converted in a day, while some conversion companies require up to 3-4 days for installation.

Convertibility advantage is the crucial point that makes CNGV different than other alternative fuel vehicles. It provides an opportunity to change the current U.S. LDV fleet without waiting the current LDVs lifetime and replacement by new LDVs. Hence, it provides significant benefits in the short to middle term.

²⁶ American Honda Motor Co., Inc., "2015 Honda Civic Natural Gas - Specifications."

²⁷ American Honda Motor Co., Inc., "2015 Honda Civic Sedan - Specifications."

No Range Anxiety: Ability to Drive Bi-fuel Vehicles on Both CNG and Gasoline

As mentioned briefly in the previous section, converted vehicles have the ability to run on both its original fuel –which is generally gasoline or diesel- and on CNG. One of the added parts that is shown in Figure 11 is a switchover, which drivers can use to switch between using the vehicle on CNG or on its original fuel. Switching is supported by the vast majority of conversion technologies while the vehicle is operating. Dedicated CNG vehicles lack this advantage as they only have one fuel tank, which is the CNG tank. All converted CNG vehicles become bi-fuel vehicle as they keep all original equipment including gasoline/diesel tank.

The number of CNG fueling stations in the U.S. is not enough to incentivize vehicle owners to convert their LDVs to CNGV. As Figure 10 illustrates above, some states (Montana, North Dakota, South Dakota, Maine) currently do not have any CNG fueling stations. It is not convenient for a CNGV driver to drive long ranges if its route includes the regions that do not have or have very few number of CNG fueling stations. The advantage of converted CNGVs to run both on its original fuel and CNG makes it convenient for drivers to drive long ranges as they can switch the vehicle to run on its original fuel.

It eliminates range anxiety in converted bi-fuel vehicles, which is the main concern of consumers for many alternative fuel vehicles. Adding CNG tank gives an extra range depending on the size of the CNG tank. Table 3 on page 81 shows a dedicated CNGV's fuel capacity. If the Honda Civic model is bought as LX model and converted to CNG by an aftermarket conversion company, its total fuel capacity becomes the sum of 13.2 gallon and the fuel size of the added tank. Accordingly, its average range becomes 684.5 miles (given that the added CNG fuel

capacity is 8.03 GGE), while it is originally 435.6 miles²⁸.

No Safety Problem

Contrary to the common wisdom about CNGVs, a dedicated CNGV is safer compared to a dedicated gasoline-fueled vehicle. A converted CNGV also has no extra safety problem related to CNG equipment installation in a dedicated gasoline/diesel vehicle.

Any fuel can be dangerous since they contain energy to be released to operate the vehicle when they are ignited. In this respect, gasoline is also dangerous. However, the safety regulations made it safe to use as a fuel for vehicles. The same thing works for natural gas as well. If it is handled properly, it does not cause any safety threat²⁹. Besides, it has safety advantages compared to gasoline and diesel. In case of a potential release, natural gas dissipates as it is lighter than air³⁰.

Federal Motor Vehicle Safety Standards are applied to the CNGVs. They are tested to be safe both in normal and extraordinary conditions. Natural gas cylinders are thicker and stronger than gasoline and diesel vehicle tanks. As an extreme case, the cylinders are tested in a bonfire and against a 30-caliber bullet.³¹

The fact that natural gas is odorized prevents a potential hazard in case of leakage. Natural gas requires a mixture of air with a 5% to 15% of natural gas for combustion. Since it is odorized, a person normally realizes its existence as low as 0.3% of its mixture with air³². This is

²⁸ Ranges are calculated according to the combined MPG of Honda Civic LX and GX models. The combined MPG and fuel size can be seen in Table 3.

²⁹ "How Safe Are Natural Gas Vehicles?," 1.

³⁰ Ibid.

³¹ Ibid., 2.

³² NGV Global, "Natural Gas Vehicle Safety."

very lower than its combustion level. In addition to its mixture level, it also requires a high temperature for the ignition. The ignition temperature of natural gas is 600 degrees Celsius while it is 350 degrees Celsius for gasoline³³.

Some safety measurements that are specific to CNGV aim to make it a safe fuel. For instance, a CNGV's tank has to be removed and replaced in 15-20 years as its lifetime ends within this period. Also, a CNGV must be inspected every three years or every 36,000 miles against a possible corrosion or abrasion³⁴.

All in all, adding CNG equipment to a gasoline- or diesel-fueled vehicle does not cause any extra safety threat. Contrary to conventional wisdom, converted CNGVs are at least as safe as conventional fuel vehicles.

Why Are BEVs Not a Good Option for the Short to Middle Term?

BEV is a type of EV³⁵ that is “propelled by one or more electric motors powered by rechargeable battery packs”³⁶. Different than HEVs and PHEVs, BEVs run solely on an electric motor and do not have an ICE. BEV “batteries are charged by plugging the vehicle into an electric power source and through regenerative braking”³⁷.

Strengths of BEVs

BEVs are better than CNGVs in many respects. They are better at converting energy to

³³ Ibid.

³⁴ Whyatt, “Issues Affecting Adoption of Natural Gas Fuel in Light- and Heavy-Duty Vehicles,” 2.18.

³⁵ Although some sources use EV and BEV interchangeably, this study considers BEV is a type of EV as there are other types of EVs as well (PHEV, HEV, NEV, etc.).

³⁶ U.S. Department of Energy, “All-Electric Vehicles.”

³⁷ U.S. Department of Energy, “Hybrid and Plug-In Electric Vehicles,” 1.

power at the wheels. As Figure 9 showed on page 69, a CNGV's range is 175 miles compared to a BEV's range of 325 miles by using one million Btu of natural gas. The reason for this is that BEVs can convert about 59%-62% of electric energy to power at the wheels while this rate is about 17%-21% for conventional ICE gasoline vehicles.³⁸

As EVs emit no tailpipe GHG, their operation might create as low as zero emission depending on how the electricity is generated for use in the vehicle. For instance, if the electricity is generated by using a nuclear-, hydro-, solar-, or wind-powered plants, they do not cause any harmful pollutants to the air. If fossil fuels are the source of electricity energy, then the lifecycle emissions of BEV change depending on the fossil fuel type that is used. This aspect also might reduce the energy dependency on foreign sources.³⁹ If the electricity is generated from indigenous sources, then it reduces energy dependency since it will replace mostly the current gasoline- and diesel-fueled vehicles which use petroleum products and most of these products are imported as discusses in the second chapter.

Vehicle performance is another superiority of BEVs when compared with regular ICE vehicles. Electric motors perform better in acceleration, operate smoother, and require less regular maintenance compared to regular ICE gasoline-fueled vehicles.

Challenges Associated with BEVs

However, BEVs have some challenges mostly caused by their current battery technology. More developments are required in this field in order to make them widely usable. Battery cost, charging time, and range anxiety are the key challenges of current BEVs. All challenges will be

³⁸ U.S. Department of Energy, "All-Electric Vehicles."

³⁹ Ibid.

diminished by technological development in the battery.

Battery Cost

Current technology makes BEVs pretty costly as lithium-ion batteries are expensive. Although automobile companies that sell BEVs keep the battery cost a trade secret, there are some estimates about its cost. A peer-reviewed study argues that battery costs decreased 14% annually between 2007 and 2015, from US\$1,000 per kWh to around US\$410 per kWh⁴⁰. It also argues that its cost among market-leading BEV manufacturers is even lower; around US\$300 per kWh in 2015. However, the study also admits that there are “large uncertainties” regarding the past, current, and future levels of battery costs⁴¹.

The 2012 Energy Technology Perspective report of the IEA has estimated the per kWh cost of a battery to be US\$352. It expects the price to drop US\$261 in 2040.⁴² If the battery cost stays around this price level in 2040, BEVs are less likely to be competitive in every car class. They may only replace C-class and higher class LDVs as their price is already higher than a BEV can compete with its high cost of the battery. Unless they drop significantly, BEVs cannot find a mass market without subsidies⁴³.

An article warns about the understanding of innovation in battery technology and says that “while countless breakthroughs have been announced over the last decade, time and again these advances failed to translate into commercial batteries.”⁴⁴ The article argues that battery technology is poorly understood because even a small change in the battery requires a long time

⁴⁰ Nykvist and Nilsson, “Rapidly Falling Costs of Battery Packs for Electric Vehicles.”

⁴¹ *Ibid.*, 329.

⁴² The International Energy Agency, “Energy Technology Perspective 2012,” 250.

⁴³ Hidrue et al., “Willingness to Pay for Electric Vehicles and Their Attributes.”

⁴⁴ Bullis, “Why We Don’t Have Battery Breakthroughs.”

to test whether it should be made commercially available⁴⁵. Some automobile companies try to create economies of scale by creating other demand areas for batteries⁴⁶. Doing so, they may make battery cost lower with a large scale of production. Even the lowest estimate, US\$300, is very high. According to this estimate, battery cost of a 60 kWh BEV is US\$18,000. Even the battery cost is higher than many conventional gasoline vehicles and also than many CNGVs.

Vehicle Range

Range and battery cost are two challenges that depend on each other. Increasing vehicle range means increasing cost of the battery, and accordingly increasing sale price of the vehicle. Although an average daily travel of an American is 28.5 miles⁴⁷, over 75% of the American people think that range is either a major or somewhat a disadvantage for an EV⁴⁸.

Currently, battery sizes range from 20 kWh to 85 kWh, which provide from 75-miles to 300-miles range. Most of the BEVs have a range about 70 to 90 miles.⁴⁹

The IEA's 2012 Energy Technology Perspective report estimates the average range of BEVs stays the same at around 90-95 miles. It predicts that the battery size will decrease, which indicates that BEVs are expected to be slightly more efficient than their current level⁵⁰.

Charging Time

Charging time is another challenge that is related to the battery technology. It depends on

⁴⁵ Ibid.

