ON THE ROAD TO REPLACING OIL:

A WELL-TO-WHEELS STUDY EXPLORING ALTERNATIVE

TRANSPORTATION FUELS AND VEHICLE SYSTEMS

by

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Prof. Gregory Bothun, Ph.D.

Growing concerns about the depletion of world oil supplies and the resulting consequences, as well as concerns about global climate change motivate us to find solutions to replace oil consumption while reducing greenhouse gas emissions. This study explores the performance of various alternative transportation fuels and vehicle systems to reduce consumption of oil and other fossil fuels as well as emissions of greenhouse gases and several harmful pollutants. This study focuses on the light-duty vehicle fleet (all vehicles less than 8,500 pounds) as this segment of the transport fleet accounts for the bulk of transportation oil consumption. To provide a means to objectively compare the energy and emission effects of various fuels and vehicle technologies, this study conducts what is known as a 'well-to-wheels' analysis of each of the full fuel/vehicle pathways considered in this study. That is, this study quantifies the energy use and emissions along the entire fuel pathway that are associated with each mile traveled by a vehicle fueled with a specific fuel.

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NOTATION

Acronyms and Abbreviations-

ANL	Argonne National Laboratory
ASPO	Association for the Study of Peak Oil
BEV	battery electric vehicle
CAIR	Clean Air Interstate Rule
CIA	United States Central Intelligence Agency
CIDI	compression-ignition direct-injection (engine)
CH_4	methane
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CTR	Center for Transportation Research (at ANL)
DOE	United States Department of Energy
EBAMM	Energy Resource Group Biofuels Analysis Meta-Model
E85	ethanol blend: 85% ethanol, 15% reformulated gasoline by volume
EIA	United States Energy Information Administration
EPA	United States Environmental Protection Agency
EtOH	ethanol
FC	fuel cell
FCV	fuel cell vehicle
FHWA	United States Department of Transportation, Federal Highway Administration
GM	General Motors
GH2	gaseous hydrogen
GHG(s)	greenhouse gas(es)
GREET	Greenhouse gases Regulated Emissions and Energy use in Transportation model
GWP	global warming potential (of greenhouse gases; 100-year time horizon)
H_2	hydrogen
HEV	hybrid-electric vehicle
HHV	higher heating value
HVDC	high voltage direct current (transmission lines)
ICE	internal combustion engine
ICEV	internal combustion engine vehicle
IEA	International Energy Agency

IGCC	integrated gasification combined cycle (power plant)
IPCC	Intergovernmental Panel on Climate Change
LH2	liquid hydrogen
LHV	lower heating value
Li ion	lithium ion (batteries)
LPG	liquefied petroleum gas
LSD	low-sulfur diesel (15-ppm sulfur)
MTBE	methyl tertiary butyl ether
NA	North American
NG	Natural gas
NiMH	nickel-metal hydride (batteries)
N-NA	Non-North American
N_2O	nitrous oxide
NO_x	oxides of nitrogen
NRC	National Research Council (of the National Academies of Science and Engineering)
NREL	National Renewable Energy Laboratory
O_2	Oxygen
OPEC	Organization of the Petroleum Exporting Countries
ORNL	Oak Ridge National Laboratory
PC	pulverized coal (power plant)
PEM	proton exchange membrane (fuel cell)
PHEV	plug-in hybrid electric vehicle
PM	particulate matter
PM10	particulate matter smaller than 10 microns in diameter
PtW	pump-to-wheels (vehicle fueling and operation stage)
RFG	reformulated-gasoline (30-ppm sulfur, EtOH oxygenate, 2.3% by weight)
S	sulfur
SI	spark-ignition
SO_x	oxides of sulfur
UC	University of California
U.S.	United States of America
USDA	United States Department of Agriculture
VMT	vehicle miles traveled
VOC(s)	volatile organic compounds

WtW	well-to-wheels (complete fuel/vehicle system pathway)
WtP	well-to-pump (feedstock and fuel production and transportation stage)

Units of Measure-

Bbbl	billion barrels (of oil)
Bbbl/y	billion barrels (of oil) per year
bbl	barrel(s) (of oil)
Btu	British thermal unit(s)
bu	bushel (of corn)
dt	dry ton (of biomass)
F	Fahrenheit
g	gram(s)
gal	gallon(s)
GW	gigawatts (1 GW = 10^9 watts)
GWh	gigawatt-hours (1 GW = 10^9 watt-hours)
in.	inch(es)
K	Kelvin
kV	kilovolt(s)
kWh	kilowatt-hours (1 kWh = 10^3 watt-hours)
lb(s)	pound(s)
m	meter(s)
mi	mile(s)
mmbbl/d	million barrels (of oil) per day
mmBtu	million British thermal units
MW	megawatts (1 MW = 10^6 watts)
ppm	parts per millions
psi	pounds per square inch
SCF	standard cubic foot

EXECUTIVE SUMMARY

The primary goal of this study is to determine the potential of various alternative transportation fuels and vehicle propulsion systems to reduce the consumption of petroleum-based fuels in the light-duty transportation sector.[1] This sector is the largest consumer of petroleum in the United States and is almost entirely reliant on petroleum-based fuels. Considering increases in global oil prices, concerns about the impending peak in world oil production and the ever increasing share of imported oil and associated consequences, it is crucial that the United States begin a transition towards alternative vehicles utilizing fuels derived from domestically available, and as much as possible, renewable energy sources. Other motivations included determining the ability of these alternative fuels and vehicles to reduce emissions of greenhouse gases (GHGs) and harmful pollutants. The light-duty transport sector is a large contributor to total United States greenhouse gas emissions, and amidst growing concern about global climate change, finding ways to reduce GHGs resulting from light-duty transport could prove equally as import as reducing petroleum use.

In light of these goals and motivations, this study seeks to evaluate the relative performance of different alternative fuels and vehicles in reducing our fossil and petroleum energy use, as well as emissions of GHGs and harmful pollutants. To provide an accurate and adequate evaluation of the energy and emission effects of various fuels and vehicle technologies, it is crucial to analyze the energy use and emissions associated with both the vehicle operation (or pump-to-wheels) stage, as well as upstream fuel production-related (or well-to-pump) stages. As such, this study conducts what is known as a 'well-to-wheels'

[1] The light-duty transport section includes all vehicles under 8,500 lbs. This includes personal and fleet vehicles including cars, minivans, sports-utility vehicles and light-duty trucks.

analysis of each of the full fuel/vehicle pathways considered in this study. That is, this study quantifies the energy use and emissions along the entire fuel pathway that are associated with each mile travel by a vehicle fueled with a specific fuel. To do so, this study utilizes the *G*reenhouse gases *R*egulated *E*missions and *E*nergy use in *T*ransportation spreadsheet model, referred to as GREET, which was developed by researchers at Argonne National Laboratory's Center for Transportation Research. All assumptions and results are relevant to the year 2025, as this time horizon was selected in order to allow several alternative technologies and fuels to develop and to allow the composition of the light-duty transport fleet to change.

This study determines relevant assumptions related to both the upstream fuel production stages and vehicle fueling and operation and generates results for a total of 70 well-to-pump fuel production pathways, 15 vehicle propulsion systems and several dozen full well-to-wheels pathways. Fuels considered by this study include reformulated gasoline (RFG), low-sulfur diesel, compressed natural gas, liquefied petroleum gas, ethanol (from both corn and cellulosic biomass feedstocks), hydrogen (from both steam methane reforming of natural gas and electrolysis of water) as well as electricity as a direct vehicle fuel for battery electric and plug-in hybrid-electric vehicles. Vehicle propulsion systems considered include: spark-ignition (SI) and compression-ignition direct-injection internal combustion engine vehicles (ICEVs) fueled with a variety of fuels; hybrid electric vehicles (HEVs); hydrogen fuel cell vehicles (FCVs); battery electric vehicles; and plug-in hybrid electric vehicle (PHEV) versions of most of the other vehicle systems. Each of these alternative vehicles was modeled to represent a vehicle equivalent in size and performance to a baseline 22-mile-per-gallon spark-ignition internal combustion engine vehicle fueled with reformulated gasoline. This baseline vehicle is meant to be representative of the average size, weight and fuel economy of the light-duty vehicle sector in 2025 under a business-as-usual scenario.

