FROM WELL TO WHEEL: A COMPREHENSIVE COMPARISON OF TRADITIONAL AND ALTERNATIVE VEHICLE-FUEL SYSTEMS

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ABSTRACT

The objective of this project is to determine the advantages of the modern alternative fueled vehicles over traditional vehicles on a well to wheel basis. Alternative fueled vehicles are often lauded for their advantages during vehicle operation. This project evaluates vehicles according to their relative values on a broader scale.

This project compares traditional, alternative fuel, and hybrid vehicles for use in the U.S. from the complete fuel cycle standpoint using points of comparison that include energy consumption, greenhouse gas emissions, and the emission of five principal pollutants. GREET software used in this study was developed at Argonne National Laboratory specifically for modeling these types of points. Financial considerations and social benefits outside the purview of GREET are also incorporated. The comparisons account for the attributes of each vehicle-fuel combination considering the feedstock, fuel production, and vehicle operation stages in order to provide a complete view of the fuel cycle. By comparing vehicles in this way, this project highlights the advantages of each combination and provides insight into the overall effect of operating these vehicle technologies.

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LIST OF ABBREVIATIONS

AFV	Alternative fuel vehicle
ANL	Argonne National Laboratory
BD	Biodiesel
BD20	Mixture of 20% biodiesel and 80% diesel by volume
CARFG	California reformulated gasoline
CC	Combined cycle
CD	Conventional diesel
CD mode	Charge depleting mode
CG	Conventional gasoline
CH_4	Methane
CI	Compression ignition
CIDI	Compression ignition, direct injection
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CS mode	Charge sustaining mode
DME	Dimethyl ether
DMP	Dry milling plant

DOE	U.S. Department of Energy
EF	Emission factor
EPA	U.S. Environmental Protection Agency
ETBE	Ethyl tertiary butyl ether
EtOH	Ethanol
EV	Electric vehicle
E10	Mixture of 10% ethanol and 90% gasoline by volume
E85	Mixture of 85% ethanol and 15% gasoline by volume
E90	Mixture of 90% ethanol and 10% gasoline by volume
ED10	Mixture of 10% ethanol and 90% diesel by volume
FCV	Fuel cell vehicle
FFV	Flexible-fuel vehicle
FG	Flared gas
FTD	Fischer-Tropsch diesel
FTN	Fischer-Tropsch naphtha
GC	Grid connected
GH_2	Gaseous hydrogen
GHG	Greenhouse gas
GI	Grid independent
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GTCC	Gas turbine combined cycle
GUI	Graphical user interface
GVW	Gross vehicle weight

H_2	Hydrogen
HEV	Hybrid electric vehicle
HTGR	High-temperature gas-cooled reactor
ICE	Internal combustion engine
IGCC	Integrated gasification combined cycle
INL	Idaho National Laboratory
LDT	Light duty truck
LG	Landfill gas
LH_2	Liquid hydrogen
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LSD	Low sulfur diesel
LT	Long-term
LWR	Light water reactor
MeOH	Methanol
MTBE	Methyl tertiary butyl ether
M85	Fuel mixture of 85% methanol and 15% gasoline by volume
M90	Fuel mixture of 90% methanol and 10% gasoline by volume
N	Nitrogen
N_2O	Nitrous oxide
NA	North American
NE U.S.	North-Eastern United States
NG	Natural gas

NGCC	Natural gas combined cycle
NNA	Non-North American
NOx	Nitrogen oxides
O_2	Oxygen
PC	Passenger car
PHEV	Plug-in hybrid electric vehicle
PM_{10}	Particulate matter with aerodynamic diameter of 10 micrometers or less
$PM_{2.5}$	Particulate matter with aerodynamic diameter of 2.5 micrometers or less
PTW	Pump to wheel
RFG	Reformulated gasoline
S	Sulfur
SI	Spark-ignition
SIDI	Spark-ignition direct-injection
SMR	Steam methane reforming
SO_2	Sulfur dioxide
SOx	Sulfur oxides
SST	Stochastic simulation tool
T&D	Transportation and distribution
TAME	Tertiary amyl methyl ether
TE	Total energy
TS	Time series
VOC	Volatile organic compound
WMP	Wet milling plant

WTP	Well to pump
WTW	Well to wheel

CHAPTER 1

INTRODUCTION

Everyday, people across the U.S. use their vehicles to commute to and from work and a variety of other destinations. Most of these people rarely think about the effect daily commuting has on the world around them. If they do think about the effect of their daily commute, it is most probably in a general reference to basic emissions and basic energy consumption caused by the vehicle operation itself. This thinking neglects key stages such as the feedstock and fuel production stages which are utterly tied to the operation of any vehicle. When it comes to purchase decisions between traditional and alternative fuel vehicles, most people do not have the information necessary to accurately judge the effectiveness of one vehicle-fuel combination versus another. This lack of understanding can affect progression toward cleaner, more efficient transportation.

Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) offers a broader perspective of many different vehicle-fuel combinations through simulations that takes into account energy consumption and emission of greenhouse gases and six air pollutants from the well to the wheels. That is, it accounts for the broader picture of the fuel cycle in an easy to analyze format from start to finish. With the information resulting from realistic and accurate simulations, vehicle technology and fuel combinations can be analyzed to offer a better understanding of the impact of our daily driving habits, and ultimately offer reasons for alternative courses of action with respect to the vehicles people choose to drive and the fuels that power these vehicles.

The purpose of this manuscript is twofold. First, this manuscript provides a thorough tutorial of GREET in order to facilitate undergraduate use of the software in the learning process in a new biofuels lab. Second, this manuscript provides several meaningful case studies which reflect vehicle-fuel comparisons between traditional, alternative, and hybrid vehicles. These comparisons are important as it is a common occurrence for people buying cars in the U.S. to want to compare these types of vehicles. The comparisons rely heavily on GREET simulations, but also incorporate other aspects outside the purview of GREET to build a comprehensive comparison of the vehicle-fuel combinations. This includes other factors such as direct and indirect economic benefits, health benefits, welfare benefits, and environmental benefits. The comparisons of these vehicle-fuel combinations ultimately result in conclusions based on simulated performance which will help educate people and hopefully be a driving factor in creating demand which will sustain cleaner and more effective transportation.

CHAPTER 2

GREETGUI USER GUIDE AND WALKTHROUGH

System Requirements

The following section pertains to the system requirements for Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) software and applies to supplemental programs as well. The GREET Read Me document discloses the requirements for GREET 1.8c.0. It requires an IBM compatible PC running Microsoft's Windows 95, Windows 98, Windows 2000, Windows Millennium Edition (ME), Windows NT, or Windows XP with Microsoft Excel 2000 or higher versions to be installed on the user machine before running GREET Graphical User Interface (GREETGUI). Microsoft Excel 97 and earlier versions are not compatible with the GREETGUI program. Microsoft Word is necessary to view the user guide files. The minimum hardware requirements include a processor at 166 MHz, 128 MB RAM, and 30 MB of free space on the hard drive. I personally recommend a hardware profile more in line with a computer capable of running Windows XP or better to decrease loading and computation times. Additionally, a pdf reader such as Adobe Reader will be necessary to view additional information files located on the Argonne National Laboratory website.

GREET Installation

The following section pertains to download and installation of the GREET 1.8c.0 Fuel-Cycle Model which became available in March 2009 and other required software. Several software component installations are required prior to the installation of GREET. Additional help with installations may be found at the Argonne National Laboratory website (http://www.transportation.anl.gov/modeling_simulation/GREET/index.html). Be aware that the content of the website is subject to updates and change. Please refer to the download page instructions for changes to the installation instructions for future versions of GREET.

Before the installation of GREET 1.8c.0, Microsoft Office XP Web Component 10 must be installed on your computer. Go to the Windows website at http://www.microsoft.com/downloads/details.aspx?FamilyID=982b0359-0a86-4fb2-a7ee-5f3a499515dd&displaylang=en to download the file "owc10.exe." When the download is complete, double-click on the file icon and follow the on-screen installation instructions.

Before the installation of GREET 1.8c.0, Microsoft Data Access Component version 2.5 or higher must be installed on your computer. In Windows, go to *Start, Find, Files or Folders*, and search for "mdac_typ.exe." If the file is found, right click on it and view its properties by clicking the Version tab. If the version found is earlier than 2.5 or if the file is not found, go to the Argonne National Laboratory website at http://www.transportation.anl.gov/modeling_simulation/GREET/downloads/mdac.zip to download and save the "mdac.zip" file to your hard drive. When the download is complete, double click the file icon to unzip the installation file. Then, double click on the installation file icon and follow the on-screen installation instructions.

To download GREET 1.8c.0 (Fuel-Cycle Model) proceed to the Argonne National Laboratory website at http://www.transportation.anl.gov/modeling_simulation/GREET/index.html. Under GREET Downloads, click the download link for GREET 1.8c.0 (Fuel-Cycle Model). Fill out the requested information and submit the form in order to access the download area for GREET model version 1.8c.0. Double click on the "Download GREET 1.8c.0" link at the top of the page to proceed to step-by-step instructions for preparing, downloading, and installing the software. Available documentation for GREET will be located just below the download link with a program description.

After confirming that the necessary programs are successfully installed on your computer, click and save the file "GREET1-8c-0.zip" to your hard drive. After completing the download, unzip the file from the folder where you saved it. Then, double click on the executable file "setup.exe" and follow the on-screen instructions to finish the installation.

As a mild warning, the software is not perfect and can be compromised in a variety of ways which will render the software unusable or corrupted. These include but are not limited to breaking Excel model formulae in the GREET Excel model, preventing parameters from being saved in GREETGUI, and the inclusion of unsolicited pathway results in the GREET output files. If trouble is experienced which indicates abnormal operation of GREET, simply uninstall and reinstall GREET 1.8c.0.

To uninstall GREET 1.8c.0, open the control panel feature in windows by going to S*tart*, *Settings*, *Control Panel*. Double click *Add/Remove Programs* and select GREET1.8 from the list of programs. Click *Remove* and follow the on screen instructions. After GREET is removed, simply reinstall GREET 1.8c.0 using the setup file from GREET1-8c-0.zip.

Introduction to GREETGUI

The following section is an introduction to GREET 1.8c.0 and includes its purpose and a broad overview of its function. GREETGUI enables access to the underlying Excel model referred to as GREET through a straightforward graphical user interface, or GUI, that streamlines analysis by allowing users to adapt the simulation based on their inputs for assumptions and parameters. That is, only pertinent menus will appear subsequent to specific inputs made by the user and non-pertinent menus will be excluded from view. GREETGUI is coupled with a stochastic simulation tool (SST) that may be configured for a stochastic simulation which takes into account probability distributions of key input parameters and produces results in the form of statistical distributions. Throughout this discussion, specific references will be made to either part of the software using GREET in reference to the hidden Excel model, GREETGUI in reference to the GUI, and SST in reference to the stochastic simulation tool.

The purpose of GREETGUI is to enable the analysis of vehicle-fuel cycles for various vehicle-fuel systems and conduct simulation studies in the underlying Excel model. These studies simulate energy use and emissions associated with the production and distribution activities of different transportation fuels (referred to as Well to Pump, or

WTP, activities), and analyze the energy use and emissions associated with vehicle operation for advanced vehicle technologies (referred to as Pump to Wheel, or PTW activities). These two analyses are collectively referred to as Well to Wheel (WTW) analysis and can provide insight into different aspects of future vehicle-fuel combinations.

For a given transportation fuel and vehicle technology combination, GREETGUI will calculate the fuel-cycle energy consumption, greenhouse gas (GHG) emissions, and the emissions of five criteria pollutants: carbon monoxide (CO), nitrogen oxides (NOx), sulfur oxides (SOx), particulate matter with an aerodynamic diameter of 10 micrometers or less (PM10), and particulate matter with an aerodynamic diameter of 2.5 micrometers or less (PM2.5) as well as volatile organic compounds (VOC). GREETGUI will also calculate energy and emissions changes for a given vehicle-fuel simulation relative to a gasoline vehicle fueled by conventional gasoline (CG). Included in the simulation is an estimation of the emissions released in an urban environment. Additionally, GREET accounts for different situational models with a series of key parametric assumptions covering fuel production, transportation and distribution, and vehicle operation.

Developed with Microsoft Visual Basic 6.0, the GREETGUI program accepts user inputs through option buttons, check boxes, and text fields. The GREETGUI communicates these inputs into GREET, the separate underlying Excel spreadsheet. When inputs are completed and the simulation started through the GREETGUI, the model runs in the background and displays results in the form of an Excel spreadsheet generated by the program as an output file. GREETGUI also generates a second Excel file as a record of all inputs made for a particular GREETGUI session.

Using the GREETGUI prevents users from accidentally altering the base Excel formulas within GREET which could cause catastrophic failures during the simulations and skew the results reported to the user. Figure 2.3.1 shows a typical GREETGUI session with interactive phases. These interactive phases streamline the sessions and guide the user through relevant matter while hiding extraneous material.

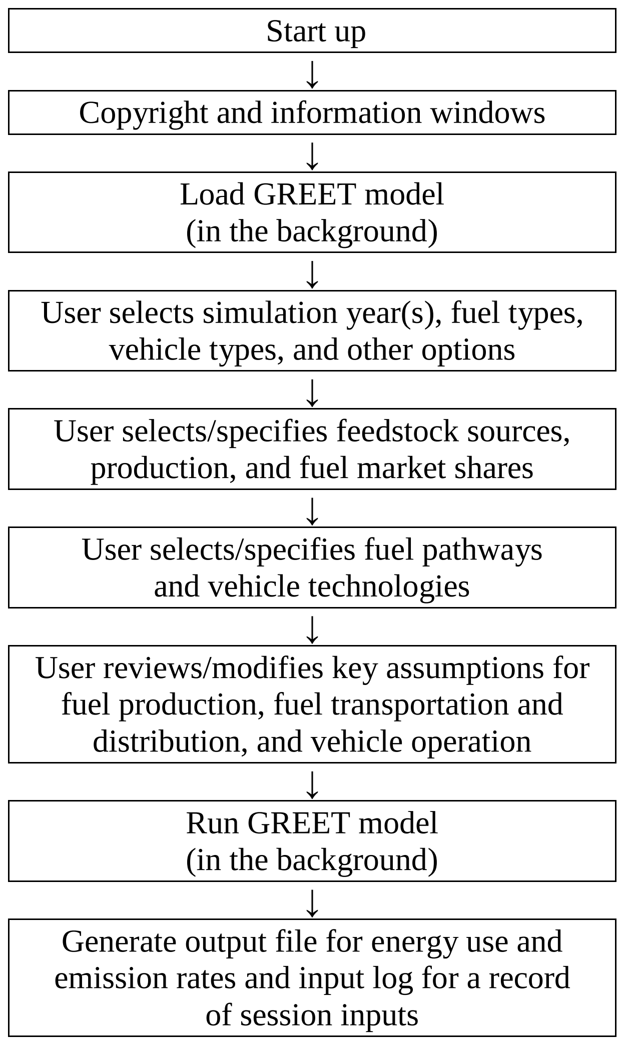


Figure 2.3.1 Interactive phases of a typical in a GREETGUI session.[1]

GREET has been utilized as an analytical tool for the simulation of the well to wheel activities associated with different vehicle fuel combinations in a wide range of publications. Sometimes, the research provided in these publications is eventually incorporated into the structure of GREET to offer a more complete tool. For example, "*Land Use Changes and Consequent CO2 Emissions due to US Corn Ethanol Production: A Comprehensive Analysis*" contains studies on land use changes associated with US corn ethanol production. The estimated land use changes from study were used to calculate greenhouse gas emissions associated with the corn ethanol production. The results of this research were eventually adapted into to the GREET model.[2] As another example, "*Well-to-Wheels Energy Use and Greenhouse Gas Emissions Analysis of Plug-in Hybrid Electric Vehicles*" examines the WTW energy use and greenhouse gas emissions of plug-in hybrid electric vehicles (PHEVs). The WTW results include separately calculated results for the blended charge depleting (CD) and charge sustaining (CS) modes of PHEV operation. These results were then combined by using a weighting factor that represented the CD vehicle miles traveled (VMT) share. GREET 1.8c.0 incorporates these changes for the simulation of PHEVs. [3] These two publications exemplify the continual endeavor to keep GREET accurate and up-to-date with the latest advances and research for modeling vehicle-fuel combinations. Additional publications may be found under the publications link on Arconne's GREET website.

Using GREETGUI

Please note that the last formal operating manual for GREET was compiled for version 1.7. Although there are summaries of expansions and revisions for each version update, they are not as thorough as the previous operating manual. The following guide is based off of my use of GREET1.8c.0 with some references to material I found to be current and helpful for explaining how to properly use the GUI. For more information on the development of this program please check the official GREET website at ANL.gov.

Starting GREET

GREETGUI is accessible by executing the GREET1.8c.exe file or double clicking the program shortcut usually located on the desktop. If no shortcut is available, click *Start*, *All Programs*, *GREET1.8*, *GREET1.8c.exe* to start the program. The About GREET window shown in Figure 2.4.1 will display upon startup. This window contains the version identification, development information, and release information of the GREET software. The About GREET window prompts the user to select 'Ok' to continue with the program or 'About' to view more information on GREET 1.8c.0 and the user's system.

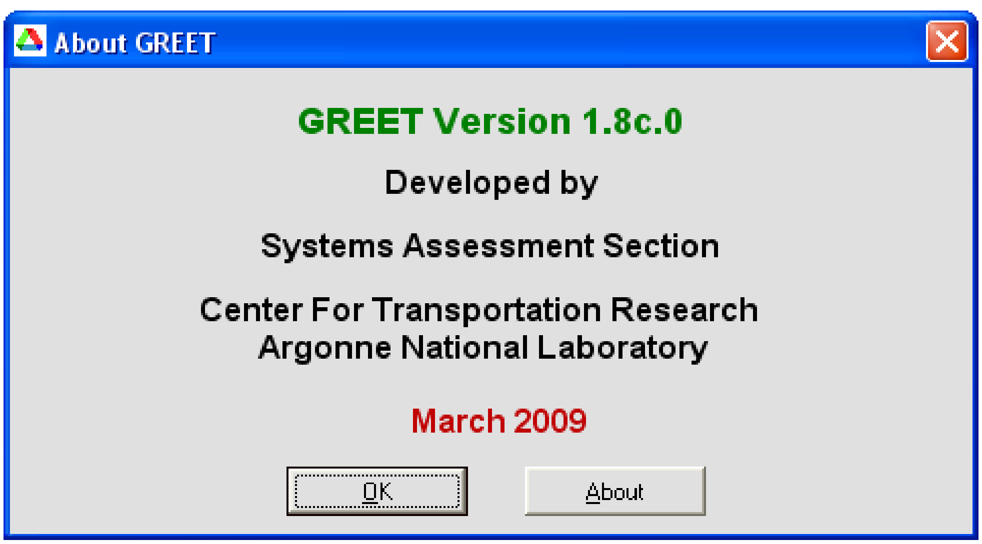


Figure 2.4.1 About GREET window displays version and other system information. [4]

After selecting 'Ok' on the About GREET window, the GREET1.8 warning window opens. Shown in Figure 2.4.2, it prompts the user to close any Excel files before continuing. If the user does not close any open Excel files before selecting 'Ok' to continue, the files will be closed without saving. The user may select 'Cancel' to exit GREETGUI at this time.

Figure 2.4.2 GREET1.8 window warns the user to close open Excel files. [4]

After selecting 'Ok' on the GREET1.8 warning window, the Copyright window opens. Shown in Figure 2.4.3, it contains the copyright notification for the GREET 1 series software. It is recommended that the user read this information prior to continuing. The copyright window prompts the user to 'Continue' or 'Exit' the program.

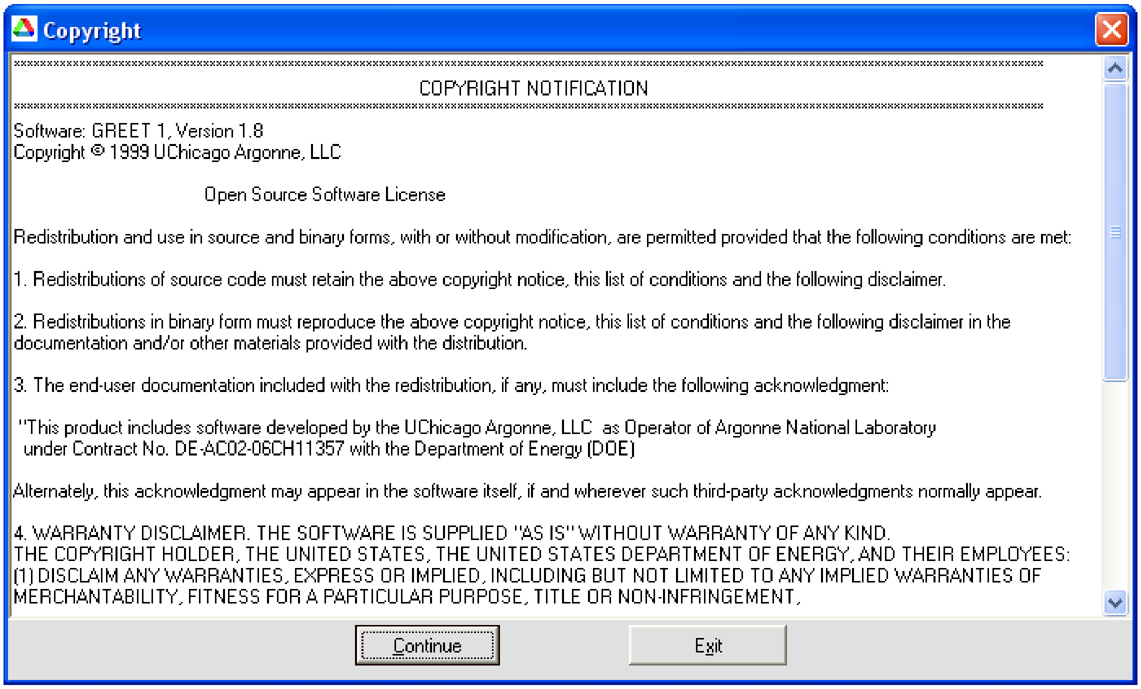


Figure 2.4.3 The Copyright window contains the legal notification to all software users. [4]

After selecting 'Continue' on the Copyright window, the GREET1.8 main menu opens. Shown in Figure 2.4.4, the main menu prompts the user to start a new session, open an existing session, or exit GREETGUI.

Figure 2.4.4 The GREET 1.8 main menu window allows the user to start a session or exit the program. [4]

From the GREET1.8 main menu, selecting ‘New Session’ opens a directory window. Shown in Figure 2.4.5, the directory window prompts the user to specify a session name. GREETGUI uses the specified name to create three separate files. GREETGUI appends “In” and “Out” to this name to designate input and output Excel files associated with the simulation. The Excel input and output files contain a log of all inputs during the session and outputs generated as a result of the simulations, respectively. The third file contains the session’s GREET Assumption File (.gaf) which is a log of all assumptions made for the session. After entering a unique File name, selecting ‘Save**’** begins the new session and opens the Scenario and Fuel Pathway Selections window. Selecting ‘Cancel’ returns the user to the GREET main menu.

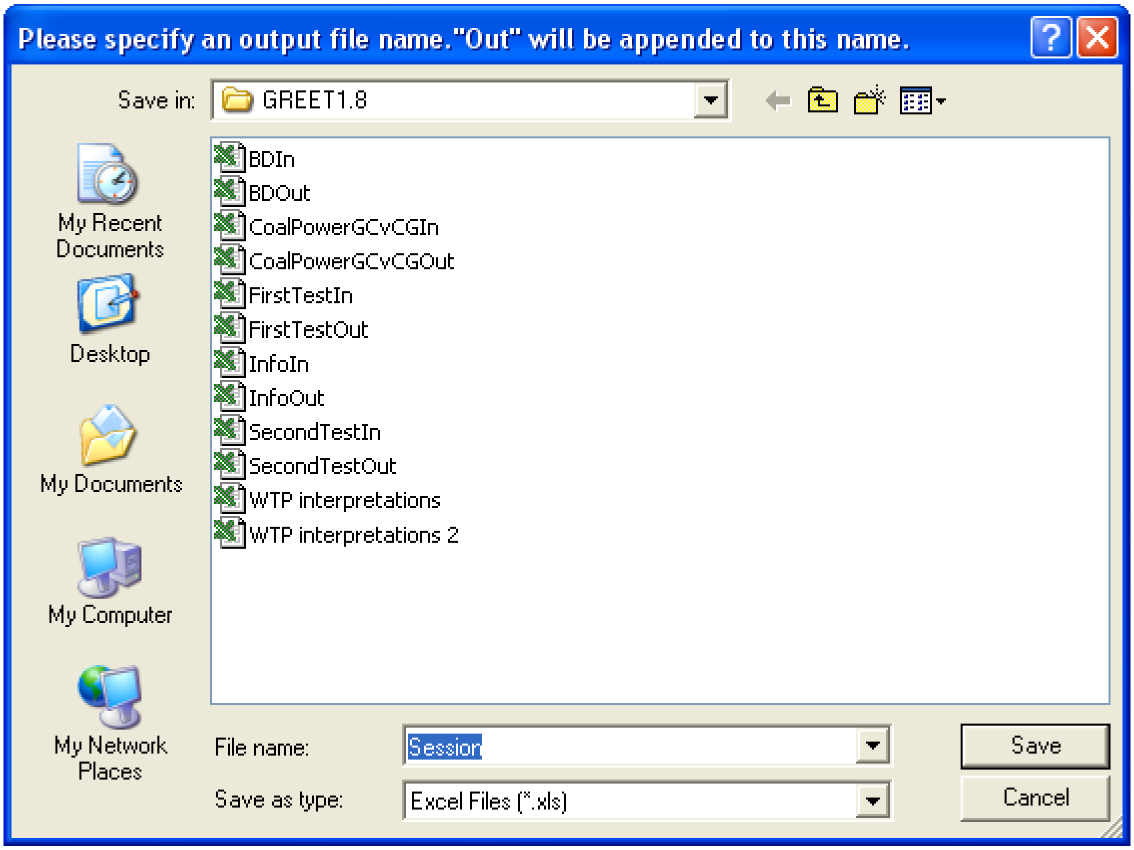


Figure 2.4.5 This directory window allows a GREETGUI session to be designated and saved. [4]

From the GREET1.8 main menu, selecting 'Open Existing Session' opens a directory window. Shown in Figure 2.4.6, it prompts the user to specify an existing GREET Assumption file. After specifying a file name and selecting 'Open,' another directory window shown in Figure 2.4.5 prompts the user to specify a session name. Once the file name is specified, GREETGUI opens the previously saved assumptions and begins the session. Selecting 'Cancel' at either window returns the user to the GREET main menu.