⁴⁶ McKenna, "Why Tesla Wants to Sell a Battery for Your Home."

⁴⁷ Trigg and Telleen, "Global EV Outlook," 26.

⁴⁸ Carley et al., "Intent to Purchase a Plug-in Electric Vehicle," 41.

⁴⁹ U.S. Department of Energy, "Hybrid and Plug-In Electric Vehicles," 2.

⁵⁰ The International Energy Agency, "Energy Technology Perspective 2012," 250.

many factors including “the type of battery, its capacity, and how depleted it is; and the size of the vehicle’s internal charger”⁵¹. There are two types of charging systems: slow charging and fast charging. Slow charging is the most common type that provides electricity to the battery. It does this by alternating current to the BEV’s battery from an external charger. Fast charging provides electricity to the battery by directly transmitting current of electricity to the BEV’s battery. The charging time may range from 4 hours to 12 hours for slow charging system while it is between 0.5 and 2 hours for fast charging one.⁵²

As for the charging time, the IEA’s Energy Technology Perspective report in 2012 predicts only small decrease. Its estimate was 8.1 hours for 2015. The charging time only decreases by half an hour and will become 7.6 hours in 2040 according to the IEA estimates⁵³.

Weight and Size of the Battery

There are other challenges related to battery technology. Their weight and size are not at the desired level yet. They take much space and make up an important amount of vehicle’s weight⁵⁴.

Conclusion

Following the previous chapter’s last section, this chapter focused on one of the ways of decreasing oil consumption: fuel switching. Firstly, it looked at viable alternatives of gasoline in the transport sector. Natural gas is prominent among all viable alternatives of oil since it is the

⁵¹ U.S. Department of Energy, “Hybrid and Plug-In Electric Vehicles,” 3.

⁵² Trigg and Telleen, “Global EV Outlook,” 14.

⁵³ The International Energy Agency, “Energy Technology Perspective 2012,” 250.

⁵⁴ U.S. Department of Energy, “All-Electric Vehicles.”

cheapest substitute fuel in both the current technology scenario and mature technology scenario. A long-term projection of the IEA indicates that its cost will be slightly higher than electricity in transportation in 2050. It means that natural gas will be the cheapest alternative fuel until sometime in the 2040s. This supports the main point of this study since it argues natural gas will be the best alternative fuel in transportation in the short to middle term.

Natural gas can be used in transportation in three different vehicle technologies: compressing it and using in an ICE vehicle; getting hydrogen out of it and using in an FCEV; and generating electricity from it and using in a BEV. Figure 8 and Figure 9 show that in both creating energy out of it and GHG emissions, BEVs come first, FCEVs are second, while CNGVs are the last optimal option. However, as the rest of the chapter argues, CNGVs have advantage of providing an immediate solution to two problems related with the U.S. transport sector. Hence, CNGVs should be supported in the short-term and middle-term projections while other two technologies should be considered within the long-term projections.

CHAPTER V
THE EFFECTS OF USING CNG IN THE U.S. GASOLINE- AND DIESEL-FUELED
LDV FLEET

Introduction

Converting the U.S. gasoline- and diesel-fueled LDV fleet into CNGV will affect the U.S. in two major ways: it will decrease oil consumption in the U.S. while simultaneously increasing natural gas consumption, and it will reduce total GWP that is created by the U.S. transport sector. System dynamics is a convenient tool to examine the extent to which conversion of LDVs cause a change in the oil and natural gas consumption and GWP.

This chapter will use a system dynamics model to evaluate the change at the systemic level. Three simulation results based on three different case scenarios will be presented. These scenarios help to better understand what the effects of converting current U.S. gasoline- and diesel-fueled LDV fleet to CNGV are. The simulation will include a period from 2015 to 2050.

The crucial point in modeling is the decision-making process of individuals whether to convert their LDVs into a CNGV. Theories of individual decision making examine how an individual makes a decision based on choices. A section of this chapter explores these theories about the decision making of individuals.

Theories of Individual Choice Behavior

A theory of choice consists of four main elements: (1) decision maker, (2) alternatives,

(3) attributes of alternatives, and (4) decision rule¹. (1) The decision maker can be individuals or group of individuals. This model will consider individual gasoline- and diesel-fueled LDV owners as the decision makers. (2) Alternatives are the choice sets that the decision makers consider to select one. Choice sets might be continuous or discontinuous. An example of the first one might be an individual choosing buying some amount of milk, bread, and butter among the set of all economically feasible alternatives of these three commodities. An example of a discontinuous choice set can be an individual choosing one television among three possible choices². (3) Attributes of alternatives are the specialties that decision makers consider while choosing among them. For instance, an individual may consider performance change in the vehicle after conversion, availability of fueling stations, and cost-effectiveness analysis of conversion for a period of time. (4) The last step, the decision rule, is about how a decision maker arrives at a unique choice within available alternatives. These rules can be categorized into four groups: dominance, satisfaction, lexicographic rules, and utility³. Dominance indicates situations in which an alternative choice dominates others with one of its attributes. For example, in the CNG conversion case, an individual chooses to convert its LDV to CNGV if all other parameters stay the same and one attribute, let's say the fuel cost in the CNG conversion case, becomes better. In some versions, this rule puts a threshold for the difference level among compared alternatives that decision makers disregard if the difference between alternatives does not exceed this threshold. In the CNG conversion case, the small change in performance and fuel consumption can be examples of these versions of the rule. The second category of decision rules, which is the satisfaction rule, assumes that decision makers seek a satisfaction level in

¹ Ben-Akiva and Lerman, *Discrete Choice Analysis*, 32.

² *Ibid.*, 34.

³ *Ibid.*, 35–38.

alternative choices. Although this rule does not lead to a choice, it helps to eliminate some alternative choices. The third category, lexicographic rules, assumes that decision makers order alternatives by their level of importance. Then, she/he chooses the most attractive for the most important attribute. The last category of decision rules, utility, is the cost a decision maker aims to minimize or the benefit she/he aims to maximize.⁴

Theories of individual choice behavior can be listed as rational behavior theory, economic consumer theory, discrete choice theory, and probabilistic choice theory. There are extensions of these theories that add some more assumptions to them.⁵ The theory that is used in this chapter for individual choice behavior is a discrete choice theory because it explains the decisions that are discontinuous and decision makers choose only one among alternatives.

Attributes of Alternatives

The attributes of alternatives are important for decision makers to make their choices. For instance, driving range, fuel cost savings, and charging time are important attributes for people who will make a decision to choose a variety of attributes of EVs⁶. For a converted CNGV, the first and last attributes are not significant concerns since a converted CNGV's attributes in driving range and refueling time dominate the alternative, which is gasoline-vehicle in this system dynamics case. However, fuel cost savings might be an important factor. The attributes that have potential to affect an individual's choice behavior to convert their gasoline- or diesel-fueled vehicle into a CNGV can be listed as:

⁴ Ibid.

⁵ Ibid., 38–58.

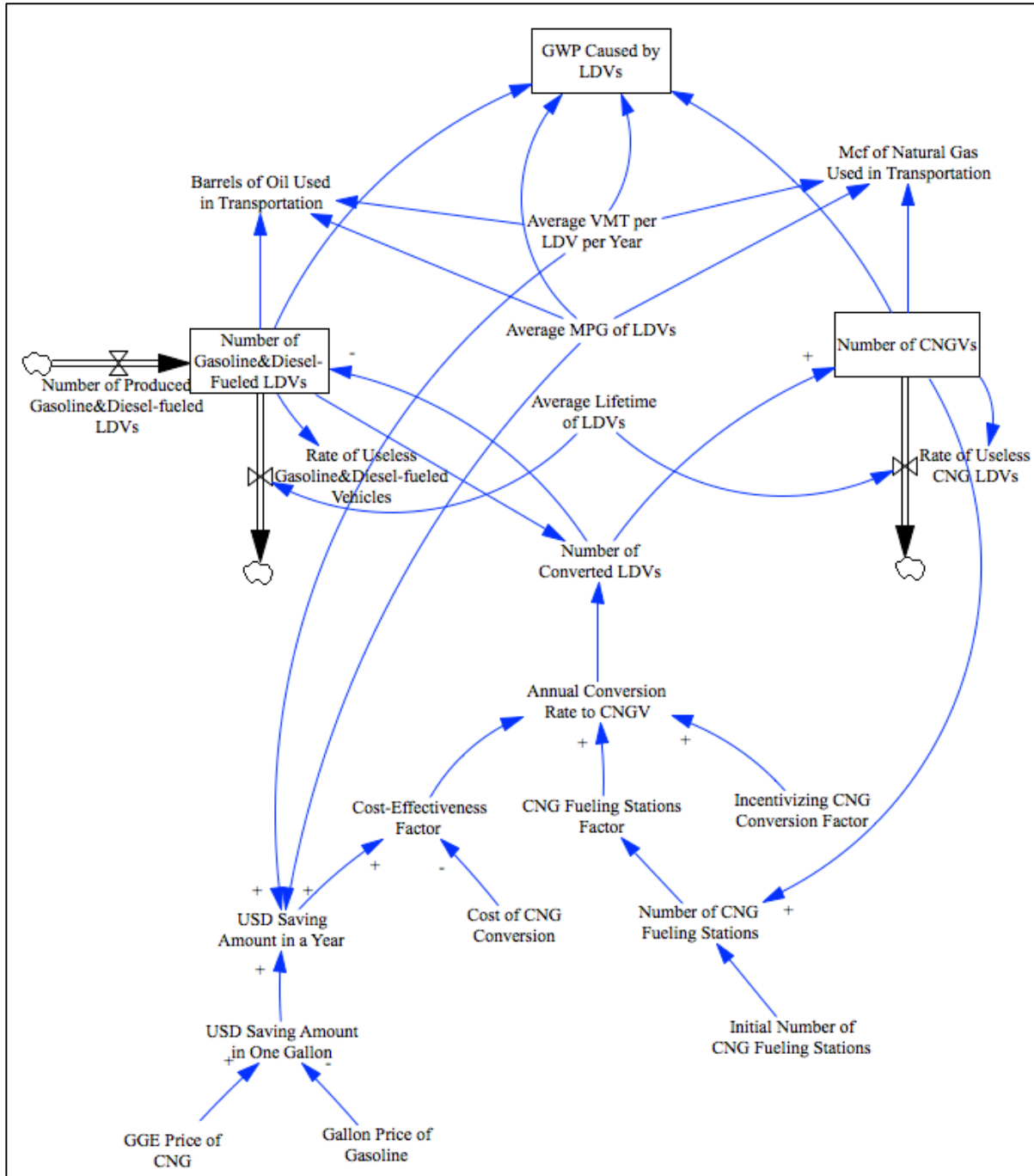
⁶ Hidrue et al., "Willingness to Pay for Electric Vehicles and Their Attributes."