This study finds that all alternative fuels and vehicles considered offer reductions in petroleum energy consumption relative to the baseline vehicle (see Figure ES-1). Alternative petroleum-based pathways, including diesel and hybrid-electric vehicles, achieve moderate reductions between 15-35%, almost entirely as a result of increased vehicle fuel economy. Natural gas and electricity-based pathways nearly eliminate petroleum energy use, although in many cases, these pathways simply substitute other fossil-derived energy for petroleum

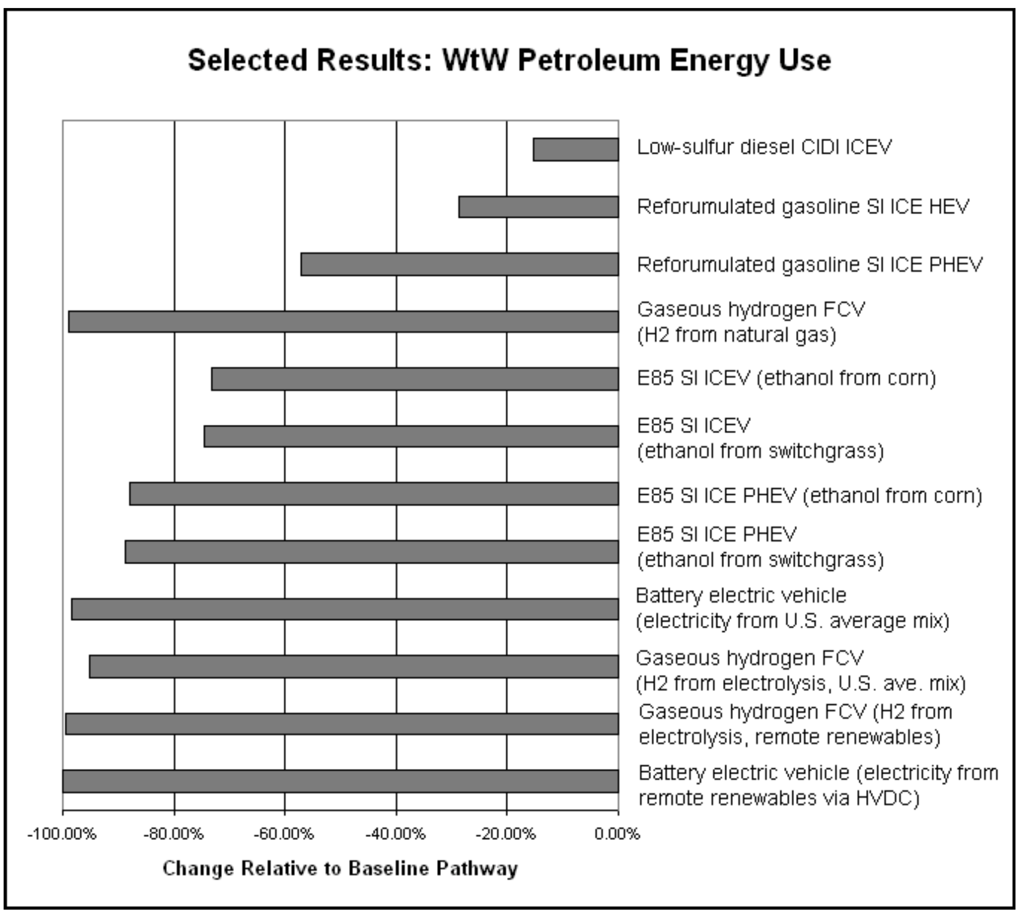

Figure ES-1: Selected Results – Well-to-Wheels Petroleum Energy Use

energy inputs. Biomass-based pathways including ethanol from corn and cellulosic biomass offer petroleum energy use approximately three-quarters less than the baseline pathway as they rely largely on biomass as a feedstock. The remaining petroleum energy use is due to the fact that this study considers ethanol in E85 blends (85% ethanol and 15% RFG by volume) and RFG makes up 21% of E85 by energy content.

In addition to offering petroleum energy reductions, several pathways considered also result in significant reductions in well-to-wheels fossil energy inputs as well (see Figure ES-2). As would be expected, pathways that rely primarily on renewable energy inputs including ethanol from cellulosic biomass and electricity or hydrogen derived from renewable energy offer the lowest fossil energy use. Several other pathways also result in significant reductions in fossil energy use between 25-65%, however, due to the overall WtW efficiency of these pathways. These include the hydrogen-from-natural gas pathways as well as the battery electric vehicle pathways and most plug-in hybrid-electric vehicles fueled with electricity from the U.S. generating mix. Additionally, the ethanol-from-corn pathway results in fossil energy use nearly 35% lower than the baseline due to the use of corn as a feedstock, although this reduction is significantly less than the reductions achieved by cellulosic ethanol pathways. This is due to the fact that ethanol production from corn relies on significant inputs of coal and natural gas for process energy, while production of ethanol from cellulosic biomass utilizes the lignin portion of the biomass feedstock to provide all of the necessary process energy (as well as to generate significant quantities of electricity for export).