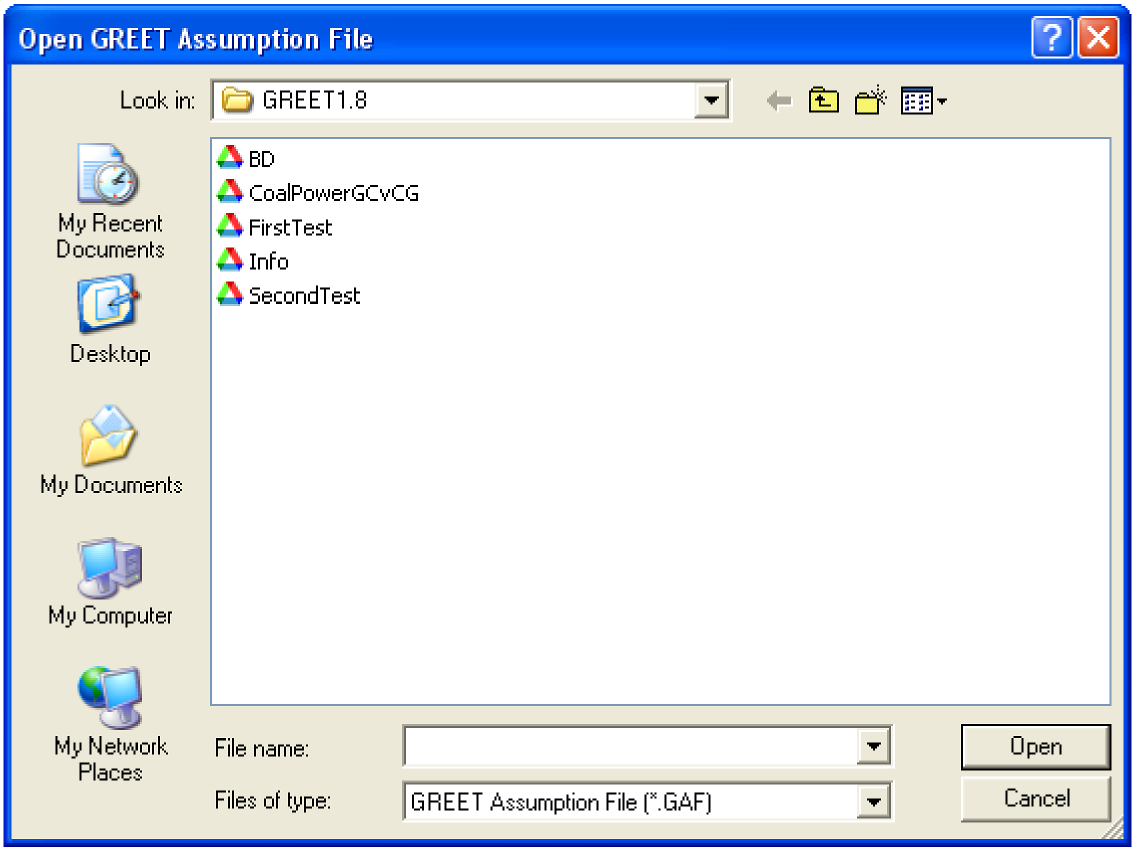


Figure 2.4.6 This directory window allows a previously saved GREET assumption file to be loaded into GREETGUI. [4]

From the GREET1.8 main menu, selecting 'Exit' closes the program.

Scenario and Fuel Pathway Selections

Shown in Figure 2.4.7, the Scenario and Fuel Pathway Selections window opens after successfully starting a new session or opening an existing session. From this window, the user selects the years to be simulated, vehicle type, and fuel pathways. In addition, the user may choose to run a stochastic simulation using the stochastic simulation tool (SST). This option only applies to single year simulations. Selecting

‘Continue>>’ saves the selections and continues the session with the Market Shares Options window.

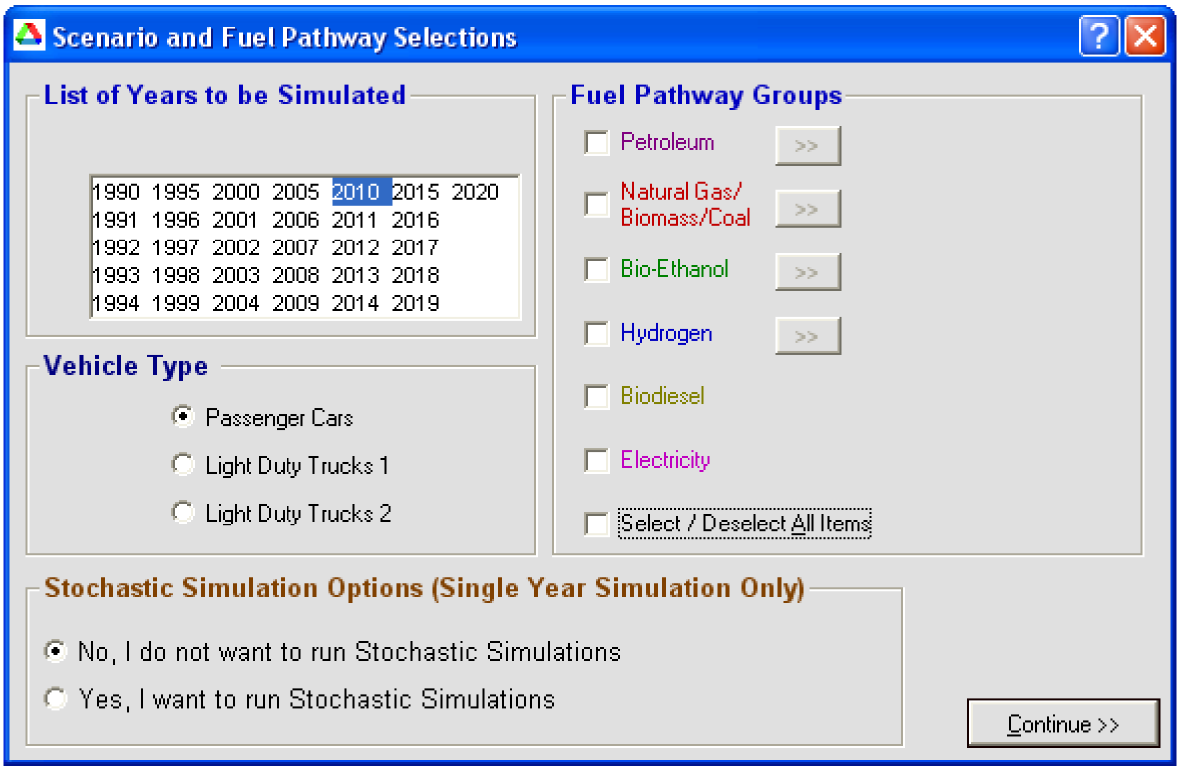


Figure 2.4.7 The scenario and fuel pathway selections window contains the most basic options of the simulation. [4]

The list of simulation years spans from 1990 to 2020. The user has the option to select a single year or multiple years for the simulation. For a single year, select the year to be simulated by left clicking the desired year. For multiple years in series, left click the first desired year in the series, hold, and drag the cursor to the last desired year in the series. Alternatively, select the first year of the series and then select the last year of the series while holding Shift. For multiple years not in series, left click all pertinent years while holding Ctrl. The selected year(s) are shown with a highlight. These selections designate the appropriate time series data for GREET to use during the simulation. The time series (TS) data includes market share information, parameters, and assumptions that are pertinent to the unique simulation. Later in the session, some of the assumptions will be available for inspection and modification, if necessary.

The user has the option to select a vehicle type corresponding to Passenger Cars (PC), Light Duty Trucks 1 (LDT1), or Light Duty Trucks 2 (LDT2). There are several subclasses for each vehicle class (i.e. the passenger car class includes sub-compact car, compact car, midsize car, large car, etc.) so the fuel economy data may vary by the vehicle subclass. The default vehicle subclasses in GREETGUI reflect the dominant vehicle types in the current U.S. market. That is, a midsize passenger car is default for the PC option, a light duty truck or midsize SUV with a gross vehicle weight (GVW) less than 6000 lbs is default for the LDT1 option, and a large, light duty truck with a GVW between 6000 and 8500 lbs is default for LDT2.[5] Examples of midsize passenger cars include an Acura TL, a Ford Fusion, a Toyota Camry, a Volkswagen Passat, and a Honda Accord. Examples of light duty trucks or midsize SUVs with a GVW less than 6000 lbs include a Chevrolet Colorado, a Ford Ranger, a Ford Escape, and a Jeep Grand Cherokee. Examples of large, light duty trucks with a GVW between 6000 and 8500 lbs include a Dodge Ram, a Ford F-150, a GMC Sierra, and a Toyota Tundra.

The user may select fuels from six different fuel pathway groups: (1) Petroleum, (2) Natural Gas/Biomass/Coal, (3) Bio-Ethanol, (4) Hydrogen, (5) Biodiesel, and (6) Electricity. The first four fuel pathway groups contain multiple fuel types which are accessible in a separate window by selecting the main fuel pathway group or clicking the ‘>>’ button next to a selected group’s name.

The Petroleum Based Fuel Types window prompts the user to select the desired petroleum based fuel types. Selecting 'Continue' saves the selections and returns the user to the Scenario and Fuel Pathway Selections window. Shown in Figure 2.4.8, the Petroleum Based Fuel Types window includes Gasoline, Diesel, California Reformulated Gasoline (CARFG), Liquefied Petroleum Gas (LPG), and Crude Naptha options. Subtypes are reflected in market share assumptions. Gasoline fuel types include Conventional Gasoline (CG) and Reformulated Gasoline (RFG) subtypes. Diesel fuel types include Conventional Diesel (CD) and Low-Sulfur Diesel (LSD) subtypes. LPG shares reflect a feedstock dependency, and in this case, LPG is a crude petroleum derivative.

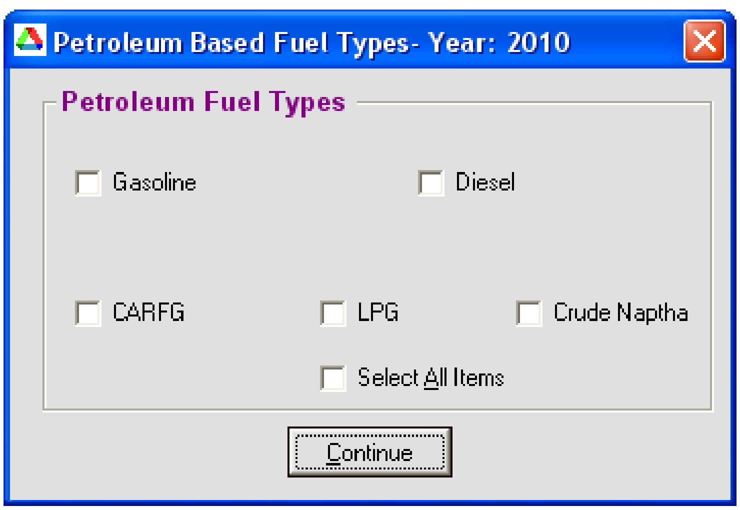


Figure 2.4.8 The petroleum based fuel types window offers the selection of gasoline, diesel, CARFG, LPG, and crude naptha. [4]

The Natural Gas (NG) Based Fuel Types window prompts the user to select desired NG based fuel types. Selecting 'Continue' saves the selections and returns the user to the Scenario and Fuel Pathway Selections window. Shown in Figure 2.4.9, the

NG Based Fuel Types window includes fuel types derived from Natural Gas, Biomass, and Coal. These fuel types include Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), Methanol (MeOH), Dimethyl Ether (DME), Fischer-Tropsch Diesel (FTD), Naptha, and LPG. LPG shares reflect a feedstock dependency, and in this case, LPG is a NG derivative.

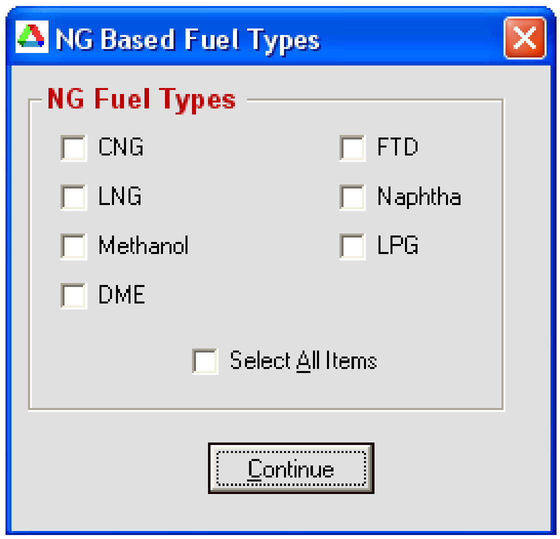


Figure 2.4.9 The NG based fuel types window offers the selection of CNG, LNG, methanol, DME, FTD, naptha, and LPG. [4]

The Ethanol Blend Level window prompts the user to select desired ethanol levels for Bio-Ethanol fuel types. Selecting 'Continue' saves the selections and returns the user to the Scenario and Fuel Pathway Selections window. Shown in Figure 2.4.10, the Ethanol Blend Level window includes a Low-Level Blend, a High-Level Blend, and 100% Ethanol. A Low-Level Blend consists of 5-15% ethanol by volume blended with either gasoline or diesel fuel. A High-Level Blend consists of 50-90% ethanol by volume with gasoline. A 100% Ethanol fuel is strictly for use in Fuel Cell Vehicles (FCV). A variety of market share dependent feedstocks are available for ethanol production.

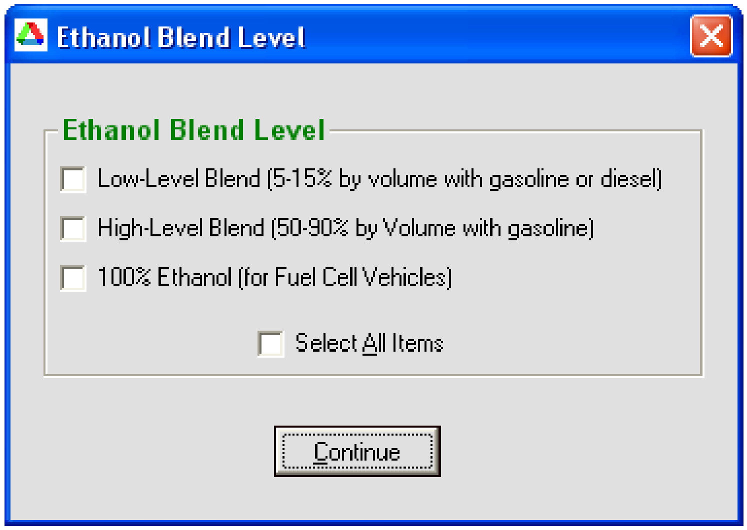


Figure 2.4.10 The ethanol blend level window offers the selection of low-level blend, high level blend, and pure ethanol. [4]

The Hydrogen (H_2) Based Fuel Types window prompts the user to select desired Hydrogen fuel types. Selecting 'Continue' saves the selections and returns the user to the Scenario and Fuel Pathway Selections window. Shown in Figure 24.11, The Hydrogen Based Fuel Types window includes Gaseous Hydrogen and Liquid Hydrogen fuel types. Production of both types occurs at a central facility or directly at a fueling station from a variety of market share dependent sources.

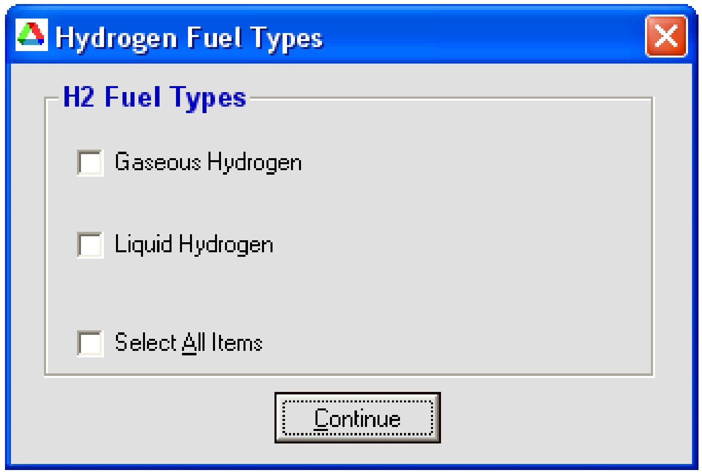


Figure 2.4.11 The hydrogen fuel types window offers the selection of gaseous and liquid hydrogen. [4]

The user may also opt to use the stochastic simulation tool (SST) for single year simulations in GREET. The SST has been built in the GREET model to address the uncertainties. It takes into account the probability distributions of key input parameters such as energy efficiencies and emission factors associated with the feedstock recovery and fuel production processes, and produces the results in the form of statistical distributions. For more information about using GREETGUI to configure the GREET model for stochastic simulations, read *Operating Manual for GREET: Version 1.7*.[6]

Market Shares Options

Shown in Figure 2.4.12, the Market Shares Options window prompts the user to select one of the market shares options for each feedstock and fuel type selected on the Scenario and Fuel Pathway Selections window (See Fig. 2.4.7). Selecting 'Continue' saves the selections and continues the session with relevant market shares windows.

Selecting ‘<< Back’ opens a drop down menu listing Scenario and Fuel Pathway Selections. Clicking the listed item returns the user to that menu.

GREET is currently designed to simulate different fuel production pathways scenarios based on estimates in time series (TS) lookup tables. The information ranges from 1990 to 2020 in five year intervals. Estimates for simulation years that are not divisible by five are calculated from simple interpolation between the estimates immediately surrounding them in the tables. All simulation years beyond 2020 which is the last available year in the GREET lookup tables are automatically assumed to have the same estimates as those for 2020. By default, GREET Default Market Shares is selected. This option automatically uses market shares for selected markets and simulation years stored within the GREET model and allows the user to view them before proceeding. The Linear Interpolation between the Start Year and End Year Shares option allows the user to specify market shares for the first and last selected simulation years and performs a linear interpolation of this market share information for all years between the first and last year specified. The Linear Interpolation is only available where three or more simulation years are selected. The User to Specify All Market Shares option allows the user to adjust default Market share values in the subsequent market shares windows for all selected years. In cases involving market shares data of historical reference (pre-2010), it is common practice to never adjust the share options and other data pertaining to historic record.

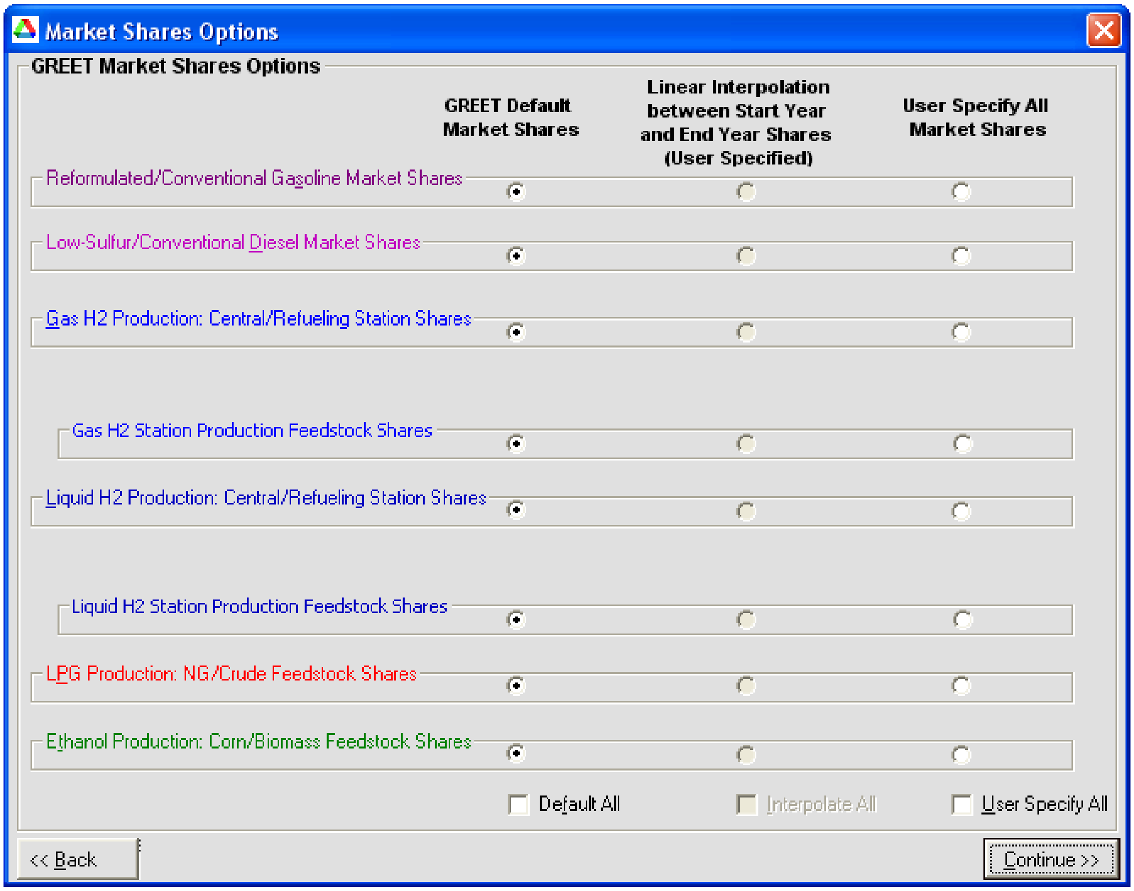


Figure 2.4.12 The market shares options window allows the method for determining market shares to be specified for individual markets. [4]

Continuing from the Market Shares Options window, relevant share windows for fuel type, feedstock, and production will open. As previously stated, these market shares may be reviewed and altered depending upon the user's selections in the Market Shares Options window. For the Linear Interpolation and User Specify All options, the user may select any of the yellow text fields to alter the shares of each type to an acceptable percent. The white cells associated with that year will automatically adjust to make sure that there is always 100% usage within the market.

Shown in Figure 2.4.13, the Gasoline and Diesel Fuel Types and Shares window provides tables displaying the market share values of relevant fuel types by simulation year. After reviewing selections on this window, the user may select '<<Back' to return to the Market Shares Options window or 'Continue' to proceed. The gasoline fuel types and shares usually consist of RFG and CG. The diesel fuel types and shares consist of LSD and CD.

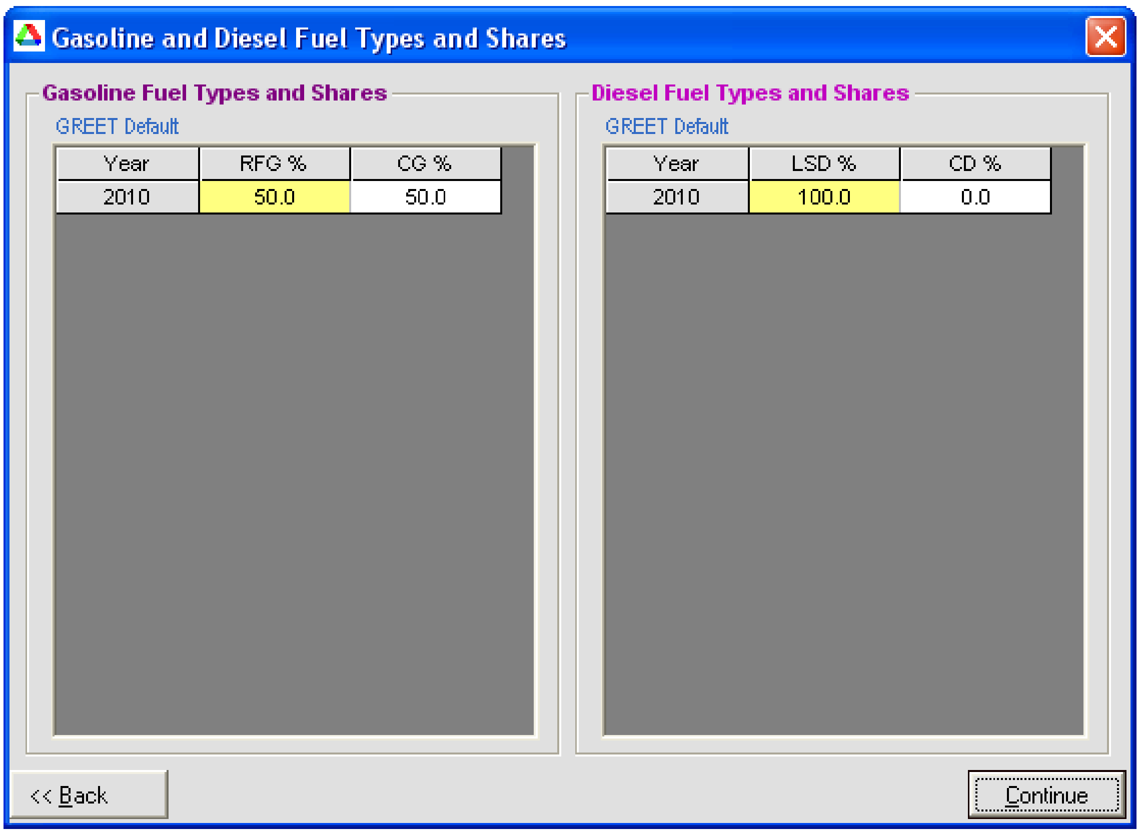


Figure 2.4.13 The gasoline and diesel fuel types and shares window lists the appropriate shares by year. [4]

Shown in Figure 2.4.14, the Hydrogen Production Shares window provides tables displaying the market share values of relevant production pathways by simulation year.