- Fuel cost savings: A decision maker expects his/her decision to be cost-effective and benefit himself/herself in the long run. Therefore, fuel cost savings can be an attribute that individuals consider investing money in any alternative fuel vehicle.
- Conversion cost of a vehicle: The cost of conversion is the most important attribute together with fuel cost savings. Cost and savings will determine the cost-effectiveness of the investment of conversion.
- Number of fueling stations: If there are not enough fueling stations, then the investment of converting his/her vehicle cannot be cost-effective for an individual. Hence, this study considers the number of CNG fueling stations as an attribute that affects individual decision.
- Incentivizing CNG conversion: This includes the efforts of government, and non-state organizations to incentivize CNG conversion of individual vehicle owners. The most important government action may be subsidizing the cost of conversion.

System Dynamics Model of CNG Conversion

The model in Figure 12 illustrates the effects of CNG conversion at the systemic level. The individual choices on conversion affect the number of gasoline- and diesel-fueled LDVs and the number of converted CNGVs, which in turn affect oil and natural gas consumption in the U.S. An increase in natural gas consumption and a decrease in oil consumption ultimately affect the GWP caused by the LDV segment of the U.S. transport sector.

Figure 12: Stock-and-Flow Diagram of the CNG Conversion Model



The Variables Used in the Model

- Annual Conversion Rate to CNGV: This variable is calculated as a percentage value for each year from 2014 to 2050. The effects of three factors are assumed to be different. A decision-maker is assumed to give different weight in his/her decision. The weights are 60%, 25%, and 15% for cost-effectiveness factor, CNG fueling stations factor, and incentivizing CNG conversion factor respectively.
- Average Lifetime of LDVs: This data is the average age of LDVs in the U.S. The last available data indicates the average lifetime was 11.4 years in 2014. The annual increase for LDV ages is 0.0162 according to last 20 years' data.⁷
- Average MPG of LDVs: This is the average fuel efficiency of LDVs, calculated based on the miles driven with one gallon of gasoline. The average fuel efficiency was 21.4 MPG in 2014 with an annual increase rate of 0.0055 in the last 20 years.⁸
- Average VMT per LDV per Year: This data shows the annual miles driven by an LDV in the U.S. There is no trend in this data. It fluctuates in the last 20 years. Therefore, the average of the last 20 years is used in the model. The average VMT in the last 20 years was about 11,250 miles.⁹
- Barrels of Oil Used in Transportation: This data converts the consumed gasoline amount into the barrel value. Since the vast majority of vehicles are gasoline, gasoline-to-barrel conversion rate is used. 19 gallons of gasoline can be produced

⁷ U.S. Department of Transportation, "Average Age of Automobiles and Trucks in Operation in the United States."

⁸ U.S. Department of Transportation, "Average Fuel Efficiency of U.S. Light Duty Vehicles."

⁹ U.S. Department of Transportation, "Light Duty Vehicle, Short Wheel Base and Motorcycle Fuel Consumption and Travel."

from one barrel of oil.¹⁰

- **Cost of CNG Conversion:** This variable represents the cost of converting an LDV into a CNGV. In the model, a 1% decrease is assumed in this cost since the development in conversion technology will decrease the conversion cost.
- **Gallon Price of Gasoline:** Different data for this variable are given in the different scenarios in the following pages.
- **GGE Price of CNG:** Different data for this variable are given in the different scenarios in the following pages.
- **GWP Caused by LDVs:** This variable uses the consumed amount of gasoline and natural gas by LDV segment of the transport sector to calculate their aggregate global warming potential value. The value calculates GWP as CO₂ emissions. Different usages of these fuels (heating, electricity generation, transportation) create different values of GWP. Conventional natural gas and shale gas create different GWP outcomes. This study uses the outcome of shale gas since the U.S. will meet its domestic demand mostly through it.¹¹
- **Incentivizing CNG Conversion:** Different data for this variable are given in the different scenarios in the following pages. It is used as percentage.
- **Mcf of Natural Gas Used in Transportation:** The amount of GGE of CNG consumed in transportation is converted to Mcf (thousand cubic feet) of natural

¹⁰ For the conversion from gasoline to one gallon of crude oil, see U.S. Energy Information Administration, “How Many Gallons of Diesel Fuel and Gasoline Are Made from One Barrel of Oil?”

¹¹ For the effect of gasoline and shale gas consumption in transportation on the GWP, see Burnham et al., “Life-Cycle Greenhouse Gas Emissions of Shale Gas, Natural Gas, Coal, and Petroleum.”

gas by using the conversion rates of U.S. Department of Energy.¹²

- Initial Number of CNG Fueling Stations: Different data are given for this variable in the different scenarios. It shows the number of CNG fueling stations in the first year of the simulation. Currently, there are 904 public CNG fueling stations¹³. However, different values are given to see their results for the purposes of simulation.
- Number of CNG Fueling Stations: This variable reinforces “number of CNGVs” variable. The increase in the number of CNGVs causes an increase in the number of CNG fueling stations. It is assumed that the number of vehicle per fueling station will be the same as the ratio for gasoline vehicles. There are approximately 150,000 gasoline fueling stations and 236,010,000 LDVs in the U.S., meaning that 1,573 LDVs use a fueling station in average. If the initial number is given higher than the calculated number of CNG fueling stations, then the initial number for the CNG fueling stations data is used for this variable.
- Number of CNGVs: There is no data for the converted bi-fuel CNG LDVs in the U.S. Therefore, the simulation starts with zero CNGV in the first year. It shows the cumulative number of LDVs converted to CNGV.
- Number of Converted LDVs: This variable calculates the number of gasoline- and diesel-fueled vehicles that are converted to CNGV each year.
- Number of Gasoline- and Diesel-Fueled LDVs: This variable estimates the

¹² GGE is converted to Mcf by using comparison chart of the Alternative Fuel Data Center. For the chart, see U.S. Department of Energy, “Fuel Properties Comparison.”

¹³ For the actual number of CNG fueling stations, see U.S. Department of Energy, “Alternative Fueling Station Locator.”

changes in the number of gasoline- and diesel-fueled LDVs. For the starting value, the number of LDVs is used.¹⁴

- Price of Converting LDVs to CNG: Different data for this variable are given in the different scenarios in the following pages.
- Number of Produced Gasoline- and Diesel-Fueled LDVs: This variable represents the number of new vehicles sold in the U.S.¹⁵
- Rate of Useless CNG LDVs: This variable represents the LDVs that exit the system once their lifetime ends. The same lifetime data is used both for gasoline- and diesel-fueled vehicles and converted CNGVs.¹⁶
- Rate of Useless Gasoline- and Diesel-Fueled Vehicles: This variable represents the LDVs that exit the system once their lifetime ends.¹⁷
- USD Saving Amount in one year: This variable calculates how many USD a converted vehicle saves.
- USD Saving Amount in One Gallon: The difference between the price of one gallon of gasoline and the price of one GGE of CNG.

The detailed information about the variables including variable names, units, formulas, values, and explanations are presented in the Appendix section.

¹⁴ Since there is no separate data for gasoline- and diesel-fueled LDVs, the number of whole LDVs are used as the number of gasoline- and diesel-fueled LDVs. For the number of LDVs, see U.S. Department of Transportation, “Number of U.S. Aircraft, Vehicles, Vessels, and Other Conveyances.”

¹⁵ As the number fluctuates in the last 20 years, the average value of the last 20 years is used as the constant value for this variable. For the number of LDV sales in the U.S., see U.S. Department of Energy, “Light-Duty Vehicles Sold in the U.S.”

¹⁶ The data for this variable is generated by dividing the total number of CNG-fueled LDVs into the average lifetime of LDVs

¹⁷ The data for this variable is generated by dividing the total number of gasoline- and diesel-fueled LDVs into the average lifetime of LDVs

Validity of the System Dynamics Model

A system dynamics model is preferred as it can cover annual changes in the components (variables) of the system at the country level. The methodological approach could be different such as using agent-based modeling because the whole system is based on what agents (LDV owners that have probability to convert to CNGV) decide on converting their vehicles. However, there should be more than one agent in an agent-based model that can interact with the other. Another reason for not using this approach is examining the change in the country level. An agent-based model would be better suited for studies that examine the case on a smaller scale.