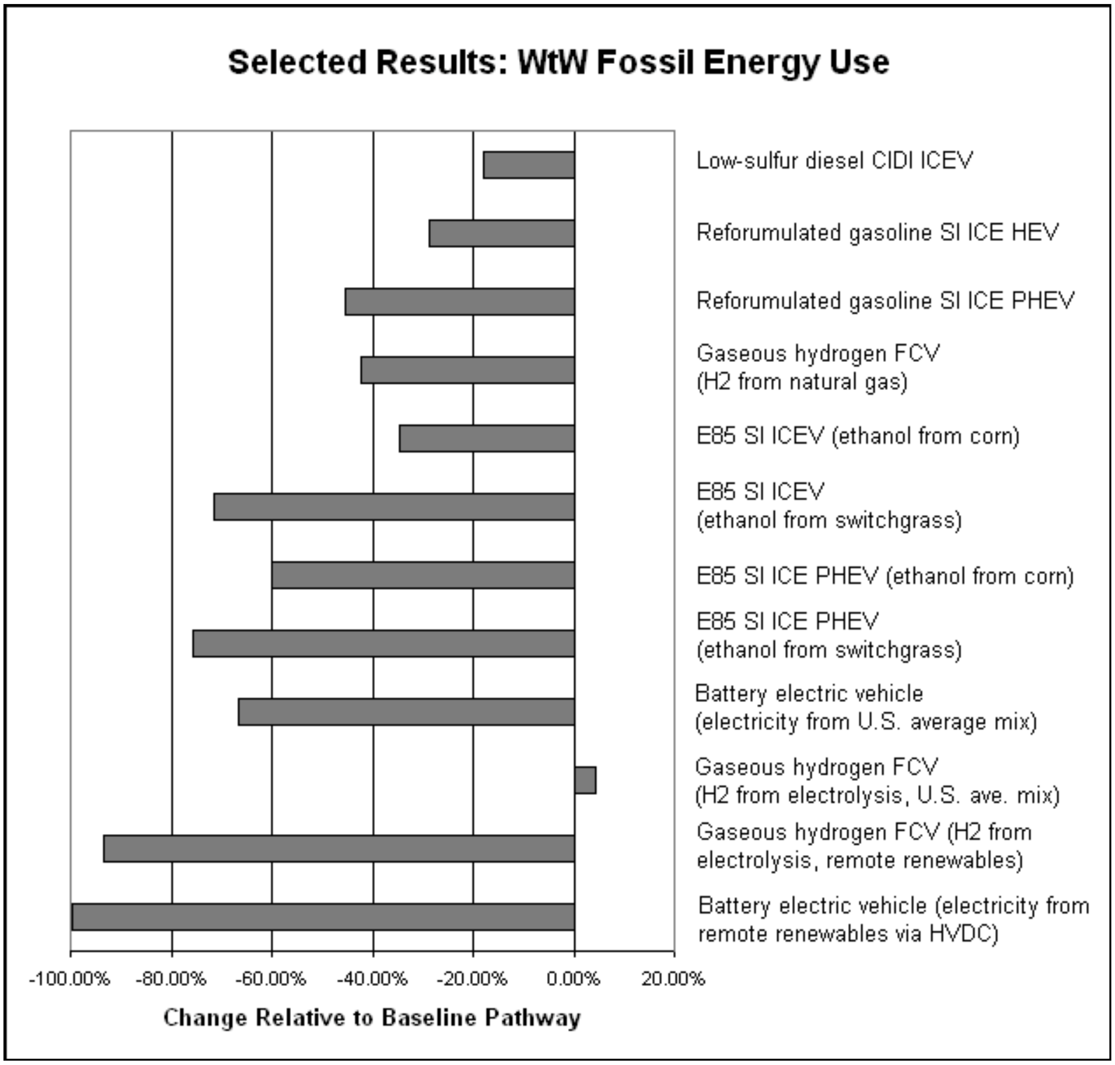

Figure ES-2: Selected Results – Well-to-Wheels Fossil Energy Use

Despite the fact that many pathways result in significant petroleum energy use reductions, several of these pathways (i.e., natural gas and electricity-based pathways) achieve these reductions by substituting other non-renewable, fossil fuel-derived energy inputs. In some cases, particularly those reliant on natural gas, this may mean that these pathways offer fewer benefits than indicated by the petroleum energy use reductions they achieve, as natural gas is also subject to resource depletion and related concerns. Natural gas supplies in North America are already tight and any increased reliance on natural gas for transportation fuels could simply displace concerns about imported oil onto concerns about imported natural gas, much of which is located in unstable areas of the world. When possible, fuel/vehicle pathways that offer reductions in fossil energy and/or rely on domestically produced energy resources should be preferred. This points to the importance of examining fossil energy use in addition to petroleum energy use.

In addition to energy use, this study presents results for the three main GHGs: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The GHG emissions reductions achieved by the various fuel/vehicle pathways are roughly correlated with fossil energy reductions. Nearly all of the pathways considered by this study offer some reduction in GHG emissions (see Figure ES-3). As with fossil energy reductions, the pathways that offer the most significant reductions in GHG emissions are those that rely on renewable energy inputs. The pathways utilizing remote stranded renewables, for example, nearly eliminate GHG emissions, while the biomass-based E85 pathways offer GHG reductions between 72-83%. The remaining GHG emissions for these E85 pathways result from the combustion of the RFG contained in E85 blends.

This study finds that several other pathways that rely on feedstocks containing carbon also achieve GHG reductions, however, primarily as a result of high overall WtP efficiencies and/or low vehicle fuel consumption. These pathways include the hydrogen-from-natural gas pathways and the various PHEV and BEV pathways fueled with electricity from the U.S. generating mix, as well as corn-based E85, CNG, LPG, diesel and the two petroleum-fueled hybrid-electric vehicles (HEVs). These pathways offer GHG emissions reductions between 10-50% relative to the baseline vehicle. Finally, in contrast to all of the other pathways considered, this study finds that the electrolytic hydrogen pathways result in significant

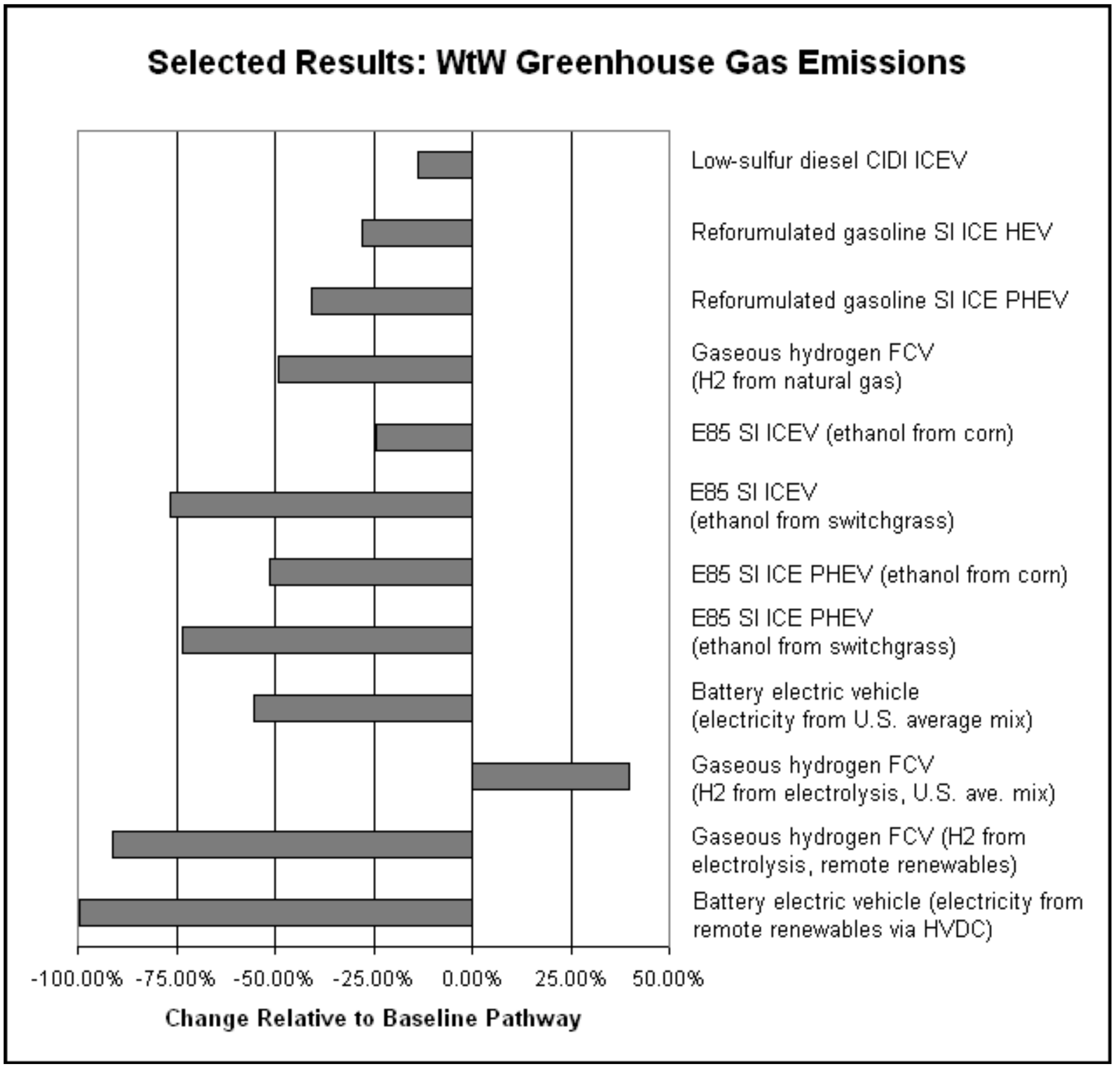

Figure ES-3: Selected Results – Well-to-Wheels Greenhouse Gas Emissions

increases in GHG emissions of approximately 40-80%, despite the fact that hydrogen itself is a carbon-free fuel and hydrogen fuel cell vehicles result in zero emissions of GHGs during vehicle operation. These increases are due to the GHG-intensive nature of the current coal-dominated U.S. electricity mix and the low WtP efficiency of electrolytic hydrogen production.

In addition to GHG emissions, this study presents results for well-to-wheels emissions of five criteria pollutants including: volatile organic compounds (VOCs); carbon monoxide (CO); oxides of nitrogen (NO_x); particulate matter (PM10); and oxides of sulfur (SO_x). This study indicates that, in general, alternative transportation fuels and vehicle propulsion systems help reduce criteria pollutant emissions associated with the light-duty transport sector. In particular, all but one of the alternative pathways results in some decrease in urban emissions of the five criteria pollutants (with the exception being urban NO_x emissions from the low-sulfur diesel pathway). However, several pathways result in increased total emissions of one or more criteria pollutants. The electricity-based pathways result in increased PM10 and SO_x emissions, for example. Additionally, the ethanol from farmed crops pathways result in increased emissions of NO_x and in the case of corn ethanol, a large increase in total PM10 emissions, both due to farming activities. The criteria pollutant results thus point to the fact that trade-offs may be necessary, as several pathways that perform well in all other metrics result in increases in total emissions of one or more criteria pollutants.