After reviewing selections on this window, the user may select ‘<<Back’ to return to the Market Shares Options window or ‘Continue’ to proceed. Central production refers to a model where production of the fuel occurs at a central center and the fuel is later transported to the refueling stations. Station production refers to a model where the production of the fuel occurs at the refueling stations.

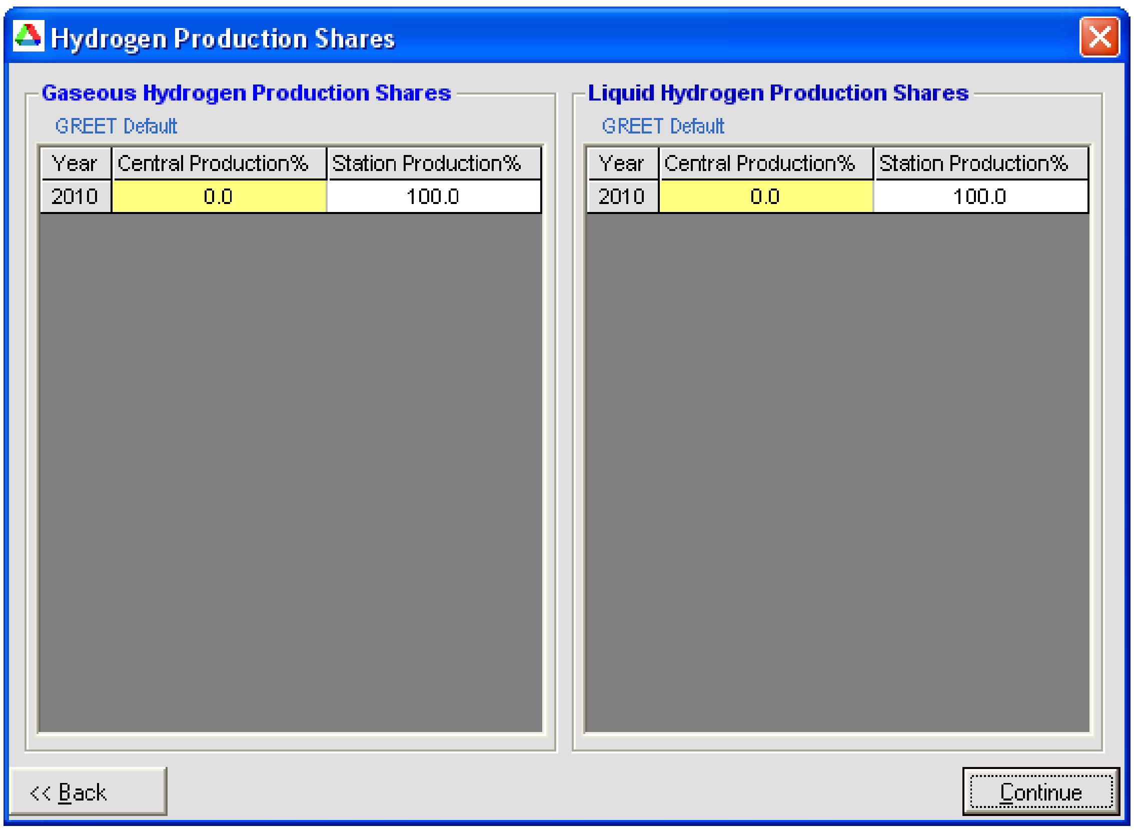


Figure 2.4.14 The hydrogen production shares window contains the yearly market share information for central and station production. [4]

Shown in Figure 2.4.15, the GH_2 (Gaseous Hydrogen) Central Feedstock Shares window provides a table displaying the market share values of relevant feedstock by simulation year. After reviewing selections on this window, the user may select ‘<<Back’

to return to the Market Shares Options window or ‘Continue’ to proceed. Feedstock shares for GH_2 central production include NG, solar photovoltaics (PV), nuclear thermo-chemical water cracking (TCWC), nuclear high-temperature gas-cooled reactor (HTGR), coal, biomass, and coke oven gas (COG).

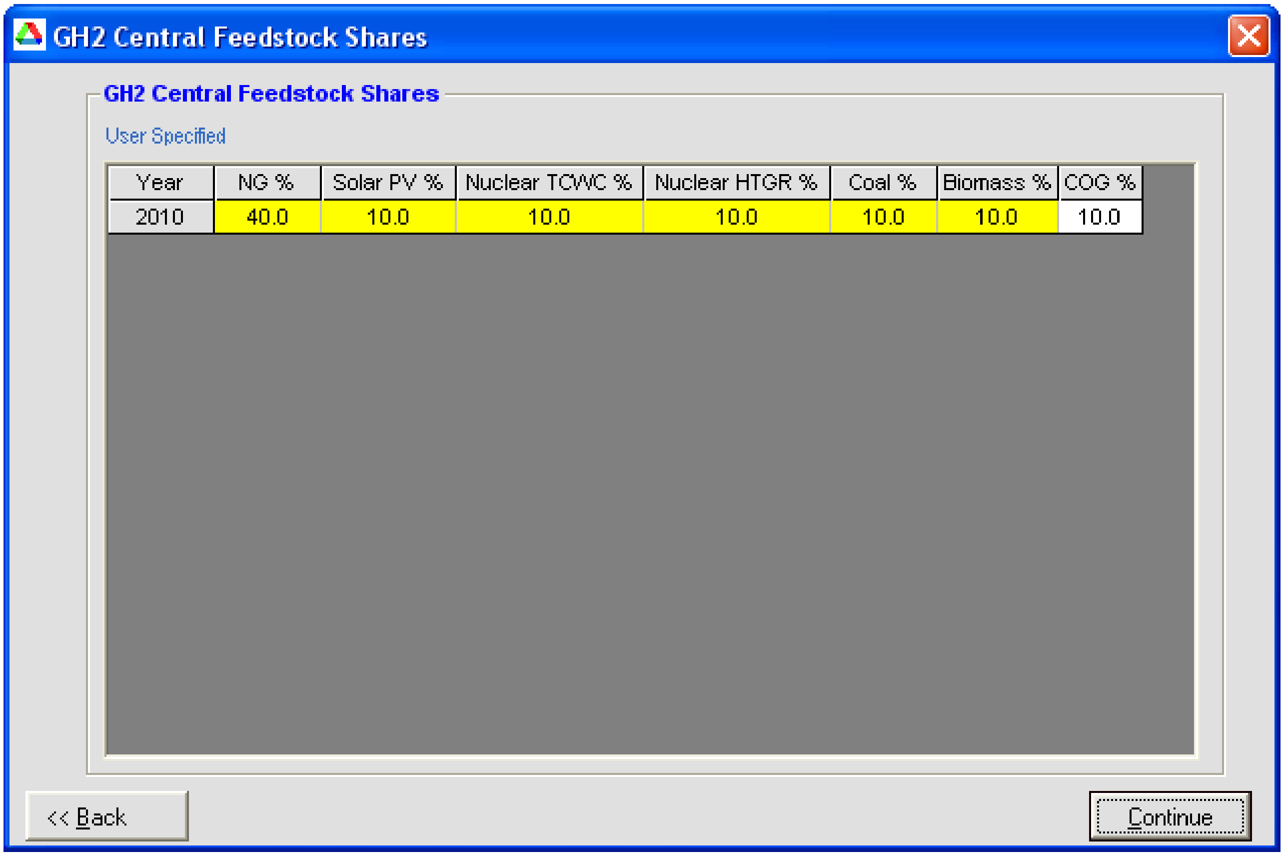


Figure 2.4.15 The GH_2 central feedstock shares window contains shares of feedstock from which gaseous hydrogen may be produced at a central production facility. [4]

Shown in Figure 2.4.16, the GH_2 Station Feedstock Shares window provides a table displaying the market share values of relevant feedstock by simulation year. After reviewing selections on this window, the user may select ‘<<Back’ to return to the

Market Shares Options window or ‘Continue’ to proceed. Feedstock shares for GH_2 station production include NG, electrolysis, ethanol, and methanol.

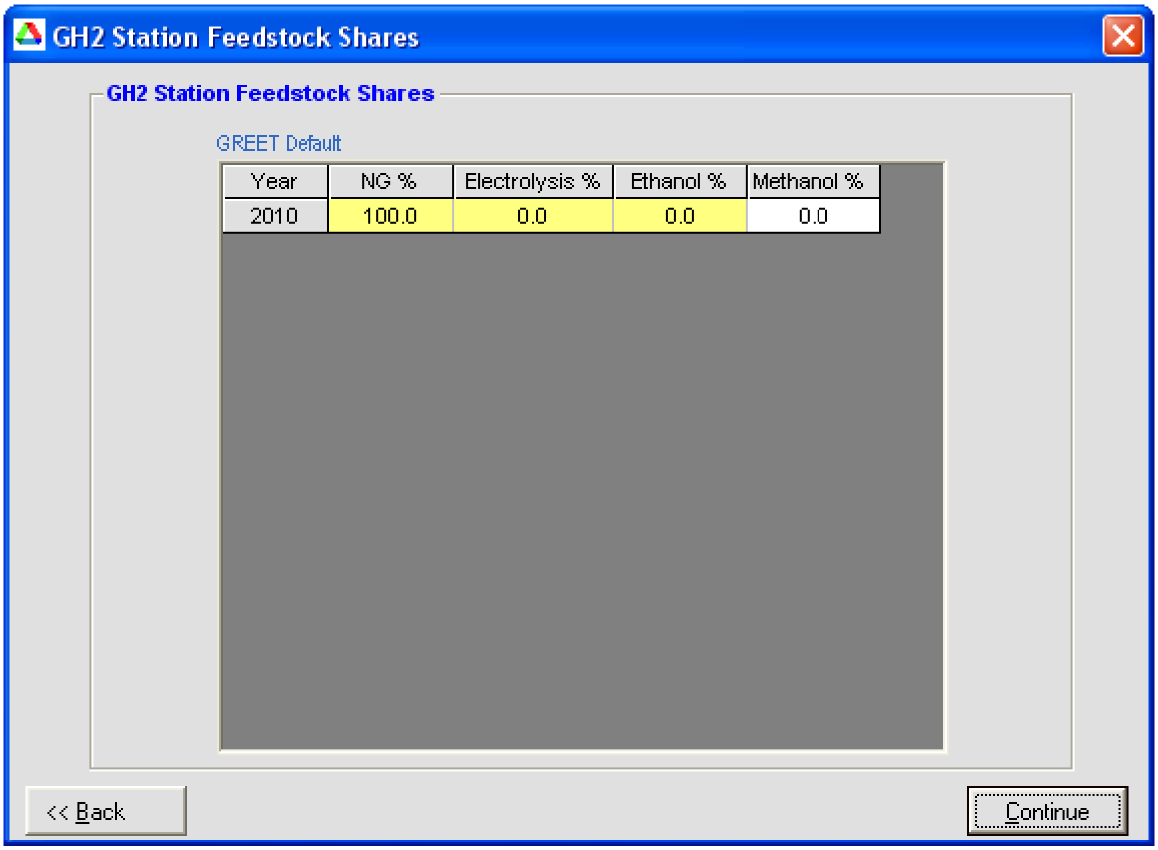


Figure 2.4.16 The GH_2 station feedstock shares window contains shares of feedstock from which gaseous hydrogen may be produced at a fueling station. [4]

Shown in Figure 2.4.17, the LH_2 (Liquid Hydrogen) Central Feedstock Shares window provides a table displaying the market share values of relevant feedstock by simulation year. After reviewing selections on this window, the user may select ‘<<Back’ to return to the Market Shares Options window or ‘Continue’ to proceed. Feedstock shares for LH_2 central production include NG, solar PV, nuclear TCWC, nuclear HTGR, coal, biomass, and COG.

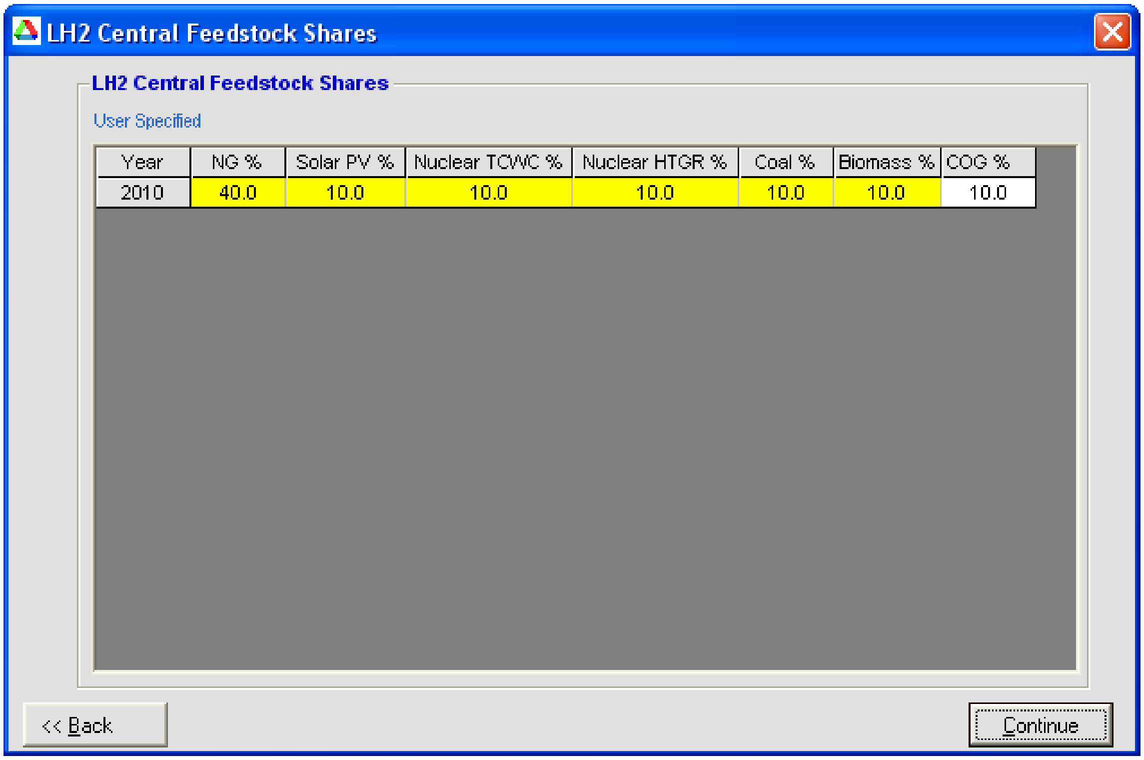


Figure 2.4.17 The LH_2 central feedstock shares window contains shares of feedstock from which liquid hydrogen may be produced at a central production facility. [4]

Shown in Figure 2.4.18, the LH_2 Station Feedstock Shares window provides a table displaying the market share values of relevant feedstock by simulation year. After reviewing selections on this window, the user may select ‘<<Back’ to return to the Market Shares Options window or ‘Continue’ to proceed. Feedstock shares for LH_2 station production include NG, electrolysis, ethanol, and methanol.

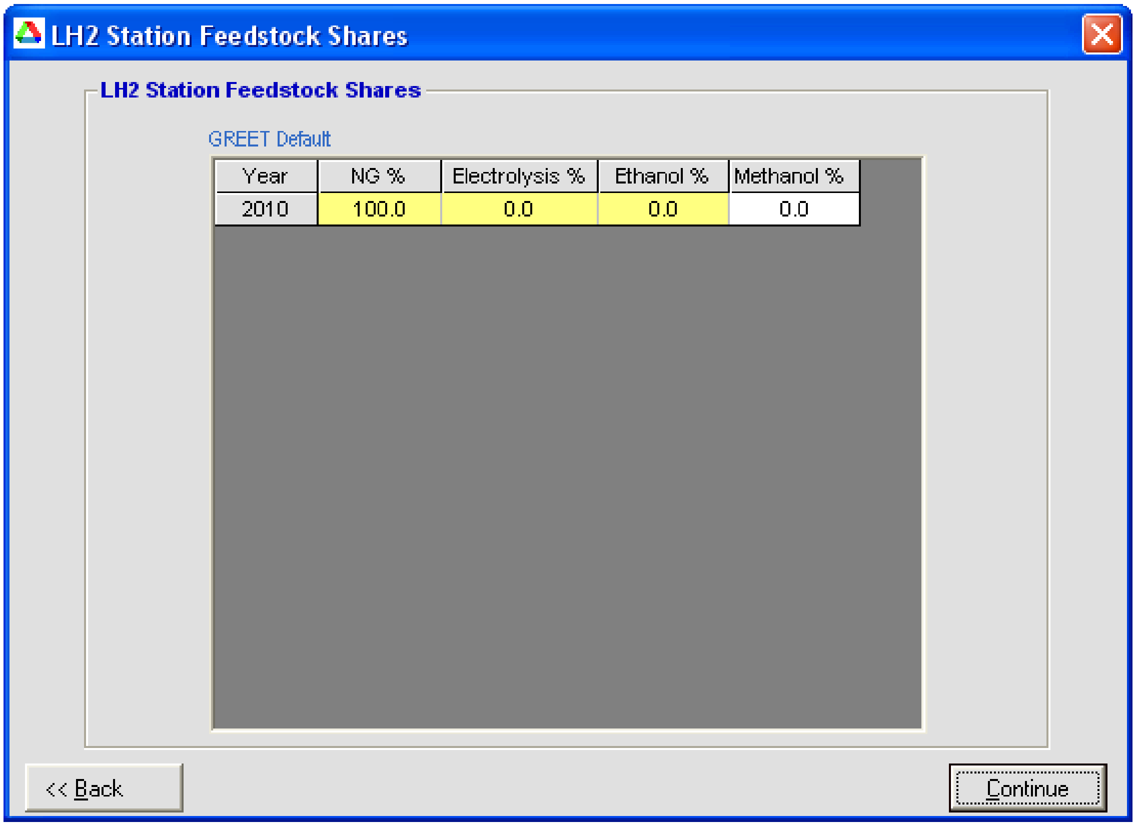


Figure 2.4.18 The LH_2 station feedstock shares window contains shares of feedstock from which liquid hydrogen may be produced at a refueling station. [4]

Shown in Figure 2.4.19, the LPG Feedstock Shares window provides a table displaying the market share values of relevant feedstock by simulation year. After reviewing selections on this window, the user may select '<<Back' to return to the Market Shares Options window or 'Continue' to proceed. LPG feedstock shares include NG-based and crude-based production.

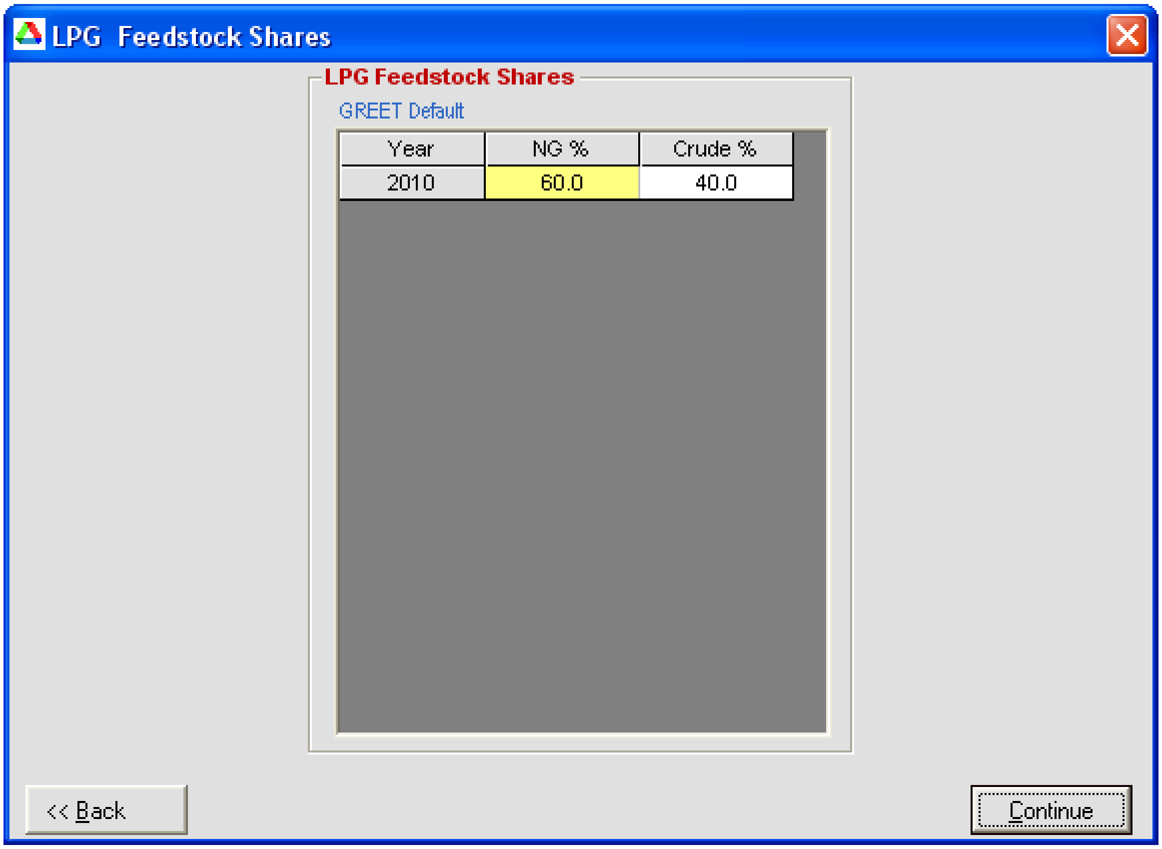


Figure 2.4.19 The LPG feedstock shares window displays shares of NG-based and crude-based feedstock. [4]

Shown in Figure 2.4.20, the Ethanol Feedstock Shares window provides a table displaying the market share values of relevant feedstock by simulation year. After reviewing selections on this window, the user may select '<<Back' to return to the Market Shares Options window or 'Continue' to proceed. Ethanol feedstock shares include corn, woody biomass, herbaceous biomass, corn stover, forest residue, and sugar cane.

Figure 2.4.20 The ethanol feedstock shares window displays shares of feedstock from which ethanol may be produced. [4]

Fuel Pathways Options

After reviewing all relevant Market Share information, the user is directed to relevant fuel pathway options windows where fuel subtype and vehicle technology options are located. The user may select '<< Back' to return to a previously listed menu or 'Continue>>' to proceed. Before being allowed to proceed, the user must review every fuel type and subtype tab on the fuel pathways option window. Individual tabs may be viewed by clicking the labeled tab inside the window. Note GREETGUI will select the closest year to 2010 as the base year for the simulation. The base year will display in the title of each window.

The Petroleum and NG Pathways Options window prompts the user to review and select pertinent options for any relevant fuel-vehicle technology combinations that are to be included in the simulation. The main fuel types are divided into tabs and include petroleum, NG/biomass/coal, naptha, and LPG. Subtypes are available in an additional series of tabs underneath each main fuel tab. Petroleum subtypes include RFG, CG, CARFG, CD, and LSD. NG/biomass/coal subtypes include CNG, LNG, methanol, FTD, and DME.

Shown in Figure 2.4.21, the petroleum pathway options for RFG include O_2 content by weight, oxygenate type, sulfur level, EtOH feedstock, and vehicle technology. The user may input changes to the default values in the yellow text fields to change O_2 content, sulfur level, and EtOH feedstock. The user may select to add methyl tertiary butyl ether (MTBE), EtOH, ethyl tertiary butyl ether (ETBE), or tertiary amyl methyl ether (TAME) as an oxygenate or select no oxygenate additive. Note, the ether options (MTBE, ETBE, and TAME) in GREETGUI are included for historical reference. Currently, ether usage has been discontinued due to health and environmental concerns. GREET will automatically blend enough oxygenate into the gasoline to meet the O_2 content by weight. However, if the “no oxygenate” option is selected, the O_2 content is automatically set to zero. The EtOH feedstock shares consist of corn, woody biomass, and herbaceous biomass. Note, the calculation pathway for ethanol produced for RFG is separate from the calculation pathway for ethanol-gasoline blends since one pathway uses content by weight and the other uses content by volume. Vehicle technologies available for RFG include spark-ignition (SI) engine, spark-ignition direct-injection (SIDI) engine, grid-independent (GI) hybrid electric vehicle (HEV) SI engine, plug-in hybrid electric vehicle (PHEV) SI engine, and fuel cell vehicle (FCV).