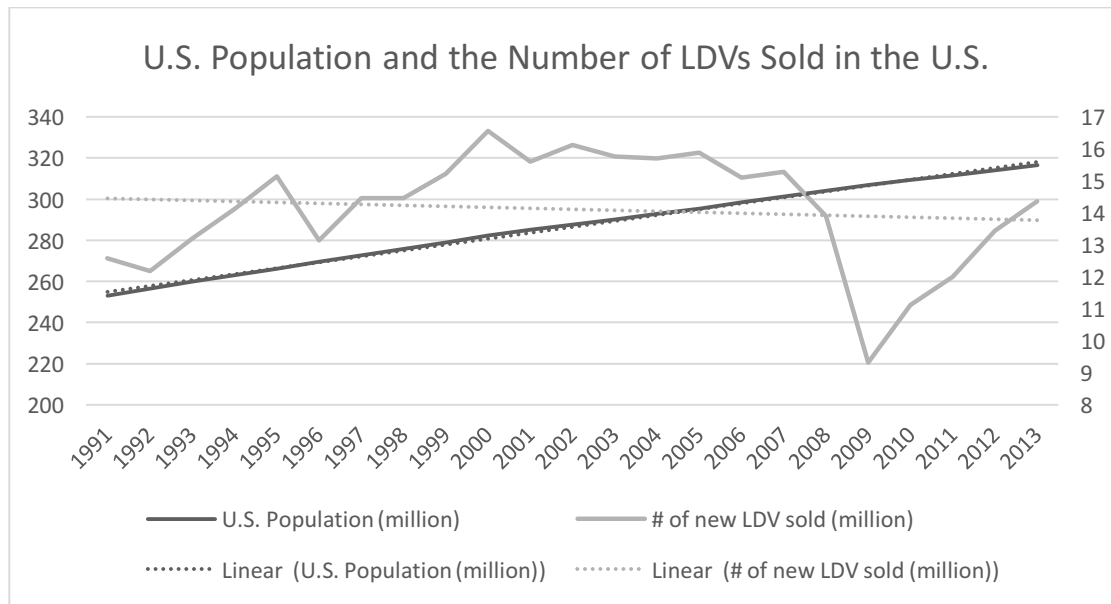
The model could have more detailed data including representations of time lags between some variables. However, the model is kept as parsimonious as possible to provide a simpler view of effects of conversion on the two major energy-related problems of the U.S. at the country level.

A growth rate based on LDV per person could have been used for the new gasoline- and diesel-fueled vehicles that enter into the system each year. However, as illustrated in Figure 13, there is no meaningful trend between the increase in the U.S. population and the number of new LDVs sold each year. Hence, a constant value that represents the average number of new LDVs sold in the last 20 years is used to represent the input value of LDVs in the system dynamics model.

The assumptions of the system are intuitive. In its ultimate point, the fossil fuels consumed, which are shale gas and gasoline/diesel in this model, cause a change in GWP. The data source for how much GWP they produce is discussed in the variables section above. An important limitation of the model is the factors that affect individual decision-making behavior to convert their vehicles to CNGVs. To the best of my knowledge, there are no studies that examine

individual decision-making in CNG conversion case either in the U.S. or in any other level.

Figure 13: U.S. Population and the Number of LDVs Sold in the U.S.



Source: The chart is created by the author with the data drawn from the World Bank Website¹⁸ and Alternative Fuel Data Center¹⁹

The causalities of three major outputs of the system are illustrated in Figure 14, Figure 15, Figure 16, and Figure 17. In the first one of these figures, the average fuel consumption of natural gas and petroleum products affect GWP. Burning these fuels causes GHG emissions, which are considered as GWP in the model. The intervening variables are the average VMT of LDVs and average MPG consumption of LDV. The second and third ones show the causality of natural gas and oil consumption respectively. Their intervening variables are average VMT of LDVs and the number of dedicated gasoline/diesel vehicles for oil consumption and the number of converted CNGVs for natural gas consumption.

¹⁸ The World Bank, "Population, Total | Data | Table."

¹⁹ U.S. Department of Energy, "Light-Duty Vehicles Sold in the U.S."

Figure 14: Causes Tree of the GWP Variable

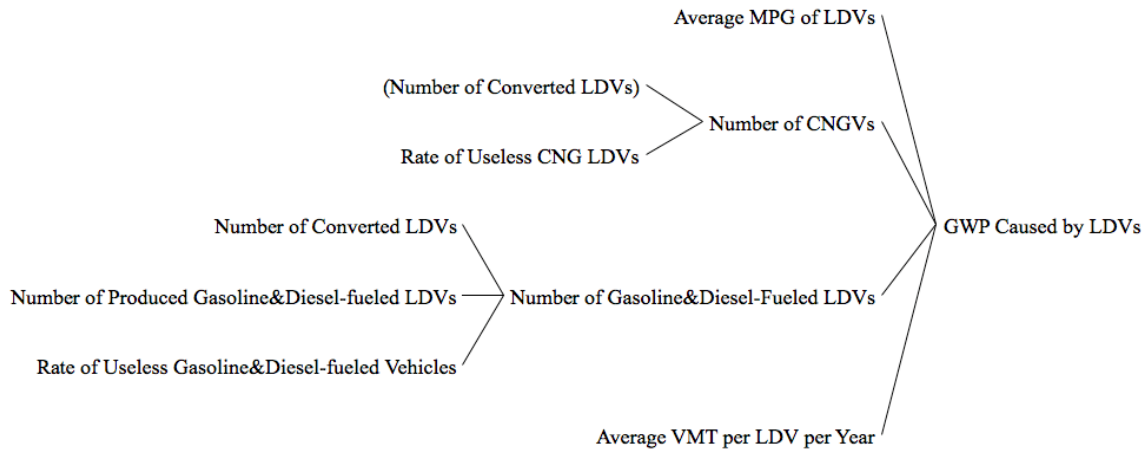


Figure 15: Causes Tree of the Amount of Natural Gas Consumed in Transportation

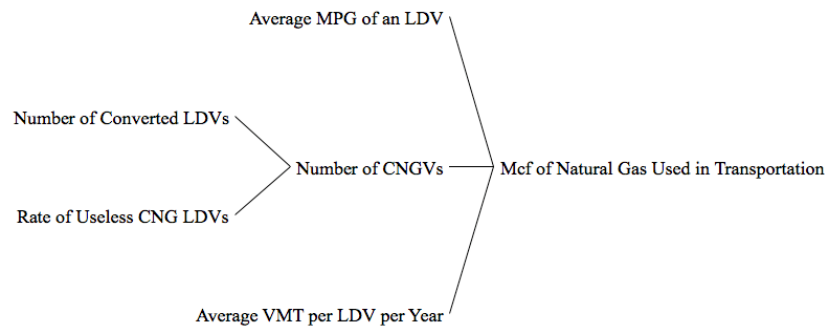


Figure 16: Causes Tree of the Amount of Oil Consumed in Transportation

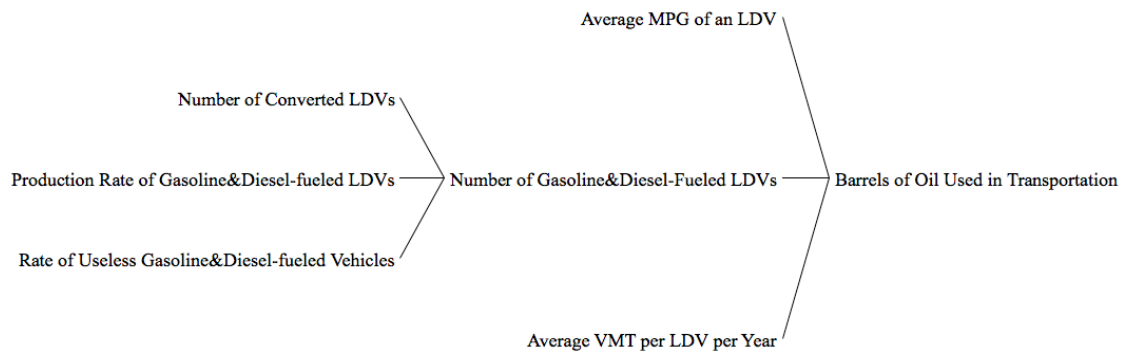
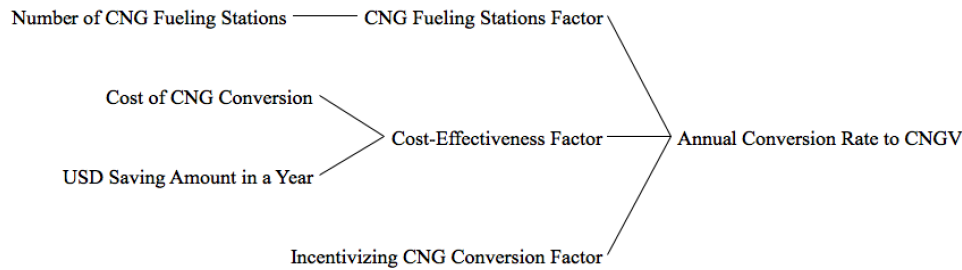


Figure 17: Causes Tree of the Annual Conversion Rate to CNGV Variable



As briefly mentioned above, the individual decision-making behavior of LDV owners is a limitation of the model. Since there are no studies on the effects of decision making to convert to CNGV, the causality is assumed. Three major factors are assumed to affect decision-makers, who are represented as “Annual Conversion Rate to CNGV” in the model as illustrated in Figure 17. These factors are the number of CNG fueling stations, the cost-effectiveness of the conversion, and incentivization of decision-makers to convert their LDVs. People are assumed to give these weights to these three factors respectively: 25%, 60%, and 15%. A survey study, which is conducted on a possible population that may convert their vehicles to CNGV, would give a better image of these factors, and their weights in individual decision-maker behavior on conversion.

Average MPG and the lifetime of LDVs are two variables that do not depend on vehicle conversion rate. They are calculated according to their increase rate in the last 20 year’s data by assuming they will keep the same trend in their increase rate. Figure 18 and Figure 19 illustrate the projected change in their value until 2050.