Considering this study's primary motivations, the well-to-wheels results generated by this study provide cause to be optimistic. This study demonstrates that there are several potential alternative vehicle fuels and propulsion systems that can significantly decrease petroleum energy use. The results also indicate that there are several promising options to drastically reduce GHG emissions related to the light-duty transport sector as well as emissions of several criteria pollutants. Care must be taken, however, to avoid simply substituting non-North American natural gas for petroleum use, lest the United States end up embroiled again in the negative consequences arising from reliance on a depleting energy source. Alterative fuels that rely on domestic energy sources should be preferred and renewable resources should be utilized as much as possible.

Some of the technologies and fuels analyzed in this study are ready and available today to contribute immediately to reducing petroleum and fossil energy use as well as emissions of GHGs and criteria pollutants. Other technologies still have unresolved technological, cost, infrastructure or other hurdles and may require additional research and financial support to reach the market quickly enough to take full advantage of their potential benefits in the timeframe considered by this study (i.e., by 2025). The results presented in this study can be used as an initial indication as to which technologies should receive the most concerted effort to bring to market. Plug-in hybrid electric vehicles, ethanol derived from woody and herbaceous biomass (i.e., cellulosic ethanol) and electric vehicles all offer a particularly good range of benefits. The pathways utilizing remote stranded renewables offer by far the best benefits, performing well in all the metrics, although developing these resources would require large capital investments and considerable planning.

In short, this study finds that the technical options are available to allow significant reductions in petroleum and fossil energy use as well as emissions of GHGs and criteria pollutants related to the light-duty transport sector. What is needed is the development of forward thinking strategies and actions to begin a concerted and rapid transition away from the current oil-addicted light-duty transport sector towards the use of vehicles fueled with energy derived from domestically available and, as much as possible, renewable energy sources. Such vehicles and fuels could also offer dramatically reduced emissions of GHGs and pollutants. This study indicates that the requisite options are available. We must now chart the road forward.

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1. INTRODUCTION

1.1 Motivations

"Oil is the lifeblood of America's economy," touts the United States Department of Energy (DOE).[2] With oil making up 40% of our total energy consumption[3] and over 96% of the energy used for transportation[4], it is hard to argue with the DOE's sentiment. The United States consumed over 20 million barrels of oil every day (mmbbl/d) in 2004[5] and our level of consumption is continuing to rise.[6] These vast quantities of oil carry our workers to industries and businesses, our customers to stores, restaurants and services, even the very food we eat to our local grocery and back to our homes. It is the basic feedstock for the plethora of petroleum-based products that we use every day, it heats many of our homes and businesses and it even powers a portion of the electricity we use.[7] If the flow of oil were to stop, so to would the flow of goods and services, products and foodstuffs that make up our nation's economy. It is not a stretch then to say, as President George W. Bush declared in his 2006 State of the Union Address, "America is addicted to oil."[8]

But is this addiction safe? Is it without consequence? Can we Americans continue to count on an endless and ever increasing supply of oil to keep our economy flowing? These

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[2] United States Department of Energy. "Oil". *Energy*. <http://www.energy.gov/engine/content.do?BT_CODE=OIL>. Accessed 11/20/2005.
[3] Total energy consumption includes electricity, heating and transportation. ibid.
[4] Davis, Stacey C. and Susan W. Diegel. *Transportation Energy Data Book: Edition 24*. (Oak Ridge, TN: Oak Ridge National Laboratory, December 2004). p. 1-1.
[5] Actual figure is 20.74 mmbbl/d. Energy Information Administration. *Annual Energy Outlook 2006: With Projections to 2030*. (Washington D.C.: Energy Information Administration, Feb. 2006). p. 151, Table A11. This publication is referred to throughout this study as *AEO2006*.
[6] ibid. p. 151, Table A11.
[7] Petroleum-fired power plants made up just over 3% of total US electricity generation in 2004. See ibid. p. 147, Table A8.
[8] Office of the President of the United States of America. "2006 State of the Union". *The White House*. <http://www.whitehouse.gov/stateoftheunion/2006/>. Accessed 4/22/06.

are the questions that we must ask, considering the importance of oil to our economy and way of life. The answer to each of these crucial questions, however, seems to be a clear 'no'.

Oil is a finite resource and as such can never be counted on to last forever, especially in the face of increasing demand from the United States and the world. Increasing evidence is mounting that the so-called 'peak' of world oil production – the point where new production cannot offset depleting production at mature oil fields, resulting in a continual and inexorable decrease in world production – has either already happened or will happen within the next five or ten years. Geophysicist M. King Hubbert, who in 1956 successfully predicted the peak of U.S. oil production – it occurred in 1971, just one year later than his predictions – also predicted that the worldwide peak would occur between 1995 and 2000.[9] His estimate did not take into account the two OPEC oil shocks of the 1970s, however, and the resulting decreases in worldwide demand. The Association for the Study of Peak Oil (ASPO) revised Hubbert's prediction and now claims that worldwide production of conventional oil peaked in Spring of 2004 and predicts that total worldwide production (including unconventional sources of oil like oil sands and deepwater deposits) will peak sometime around 2010 (Figure 1-1).[10] Official U.S. DOE estimates, which have been criticized by scholars as too optimistic,[11] lie on the other side of the spectrum. Estimates

[9] Hubbert, M. King. *Nuclear Energy and Fossil Fuels*. (Houston, TX: Shell Development Company, June 1956).

[10] Aleklett, K. and Campbell, C.J. "The Peak and Decline of World Oil and Gas Production." *Minerals & Energy* 18 (2003): 15-20.

[11] Critics point out, for example, that the government estimates accept at face value the reserve figures provided by OPEC countries. However, OPEC countries have a strong incentive to overestimate their reserves in order to boost their production quotas (which are tied to reserves). Reuters News Agency reported on January 20th, 2006, for example, that "Kuwait's oil reserves are only half those officially stated." See Reuters. "Kuwait oil reserves only half official estimate – PIW". *Reuters*. 1/20/06. <http://today.reuters.com/business/newsarticle.aspx?type=tnBusinessNews&storyID=nL20548125&imageid=&cap=>. Accessed 4/22/06.

from the DOE's Energy Information Administration (EIA), for example, project that the peak will not occur until sometime around 2030.[12]

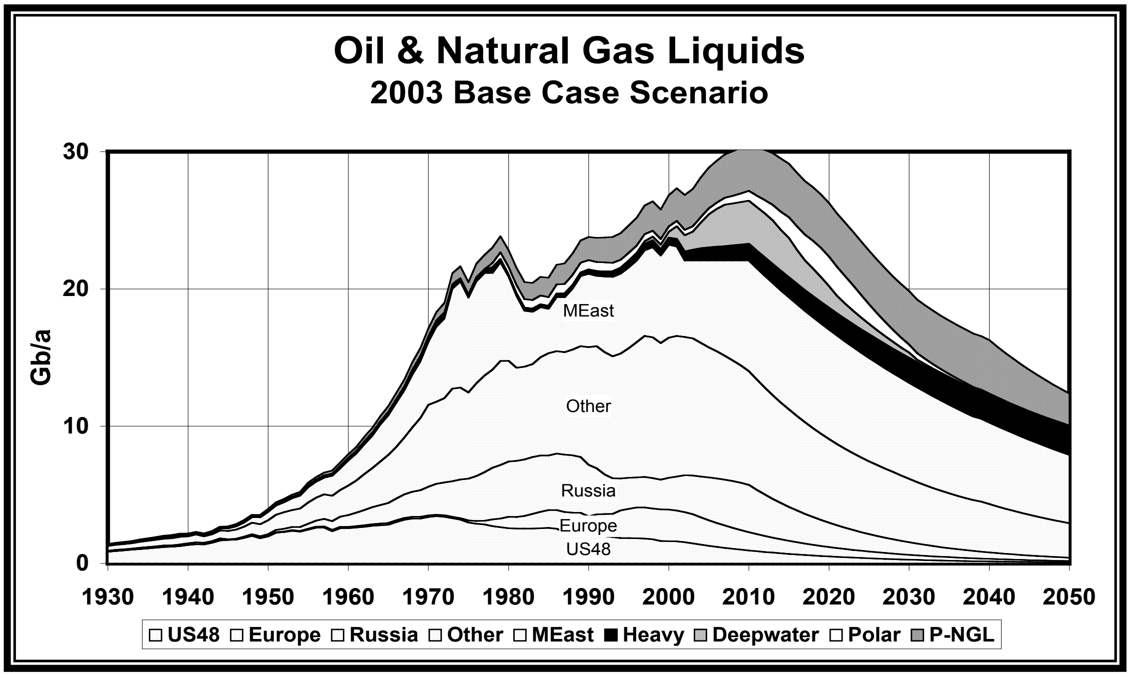

Figure 1-1: ASPO World Oil Production ('Peak Oil') Chart[13]