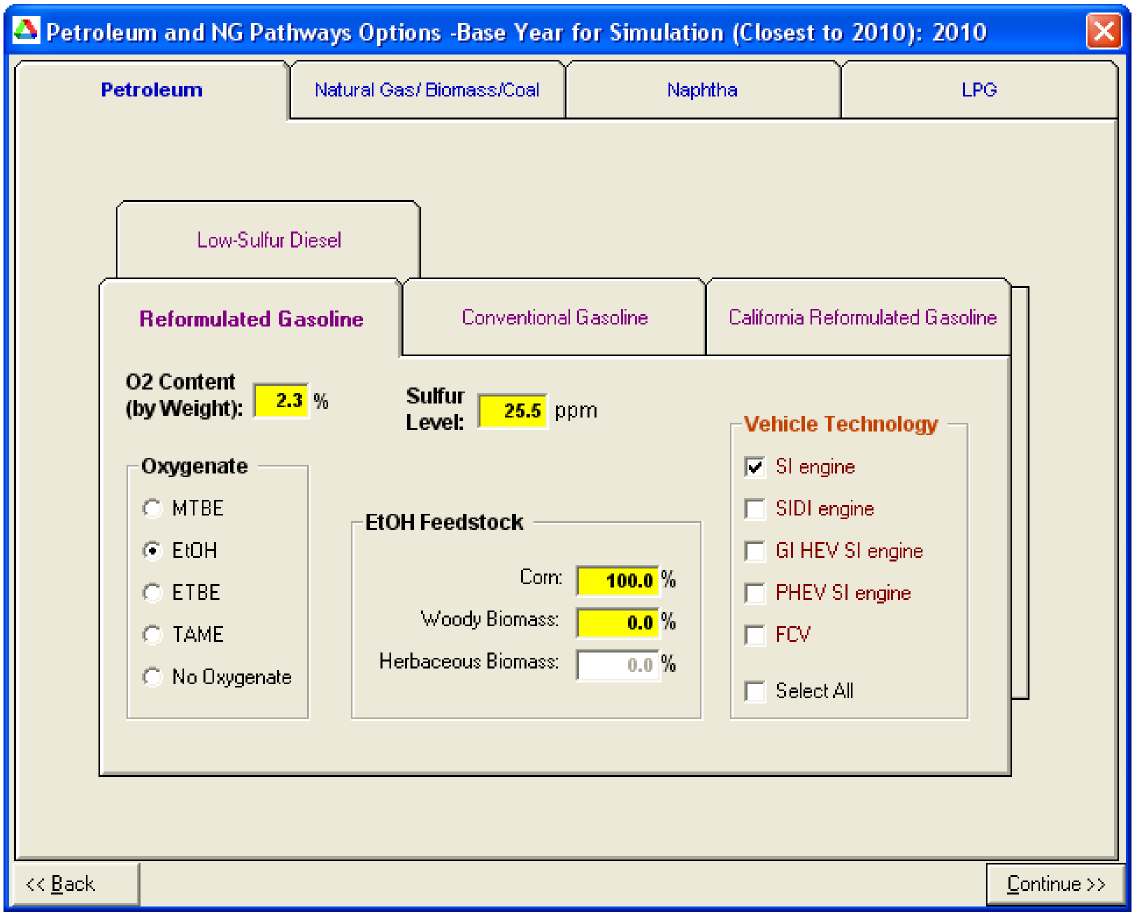


Figure 2.4.21 The petroleum and NG pathways options window for RFG contains options for the fuel and vehicle technology. [4]

Shown in Figure 2.4.22, the petroleum pathway options for CG include only sulfur levels. Vehicle technologies available for CG include SI engine, SIDI engine, GI HEV SI engine, and PHEV SI engine. The vehicle technologies paired with CG are automatically selected to be the same as the corresponding technologies selected for

RFG. If no market shares exist for RFG, the vehicles technologies may be selected normally for CG.

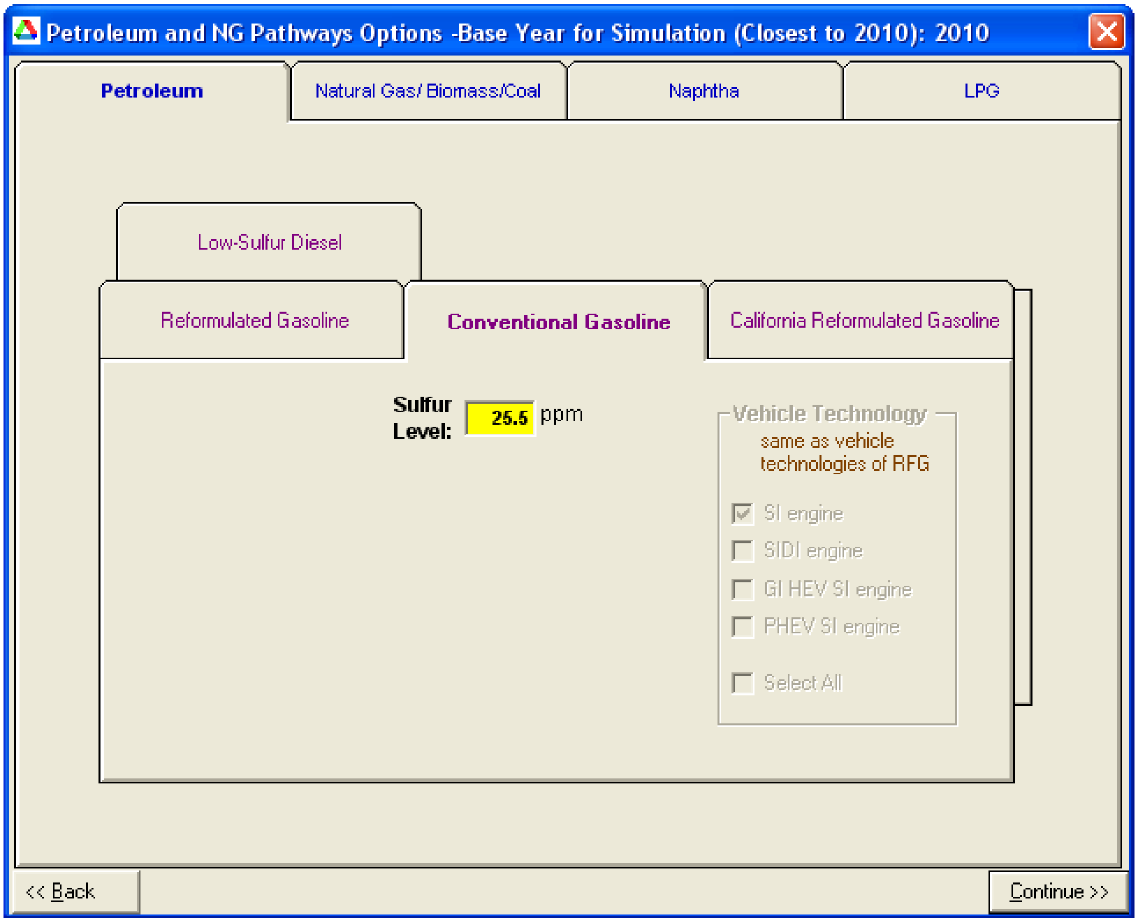


Figure 2.4.22 The petroleum and NG pathways options window for CG contains options for the fuel and vehicle technology.[4]

Shown in Figure 2.4.23, the petroleum pathway options for CARFG include O_2 content by weight, oxygenate type, sulfur level, EtOH feedstock, and vehicle technology. If an oxygenate is required, the user may select to add MTBE, EtOH, ETBE, or TAME with the same caveats presented for RFG. The EtOH feedstock shares consist of corn, woody biomass, and herbaceous biomass. Note, the calculation pathway for ethanol produced for CARFG is separate from the calculation pathway for ethanol-gasoline blends since one pathway uses content by weight and the other uses content by volume. Vehicle technologies available for CARFG include spark-ignition (SI) engine, spark-ignition direct-injection (SIDI) engine, grid-independent (GI) hybrid electric vehicle (HEV) SI engine, plug-in hybrid electric vehicle (PHEV) SI engine, and fuel cell vehicle (FCV).

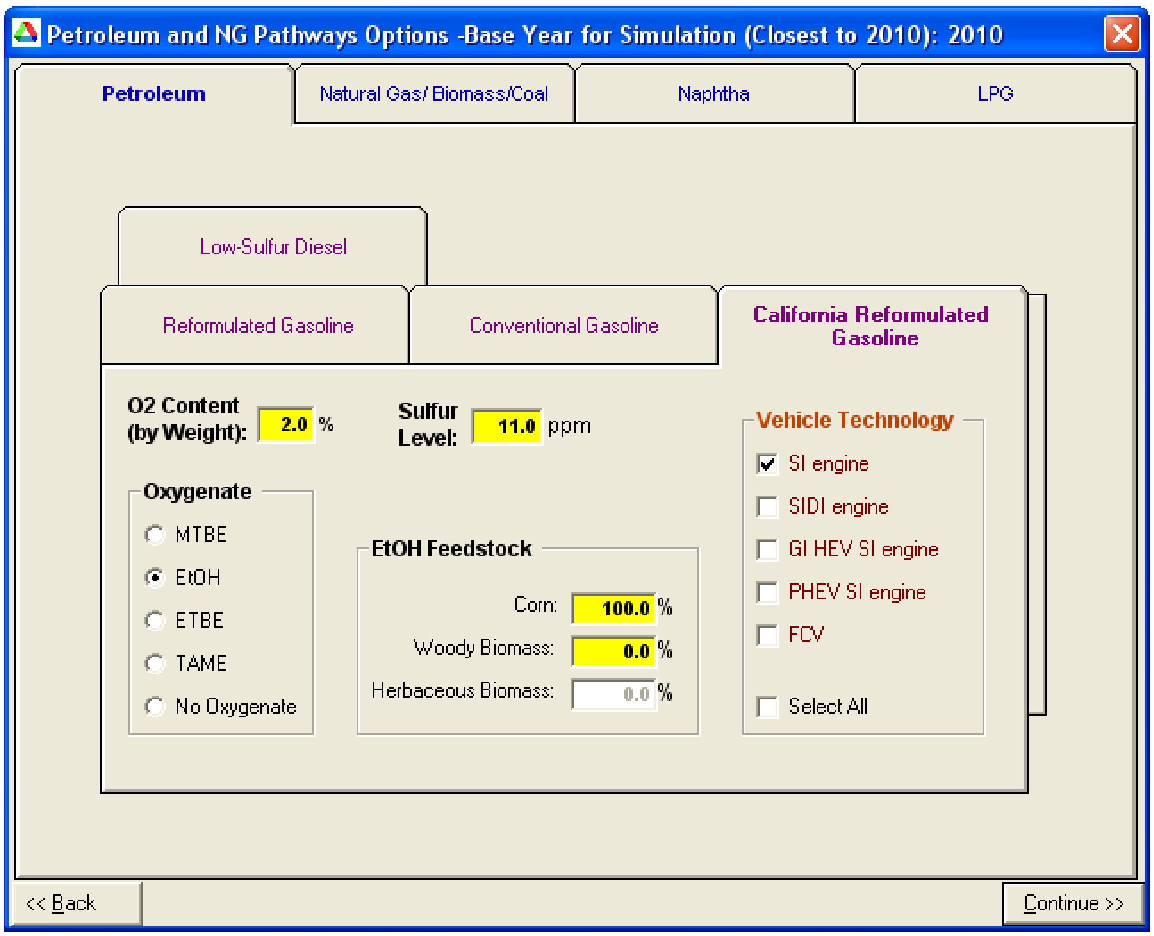


Figure 2.4.23 The petroleum and NG pathways options window for CARFG contains options for the fuel and vehicle technology. [4]

Shown in Figure 2.4.24, the petroleum pathway options for LSD include sulfur level, location for use, and vehicle technology. The default location for use is the entire U.S. If California is selected, the transportation mode and distance between crude oil fields and California refineries are used in the simulation for diesel fuels. The vehicle technologies available for LSD include compression-ignition direct-injection (CIDI) engine, GI HEV CIDI engine, PHEV CIDI engine, and FCV.

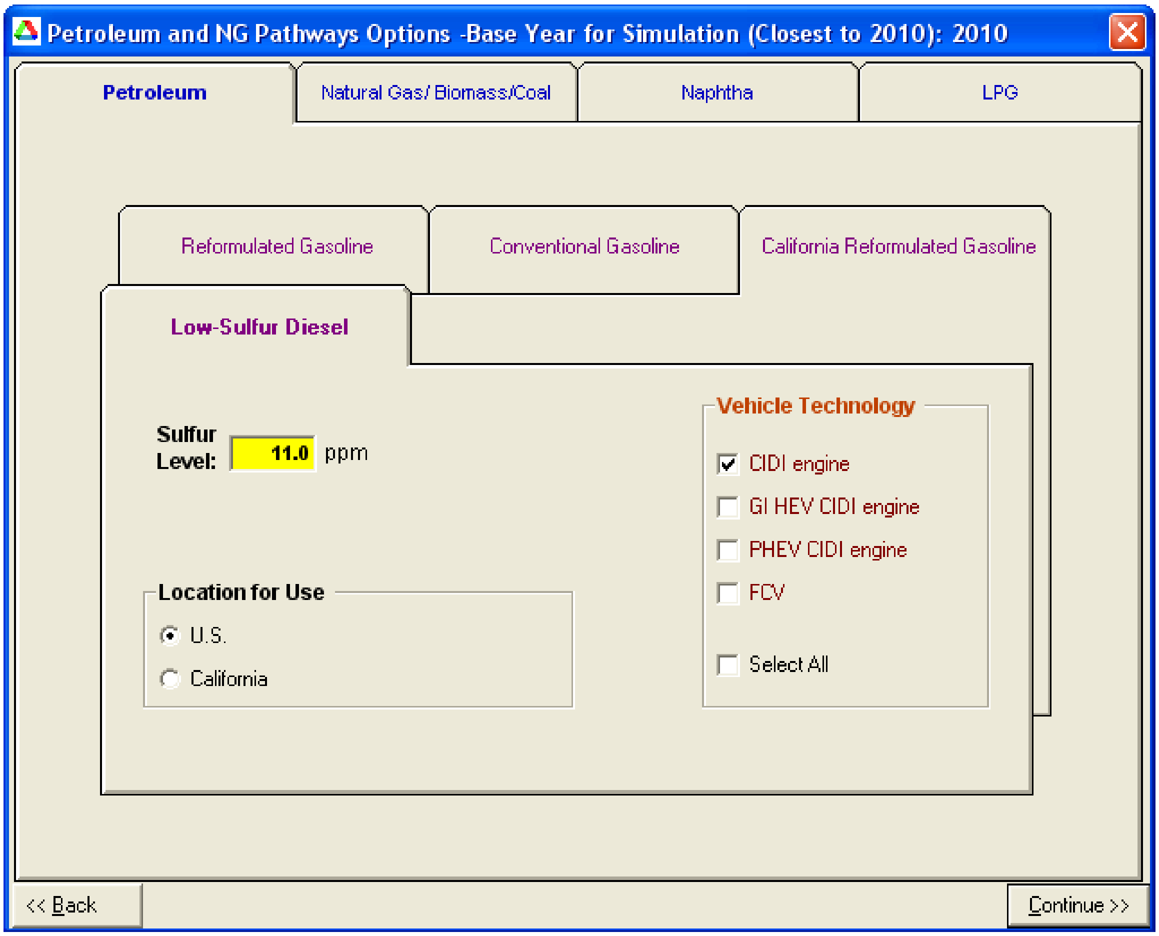


Figure 2.4.24 The petroleum and NG pathways options window for LSD contains options for the fuel, location of use, and vehicle technology. [4]

Shown in Figure 2.4.25, the petroleum pathway options for CD include sulfur level, location for use, and vehicle technology. The location of use remains the same as LSD. The vehicle technologies available for CD will remain the same as the corresponding technologies selected for LSD. If no LSD market shares exist, then the vehicle technologies for CD may be selected normally.

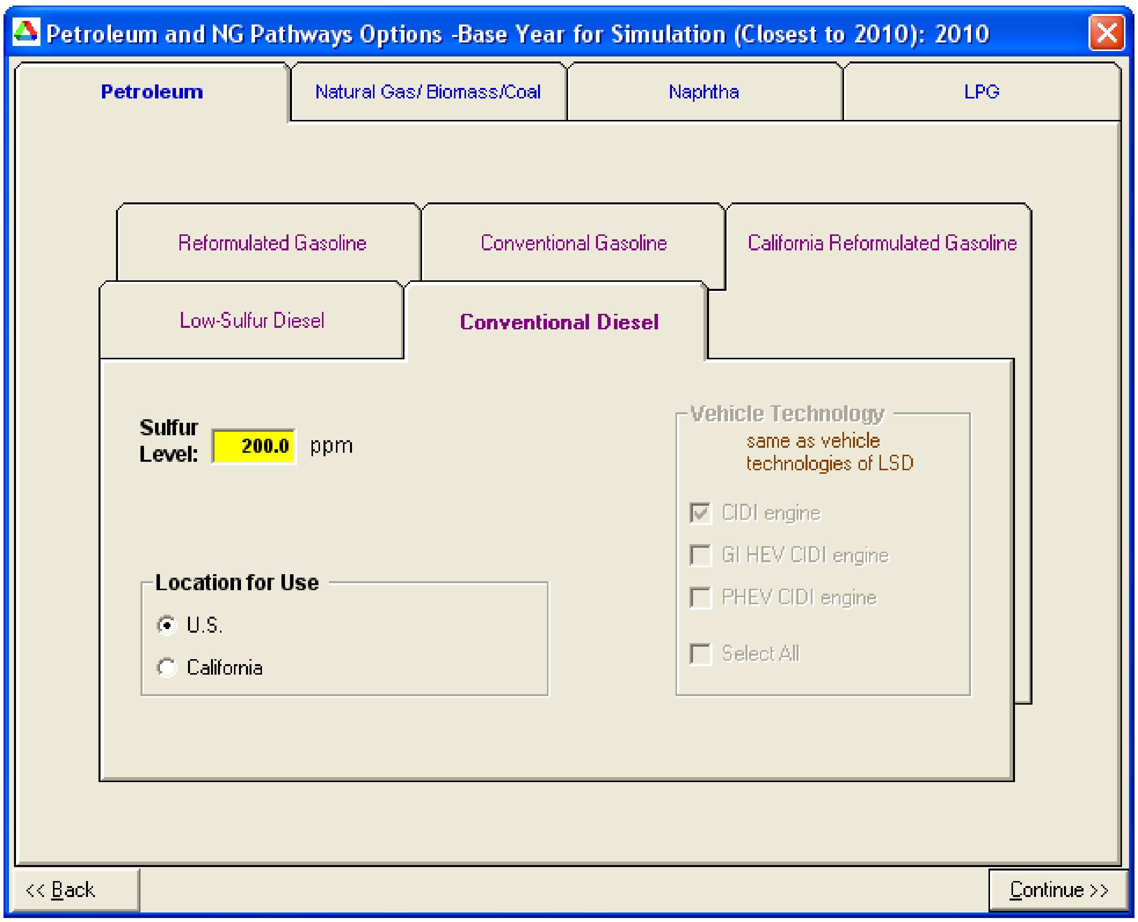


Figure 2.4.25 The petroleum and NG pathways options window for CD contains options for the fuel, location of use, and vehicle technology. [4]

Shown in Figure 2.4.26, the NG/biomass/coal pathway options for CNG include feedstock source and vehicle technology. Feedstock sources include North American

(NA) NG, non-North America (NNA) NG, and NNA flared gas (FG). The vehicle technologies available for CNG include bi-fuel SI engine, dedicated SI engine, GI HEV SI engine, PHEV SI engine, and FCV.

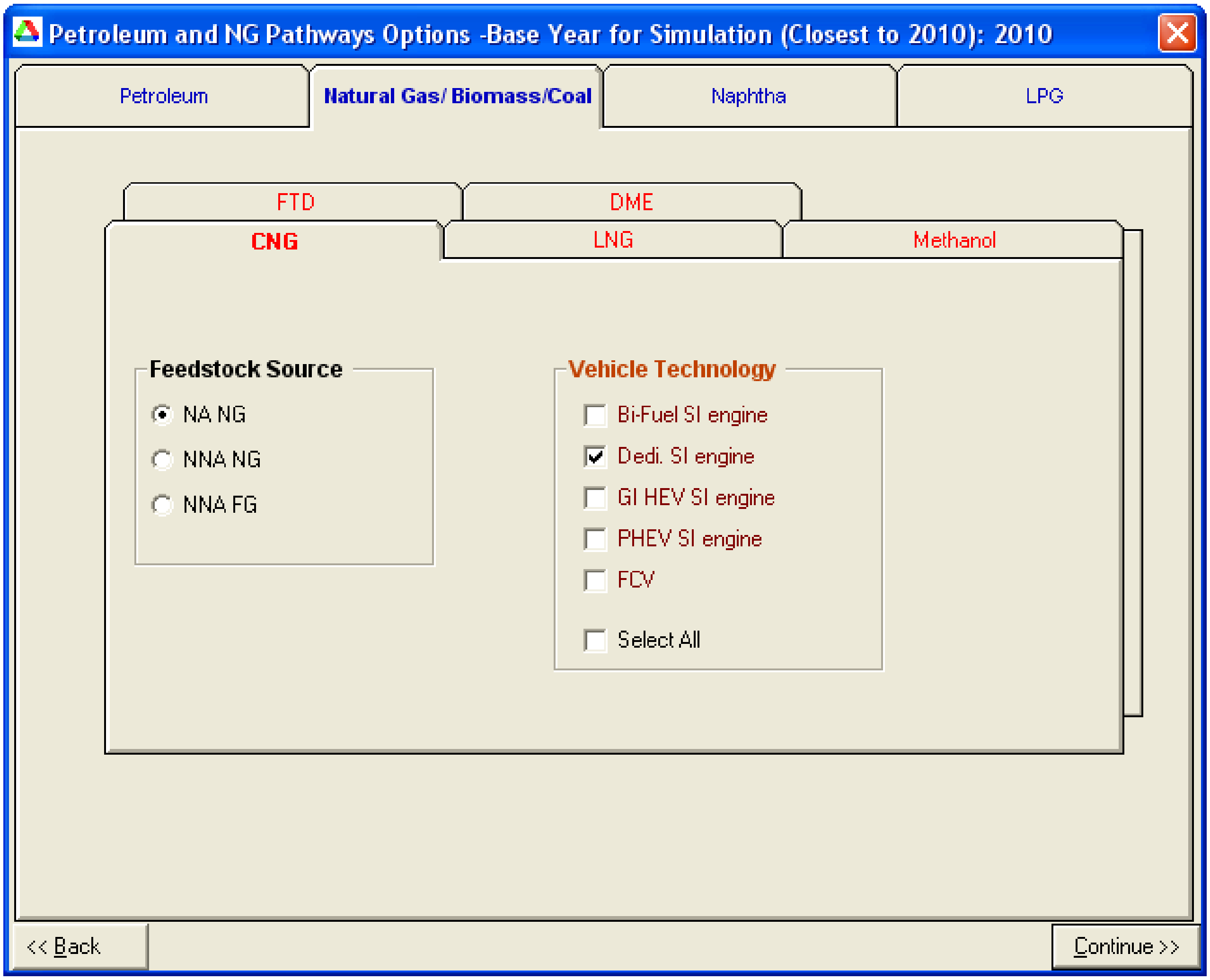


Figure 2.4.26 The petroleum and NG pathways options window for CNG contains options for the feedstock source and vehicle technology. [4]

Shown in Figure 2.4.27, the NG/biomass/coal pathway options for LNG include feedstock source and vehicle technology. Feedstock sources include NA NG, NNA NG, and NNA FG. The vehicle technologies available for LNG include dedicated SI engine, GI HEV SI engine, PHEV SI engine, and FCV.

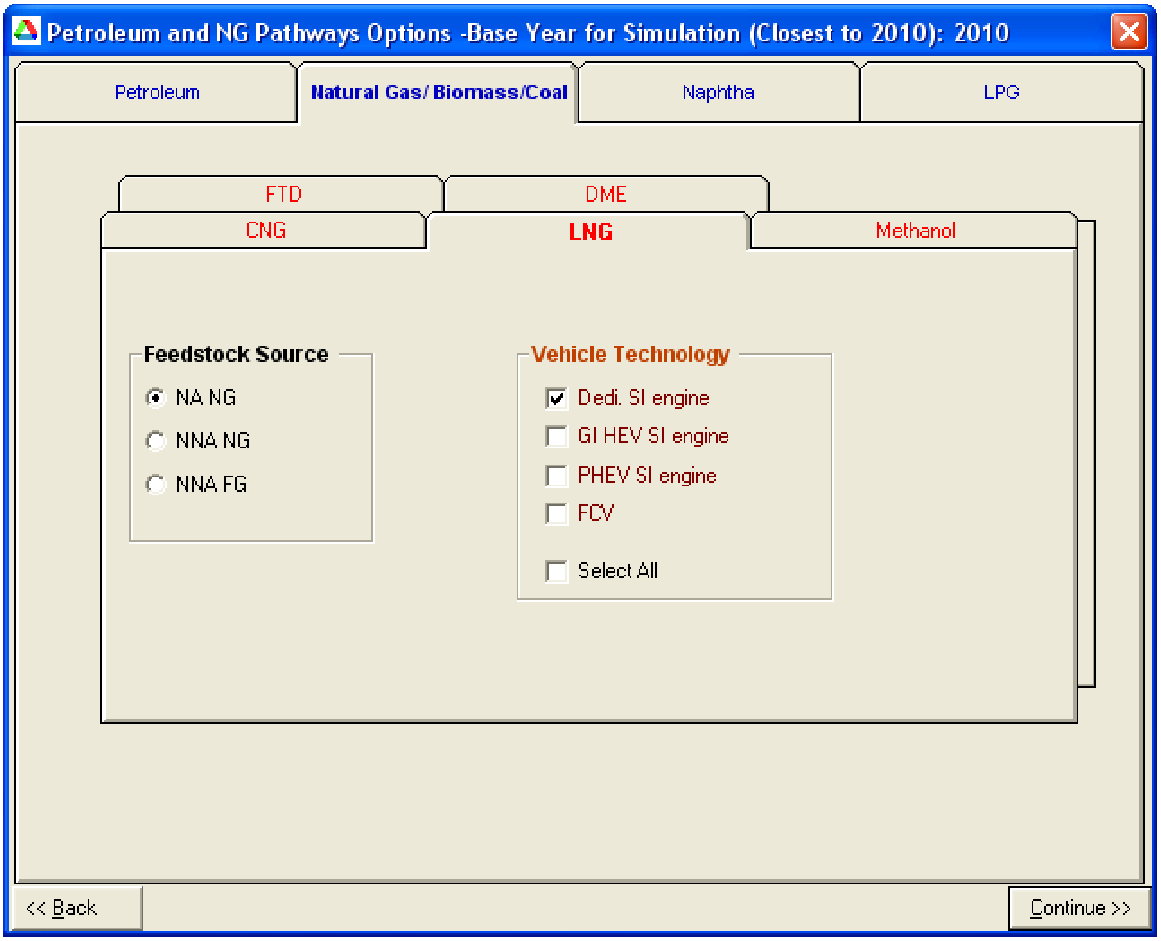


Figure 2.4.27 The petroleum and NG pathways options window for LNG contains options for the feedstock source and vehicle technology. [4]

Shown in Figure 2.4.28, the NG/biomass/coal pathway options for methanol include feedstock source, plant design type, and vehicle technology. Feedstock sources include NA NG, NNA NG, NNA FG, landfill, coal, and biomass. CO_2 sequestration may be specified in coal based central plants for methanol production. Plant design types include options for without export, with steam export, and with electricity export. For the second and third options, the energy and emission credits from the co-generated steam or electricity are automatically estimated in GREET. Note, there are no plant design types that allow export of steam and electricity from a landfill. Also note, there are no plant design types with steam export for coal and biomass options. The vehicle technologies available for methanol include flexible-fuel vehicle (FFV), SI engine, dedicated SI engine, SIDI engine, GI HEV SI engine, PHEV SI engine, and FCV.