Figure 18: Average MPG of LDVs from 2014 to 2050

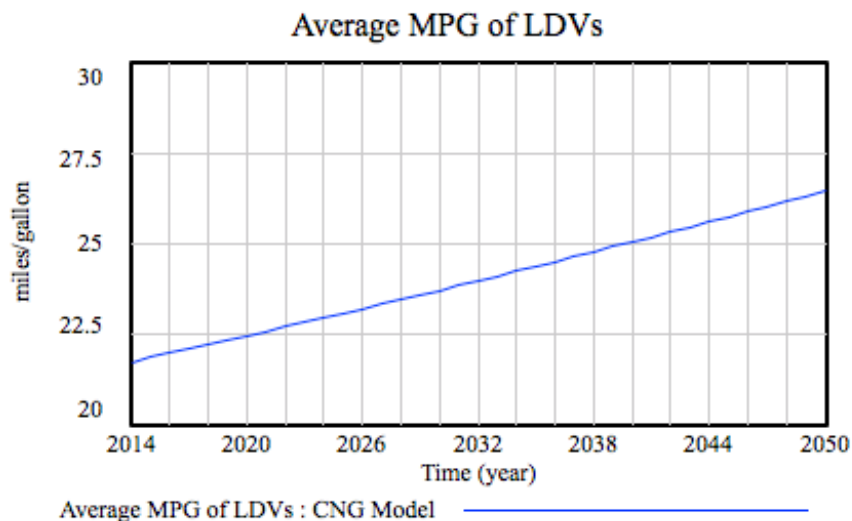
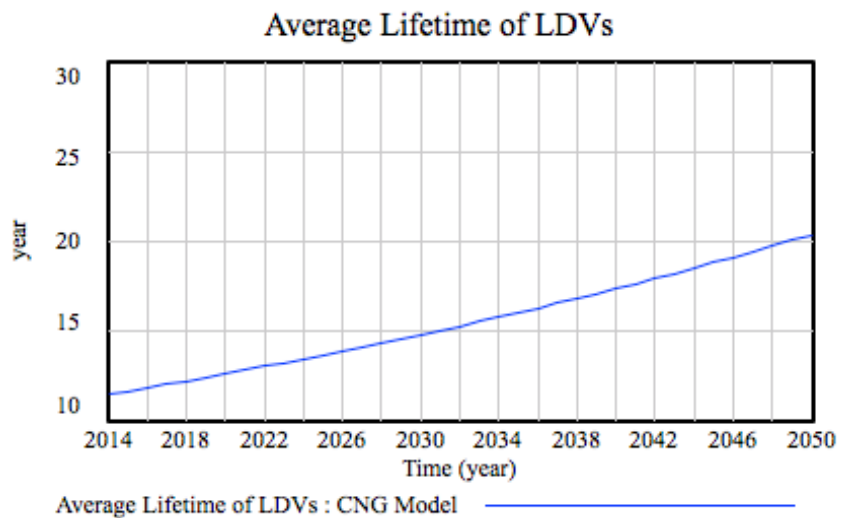


Figure 19: Average Lifetime of LDVs from 2014 to 2050



Three Scenarios Based on Different Values

Three different scenarios, as well as a no-conversion scenario, are created according to different values of attributes that affect the decision-making of individuals. The variables that can be changed in the model are:

- GGE Price of CNG
- Gallon Price of Gasoline
- Cost of CNG Conversion
- Number of CNG Fueling Stations
- Incentivizing CNG Conversion Factor

The remaining variables are calculated according to changes in these variables. The scenarios are created to see their effect on the output of oil and natural gas consumption and GWP potential at the country level.

Table 4: The Data Used in Three Scenarios

	Scenario 1	Scenario 2	Scenario 3
GGE Price of CNG	US\$1.00	US\$1.50	US\$1.00
Gallon Price of Gasoline	US\$1.50	US\$3.00	US\$3.50
Cost of CNG Conversion	US\$5,000	US\$4,000	US\$3,500
Incentivizing CNG Conversion	%20	%50	%70
Initial Number of CNG Fueling Stations	3,000	10,000	50,000

Simulation Results

Figure 20: Annual Conversion Rate in Three Scenarios and No Conversion Case from 2014 to 2050

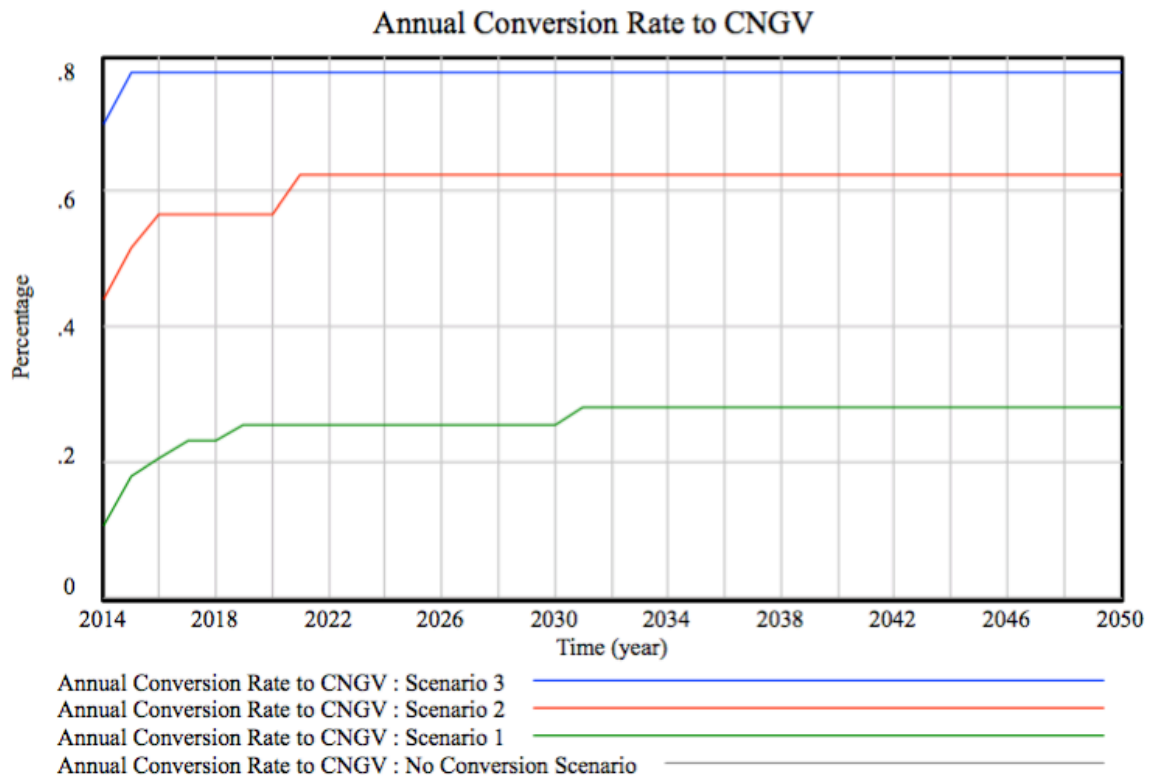


Figure 21: Number of Converted LDVs in Three Scenarios and No Conversion Case from 2014 to 2050

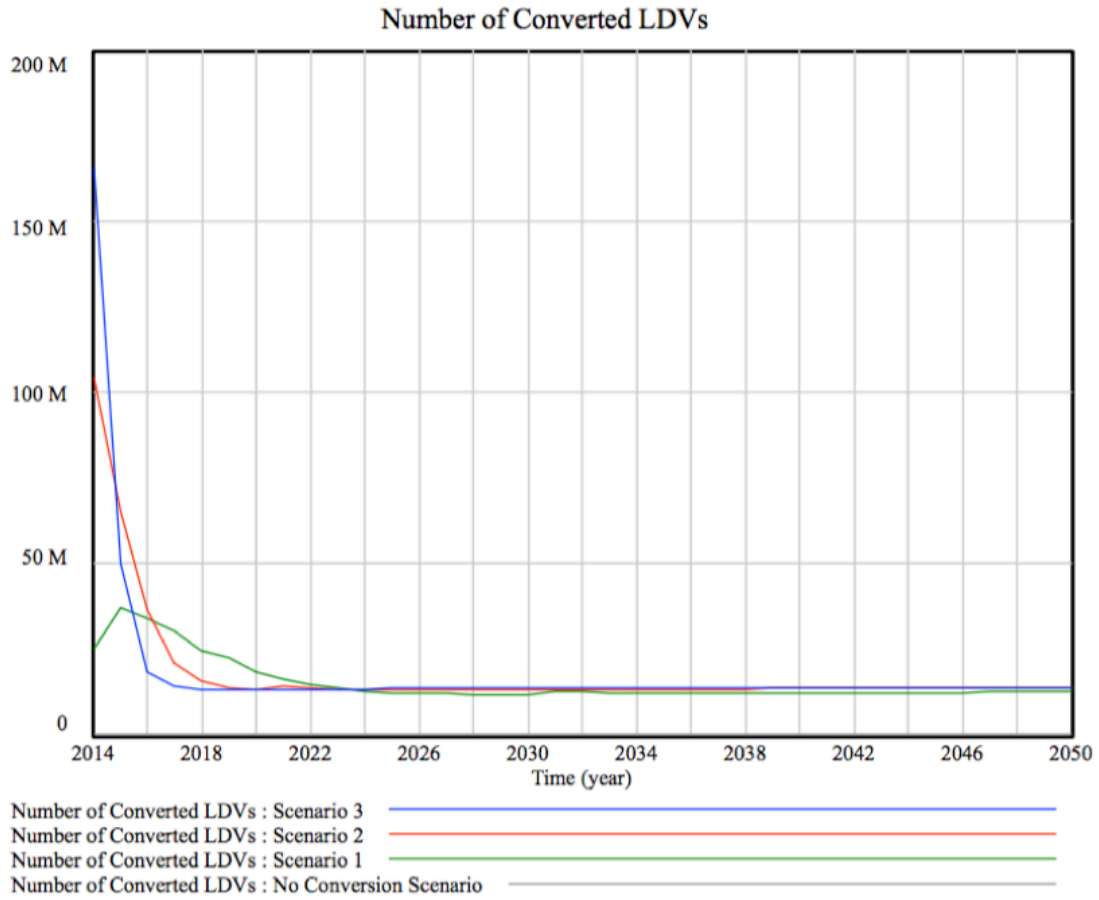


Figure 22: Number of CNGVs in Three Scenarios and No Conversion Case from 2014 to 2050