Some of the predicted peak oil dates have come and gone, while others still lie in the future. However, as Dr. Roger Bezdek, the coauthor of another peak oil study known as the 'Hirsch Report',[14] points out, while some critics have accused those who have made peak oil predictions of crying wolf, "wrong is not wrong forever … The message of that parable is

[12] The EIA does not explicitly predict when the peak will occur. This is my projection based on the EIA's published figures for total world oil reserves and production rates and is based on a simple 'bell-shaped' depletion curve. The equation for such a curve is: T = 1/k*LN(Rk/r+1) where T = total depletion time (note: the peak time = 1/2T), k = the rate of growth in production/consumption, R = total reserves, and r = initial production/consumption. The EIA optimistically estimates total world reserves (R) at 2,946.8 billion barrels (Bbbl), total world production in 2002 (r) at 28.5 Bbbl/y and the annual growth rate of production (k) at 2.09%/year. These figures yield a total depletion time of just over 55 years and the projected peak midway through 2029 (i.e., 2002 + 1/2*55). See EIA. *International Energy Outlook 2005.* (Washington D.C.: EIA, July. 2005).

[13] Aleklett and Campbell (2003), p. 13.

[14] Hirsch, Robert L. et al. *Peaking of World Oil Production: Impacts, Mitigation, and Risk Management.* (DOE National Energy Technology Laboratory, Feb. 2005).

that people were eventually eaten by the wolf."[15] The question of peak oil is not a matter of if, but when, and the answer is almost certainly soon.

Furthermore, while the United States continues to demand more and more oil and the world's production approaches its peak, we will not be the only country with a taste for crude. While the United States currently consumes about a quarter of the entire world's production of oil, our piece of the pie is shrinking.[16] The consumption rates of developing nations – notably China and India – are growing at twice the rate of the United States and other developed nations.[17] Increasing demand and tightening supplies will likely lead to higher oil prices, economic recessions and increased geopolitical conflict.

Our current levels of consumption are not without their costs either. As mentioned above, the United States' production of oil peaked in 1971 and has fallen steadily ever since. Meanwhile, our demand has continued to rise. The ever-growing gap between U.S. demand and U.S. production – now nearly 13 mmbbl/d[18] – has been filled by an increasing reliance on foreign sources of oil. Not only does this reliance on foreign oil mean that increasing amounts of U.S. currency are making their way abroad, contributing to the bulk of our trade deficit, but this dependence leaves our economy largely at the mercy of a foreign oil cartel: the Organization of Petroleum Exporting Countries (OPEC).[19] A study by the Oak Ridge National Laboratory[20] (ORNL) reports that the oil market upheavals caused by the OPEC cartel over the past three decades have cost the United States in the vicinity of $7 trillion

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[15] Quoted in Stantiford, Stuart. "ASPO-USA Denver Conference Report." *The Oil Drum*. Nov. 12, 2005. <http://www.theoildrum.com/story/2005/11/12/0150/4833>. Accessed 11/20/2005.
[16] Davis and Diegel, p. 1-5.
[17] ibid. p. 1-5.
[18] ibid. p. 1-1. In 2003, the U.S. consumed 20.04 mmbbl/d and produced only 7.46 mmbbl/d for net imports of 12.58 mmbbl/d.
[19] OPEC member states: Algeria, Indonesia, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, the United Arab Emirates, and Venezuela.
[20] Greene, D. and N. Tishchishyna, *The costs of oil dependence: a 2000 update*. (ORNL, May 2000).

(adjusted to 1998 dollars) in total economic costs.[21] This is, incidentally, about as large as the sum total of payments on the national debt over the same period. Furthermore, estimates of military expenditures to defend U.S. oil interests in the Middle East range from \$6 to \$60 billion per year[22] with a recent study by the National Defense Council Foundation putting the price tag at \$49 billion per year for the defense of Middle Eastern oil.[23] This estimate does not include the costs of the latest Iraq War and occupation.

There are significant environmental costs to our dependence on oil as well. Criteria pollutants[24] spewed from vehicle tailpipes pollute our urban centers. These include: acid rain and smog forming nitrous oxides (NO_x); haze and acid rain inducing sulfur dioxide (SO_2); particulate matter (PM), which is damaging to the respiratory system and is another contributor to haze; volatile organic compounds (VOCs), which also contribute to the formation of ozone and smog; as well as poisonous carbon monoxide gas (CO). Furthermore, growing concerns about global climate change call attention to the massive quantities of carbon dioxide (CO_2) and other greenhouse gases (GHGs) emitted each year from U.S. vehicles. Consumption of oil for transportation needs accounts for nearly one third of all U.S. CO_2 emissions, amounting to nearly 1.9 billion metric tons of CO_2 in 2004.[25]

Clearly, there are a number of different but interconnected motivations that impel us to break our addiction to oil, particularly from foreign sources. These include (a) concerns about peak oil, (b) worries about the strategic and economic costs of our growing dependence

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[21] Greene and Tishchishyna quoted in Davis and Diegel, p. 1-10.
[22] Davis and Diegel, p. 1-11.
[23] Copulas, Milton R. *America's Achilles Heel – The Hidden Costs of Imported Oil*. (Washington D.C.: National Defense Council Foundation, Oct. 2003). Quoted in Davis and Diegel, p. 1-11.
[24] Criteria pollutants are those regulated by the United States Environmental Protection Agency (EPA) as mandated by the National Ambient Air Quality Standards. See EPA "National Ambient Air Quality Standards (NAAQS)". *Air and Radiation*. 3/1/06. <http://www.epa.gov/air/criteria.html>. Accessed 4/22/06.
[25] EIA 2006, p 160, Table A18.

on foreign oil, and (c) a desire to cut back criteria pollutants and (d) combat global climate change. These four major concerns provide the central motivation for this study.

1.2 Overview

Transportation accounts for two-thirds of total U.S. petroleum consumption.[26] Transport needs alone far outweigh our domestic production of oil, with nearly 13.7 mmbbl/d consumed for transport in the U.S. in 2004 while domestic production was just under half that at 7.23 mmbbl/d.[27] And if our economy is addicted to oil, our transportation sector is the worst 'junkie,' with over 96.4% of our transportation energy coming from oil.[28] Thus, no attempt to break our dependency on oil can succeed unless we find a way to wean our transportation sector off of petroleum, and so we must ask: are there viable alternatives that could transform our oil-guzzling transport fleet into something new, something cleaner, more renewable, domestically-fueled and even CO2-free?

This study seeks to begin to address that question. The aim of this study is to explore potential alternative transportation fuels and energy sources that can replace, in part or in full, the use of oil for the transport sector. This study focuses on fuels and technologies for the light-duty transportation fleet – i.e., vehicles weighing less than 8,500 pounds, which includes cars, minivans, sports-utility vehicles and light-trucks. The light-duty sector includes our personal vehicles as well as many of the vehicles maintained by commercial and governmental fleets. Light-duty vehicles account for the majority of energy consumption in

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[26] EIA *AEO2006* p. 152, Table A11.
[27] ibid. p. 152, Table A11. Domestic petroleum production includes crude oil and natural gas plant liquids.
[28] Davis and Diegel, p. 2-1. Figure is for 2003.

the U.S. transportation sector[29] and are thus a logical place to begin looking for alternatives to oil use.