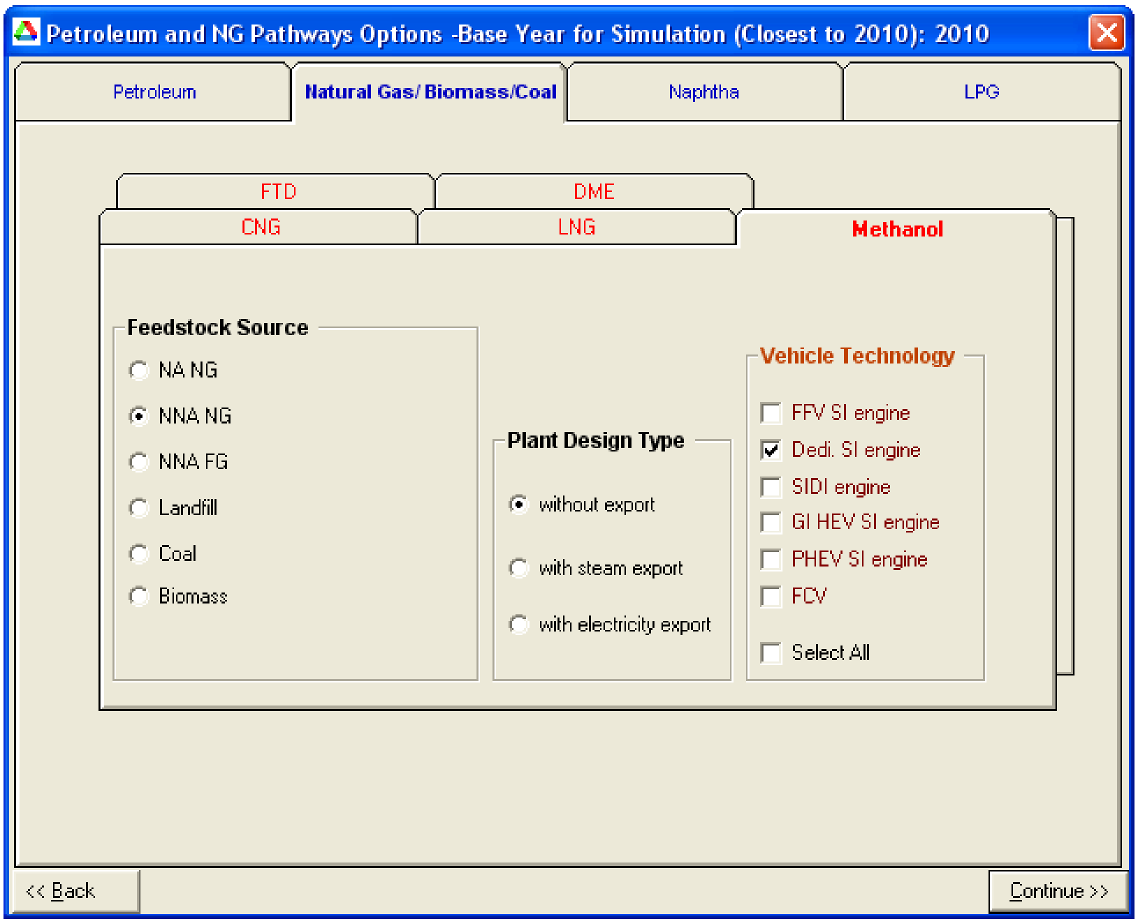


Figure 2.4.28 The petroleum and NG pathways options window for methanol contains options for the feedstock source, plant design, and vehicle technology. [4]

Shown in Figure 2.4.29, the NG/biomass/coal pathway options for FTD include feedstock source, plant design type, and vehicle technology. Feedstock sources include NA NG, NNA NG, NNA FG, coal, and biomass. CO_2 sequestration may be specified in coal based central plants for FTD production. Plant design types include options for without export, with steam export, and with electricity export. Again, the energy and emission credits from the co-generated steam or electricity are automatically estimated in GREET. Note, there are no plant design types with steam export for coal and biomass options. The vehicle technologies available for FTD include CIDI engine, GI HEV CIDI engine, and PHEV CIDI engine.

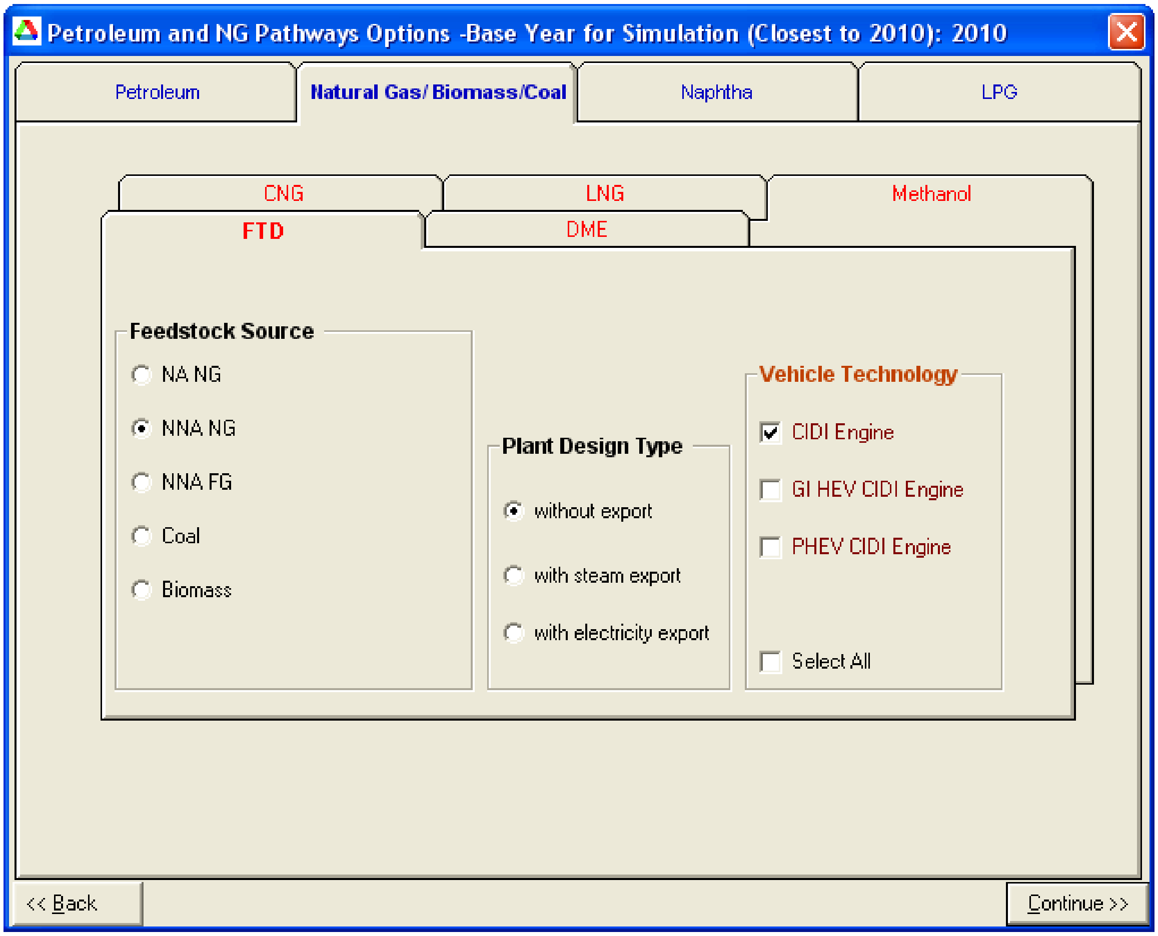


Figure 2.4.29 The petroleum and NG pathways options window for FTD contains options for the feedstock source, plant design, and vehicle technology. [4]

Shown in Figure 2.4.30, the NG/biomass/coal pathway options for DME include feedstock source, plant design type, and vehicle technology. Feedstock sources include NA NG, NNA NG, NNA FG, coal, and biomass. CO_2 sequestration may be specified in coal-based central plants for DME production. Plant design types include options for without export, with steam export, and with electricity export. Again, the energy and emission credits from the co-generated steam or electricity are automatically estimated in

GREET. Note, there are no plant design types with steam export for coal and biomass options. The vehicle technologies available for DME include CIDI engine, GI HEV CIDI engine, and PHEV CIDI engine.

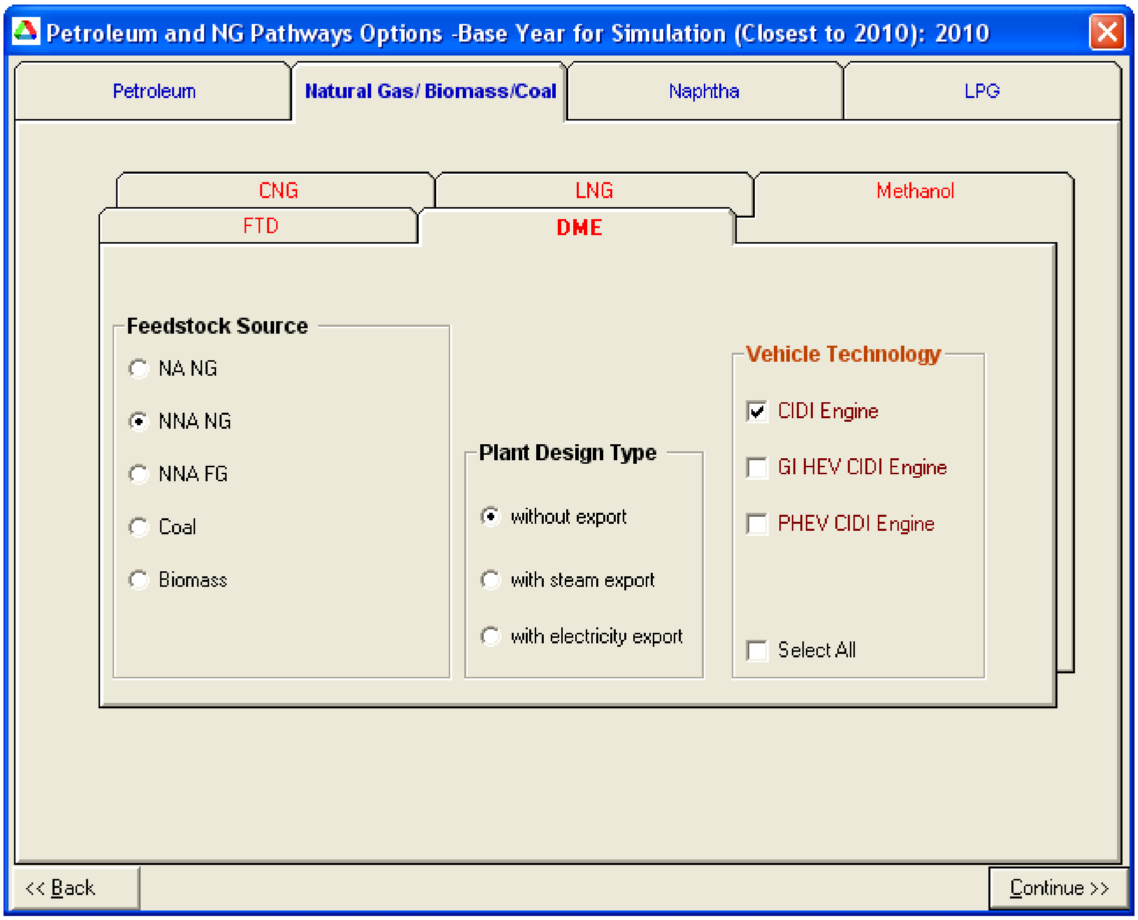


Figure 2.4.30 The petroleum and NG pathways options window for DME contains options for the feedstock source, plant design, and vehicle technology. [4]

Shown in Figure 2.4.31, the naphtha pathway options include shares for FT and crude naphtha, and vehicle technology. If shares of crude naphtha are selected, additional options include location for use and sulfur levels. Locations for use options include U.S. and California. If shares of FT naphtha are selected, additional options include feedstock source and plant design type. Feedstock sources for FT naphtha include North American (NA) natural gas (NG), Non-North American (NNA) NG, and NNA flared gas (FG). Plant design types for FT naphtha include options for without export, with steam export, and with electricity export. Again, the energy and emission credits from the co-generated steam or electricity are automatically estimated in GREET. The only vehicle technology available for naphtha is a FCV.

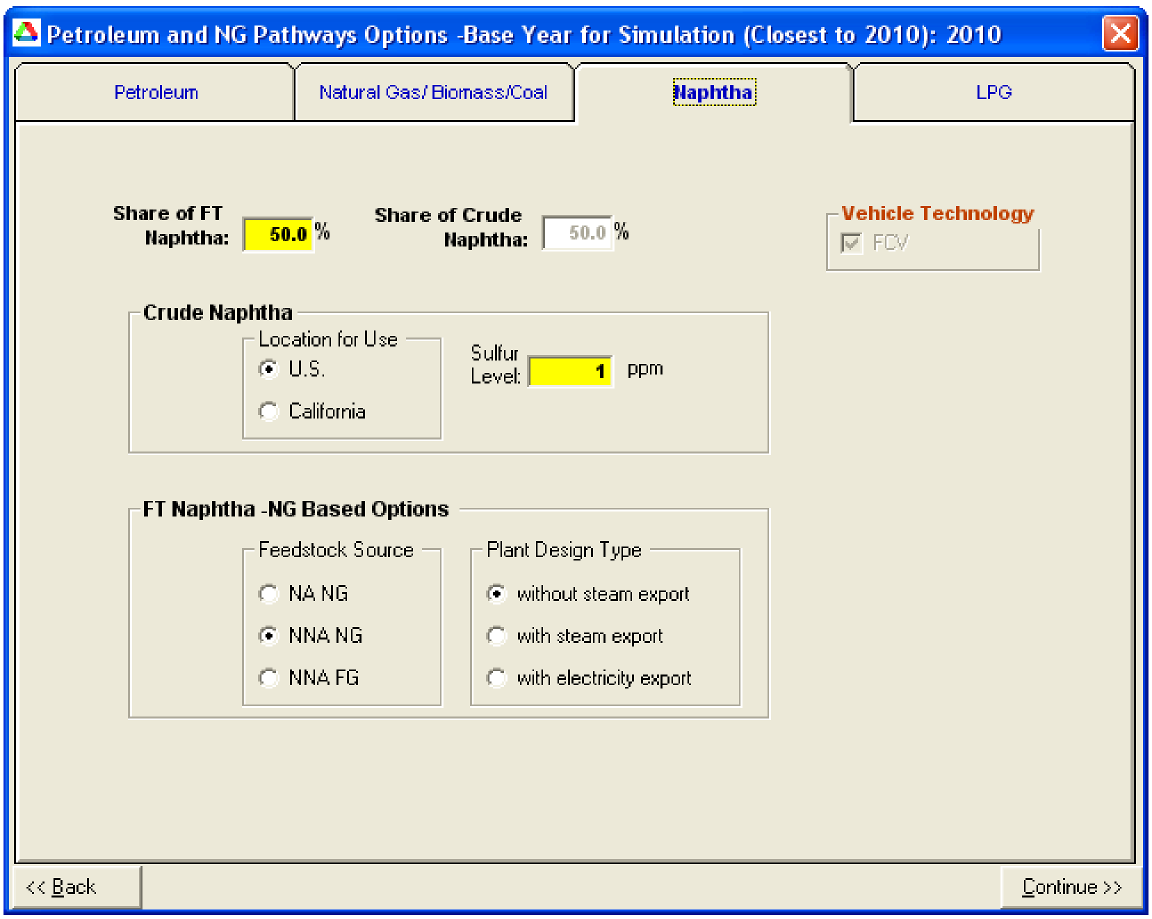


Figure 2.4.31 The petroleum and NG pathways options window for Naptha contains options for the feedstock market shares and vehicle technology with other market share relevant options for location of use, sulfur level feedstock source, and plant design. [4]

Shown in Figure 2.4.32, the LPG options include NG-based feedstock source and vehicle technology. There are no crude based options for LPG production in the GREETGUI 1.8c.0. Feedstock sources for NG based LPG include NA NG and NNA NG. The vehicle technologies available for LPG include dedicated SI engine, GI HEV SI engine, PHEV SI engine, and FCV.

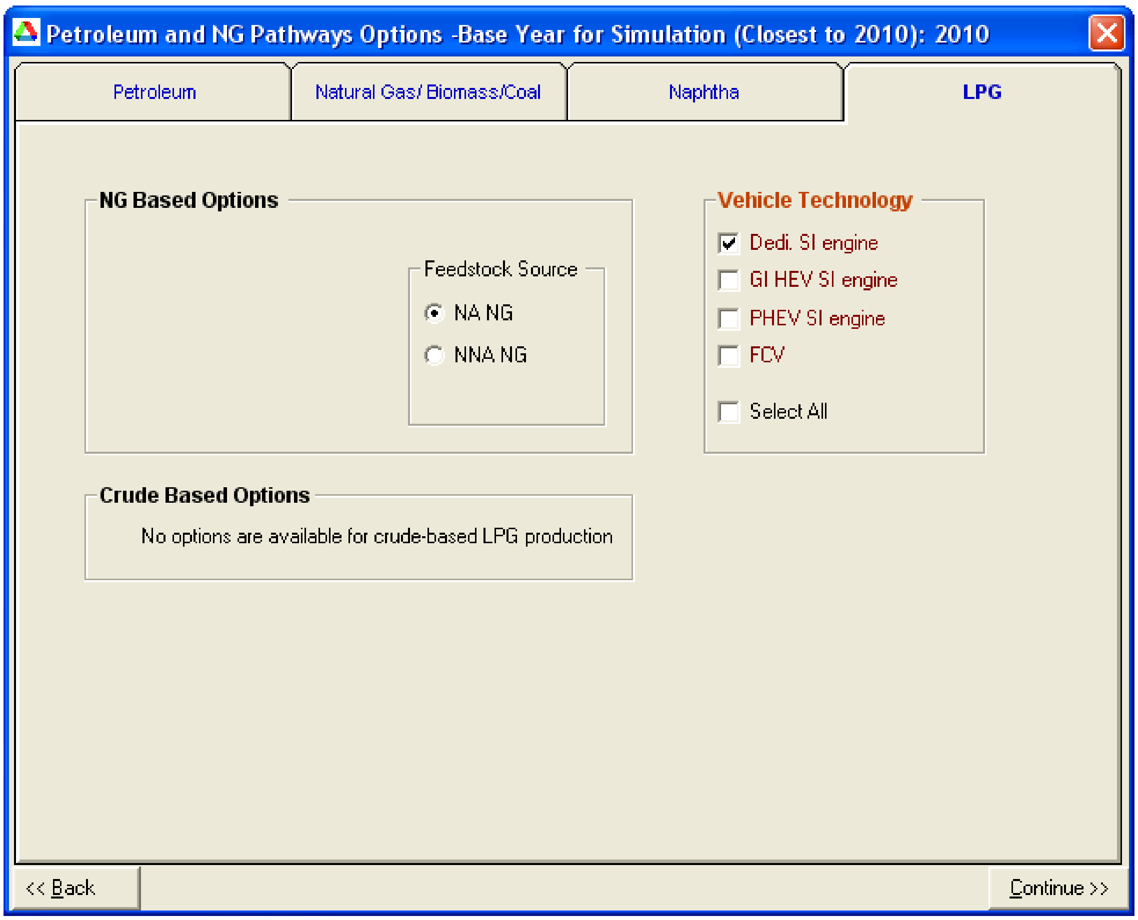


Figure 2.4.32 The petroleum and NG pathways options window for LPG contains options for NG based production and vehicle technology. [4]

The Biofuels and H_2 Pathways Options window prompts the user to review and select pertinent options for any relevant fuel-vehicle technology combinations that are to be included in the simulation. Selecting '<<Back' will allow the user to return to the

scenario and fuel pathways selection window. After viewing all the pathway tabs on the biofuels and H_2 Pathways options window, selecting 'Continue>>' will allow the user to continue with the simulation options. The main fuel types included in this window are ethanol, electricity, biodiesel, centrally produced gaseous H_2, centrally produced liquid H_2, station produced gaseous H_2, and station produced liquid H_2.

The biofuels and H_2 pathways options for ethanol include corn ethanol options, biomass ethanol options, and vehicle technology. Vehicle technologies are available for 100% ethanol blend, high-level blends with gasoline, low-level blends with gasoline, and low-level blends with diesel. For 100% ethanol, the vehicle technology is limited to FCV. For high-level blends with gasoline, vehicle technologies include FFV SI engine, dedicated SI engine, SIDI engine, GI HEV SI engine, and PHEV SI engine. For low-level blends with gasoline, vehicle technologies include SI engine, SIDI engine, GI HEV SI engine, and PHEV SI engine. For low-level blends with diesel, vehicle technologies include CIDI engine, GI HEV CIDI engine, and PHEV CIDI engine.

Shown in Figure 2.4.33, corn based ethanol options include shares of ethanol plant types, shares of process fuels, and co-products credit calculation methods. The user may specify shares for dry milling plants (DMP) and wet milling plants (WMP). Depending on the plant shares, the user may also specify shares of process fuels for DMP and WMP. Wet milling plants produce ethanol from cornstarch along with other co-products such as high-fructose corn syrup, glucose, gluten feed, and gluten meal. The smaller dry milling plants are designed primarily for ethanol production from cornstarch while other constituents of the corn kernel end up in distillers' dried grains and solubles (DDGS). Process fuels for both plant types typically include NG and coal. Due to the variety of co-products generated during ethanol production, GREET allocates emissions and energy use charge between ethanol and its co-products by using either a product displacement method or a market value-based method.

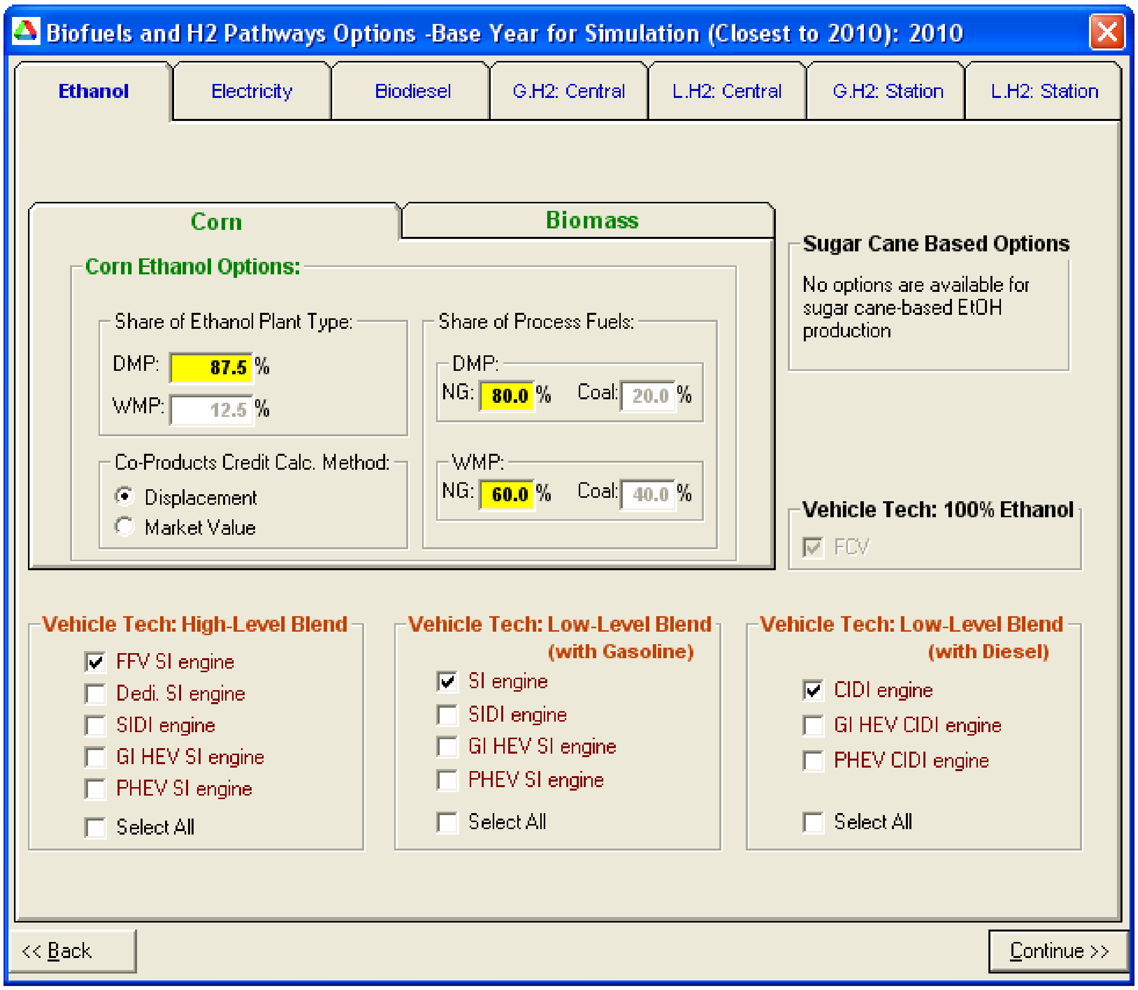


Figure 2.4.33 The biofuels and H_2 pathways options window for ethanol contains corn based ethanol options and vehicle technology. [4]

Shown in Figure 2.4.34, biomass based ethanol options include plant types for farmed trees, corn stover, herbaceous biomass, and forest residue. The user must specify either fermentation or gasification for each market share's plant type. Note, there are no options for sugar cane based EtOH production in GREETGUI 1.8c.0. Also, note that GREETGUI defaults ethanol production from corn only in this version.