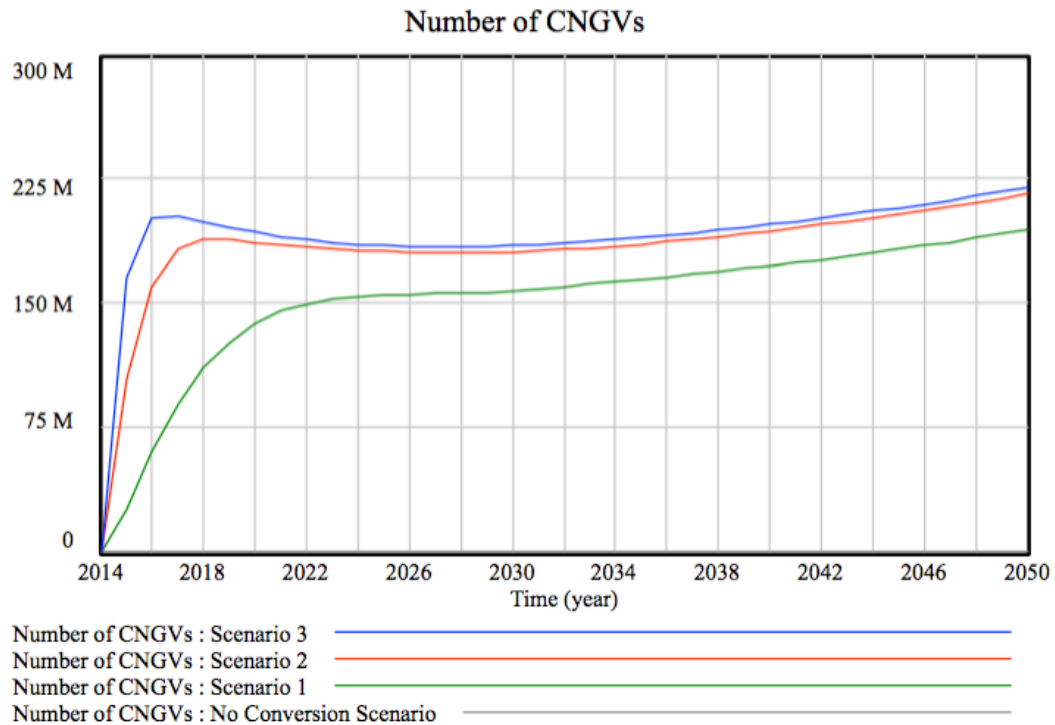


Figure 23: Number of Gasoline- and Diesel-Fueled LDVs in Three Scenarios and No Conversion Case from 2014 to 2050

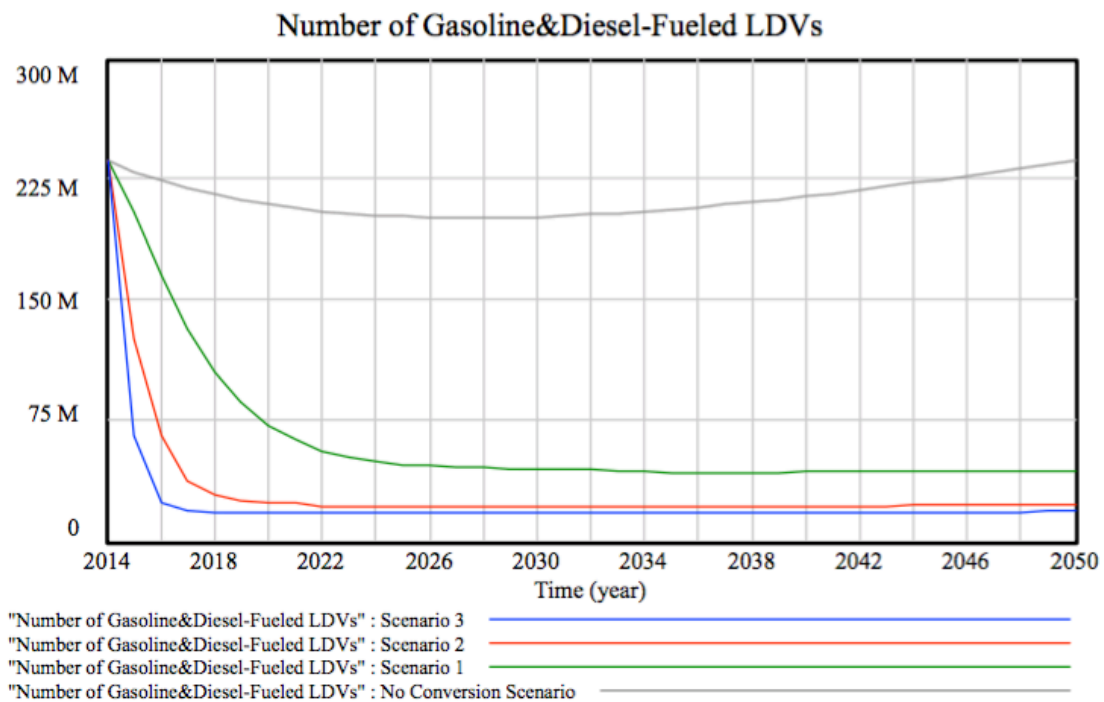


Figure 24: Mcf of Natural Gas Consumed in Three Scenarios and No Conversion Case from 2014 to 2050

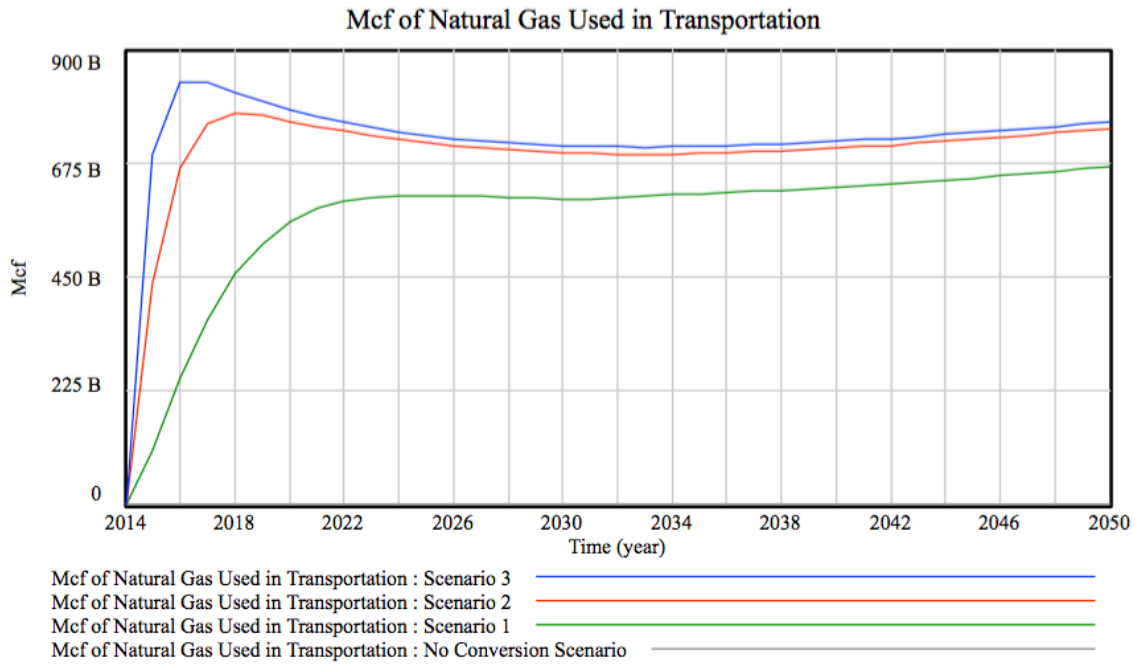


Figure 25: Barrels of Oil Consumed in Three Scenarios and No Conversion Case from 2014 to 2050