In light of the four primary motivations described in Section 1.1 above, this study seeks to evaluate the relative performance of different fuel options in reducing our fossil and petroleum energy use, as well as emissions of GHGes and criteria pollutant. To provide an accurate and adequate evaluation of the energy and emission effects of various fuels and vehicle technologies, it is important to consider emissions and energy use from upstream fuel production processes as well as from vehicle operations. This is especially important for fuels with distinctly different primary energy sources (feedstocks) and fuel production processes, for which upstream emissions and energy use can be significantly different. Additionally some of the fuel options and vehicle technologies considered in this study, including hydrogen fuel cell and battery electric vehicles, result in zero vehicle 'tailpipe' emissions, while upstream energy use and emissions associated with producing and distributing these fuels can be considerable. These and other similar concerns make an objective comparison of different transportation fuels and vehicle technologies difficult unless the *entire* fuel pathway from feedstock recovery or production through the use of the fuel at the vehicle itself is considered.[30] As such, this study performs what has become known as a 'well-to-wheels' (WtW) analysis, after the traditional petroleum fuel pathway, which begins at an oil *well* and ends at the *wheels* of a gasoline-powered vehicle. That is,

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[29] ibid. p. 2-1. Figure is 56.6% and is for 2002.

[30] Note: it may also be important to consider the energy use, emissions and materials costs associated with the life-cycle of the vehicle, i.e., from production to disposal of the vehicle. When such an analysis is paired with a well-to-wheels fuel cycle analysis, it is known as a full 'life-cycle analysis' or 'cradle-to-grave' study. While analyzing the life-cycles of the various vehicle systems examined in this study is beyond the scope of the study, it could be extended by a future research effort in order to construct a full life-cycle analysis of the various fuel pathways and vehicle systems. For an example of a full life-cycle analysis, see Weiss, Malcom A. et al. *On the Road in 2020: A Life-cycle Analysis of New Automobile Technologies*. (Cambridge, MA: MIT Energy Laboratory, Oct. 2000).

this study quantifies the energy use and emissions along the entire fuel pathway that are associated with each vehicle mile traveled. This study utilizes the *G*reenhouse gases *R*egulated *E*missions and *E*nergy use in *T*ransportation spreadsheet model, referred to as GREET, to perform its well-to-wheels analysis. The GREET model, developed by Argonne National Laboratory, is discussed in Section 2.

A WtW analysis is often broken up into two main components (see Figure 1-2). The fuel production and distribution or 'well-to-pump' (WtP) portion encompasses every stage from feedstock production or recovery and transportation to fuel production on through distribution of the fuel at the 'pumps' of fueling stations.[31] The vehicle operation portion includes the fueling and operation of the vehicle and is referred to as the 'pump-to-wheels' (PtW) stage.

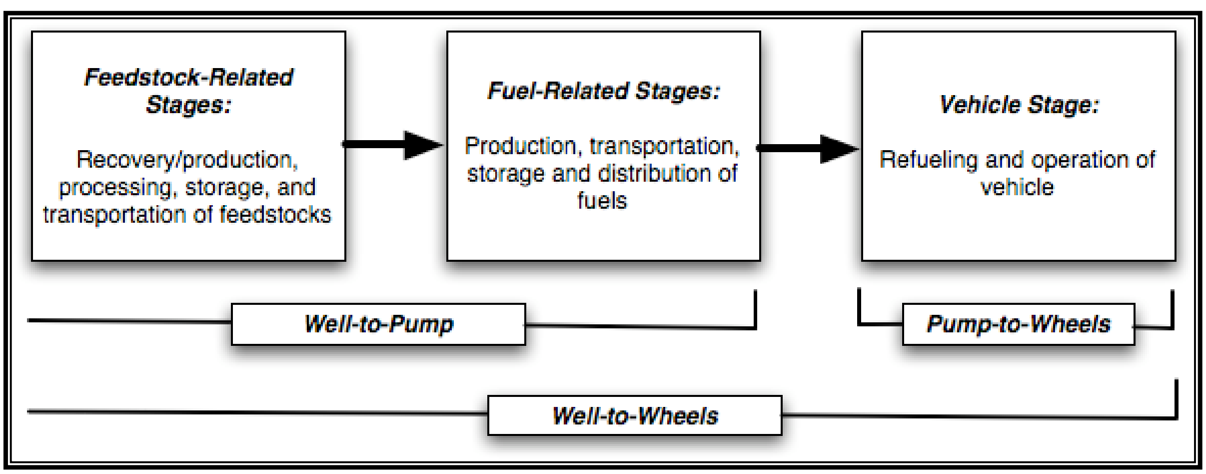

Figure 1-2: Scope of a Well-to-Wheels Analysis For Fuel/Vehicle Pathways

[31] Note: the feedstock and fuel production, transportation and distribution pathway is often referred to as the 'well-to-tank' portion of the WtW pathway. However, this is a misnomer in most cases as most of the literature, including this study, includes emissions and losses associated with vehicle fueling in the vehicle fueling and operation portion of the pathway. Thus, the 'well-to-tank' portion is more accurately called the 'well-to-pump' portion, as is done in this study, as it properly ends at the fueling station, or the gasoline pumps in the traditional petroleum to gasoline fuel pathway.

This study analyses the WtP fuel production pathways for several transportation fuels, as well as several vehicle types that utilize those fuels. The WtP fuel pathways fall into four main categories based on feedstock as follows: petroleum, natural gas, biomass, and electricity (see Figure 1-3). The WtP fuel production pathways considered in this study are discussed in detail in Section 3.