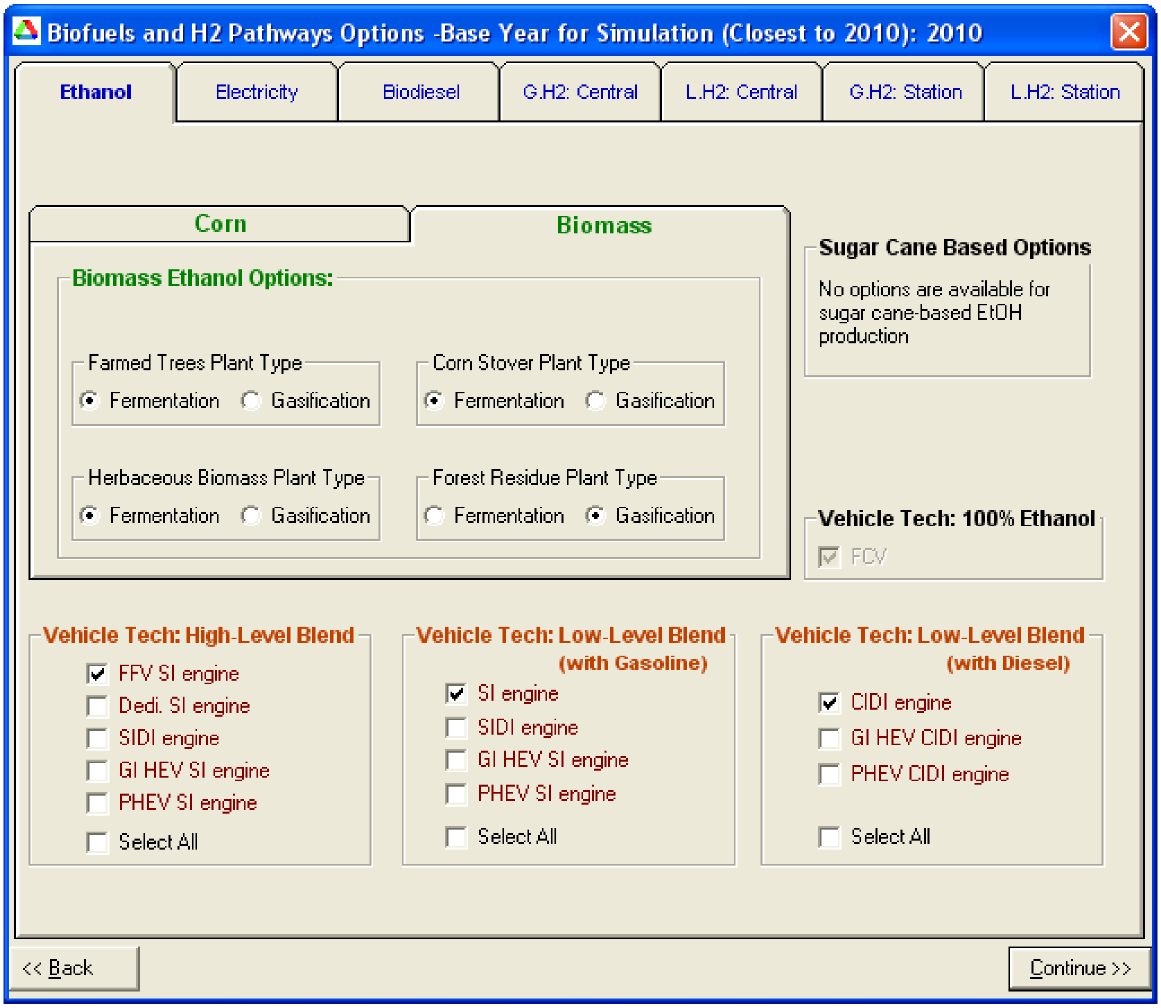


Figure 2.4.34 The biofuels and H_2 pathways options window for ethanol contains biomass based ethanol options and vehicle technology. [4]

The biofuels and H_2 pathways options for electricity are necessary not only for vehicles utilizing electricity for power but for WTP activities related to non-electric fuels, too. The GREET model calculates emissions associated with electricity generation at the plant site as well as emissions associated with the production and delivery of the fuels. As such, this tab will always be present regardless of selected fuel type. Note, GREET does not include estimation of emissions associated with construction of facilities. Shown in Figure 2.4.35, electricity options include generation mixes, electricity displacements, advanced power plant technology shares, and vehicle technology.

The marginal generation mix for transportation use option is used for electric vehicles (EV), grid-connected HEVs and FCVs with H_2 production via electrolysis at refueling stations. The average generation mix for stationary use option is used in all WTP activities. The user must specify a mix option in both cases. These options include U.S. mix, Northeast (NE) U.S. mix, California (CA) mix, and a user defined mix. The change default generation mix button located next to the option group allows the user to modify the currently selected option's defaults through a secondary window. This window provides text fields to change the percentage of electricity produced by residual oil, natural gas, coal, nuclear power, biomass, and other sources. Note, electricity generated from hydropower, solar, wind, and geothermal sources are treated as zero-emission plants in GREET and are included together under the "Others" category. By default, the marginal mixes are assumed to be the same as the average generation mixes.

GREET includes options for power plant technologies using NG, coal, biomass, and nuclear materials. For advanced power plant technology shares, the user may specify shares for NG turbine combined-cycle technology, NG turbine simple-cycle technology, advanced coal technology, and advanced biomass technology. For biomass power plant feedstock shares, the user may specify shares of woody and herbaceous biomass. The default feedstock share is 100% woody biomass. LWR and HTGR reactors are both included for nuclear electricity generation. The user may specify technology shares of uranium enrichment for each reactor type. Uranium enrichment technologies include gas diffusion and centrifuge enrichment.

As mentioned earlier, the energy and emission credits from the co-generated electricity are automatically estimated in GREET for selected electricity export from production plants with the design option of electricity export. GREETGUI provides various types of electricity and electricity mixes which could be displaced by the co-generated electricity. For electricity co-generated in NG-based fuel production plants, the electricity type for displacement can be the average U.S. mix, natural gas combined cycle (NGCC) electricity, coal integrated gasification combined cycle (IGCC) electricity, or biomass IGCC electricity. For electricity co-generated in coal-based fuel production plants, the electricity type for displacement can be the average U.S. mix, NGCC electricity, or IGCC electricity. For electricity co-generated in biomass-based fuel production plants, the electricity type for displacement can be the average U.S. mix, NGCC electricity, or biomass IGCC electricity. The only vehicle technology available on the electricity tab is an EV.

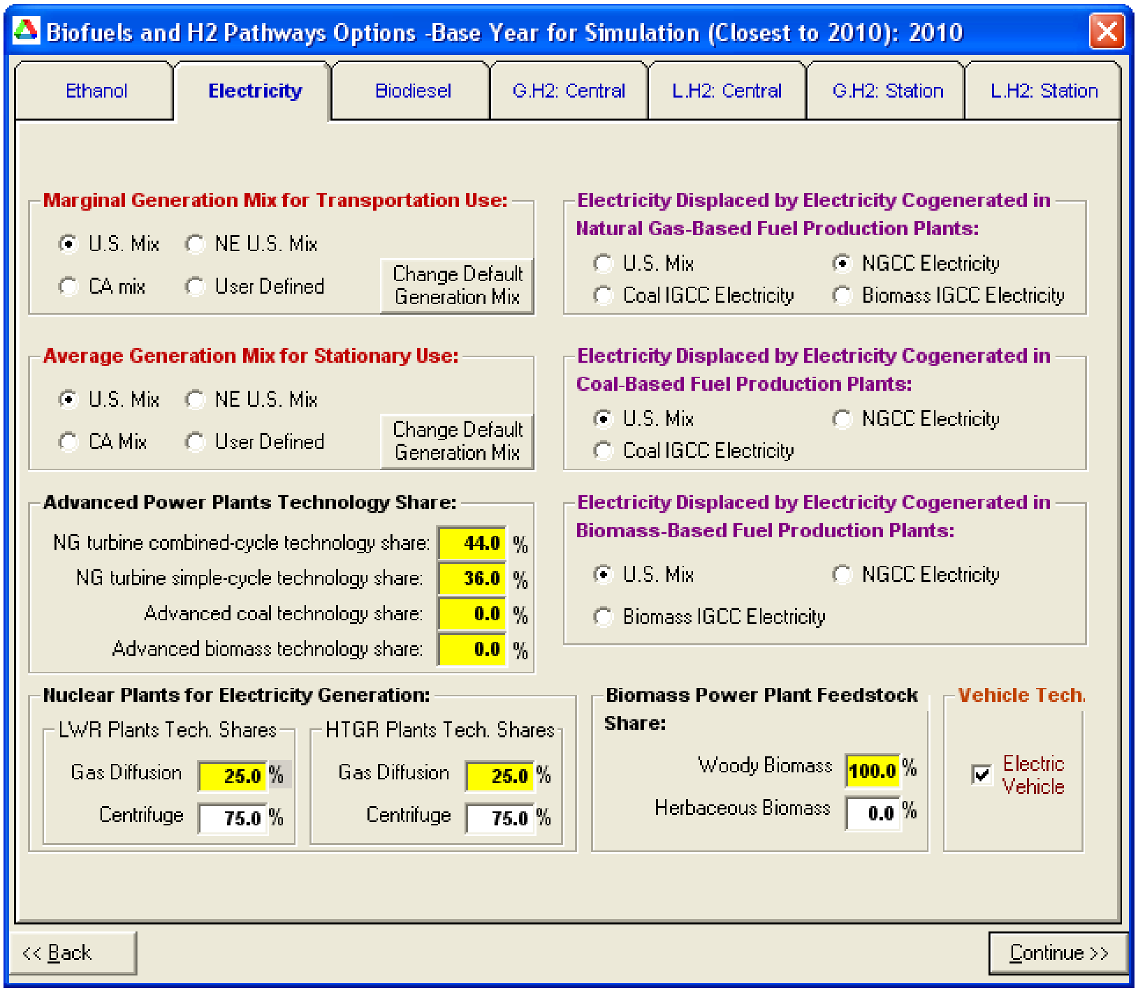


Figure 2.4.35 The biofuels and H_2 pathways options window for electricity contains options for electricity generation for use in all aspects of the WTW and associated vehicle technology. [4]

Shown in Figure 2.4.36, the biofuels and H_2 pathways options for biodiesel include only vehicle technologies in GREET 1.8c.0. Biodiesel is blended with petroleum diesel for vehicle applications. The vehicle technologies available for biodiesel include CIDI engine, GI HEV CIDI engine, and PHEV CIDI engine.

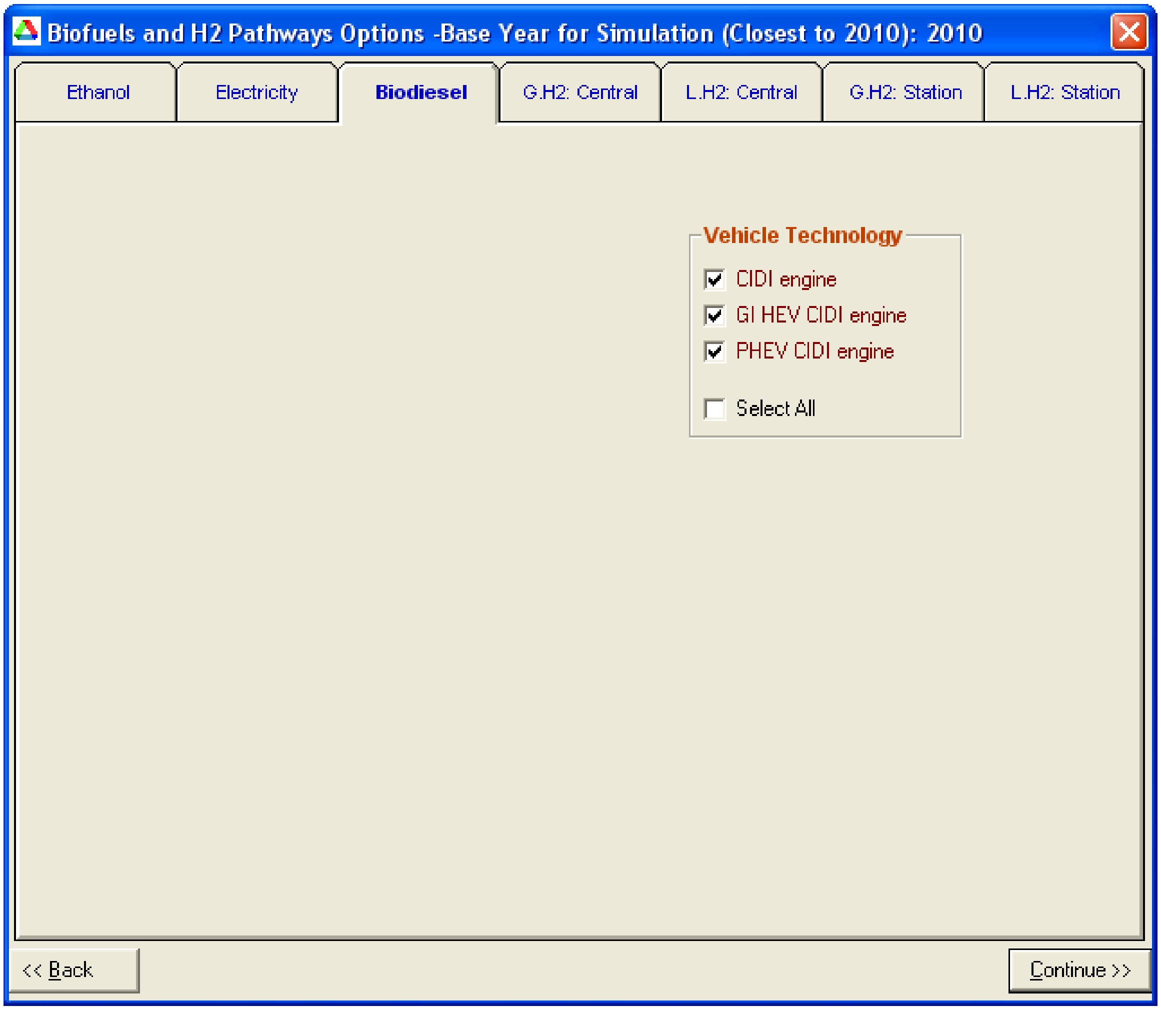


Figure 2.4.36 The biofuels and H_2 pathways options window for biodiesel contains vehicle technology. [4]

Shown in Figure 2.4.37, the biofuels and H_2 pathways options for the central production of gaseous H_2 consist of feedstock based options and vehicle technology options. Feedstock options are available for NG, coal, biomass, COG, and nuclear based feedstock. Vehicle technologies available for the GH_2 central pathway include SI engine, GI HEV SI engine, PHEV SI engine, FCV, and PHEV FC.

For NG based options, feedstock sources include NA NG, NNA NG, and NNA FG, and plant designs include options with steam export, with electricity export, or without export. For coal based options, plant designs include electricity export and no export. For biomass based options, market shares include woody and herbaceous biomass, and plant designs are either with or without electricity export. For NG, coal, and biomass based production, the user may also specify whether or not to sequester CO_2 emissions. Note, for the amount of CO_2 emissions, all carbon contained in each of the carbon based feedstock sources ends up as CO_2. Because CO_2 emissions from some processes in NG, coal, and biomass-based H_2 plants cannot be sequestered, it is not realistic to specify 100% CO_2 sequestration for these pathways in GREET. If CO_2 sequestration is selected, a default CO_2 sequestration rate of 85% is applied and is not allowed to change through GREETGUI. Additionally, an energy penalty and related emissions are accounted for by GREET. For COG based options, the user must specify whether the COG is treated as a co-product, treated as a byproduct, or is supplemented with NG for energy in H_2. For the nuclear based options, the user must specify technology shares between gas diffusion and centrifuge enrichment for uranium production.

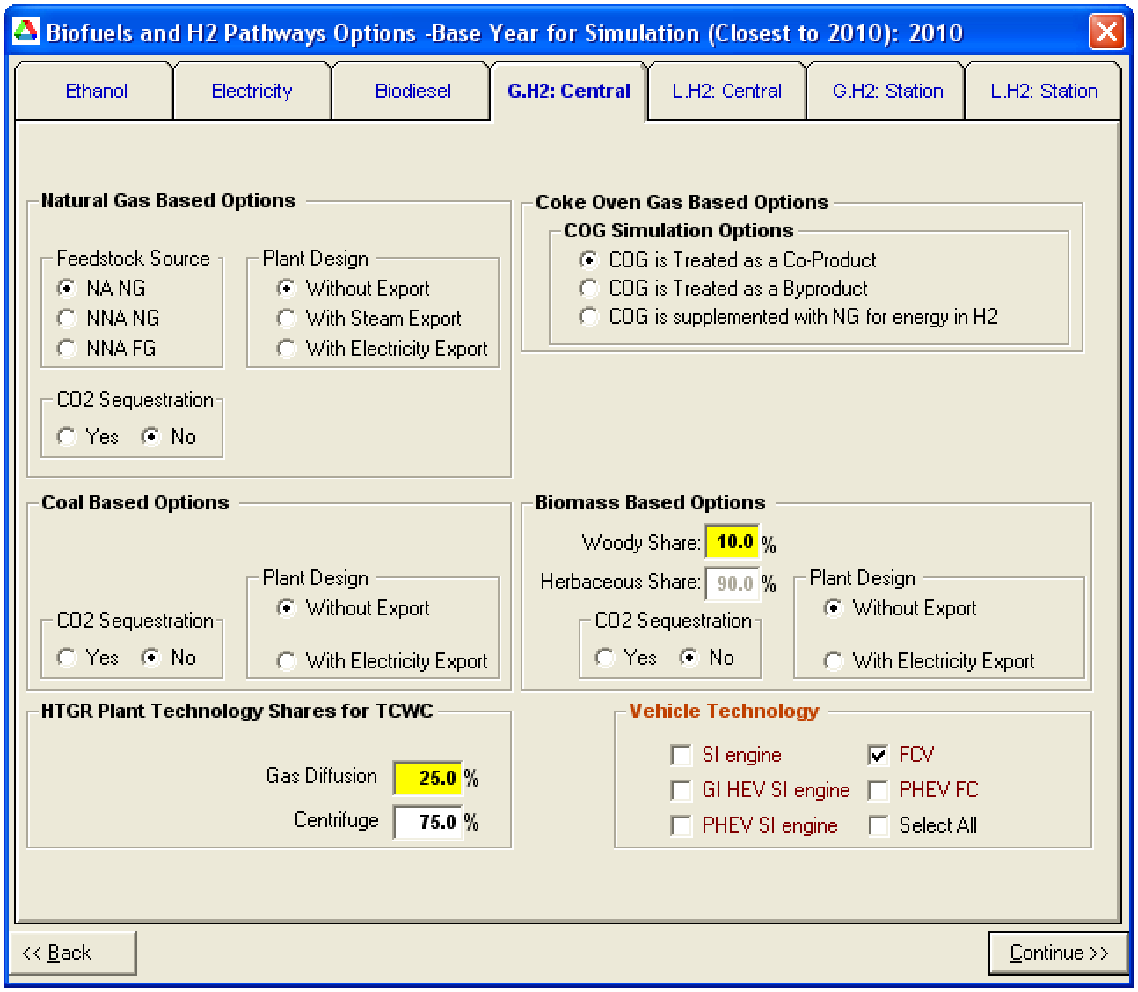


Figure 2.4.37 The biofuels and H_2 pathways options window for central production of gaseous hydrogen contains feedstock based production and vehicle technology options. [4]

Shown in Figure 2.4.38, the biofuels and H_2 pathways options for the central production of liquid H_2 include feedstock based options, energy for liquefaction, and vehicle technology options. Feedstock options are available for NG, coal, biomass, COG, and nuclear based feedstock. The energy for liquefaction may be selected separately for each feedstock. Vehicle technology available for the LH_2 central pathway includes SI engine, GI HEV SI engine, PHEV SI engine, FCV, and PHEV FC.

For NG-based options, feedstock sources include NA NG, NNA NG, and NNA FG. Plant designs are included with steam export, with electricity export, or without export. For coal based options, plant designs are included with or without electricity export. For biomass based options, market shares include woody and herbaceous biomass, and plant designs are included either with or without electricity export. The user may also specify whether or not to sequester CO_2 emissions for NG, coal, and biomass based production. For COG based options, the user must specify whether the COG is treated as a co-product, treated as a byproduct, or is supplemented with NG for energy in H_2. For the nuclear based options, the technology shares for uranium enrichment will stay the same as GH_2 central production if available. Otherwise, the user may specify shares between gas diffusion and centrifuge enrichment.

Note, the liquefaction of H_2 requires a large amount of electricity. The user may specify for each feedstock share what energy to use for liquefaction. For NG feedstock, the user may specify either the defaulted NGCC electricity or the average U.S. mix. For solar PV feedstock, the user may specify either the defaulted solar electricity or the average U.S. mix. For nuclear (TCWC) feedstock, the user may specify either the defaulted nuclear (HTGR) electricity or the average U.S. mix. For coal feedstock, the user may specify either the defaulted coal based electricity or the average U.S. mix. For biomass feedstock, the user may specify either the defaulted biomass based electricity or the average U.S. mix. For COG feedstock, the user may specify either coal based electricity or the defaulted average U.S. mix.

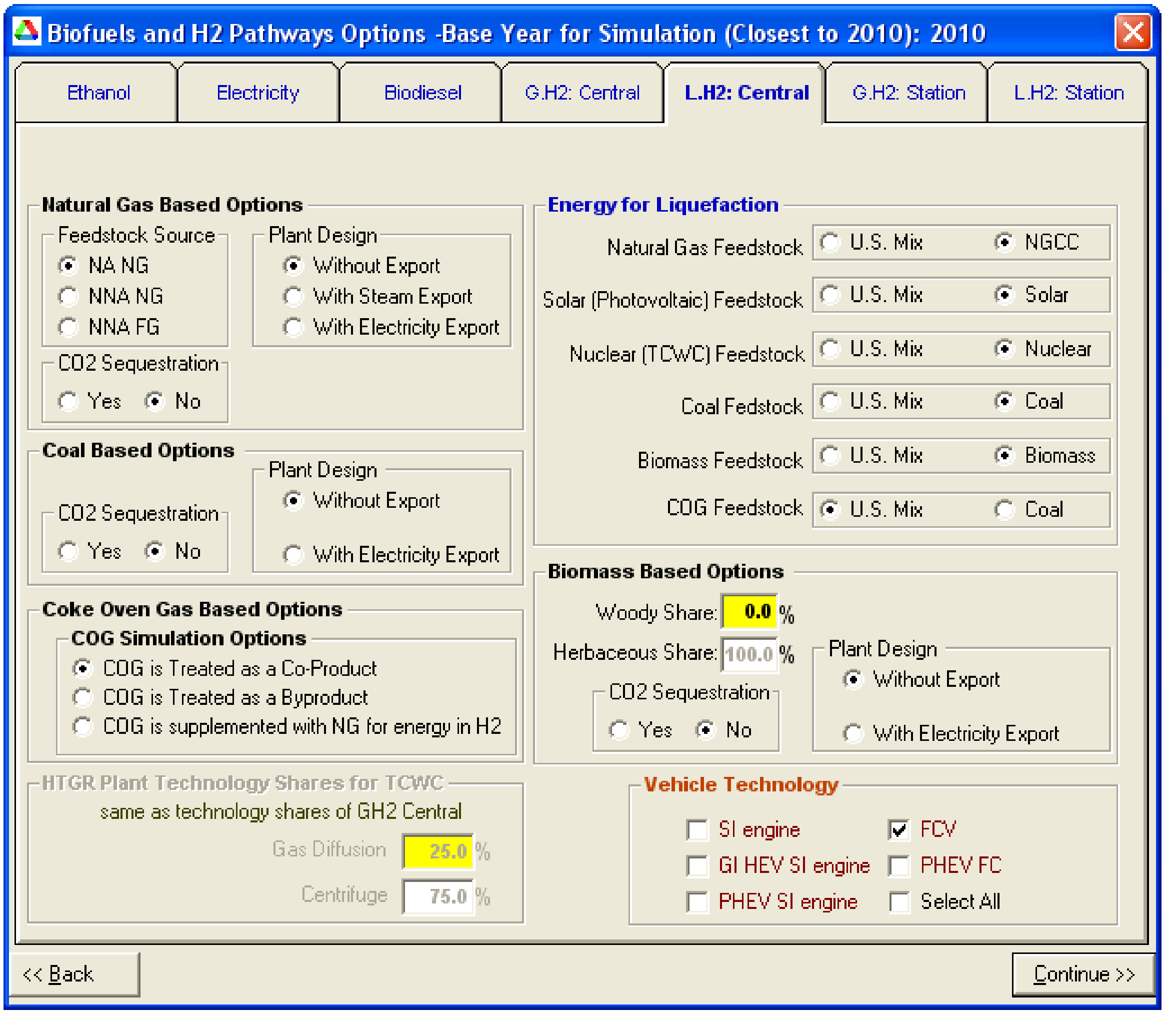


Figure 2.4.38 The biofuels and H_2 pathways options window for the central production of liquid hydrogen contains feedstock based production, liquefaction energy, and vehicle technology options. [4]

Shown in Figure 2.4.39, the biofuels and H_2 pathways options for the production of gaseous H_2 at refueling stations include feedstock based options and vehicle technology options. For NG based feedstock, the user may specify the feedstock source as NA NG, NNA NG, or NNA FG. For electrolysis, the user may specify one of the electricity generation options for GH_2 which include oil power plant, NG power plant, coal power plant, nuclear power plant, hydro power plant, U.S. mix, and NGCC turbine power plant. For nuclear power plants, nuclear technology may also be specified between LWR and HTGR. The U.S. marginal generation mix is consistent with the marginal electricity generation mix for transportation use selected earlier in the electricity tab (See Figure 2.4.35). Vehicle technologies available for the GH_2 station pathway are the same as those chosen for the GH_2 central pathway. If there are no market shares for the GH_2 central pathway, the vehicle technologies may be selected normally.