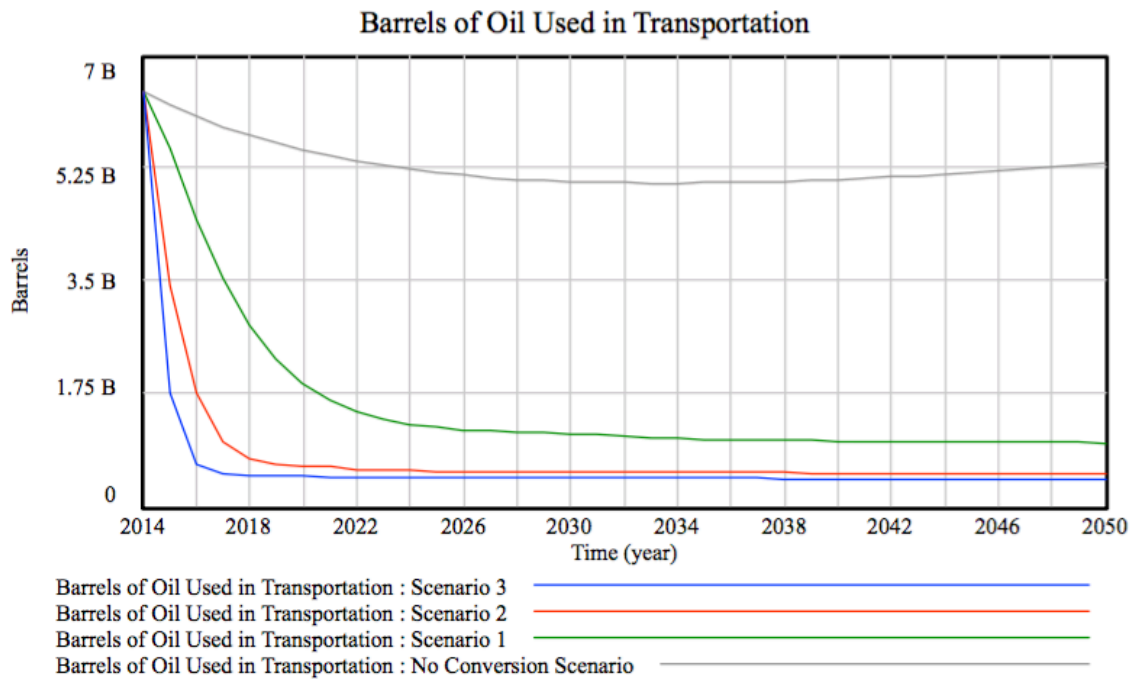
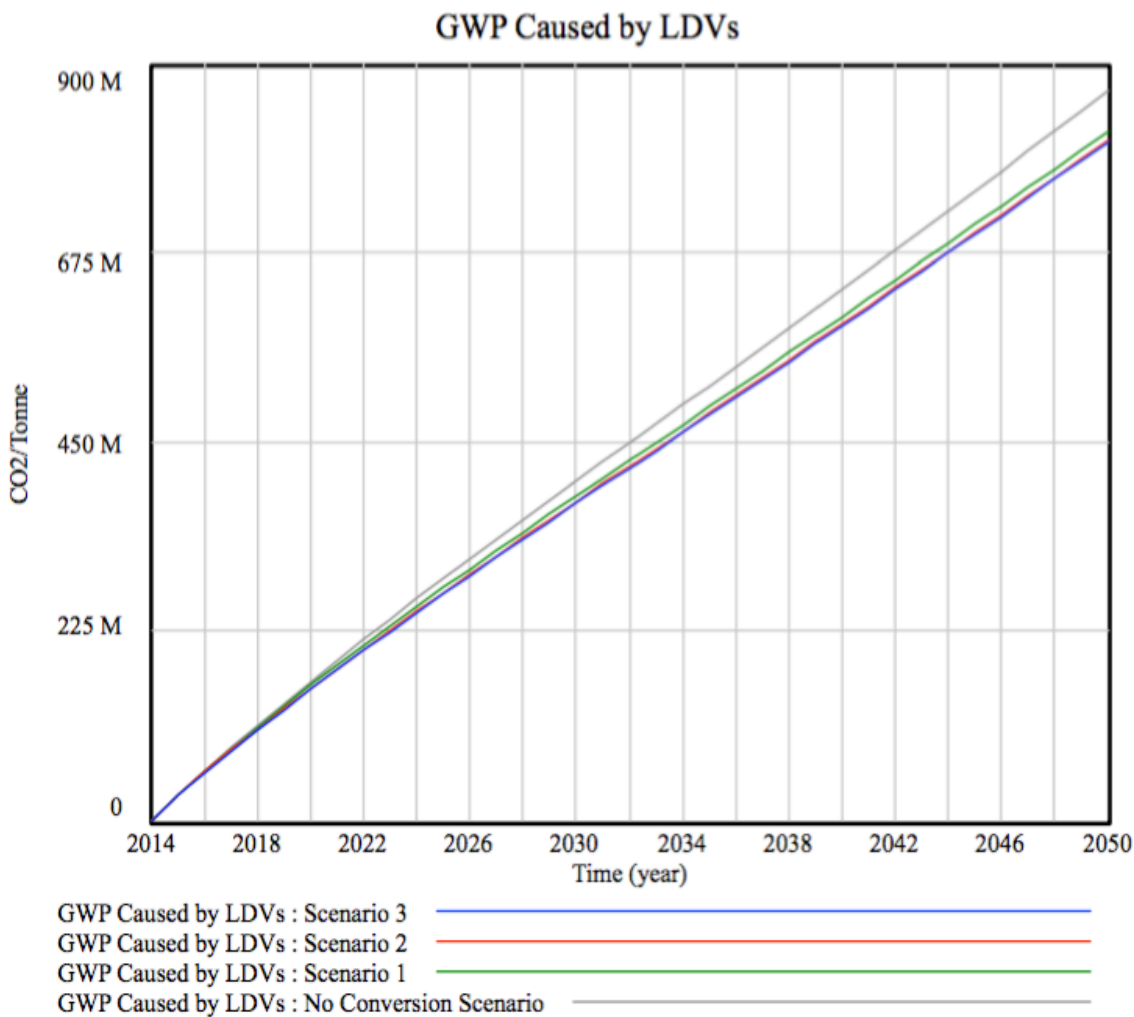


Figure 26: GWP Caused by LDVs in Three Scenarios and No Conversion Case from 2014 to 2050



Conclusion

This chapter evaluated the effects of switching to CNG in the U.S. LDV fleet by using system dynamics model. The model's ultimate outputs are the amounts of natural gas and oil consumption and GHG emissions caused by the LDV transport sector. Three scenarios are used to evaluate different outcomes for the different values that can change these outputs. The changes in GGE price of CNG, gallon price of gasoline, cost of CNG conversion, the number of

CNG fueling stations, and incentivizing CNG conversion factor have the ability to affect the ultimate outputs. Therefore, the model suggests making changes in these variables in order to increase usage of CNG in LDVs by many people.

Based on the findings of the model and the information that is available, this research recommends that there be a shift towards the use of CNGVs in the short to middle term in the U.S LDV fleet. This is because doing so has economic and environmental benefits which can also help the U.S. to become more energy independent and rely less on foreign energy sources.

CHAPTER VI

CONCLUSION

This study evaluated the impact of switching to CNG in the U.S. LDV fleet. The findings suggest that converting the current LDV fleet to CNGV will provide important benefits. This study's argument is significant as it provides an alternative to an important amount of U.S. oil consumption in the short to middle term via fuel-switching in the transport sector. It provides a solution for decreasing both U.S. dependence on foreign oil and its anthropogenic GHG emissions.

The study started with evaluating the energy security after the shale boom. The shale boom changed the understanding of energy security in the U.S. The first chapter compared oil and natural gas by using a definition of energy security. This definition used availability, accessibility, acceptability and affordability criteria for comparison. The reason only oil and natural gas are compared is that this study aims to replace oil with natural gas in transportation. The analysis of the U.S. energy security in terms of 4A's of energy security showed that the U.S. is better off using natural gas.

The share of transport sector at both the global and U.S. levels is presented in Chapter 3. The transport sector accounts for 28% of energy consumption in the U.S. and 19% in the world. In both the U.S. and in the world, the transport sector is heavily dependent on oil products by over 90%. LDVs make up of 58% of transport sector's energy consumption in the U.S. There are various ways to reduce oil consumption in the U.S. These include improving fuel efficiency, improving operation practices, reducing travel demand by car, and switching towards other alternative fuels. Although this study focuses on fuel switching, it is important to note that this

strategy can provide the best solution in the long term if it is used together with the first three strategies. The U.S. Department of Energy features six types of alternative fuel vehicle fuels: biodiesel, electricity, ethanol, hydrogen, natural gas, and propane. This study focuses on natural gas via using it in a compressed form in LDVs.

Chapter 4 examines what the role of shale gas can be for the U.S. LDV fleet. It starts with a price comparison of featured alternative fuel vehicles in the U.S. This incorporates their use in the current and mature technology scenarios. The cost makes natural gas the most prominent among others. It becomes slightly more expensive in a long-term projection to 2050. This supports the argument of this study that says natural gas is the best solution in the short to middle term. However, as discussed in this chapter, it should not be considered as a long-term solution as its usage in BEVs and FCEVs provide a better solution. The long-term projections should be based on its usage in electricity generation.

The last chapter sets up a system dynamics model to examine the effects of switching to CNG in LDVs in the U.S. The model's main outputs are oil and natural gas consumption, and GHG emissions. These values change depending on changes in GGE price of CNG, gallon price of gasoline, cost of CNG conversion, the number of CNG fueling stations, and incentivizing CNG conversion factor. Three different scenarios are simulated in this system dynamics model as well as a no conversion scenario. These scenarios produce very different outcomes depending on the aforementioned variables that can be manipulated by policy makers.

Policy Suggestions

Natural gas can provide benefits for decreasing U.S. energy dependency and GHG emissions in an important way only if it is used widely. In order to increase utilization rate,

policy makers can manipulate the variables that are used in the scenarios of this study. Carbon taxes might be important to increase the price of gasoline while keeping natural gas prices constant.

Incentivizing CNG conversion can happen in many ways. As quoted from President Obama at the beginning of the study, policy figures can promote CNGVs more in their speeches. This can raise awareness and help to increase the number of people that convert their vehicles to CNG. The second way of promoting this initiative can be using incentives for alternative fuel vehicles. The government can support people by paying some part of conversion cost. Also, financial institutions can provide long-term credits to allow people to pay as they save from the difference between gasoline and CNG prices.

The cost of CNG conversion and the number of CNG fueling stations are mostly dependent on demand. The number of CNG fueling stations will increase and the cost of CNG conversion will decrease as the demand rises. Therefore, policy makers are the key actors in the solution. If they implement some policies such as carbon taxation and incentivize people to convert their vehicles to CNG, they can contribute to the solution of two important energy-related problems of the U.S.