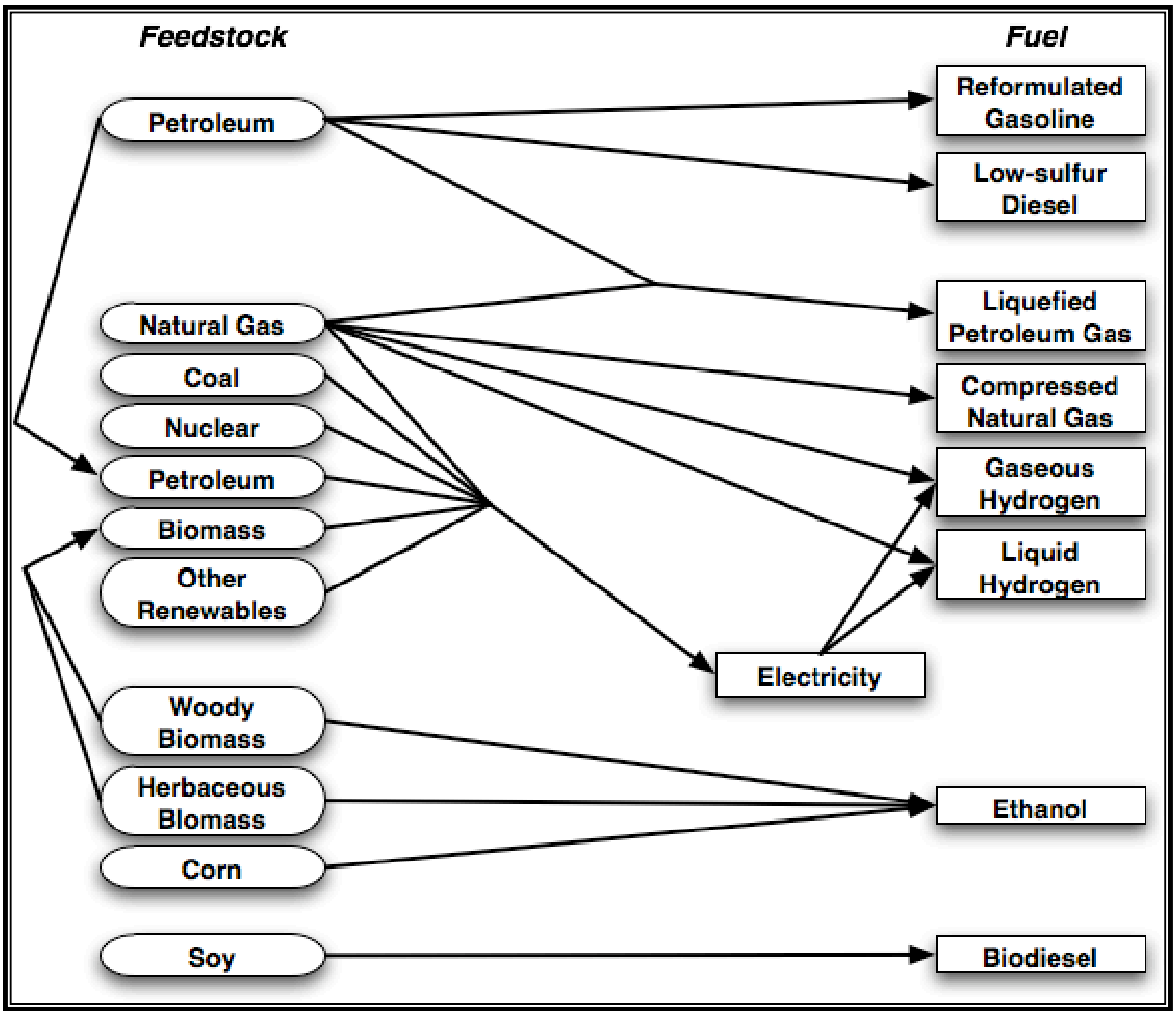

Figure 1-3: Energy Feedstocks and Fuels Examined in this Study

The PtW vehicle systems fall into five main categories, this time based on the fuel type: petroleum-based fuels, natural gas-based fuels, hydrogen, biofuels, and electricity (see

Table 1-1). These vehicle systems are presented in Section 4. When combined, the different WtP and PtW pathways yield several dozen complete WtW fuel cycles that can be compared in an objective manner. The results of the complete WtW fuel cycles analyzed by this study are presented in Section 5. Overall conclusions are presented in Section 6.

Table 1-1: Fuels and Vehicle Systems Examined in this Study

Fuel	*Vehicle Systems*
Reformulated gasoline	Spark-ignition (SI) gasoline internal combustion engine vehicle (ICEV); SI gasoline internal combustion engine (ICE) hybrid-electric vehicle (HEV); SI gasoline ICE plug-in hybrid-electric vehicle (PHEV)
Low-sulfur diesel	Compression-ignition direct-injection (CIDI) diesel ICEV; CIDI diesel ICE HEV; CIDI diesel ICE PHEV
Liquefied petroleum gas	SI liquefied petroleum gas ICEV
Compressed natural gas	SI compressed natural gas ICEV
Gaseous hydrogen	Gaseous hydrogen fuel cell vehicle (FCV); Gaseous hydrogen fuel cell (FC) PHEV
Liquid hydrogen	Liquid hydrogen FCV; Liquid hydrogen FC PHEV
Electricity	Battery electric vehicle (BEV); Plug-in hybrid vehicles (listed with other fuels)
Ethanol (E85)	SI E85 ICEV; SI E85 ICE PHEV

Some studies examining alternative transportation fuels focus on only one energy metric – i.e. 'net-energy-ratio'. That is, they focus on whether or not the production of the alternative fuel results in the use of more non-renewable energy than is contained in the resulting fuel. For example, much of the public debate over the merits of corn ethanol has focused on determining the net-energy-ratio of ethanol from corn (see Section 3.3). A number of WtW or life-cycle studies have been performed in the past two decades that attempt to determine of corn ethanol has a positive net-energy ratio, and the results have varied. Some – particularly professors, Ted Patzek of Cornell University and David Pimentel of University of California, Berkeley[32] – have concluded that corn ethanol requires more energy to produce than it yields, while (multiple) others have concluded that corn ethanol has a moderately positive net energy balance.

The debate over the net-energy ratio of corn ethanol aside, focusing solely on net-energy ratio can result in misleading results, particularly when the metric is considered 'in a vacuum' and not compared to the fuel that the alternative fuel is likely to replace – i.e. gasoline. In particular, a net energy metric ignores the fact that not all fossil fuels 'are created equal' – that is, there are vast differences in the energy, environmental, and policy implications of the use of various fossil fuels (coal, petroleum and natural gas) that a simple net energy metric ignores. Furthermore, a net energy ratio does not provide a sufficient environmental metric either, as it is not an accurate indicator of emissions of GHGs or criteria pollutants, or of other environmental factors including soil erosion or deforestation. Finally, focusing on a net energy ratio for a given fuel obscures the fact that not all forms of energy are equally valuable. For example, electricity is clearly more valuable than the potential fossil energy in coal, natural gas or petroleum, which is why we routinely accept 'negative' net energy ratios for electricity generation. Likewise, liquid fuels for transportation are considered more valuable than the various feedstocks that are used to produce them. Thus, the direct comparison of various fuels for use in specific contexts using

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[32] See Patzek, Tad W. "Thermodynamics of the Corn-Ethanol Biofuel Cycle". *Critical Reviews in Plant Sciences*, 23(6) (2004): 519-567; and Pimentel, David and Tad W. Patzek. "Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower". *Natural Resource Research*, 14(1) (2005): 65-76.

multiple energy and environmental metrics yields the most valuable insights into the relative benefits and costs of these fuels.

For these reasons, this study provides several different metrics to compare alternative fuels and vehicles, both with the baseline fuel (gasoline) and with each other. This study presents results for WtW total, fossil and petroleum energy use, as well as emissions of the three main GHGs and five harmful pollutants. The author hopes that the several metrics included in this study (i.e. total, fossil and petroleum energy, GHG and criteria pollutant emissions), as well as the easy and objective comparison of each fuel to gasoline and the other alternative fuels will provide a more accurate analysis of the merits of the various fuels included in this study than a simple net energy metric. However, this study does provide net (fossil) energy ratios for the various fuel production pathways analyzed so as to allow comparison with other literature.

Finally, it must be noted that this study seeks to consider several fuel and vehicle technologies that are either just being commercialized or are still in development stages and are expected to reach the market in the near future. A horizon of time must therefore be provided in order for these fuels and technologies to develop and to allow the requisite distribution infrastructures to be deployed. Additionally, the composition of the light-duty transport sector does not change overnight. It takes approximately 15-20 years for all (or nearly all) of the vehicles on the road today to be replaced by new vehicles.[33] Due to these considerations, this study performs its WtW analysis for the year 2025.

[33] See ibid. Supplemental Tables 45 and 46.

1.3 Study Limitations

As discussed above, the primary intent of this study is to explore the potential of several different alternative transportation fuels and vehicles to reduce petroleum consumption in the light-duty transport sector, although special attention will also be paid to alternatives that reduce fossil energy use and emissions of GHGs and harmful pollutants. To do so, this study conducts a WtW analysis of the full fuel production and vehicle operation stages – i.e. the WtW pathway – providing results for 17 different metrics including total, fossil and petroleum energy inputs as well as emissions of GHGs and criteria pollutants (see Section 2 below). This should allow objective comparisons between the various alternative fuels/vehicles considered using each of the metrics included in this study. However, this study has several limitations that should be openly acknowledged.

First, while this study makes objective comparisons between various alternative fuels/vehicles easy using each of the individual metrics, it does not attempt to provide an overarching index of comparison that incorporates overall performance on all of the various metrics. To do so would require a continued analysis to determine the appropriate weight to apply to each of the 17 metrics in order to at least approximate their relative importance. This is a difficult task as each of the metrics is related to a number of different but important concerns including resource depletion concerns, environmental degradation, and impacts on health, domestic energy security and foreign policy, etc. Providing an overarching index of comparison could be useful, but would clearly involve somewhat arbitrary decisions as to the relative importance of this diverse range of impacts and concerns and would require detailed analysis to ensure that the resulting index was as useful as possible.

Additionally, like most WtW studies, this study (for the most part) does not attempt to examine the economics or relative market competitiveness of the various alternative fuels and vehicle technologies considered. Ultimately, fuel and technology costs, time-to-market readiness and consumer acceptance may determine what degree of market penetration and impact each of these alternatives can achieve. However, accurately analyzing the diverse range of economic factors affecting the ultimate costs and competitiveness of these alternative fuels and vehicles, especially with a time horizon twenty years into the future, is beyond the scope of this study. Furthermore, the intent of this study is in part to offer guidance as to which of these alternative fuels are deserving of the most attentive research and development efforts and, if necessary, financial support to aid their ultimate ability to achieve market penetration and realize the potential benefits these pathways offer.