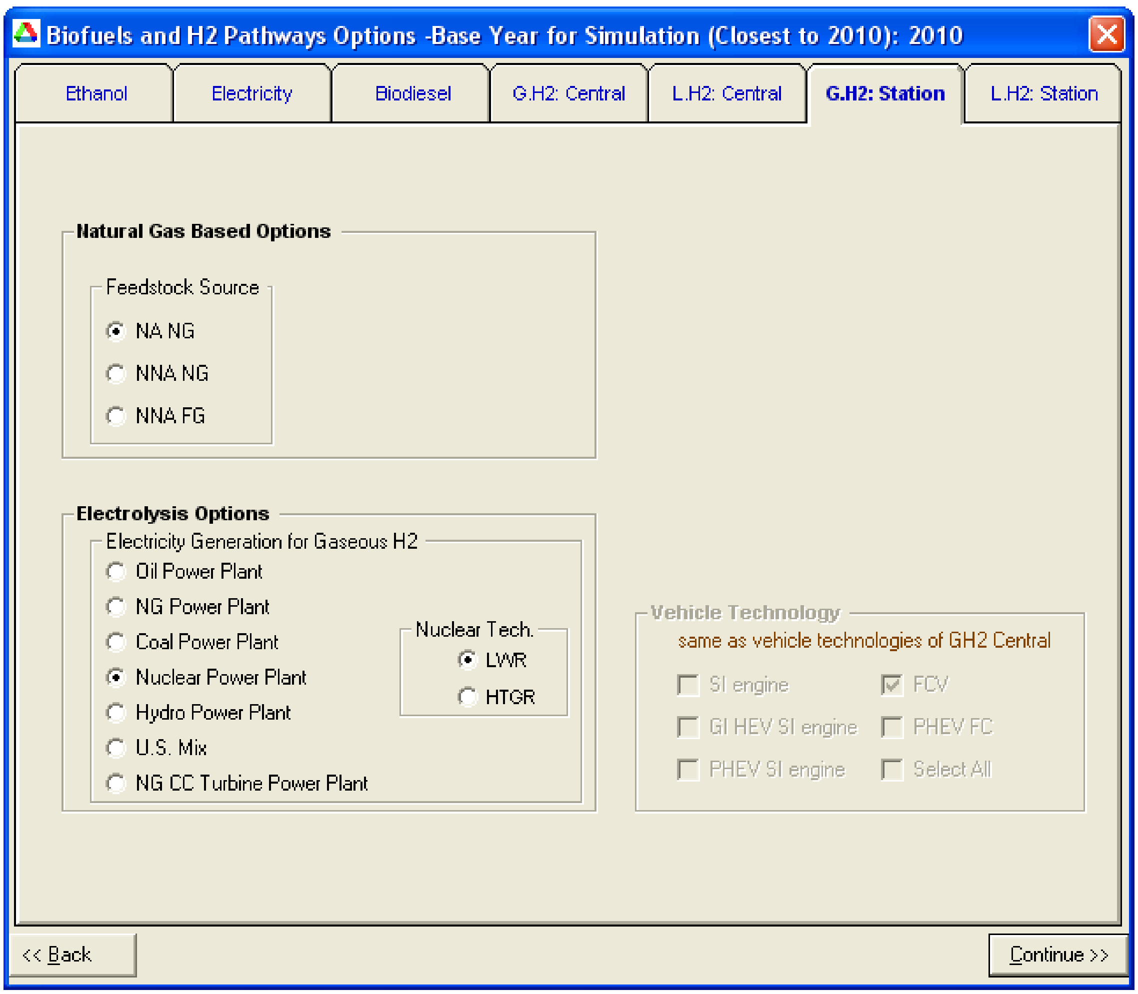


Figure 2.4.39 The biofuels and H_2 pathways options window for gaseous hydrogen production at refueling stations contains feedstock based production and vehicle technology options. [4]

Shown in Figure 2.4.40, the biofuels and H_2 pathways options for the production of liquid H_2 at refueling stations include feedstock based options and vehicle technology options. For NG based feedstock, the user may specify the feedstock source as NA NG, NNA NG, or NNA FG. For electrolysis, the user may specify one of the electricity generation options for GH_2 which include oil power plant, NG power plant, coal power plant, nuclear power plant, hydro power plant, U.S. mix, and NGCC turbine power plant. For nuclear power plants, nuclear technology may also be specified between LWR and HTGR. The U.S. marginal generation mix is consistent with the marginal electricity generation mix for transportation use selected earlier in the electricity tab (see Figure 2.4.35). Vehicle technologies available for the LH_2 station pathway are the same as those chosen for the LH_2 central pathway. If there are no market shares for the LH_2 central pathway, the vehicle technologies may be selected normally.

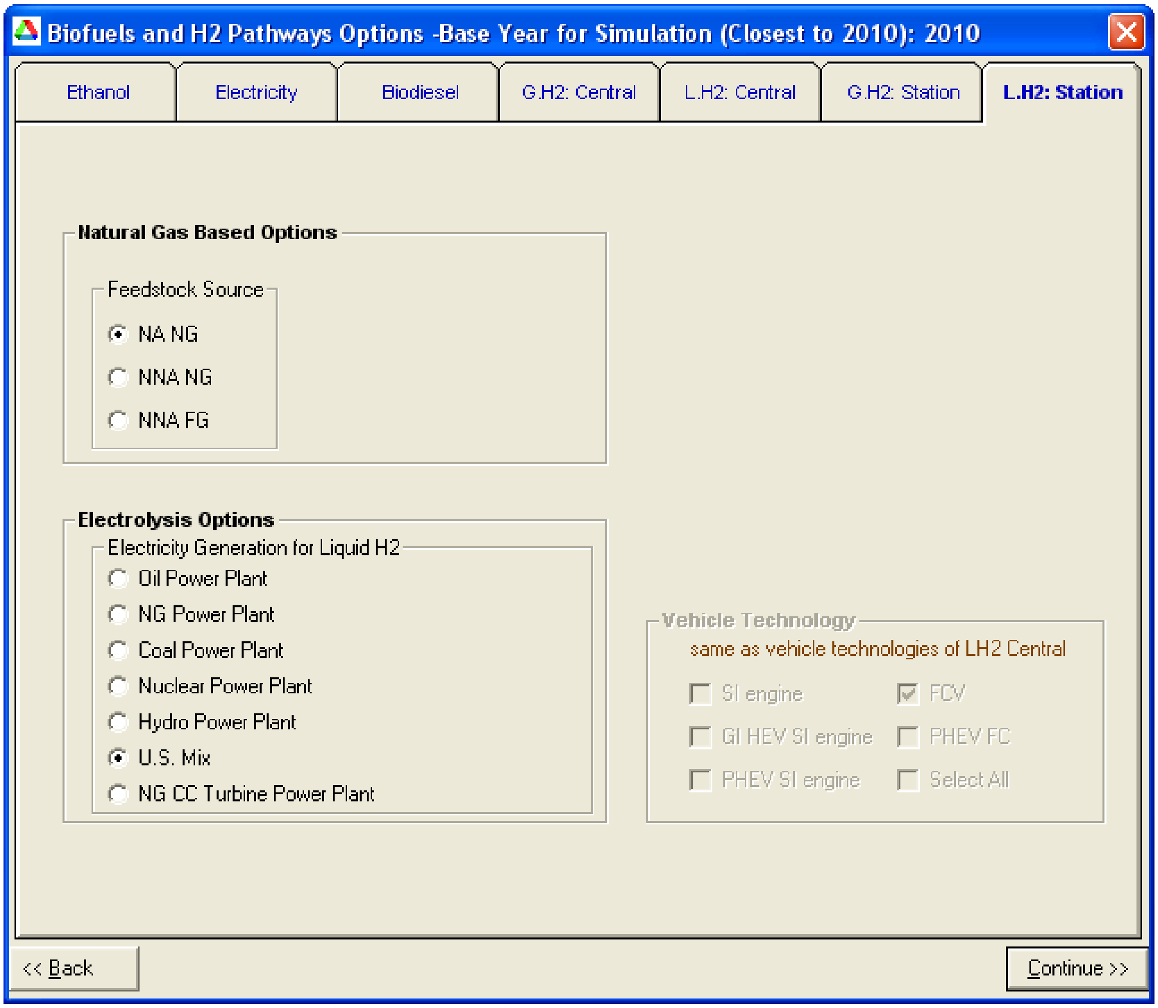


Figure 2.4.40 The biofuels and H_2 pathways options window for liquid hydrogen production at refueling stations contains feedstock based production and vehicle technology options. [4]

Shown in Figure 2.4.41, the simulation options for alternative fuel blends window displays shares of alternative fuels for blending and shares of gasoline and diesel for blending with alternative fuels. For alternative fuel blends, the user may specify the volumetric shares of alternative fuels for blending with specified shares of gasoline or diesel. For blending with alternative fuels, the user may specify shares of gasoline and diesel.

There are two levels of ethanol-gasoline blends. The low-level ethanol blend option is designed to have a specification of 5-15% by volume and is defaulted to 10%, the value associated with E10. The high-level ethanol blend option is designed to have a specification of 15-90% by volume and is defaulted to 85%. It is important to note that if a blend level is far from the default value, then the vehicle fuel economy and emission factors in GREET should revised to reflect the new blend level.

When blending an alternative fuel with gasoline, the user must specify the specific market shares of CG, RFG, or a combination of these two fuels for blending with methanol and ethanol. GREET assumes that ethanol is blended with CG for low-level blends which is similar to wintertime oxygenated fuel. For high-level blends, GREET assumes a blend with a market share-weighted combination of CG and RFG. Note, for ethanol used as a RFG oxygenate, the calculations are made separately under the RFG options tab (see Fig. 2.4.21) and are not included in the ethanol blend simulation options. GREET assumes that methanol is blended with market share-weighted combination of CG and RFG.

When blending an alternative fuel with diesel, the user must specify the specific market shares of LSD, CD, or a combination of these two fuels for blending with ethanol, FTD, and BD. GREET assumes that ethanol, FTD, and biodiesel are blended with the market share-weighted combination of CD and LSD.

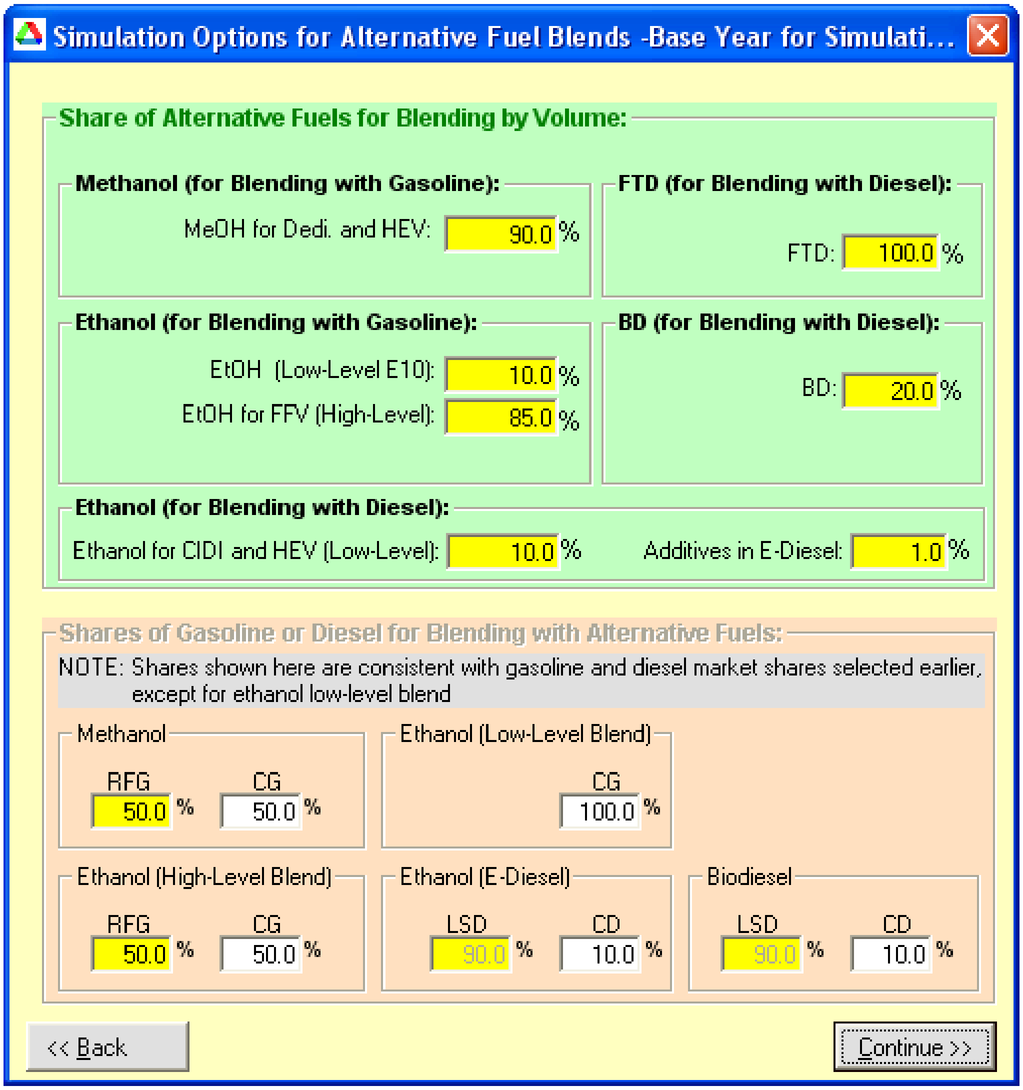


Figure 2.4.41 The simulation options for alternative fuel blends window contains shares of alternative fuels, gasoline, and diesel for blending. [4]

Key Assumptions

Continuing from the fuel pathways options, the user will be prompted to proceed to key assumptions as shown in Figure 2.4.42. Selecting ‘Yes Continue’ will bring up the simulation options at the Parametric Assumptions Options window. Selecting ‘No, Review selected scenario options’ will return the user to the first fuel pathways and simulations option window for review. Selecting ‘No, Start a new session without saving’ will return the user to the user to the beginning of the program and the current session will be erased.

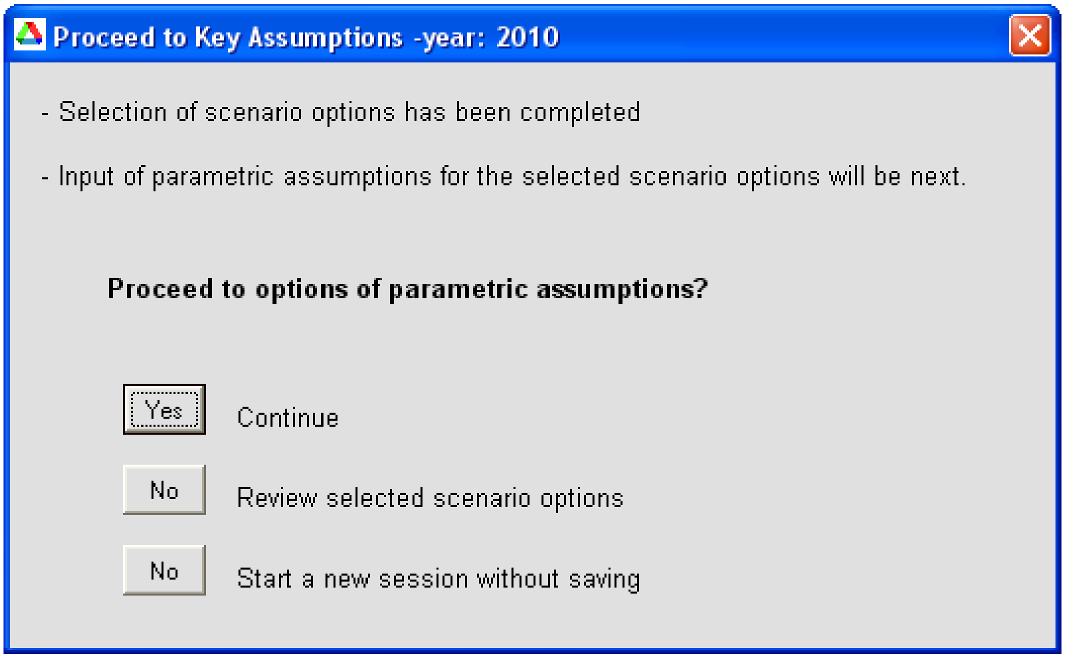


Figure 2.4.42 The proceed to key assumptions window allows the user to navigate between the fuel pathways options and key assumptions. [4]

Shown in Figure 2.4.43, the Parametric Assumptions Options window allows the user to specify the parametric assumptions that will be used for the simulation. Selecting “Use GREET default assumptions estimates” option tells GREETGUI to use the default tabulated parametric assumptions. Selecting “Revise base year assumptions which adjust the assumptions of all years” will allow the user to adjust parametric assumptions for all years in the subsequent windows. Selecting “Revise base year assumptions which adjust the assumptions of future years” will allow the user to adjust parametric assumptions for all future years in the subsequent assumption windows while preserving historical record. Additionally, specific years may be specified for view by selecting “View parametric assumptions for specific years” option and then selecting the appropriate years from the list. Clicking ‘Proceed>>’ will continue the session with the parametric assumptions windows.

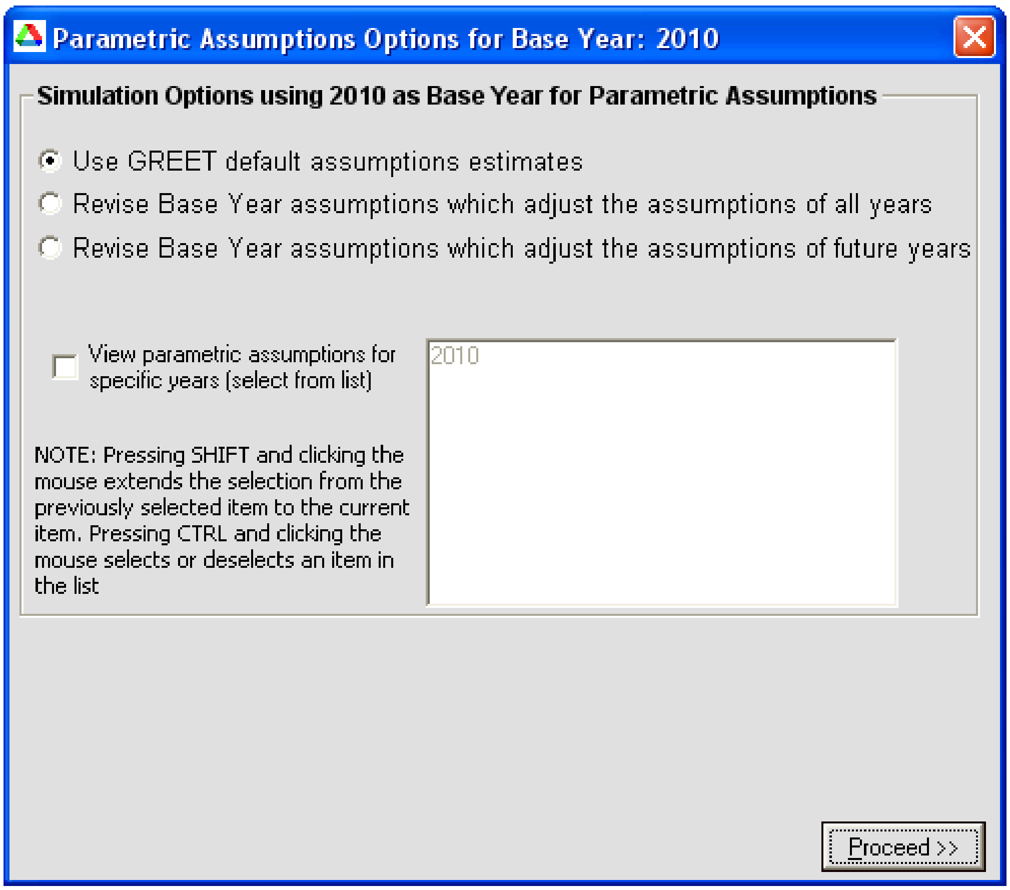


Figure 2.4.43 The parametric assumptions options window contains options for dealing with assumption estimates. [4]

The parametric assumptions considered in GREET fall under three categories: fuel production assumptions, transportation and distribution assumptions, and vehicle operation assumptions. The fuel production assumptions in GREETGUI cover most of the variable aspects pertaining to the different production pathways and include process efficiencies and other factors associated with fuel production. The transportation and distribution assumptions dictate the transportation pathways, shares of transportation modes, size of transportation, and other similar options from the point of origin to the destination. The vehicle operation assumptions form the backbone of the PTW operation and provide fuel economy and emission rates for baseline, alternative fueled, and advanced vehicles. Since these parameters may change over time, time-series tables were developed in GREET for the energy efficiencies of production-related processes

Shown in Figure 2.4.44, fuel production assumptions are subdivided into tabs for petroleum, NG/biomass, ethanol, electricity, gaseous hydrogen, and liquid hydrogen. The petroleum assumptions tab includes energy efficiencies of crude oil recovery and the refining processes associated with the production of petroleum-based fuels. The natural gas/biomass assumptions tab includes energy efficiencies associated with NG recovery and processing, NG-based fuels production, and steam and electricity credits. Note, the energy efficiency of steam boilers for the steam co-generation in many fuel production facilities is used to calculate the steam export credit for fuel production plants with steam export. The natural gas/biomass assumptions tab also includes energy efficiencies and electricity credit associated with the production of biomass-based fuels. The ethanol assumptions tab includes energy use in corn and biomass farming, ethanol production, and CO_2 emissions due to land use changes by corn and biomass farming. The electricity assumptions tab includes efficiency of electric power generation at various types of power plant, electricity transmission and distribution loss, and parameters for nuclear-based electricity generation processes. The gaseous hydrogen assumptions tab includes energy efficiencies for H_2 production from various feedstock sources, steam and electricity credits, energy use for CO_2 sequestration, and H_2 compression efficiencies. The liquid hydrogen assumptions tab includes energy efficiencies for LH_2 production from various feedstock sources, steam and electricity credits, energy use for CO_2 sequestration, and H_2 liquefaction efficiencies.

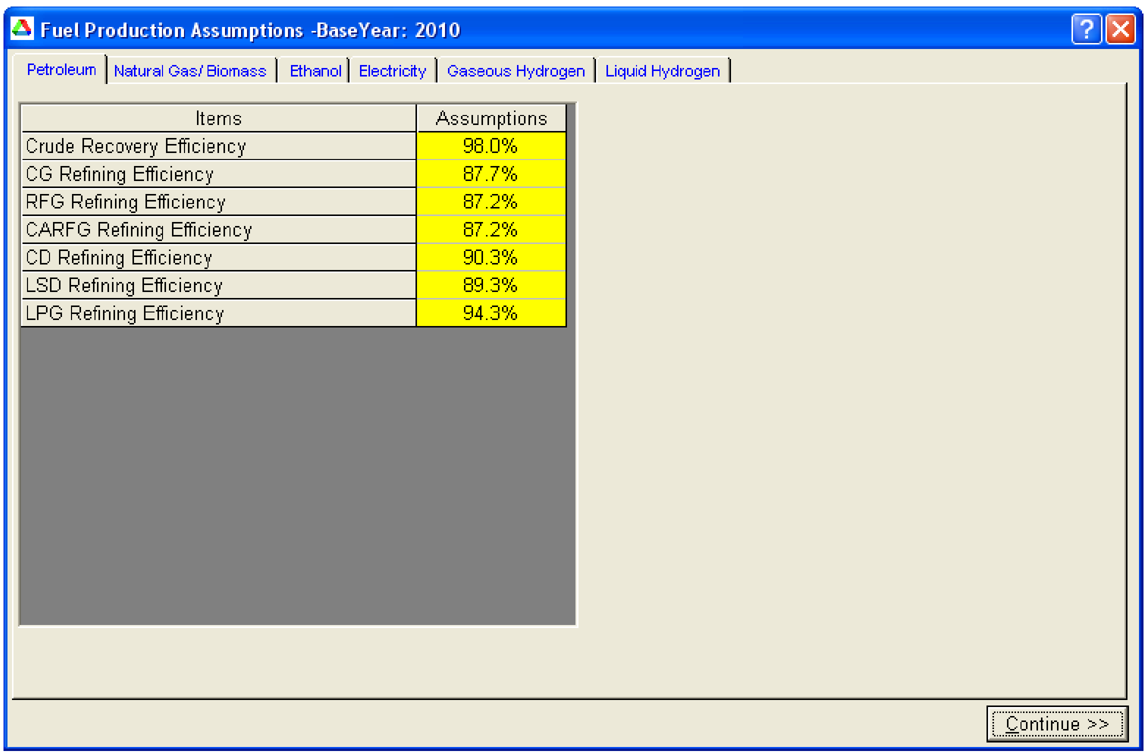


Figure 2.4.44 The fuel production assumptions window tabulates relevant assumptions for petroleum, natural gas/biomass, ethanol, electricity, gaseous hydrogen, and liquid hydrogen. [4]

In GREETGUI, transportation and distribution related activities are generally presented using flow charts mapping market shares of feedstock or fuels from origin to destination, transportation mode, transportation mode share, and transportation distance as shown in Figure 2.4.45. The flow charts are sorted by fuel and feedstock pathways. There may be multiple sources that provide a feedstock or fuel to a particular destination. There may be multiple transportation modes by which the feedstock or fuel may be delivered. In some cases, an intermediate destination may be used to define the transportation pathways allowing easy access to changes in transportation distance. The user may specify market shares that travel each route, the transportation mode shares, and transportation distance. Note, the T&D_Flowcharts spreadsheet will appear in GREET1.8c.0 unless one of the revision options in the parametric assumptions options window (See Fig. 2.4.43) was selected. To proceed from the spreadsheet, click the “Click here to continue” button located directly below the flow chart example illustration. If the “Use GREET default assumptions estimates” option was selected (See Figure 2.4.43), GREETGUI will skip the T&D flowcharts and instead go directly to the vehicle operation assumptions.