Limitations of the Study

There are researches about individual decision-making behavior for EV types. To date however, there is no study that examines the factors a decision maker consider when making his/her decision to convert his/her gasoline- and diesel-fueled LDV to CNGV. The formulation of the decision-making part of the system dynamics model is based on assumptions. The magnitude of these factors is also needed to be collected from the potential individual decision

makers on this issue. Although the system dynamics model is flexible enough to manipulate and get different results based on the different scenarios, an accurate knowledge of individual decision-making behavior for CNG conversion would make the model stronger.

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APPENDIX

THE VARIABLES USED IN THE SYSTEM DYNAMICS MODEL

(01) Annual Conversion Rate to CNGV = CNG Fueling Stations Factor*0.25+"Cost-Effectiveness Factor"*0.6+Incentivizing CNG Conversion Factor*0.15

Units: Percentage

The weights of three factors are assumed to be different for decision makers.

(02) Average Lifetime of LDVs = INTEG (Average Lifetime of LDVs*0.0162, 11.4)

Units: year

There is a lifetime for LDVs. After completing their lifetime, LDVs exit the system. Average lifetime of the US LDV fleet is 11.4 as of 2014. The average age has increased 0.0162 every year from 1995 to 2014. Average lifetime for next years is calculated based on the increase rate in the past 20 years.

(03) Average MPG of LDVs = INTEG (Average MPG of LDVs*0.0055, 21.7)

Units: miles/gallon

The annual change in average fuel efficiency of the whole U.S. LDV fleet was 0.0055 in the last 20 years. The calculation of MPG in the next years is based on the increase rate of the last 20 years.

(04) Average VMT per LDV per Year = 11250

Units: miles

Although there are fluctuations in this value, it remains pretty same (In 1995, it was 11,234 miles. In 2012, it was 11,264). Hence, it is used as a constant value.

(05) Barrels of Oil Used in Transportation =

"Number of Gasoline&Diesel-Fueled LDVs"*(Average VMT per LDV per Year/Average MPG of LDVs)/19

Units: Barrels

"Refineries in the United States produced an average of about 12 gallons of diesel fuel and 19 gallons of gasoline from one barrel (42 gallons) of crude oil in 2014". (US EIA) This study took 19 gallons to calculate barrels of oil consumed because gasoline consumption has always been much higher in the US compared to diesel consumption.

```

(06)           CNG Fueling Stations Factor = IF THEN ELSE( Number of
CNG Fueling Stations>1:AND:Number of CNG Fueling Stations<=1000, 0.1,
           IF THEN ELSE( Number of CNG
Fueling Stations>1000:AND:Number of CNG Fueling Stations<=2500 , 0.2 ,
           IF THEN ELSE( Number of CNG
Fueling Stations>2500:AND:Number of CNG Fueling Stations<=5000 , 0.3 ,
           IF THEN ELSE( Number of CNG
Fueling Stations>5000:AND:Number of CNG Fueling Stations<=7500 , 0.4 ,
           IF THEN ELSE( Number of CNG
Fueling Stations>7500:AND:Number of CNG Fueling Stations<=10000 , 0.5
,
           IF THEN ELSE( Number of CNG
Fueling Stations>10000:AND:Number of CNG Fueling Stations<=25000 , 0.6
,
           IF THEN ELSE( Number of CNG
Fueling Stations>25000:AND:Number of CNG Fueling Stations<=50000 , 0.7
,
           IF THEN ELSE( Number of CNG
Fueling Stations>50000:AND:Number of CNG Fueling Stations
           <=75000 , 0.8 ,
           IF THEN ELSE( Number of CNG
Fueling Stations>75000:AND:Number of CNG Fueling Stations
           <=100000 , 0.9 ,
           IF THEN ELSE( Number of
CNG Fueling Stations>100000 , 1 ,
           0.01
           )
           )
           )
           )
           )
           )
           )
           )
           )
           )

```

Units: **undefined**

The rate of the number of CNG fueling stations per gasoline- and diesel-fueled LDV affects individual decision-making on converting their vehicle to CNGV.

```

(07)           Cost of CNG Conversion= INTEG (IF THEN ELSE( Cost of
CNG Conversion>=2000 , -Cost of CNG Conversion*0.01, 0 ),3500)

```

Units: usd

Conversion price will lower over time. A 0.01% decrease is assumed to lower each year. The price will not go lower than \$2000, which is the minimum cost for conversion companies.

```
(08)          "Cost-Effectiveness Factor"=
              IF THEN ELSE( Cost of CNG
Conversion <= USD Saving Amount in a Year , 0.9,
              IF THEN ELSE( Cost of CNG
Conversion <= USD Saving Amount in a Year*2 , 0.8 ,
              IF THEN ELSE( Cost of CNG
Conversion <= USD Saving Amount in a Year*3 , 0.7 ,
              IF THEN ELSE( Cost of CNG
Conversion <= USD Saving Amount in a Year*4 , 0.6 ,
              IF THEN ELSE( Cost of CNG
Conversion <= USD Saving Amount in a Year*5 , 0.5 ,
              IF THEN ELSE( Cost of CNG
Conversion <= USD Saving Amount in a Year*6 , 0.4 ,
              IF THEN ELSE( Cost of CNG
Conversion <= USD Saving Amount in a Year*7 , 0.3 ,
              IF THEN ELSE( Cost of CNG
Conversion <= USD Saving Amount in a Year*8 , 0.2 ,
              IF THEN ELSE( Cost of CNG
Conversion <= USD Saving Amount in a Year*9 , 0.1 ,
              0
              )
              )
              )
              )
              )
              )
              )
              )
              )
              )
```

Units: **undefined**

If the conversion is cost-effective in a year, then this will affect 90% of its rate in annual conversion rate.

```
(09)          FINAL TIME = 2050
              Units: year
              Simulation runs until 2050.
```

```
(10)          Gallon Price of Gasoline = 3.5
              Units: usd
              Average Gallon Price of Gasoline
```

- (11) GGE Price of CNG = 1
Units: usd
GGE Price of CNG.
- (12) GWP Caused by LDVs= INTEG ("Number of Gasoline&Diesel-Fueled LDVs"*(Average VMT per LDV per Year/Average MPG of LDVs)*0.00024+Number of CNGVs*(Average VMT per LDV per Year/Average MPG of LDVs)*0.0002208, 0)
Units: CO₂/Tonne
100 years GWP used too see their effects. The GWP values are taken from Burnham et al's study (2012). All natural gas consumption assumed to be met by shale gas production.
- (13) Incentivizing CNG Conversion Factor=0.7
Units: **undefined**
This variable represents what government and NGOs do to encourage people to convert their vehicle to CNGV. This is rated between 1 and 10 indicating the least encouragement and the most encouragement respectively.
- (14) Initial Number of CNG Fueling Stations = 50000
Units: **undefined**
- (15) INITIAL TIME = 2014
Units: year
Simulation starts in 2014 since the last available data belongs to 2014 for most of variables.
- (16) Mcf of Natural Gas Used in Transportation = Number of CNGVs*(Average VMT per LDV per Year/Average MPG of LDVs)/0.123581
Units: Mcf
1 GGE of CNG is equal to 0.123580786026201 Mcf of natural gas.
- (17) Number of CNG Fueling Stations = IF THEN ELSE(Number of CNGVs/1573.4 < Initial Number of CNG Fueling Stations , Initial Number of CNG Fueling Stations , Number of CNGVs/1573.4)
Units: **undefined**
This variable calculates the ideal number of CNG fueling stations that depends on the number of converted CNGVs. If the ideal number is less than the initial number of CNG fueling stations, then the value of this variable becomes the ideal number of CNG fueling stations. (1587 is the data found by dividing current number of LDVs 238 million to the current number of gasoline fueling station 150k.)

(18) Number of CNGVs= INTEG (Number of Converted LDVs-Rate of Useless CNG LDVs,0)

Units: **undefined**

The number of CNGVs starts with zero since there is no available data on the number of converted CNGVs.

(19) Number of Converted LDVs = Annual Conversion Rate to CNGV*"Number of Gasoline&Diesel-Fueled LDVs"

Units: **undefined**

This variable represents changes in each year. The data created by this variable are added to the number of CNGVs and subtracted from the number of gasoline- and diesel-fueled LDVs.

(20) "Number of Gasoline&Diesel-Fueled LDVs"= INTEG ("Number of Produced Gasoline&Diesel-fueled LDVs"- "Rate of Useless Gasoline&Diesel-fueled Vehicles"-Number of Converted LDVs, 2.3601e+08)

Units: **undefined**

As there is no separate data for the number of gasoline- and diesel-fueled LDVs, the number of all LDVs in the U.S. fleet is considered as the number of gasoline- and diesel-fueled LDVs.

(21) "Number of Produced Gasoline&Diesel-fueled LDVs"= 1.4283e+07

Units: **undefined**

Since the US car market is saturated, the number of new vehicles sold every year is almost constant. Therefore, a constant value is used here. (The value is the average of last 20 years' data for LDV sales in the US.)

(22) Rate of Useless CNG LDVs = Number of CNGVs/Average Lifetime of LDVs

Units: **undefined**

This variable calculates the rate of CNGVs that complete their lifetimes.

(23) "Rate of Useless Gasoline&Diesel-fueled Vehicles" = "Number of Gasoline&Diesel-Fueled LDVs"/Average Lifetime of LDVs

Units: **undefined**

This variable calculates the rate of gasoline- and diesel-fueled LDVs that complete their lifetimes.

(24) SAVEPER = TIME STEP

Units: year [0,?]

The frequency with which output is stored.

(25)

TIME STEP = 1

Units: year [0,?]

The time step for the simulation.

(26)

USD Saving Amount in a Year = USD Saving Amount in
One Gallon*(Average VMT per LDV per Year/Average MPG of LDVs)

Units: usd

(27)

USD Saving Amount in One Gallon = Gallon Price of
Gasoline-GGE Price of CNG

Units: usd

This variable calculates the saving of an individual
LDV owner in one gallon if s/he converts her/his vehicle into a CNGV.

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