Furthermore, this study does not include the energy and emissions embodied in the materials and structures utilized throughout the various pathways. That is, this study is not a full life-cycle analysis, as it does not take into account the energy use and emissions related to the manufacture and eventual disposal of the vehicles themselves or of the various buildings, structures, vehicles and technologies used to produce, transport and distribute the feedstocks and fuels considered by this study (see Figure 1-3 below). Undertaking such a study inevitable involves greatly extending the boundaries of the systems analyzed and involves considerable additional work. Generally, life-cycle analyses are conducted for one or perhaps a few specific fuels that deserve more in-depth analysis. Thus, a crucial step in beginning a life-cycle analysis is analyzing the WtW performance of various fuels/vehicles in order to determine which are deserving of further analysis. This study is intended to provide that initial analysis over a much wider variety of fuels and vehicles than is generally possible in a life-cycle analysis. Further analysis of the energy use and emissions embodied in the various structures, materials, vehicles and technologies relating to each of these fuel/vehicle pathways is welcomed, but is beyond the scope of this study.

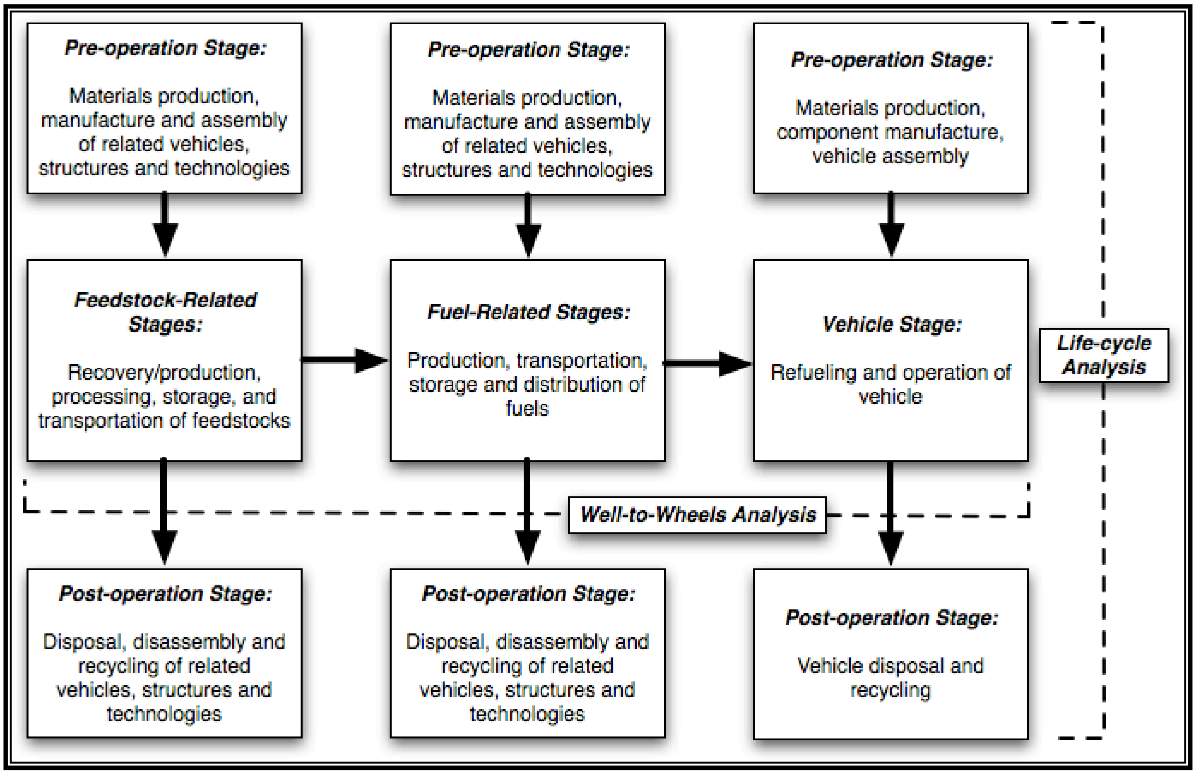

Figure 1-3: Comparative Scope of Life-cycle and Well-to-Wheels Analyses

In addition to the above limitations, this study does not address uncertainties in its assumptions through stochastic or probabilistic modeling. The version of the GREET model used to perform this study's WtW analysis (i.e., version 1.6, see Section 2 below) does not include stochastic variables. Past WtW studies utilizing GREET have made use of commercially available stochastic modeling software (i.e., Monte Carlo simulation software), but this study was unable to use such software. It appears that upcoming versions of GREET (i.e., GREET 1.7, see Section 2 below) will include stochastic variables that should allow analysis of the range of uncertainties and their affects. This may allow the further refinement of this study's conclusions.

This study also does not address the benefits of simply increasing fuel economy in conventional petroleum-fueled vehicles. Clearly, increased fuel economy translates directly to decreased fuel consumption which results in reduced petroleum energy use and emissions of GHGs and harmful pollutants. The omission of increased efficiency options from this study is not intended to imply that these options are not important. In fact, increasing the fuel economy of the light-duty transport fleet may be the best near-term option the United States has for reducing its petroleum consumption and mitigating its effect on global climate change. However, this study's focus is on determining long-term alternatives to oil-dependent transportation that can provide lasting replacements for petroleum-based fuels. As such, it does not, for the most part, consider fuel economy improvements, excepting those resulting from hybrid-electric vehicles. However, the effects of increased fuel economy can easily be extrapolated from this study's results by simply scaling the overall WtW energy use and emissions proportionate to the increase in fuel economy relative to the vehicle fuel economies assumed by this study. This should yield accurate results for the energy use and GHG metrics. Criteria pollutant emissions do not directly scale with fuel economy however, as regulations on vehicle tailpipe emissions complicate matters.

Perhaps most importantly, this study does not provide an examination of the scalability of the various alternative fuel/vehicle pathways considered. Such a scalability analysis is particularly important as several pathways are subject to fundamental constraints that may ultimately determine the degree to which these pathways can contribute to reducing petroleum energy use or emissions. There were over 211 million light-duty vehicles in the

United States in 2004, responsible for logging more than 2.6 trillion vehicle miles traveled.[34] That's more than enough for each person in the United States to drive alone from New York City to Los Angeles (or the reverse) three times each year![35] At that level of travel, the light-duty sector consumes over 16.2 quadrillion British thermal units (Btus) of energy,[36] nearly 1/6th of total United States energy consumption.[37] Clearly then, finding a true alternative to oil use in the light-duty transportation sector will require a solution that can scale to this level of consumption and beyond. Thus, a further analysis of the scalability of the alternative transportation fuels and vehicle systems considered in this study would be very fruitful. Particular attention should be paid to constraints in availability of fuel feedstocks and raw materials for vehicle systems, as well as the technical feasibility and scalability of distribution infrastructures.

Finally, it must be noted that this study in no way exhausts the range of possible fuel production and vehicle systems pathways potentially available. In particular, it does not include several potentially viable hydrogen production pathways including hydrogen produced from gasification of coal or biomass, or from high temperature electrolysis of water at next-generation nuclear power plants. Additionally, it does not include the coal or natural gas-to-liquids synthetic fuel production processes that are currently being considered for expanded use. Furthermore, none of the pathways included in this study assume that carbon capture and storage (carbon sequestration) is utilized. If carbon sequestration were used at coal or biomass gasification plants or at hydrogen production plants utilizing steam methane

[34] ibid. Supplemental Tables 46 and 48.
[35] Assumes a driving distance from Los Angeles to New York City of 2,780 miles and a U.S. population of 298.5 million.
[36] EIA, *AEO2006* Supplemental Table 34.
[37] ibid. p. 133, Table A1. Total U.S. energy consumption in 2004: 99.68 quadrillion Btus.

reforming of natural gas, several of the pathways could see considerably improved WtW emissions of GHGs.

Clearly then, there are several areas where this study and its methodologies could be further refined. However, the author hopes this study will offer an initial inquiry into the relative benefits and costs associated with adopting alternative fuels and vehicle systems. The results presented by this study should provide guidance as to which fuels and vehicles have the most potential and which WtW pathways are deserving of additional attention and continued analysis.