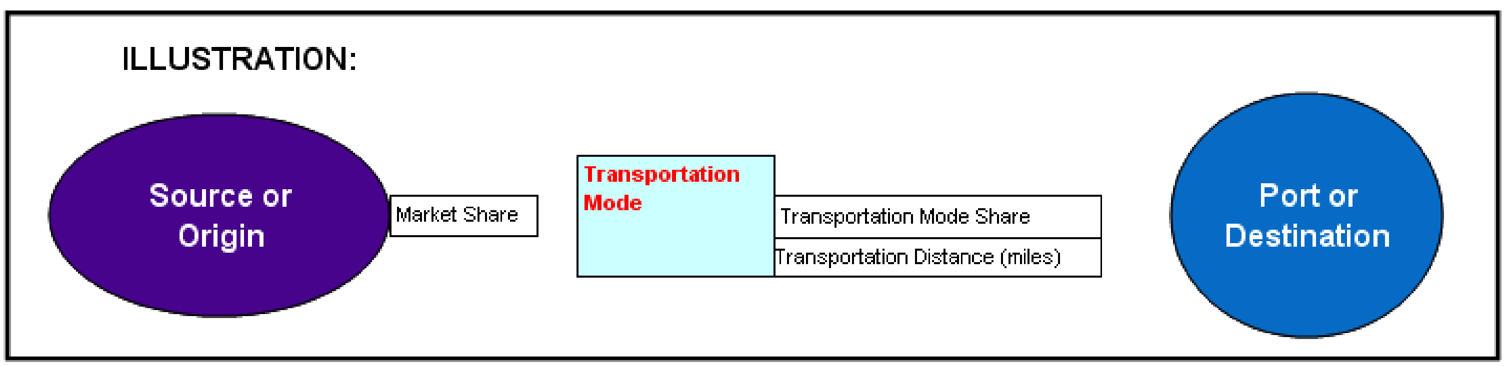
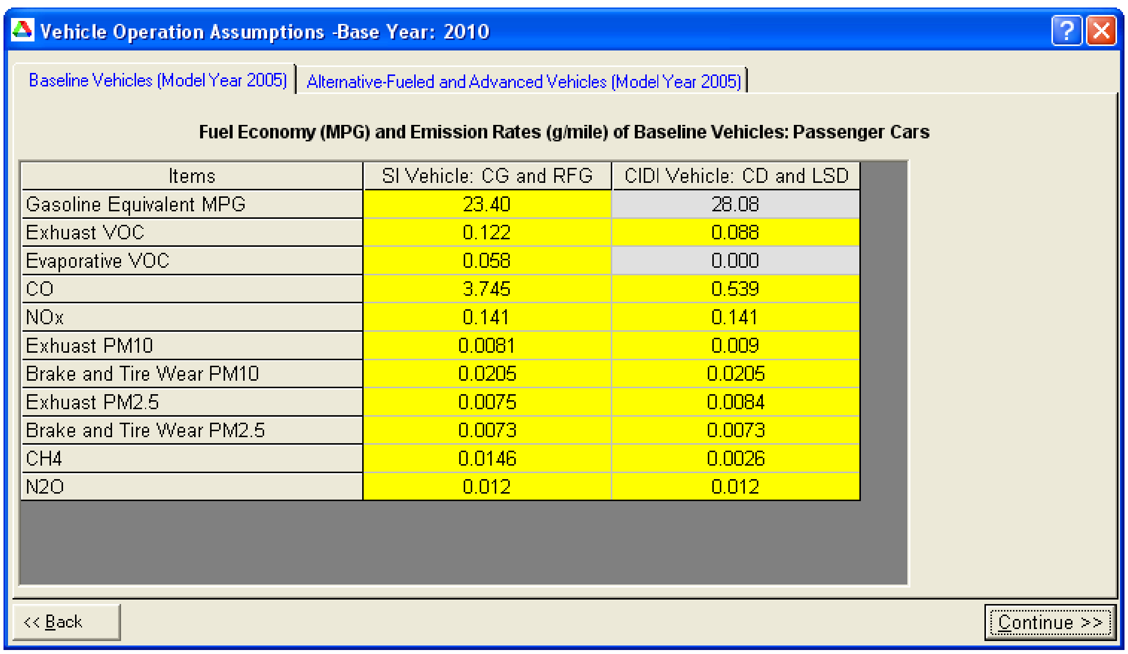


Figure 2.4.45 The transportation and distribution flowcharts follow this general model when moving fuel or feedstock from a source to destination. [4]

The vehicle operation assumptions window contains the fuel economy and emission rates for the modeled vehicles. These assumptions are divided into the baseline vehicles, and the alternative-fueled and advanced vehicles. The vehicle model year appears on the tabs of each group.

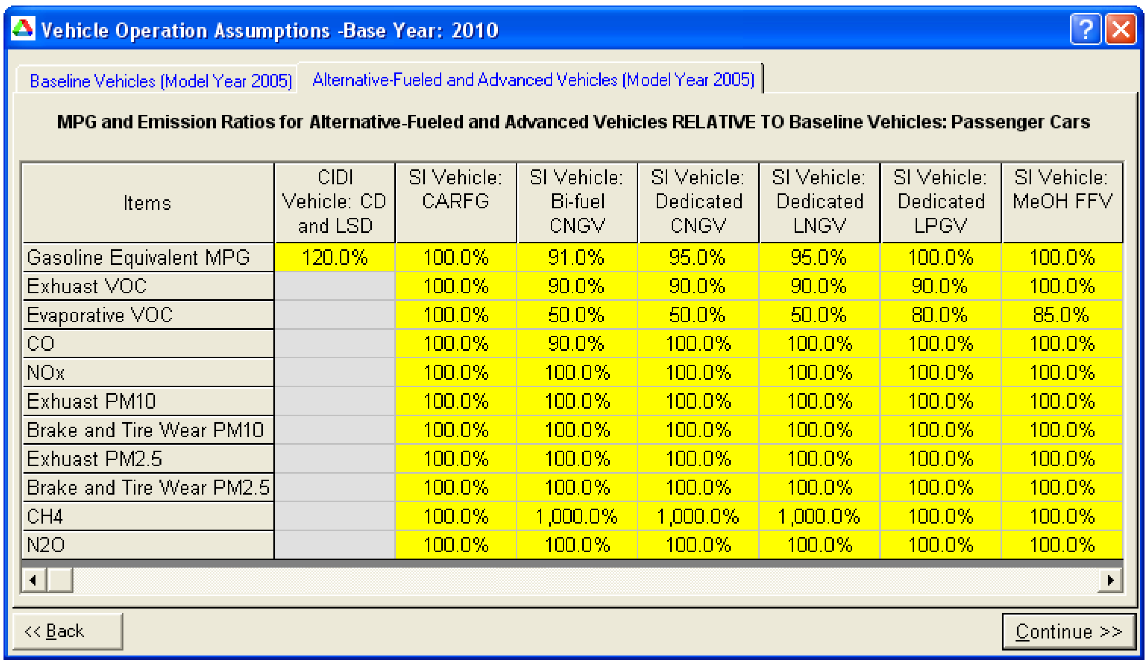
Shown in Figure 2.4.46, the baseline vehicles include a SI vehicle fueled by the selected market shares of CG and RFG, and a CIDI vehicle fueled by the selected market shares of CD and LSD. Listed under each vehicle are the parameter values for the corresponding fuel economy and emission rate items. The fuel economy is listed in gasoline equivalent MPG. The emissions rates of principal air pollutants (VOC, CO, NO_X, PM_{10}, and $PM_{2.5}$) and greenhouse gases (CH_4 and N_2O) are listed below the fuel economy and are measured in g/mile. The user may not specify a fuel economy value for the baseline CIDI vehicle because it is calculated directly from the baseline SI vehicle.



Items	SI Vehicle: CG and RFG	CIDI Vehicle: CD and LSD
Gasoline Equivalent MPG	23.40	28.08
Exhuast VOC	0.122	0.088
Evaporative VOC	0.058	0.000
CO	3.745	0.539
NOx	0.141	0.141
Exhuast PM10	0.0081	0.009
Brake and Tire Wear PM10	0.0205	0.0205
Exhuast PM2.5	0.0075	0.0084
Brake and Tire Wear PM2.5	0.0073	0.0073
CH4	0.0146	0.0026
N2O	0.012	0.012

Figure 2.4.46 The vehicle operation assumptions window for baseline vehicles lists the parameters for fuel economy and emission rates. [4]

Shown in Figure 2.4.47, the alternative-fueled and advance vehicles include all the selected vehicle-fuel combinations. Each vehicle-fuel combination has its own parameters for fuel economy and emission rates. Unlike the baseline vehicles, however, these vehicle operation parameters are specified as a percentage change from the corresponding item for baseline SI gasoline vehicle.



Items	CIDI Vehicle: CD and LSD	SI Vehicle: CARFG	SI Vehicle: Bi-fuel CNGV	SI Vehicle: Dedicated CNGV	SI Vehicle: Dedicated LNGV	SI Vehicle: Dedicated LPGV	SI Vehicle: MeOH FFV
Gasoline Equivalent MPG	120.0%	100.0%	91.0%	95.0%	95.0%	100.0%	100.0%
Exhuast VOC		100.0%	90.0%	90.0%	90.0%	90.0%	100.0%
Evaporative VOC		100.0%	50.0%	50.0%	50.0%	80.0%	85.0%
CO		100.0%	90.0%	100.0%	100.0%	100.0%	100.0%
NOx		100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Exhaust PM10		100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Brake and Tire Wear PM10		100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Exhaust PM2.5		100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Brake and Tire Wear PM2.5		100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
CH4		100.0%	1,000.0%	1,000.0%	1,000.0%	100.0%	100.0%
N2O		100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Figure 2.4.47 The vehicle operation assumptions window for alternative-fueled and advanced vehicles lists the parameters for fuel economy and emission rates as a percentage change from the baseline SI gasoline vehicle. [4]

CHAPTER 3

VEHICLE-FUELS COMPARISON: TRADITIONAL VS. ALTERNATIVE FUEL SYSTEMS

Introduction

In this study, the energy consumption and emissions of several prominent vehicle-fuel combinations are analyzed using results from the GREET 1.8c.0 simulations for passenger car (PC) vehicle types. The purpose is to compare different combinations to investigate the energy consumption and emissions in each category and to assess if any of the combinations perform better than the others in all considered categories for PC vehicle types. In this case study, the general assumptions and parameters developed by ANL for the U.S. vehicle-fuel combinations considered utilized. Vehicle-fuel combinations include spark ignition (SI) vehicles fueled by a conventional gasoline (CG) and reformulated gasoline (RFG) market share blend and a low-level ethanol (LL-EtOH) blend with CG, spark ignition direct injection (SIDI) vehicles fueled by a CG and RFG market share blend and a LL-EtOH blend with CG, and compression ignition direct injection (CIDI) vehicles fueled by low sulfur diesel (LSD) and 20% biodiesel blend (BD20) with LSD. The potentials of each vehicle-fuel combination will be highlighted in terms of Well-to-Pump (WTP) performance, Well-to-Wheel (WTW) performance, and changes relative to the baseline model. Overall performance will be determined using WTW results.

Driving a vehicle is an everyday occurrence for many people in the U.S., but the effects of the daily routine of driving a personal vehicle is often overlooked. These effects are not limited just to energy consumption and emissions from vehicle operation, but include primary and secondary sources of energy consumption and emissions during the feedstock and fuel stages as well. GREET simulations offer a unique perspective of the effect of daily driving by modeling the vehicle-fuel combinations under a variety of different parameters given a unique set of assumptions. This perspective offers insight to undergraduate students learning about traditional and alternative fuels and can enhance their understanding of the processes that occur during WTW activities.

This case study is structured as follows. After the introduction is the procedure for replicating the simulation in GREETGUI. Then, the simulation results give a brief overview of the itemizations as well as the results obtained in the simulation. Next, the significant simulation results are discussed using comparisons in terms of WTP comparisons for fuels and WTW comparisons by fuel-vehicle combination. A short summary of the discussion will precede a concluding statement for the case study.

Procedure

The following section summarizes the procedure used to simulate several vehicle-fuel combinations using GREET 1.8c.0. The GREETGUI is preferred for this simulation due to its ease of use and streamlined modeling. GREETGUI also offers access to first tier assumptions and parameters which can be tweaked to simulate slightly different scenarios for vehicle-fuel combinations. Simulated passenger car (PC) vehicle types include SI vehicles fueled by CG and RFG market share blend and a LL-EtOH blend with CG, SIDI vehicles fueled by CG and RFG market share blend and a LL-EtOH blend with CG, and CIDI vehicles fueled by LSD and a BD20 blend with LSD. The vehicle parameters used in the simulation correspond to 2005 vehicles while the feedstock and fuel production parameters used in the simulation correspond to 2010 values for the U.S. The exact procedure for reproducing the modeled scenario for this particular case study, including references to figures of GREETGUI, is located in Appendix A.1.

Results

The following results are derived from the output file created by GREET after the simulation. They include energy consumption and emissions reports for the simulation year 2010 WTP activities, WTW activities, and WTW changes relative to the baseline vehicle. Included with the results this section is a short explanation of the outputs generated by GREET.

The WTP information is limited to the feedstock and fuel stages of fuel production and distribution. Shown in Table 3.3.1, the WTP results for the simulation year 2010 include the energy consumption, energy efficiency, and emissions produced on a basis of a mmBTU of fuel available at fuel station pumps. Thus, the WTP results are independent of the vehicle type (i.e. PC, LDT1, and LDT2) and vehicle operation parameters.

Table 3.3.1 Well to Pump Energy Consumption, Energy Efficiencies, and Emissions for Passenger Car Vehicle Types (The data is in units of BTU or grams per mmBtu of fuel available at fuel station pumps for energy consumption and emissions, respectively.)

2010	**Baseline CG and RFG**	**Gasoline Vehicle: Low-Level EtOH Blend with Gasoline**	**Baseline Conventional and LS Diesel**	**CIDI Vehicle: BD20**
Total Energy	250,743	305,772	193,718	496,698
WTP Efficiency	80.0%	76.6%	83.8%	66.8%
Fossil Fuels	228,700	246,231	190,215	211,552
Coal	40,433	46,608	32,158	32,086
Natural Gas	92,970	107,103	76,092	97,978
Petroleum	95,297	92,520	81,966	81,488
CO_2 (w/ C in VOC & CO)	16,812	14,791	15,488	1,272
CH_4	108.738	106.594	104.527	93.059
N_2O	1.140	2.918	0.248	2.215
GHGs	19,871	18,326	18,175	4,259
VOC: Total	27.345	28.606	7.774	26.431
CO: Total	14.229	15.332	12.630	15.035
NO_x: Total	47.526	50.357	42.768	46.174
PM_{10}: Total	10.990	12.967	8.676	8.862
$PM_{2.5}$: Total	4.270	4.873	3.470	3.753
SO_x: Total	23.734	26.075	20.615	23.574
VOC: Urban	15.527	15.431	2.990	2.584
CO: Urban	3.805	3.643	3.412	2.934
NO_x: Urban	10.417	10.035	9.233	8.064
PM_{10}: Urban	1.838	1.735	1.603	1.336
$PM_{2.5}$: Urban	1.071	1.011	0.932	0.779
SO_x: Urban	7.222	7.042	6.588	5.739

Energy consumption items such as total energy, fossil fuels, coal, natural gas, and petroleum describe the energy source being consumed and are measured in BTU/mmBTU of fuel available at fuel station pumps. The total energy item includes all fossil fuel sources of energy consumption as well as other sources of energy consumption (i.e. nuclear, hydro, wind, solar, etc.). The total energy consumed is also used to estimate the WTP efficiency of producing and distributing a mmBTU of fuel to fuel pumps. The WTP efficiency is a measure of how effective it is to deliver a mmBtu of fuel to a fuel station pump and is calculated using the equation

$$E = \frac{P}{P + C}, \tag{3.1}$$

where E is the WTP efficiency (%), P is the energy delivered to the pump (i.e. a mmBtu of fuel), and C is the energy consumed to produce a mmBtu of fuel. For example, the total energy consumed for the baseline CG and RFG in Table 3.3.3.1 is 250,743 Btu per mmBtu available at fuel station pumps. This value corresponds to the variable C in Equation 1. The energy delivered to the pump, P, from Equation 3.1 is always 1,000,000 Btu per mmBtu available at fuel station pumps for all WTP calculations in GREET. Inputting the appropriate values into Equation 3.1, the resulting WTP efficiency is approximately 80.0% as shown in Table 3.3.1 for baseline vehicles fueled by CG and RFG. The fossil fuels item consists of a summation of the coal, natural gas, and petroleum energy consumed. The coal, natural gas, and petroleum items are the respective breakdowns of fossil fuel energy consumed by source.

Emissions items such as GHGs and principal pollutants describe the emissions produced and are measured in grams/mmBtu of fuel available at fuel station pumps. The

CO_2, CH_4, and N_2O items are all GHGs. The CO_2 (w/ C in VOC & CO) item is an estimate of the direct CO_2 emissions and indirect CO_2 emissions due to chemical reactions of direct VOC and CO emissions based on carbon ratios. The GHGs item is a measure of the global warming potential equivalent to CO_2. That is in essence an adjusted summation of the CO_2, CH_4, and N_2O items based on their CO_2 equivalent global warming potentials. The potentials used in the simulation are based on the IPCC Climate Change 2007.[4] The principal pollutants (VOC, CO, NO_x, SO_x, PM_{10}, and $PM_{2.5}$ items) are listed by both total emissions and urban emissions. The total amount emitted is listed with respect to each pollutant followed by the amount that is estimated to have been emitted in urban areas.

The WTW relative change results, shown in Table 3.3.2, indicate the percent changes in WTW items for a particular vehicle-fuel combination relative to the baseline vehicle. The relative change of each item is calculated using the formula

$$RC = \frac{AT - OT}{OT}, \tag{3.2}$$

for every item and vehicle technology compared to the baseline technology where *RC* is the relative change (%), *AT* is the alternative technology item, and *OT* is the baseline technology item. In this case, the baseline vehicle is modeled by a GV with a SI engine fueled with CG and RFG which means that the corresponding item from this vehicle represents the OT value. The AT value is represented by the value of the corresponding item for another vehicle. For example, the total energy consumptions for the baseline vehicle with CG and RFG (*OT*) and the gasoline vehicle with LL-EtOH blend (*AT*) are 6,139 Btu/mile (see Table A.5) and 6,409 Btu/mile (see Table 3.3.3), respectively.

Subtracting the *OT* value, 6,139 Btu/mile, from the *AT* value, 6,409 Btu/mile, and then dividing the quantity by the *OT* value, 6,409 Btu/mile, results in a relative change of 4.4% as shown in Table 3.3.2 under the gasoline vehicle fueled by a LL-EtOH blend for total energy consumption. The WTW relative change results for this case study offer a way to quickly compare one vehicle-fuel combination to another by comparing the relative changes to the baseline vehicle. The listed items are the same as those covered in the WTP results.

Table 3.3.2 Well to Wheel Relative Change Results for Passenger Car Vehicle Types

2010 (%, relative to GVs fueled with CG and RFG)	**GV: Low-Level EtOH Blend with Gasoline**	**SIDI Vehicle: CG and RFG**	**SIDI Vehicle: Low-Level EtOH Blend with Gasoline**	**CIDI Vehicle: Conventional and LS Diesel**	**CIDI Vehicle: BD20**
Total Energy	4.4%	-13.0%	-9.2%	-20.5%	-0.3%
Fossil Fuels	-2.2%	-13.0%	-14.9%	-17.9%	-29.4%
Coal	15.3%	-13.0%	0.2%	-33.7%	-33.9%
Natural Gas	15.2%	-13.0%	0.2%	-31.8%	-12.2%
Petroleum	-4.3%	-13.0%	-16.8%	-16.1%	-30.7%
CO_2 (w/ C in VOC & CO)	-2.2%	-13.0%	-15.0%	-15.8%	-28.3%
CH_4	-1.9%	-12.7%	-14.4%	-21.6%	-30.1%
N_2O	49.6%	-4.1%	39.0%	-26.0%	19.7%
GHGs	-1.7%	-12.9%	-14.4%	-16.1%	-27.8%
VOC: Total	2.0%	-5.6%	-3.9%	-61.9%	-37.6%
CO: Total	0.1%	-0.2%	-0.1%	-84.5%	-84.3%
NO_x: Total	3.7%	-8.1%	-4.9%	-15.6%	-11.9%
PM_{10}: Total	11.8%	-8.5%	1.7%	-21.3%	-20.3%
$PM_{2.5}$: Total	8.3%	-7.6%	-0.5%	-16.4%	-13.2%
SO_x: Total	9.0%	-13.0%	-5.2%	-29.4%	-19.9%
VOC: Urban	-0.3%	-5.3%	-5.5%	-64.4%	-65.3%
CO: Urban	0.0%	-0.1%	-0.1%	-85.1%	-85.2%
NO_x: Urban	-1.4%	-4.8%	-6.0%	-9.6%	-13.1%
PM_{10}: Urban	-1.9%	-4.4%	-6.0%	-7.1%	-11.2%
$PM_{2.5}$: Urban	-2.0%	-4.7%	-6.5%	-6.1%	-10.4%
SO_x: Urban	-3.0%	-13.0%	-15.6%	-27.9%	-37.4%

The WTW results offer a more detailed perspective of vehicle fuel combinations due to vehicle use. The results for the baseline vehicle shown in Table 3.3.3 encompass the feedstock, fuel, and vehicle operation stages of the operation of a GV fueled by CG and RFG and provide an overview of all energy consumed and emissions produced on a per mile basis. The energy items are measured in Btu/mile and the emissions items are measured in grams/mile. The feedstock stage includes all energy consumption and emissions from the gathering, transporting, and distributing of feedstock material. The fuel stage includes all energy consumption and emissions from the production and transportation of the fuel. The vehicle operation stage includes all energy consumption and emissions from the operation of the vehicle. The WTW results for the SIDI vehicle fueled by CG and RFG, the SI and SIDI vehicles fueled by a low-level EtOH blend with CG, the CIDI vehicle fueled by LSD, and the CIDI vehicle fueled by BD20 are located in Appendix A.3.

Table 3.3.3 Well to Wheel Results for a Passenger Car Vehicle Type Gasoline Vehicle with SI Engine Fueled by CG and RFG

	Btu/mile or grams/mile			
Item	**Feedstock**	**Fuel**	**Vehicle Operation**	**Total**
Total Energy	263	968	4,908	6,139
Fossil Fuels	255	868	4,806	5,928
Coal	38	160	0	198
Natural Gas	158	298	0	456
Petroleum	58	409	4,806	5,274
CO_2 (w/ C in VOC & CO)	17	66	377	459
CH_4	0.456	0.077	0.015	0.548
N_2O	0.000	0.005	0.012	0.018
GHGs	28	69	381	478
VOC: Total	0.017	0.117	0.180	0.314
CO: Total	0.032	0.037	3.745	3.815
NO_x: Total	0.121	0.112	0.141	0.374
PM_{10}: Total	0.010	0.044	0.029	0.083
$PM_{2.5}$: Total	0.005	0.016	0.015	0.036
SO_x: Total	0.041	0.076	0.006	0.123
VOC: Urban	0.003	0.073	0.112	0.188
CO: Urban	0.001	0.017	2.329	2.348
NO_x: Urban	0.005	0.046	0.088	0.139
PM_{10}: Urban	0.000	0.009	0.018	0.027
$PM_{2.5}$: Urban	0.000	0.005	0.009	0.014
SO_x: Urban	0.003	0.032	0.004	0.039

Discussion

Well to Pump Results

The WTP results offer a basis for comparison of different types of fuel in the listed categories. While this has no bearing on vehicle operation, it does offer an idea of how different fuels compare to each other with a given basis of a mmBtu of fuel available at the fueling pump. In this section, a general overview of each process will be discussed to make clear the effects of different processes on the WTP results. Additionally, the relevant energy consumption and emissions will be discussed for the WTP process of two pairs of related fuels. An overall assessment of the fuels as it relates to this model will also be provided.

For CG/RFG and LL-EtOH, the general WTP processes described here are the same. In this simulation, CG and RFG each share half of the market, and RFG is CG containing EtOH as an additive. This results in two major fuel processes being simulated in conjunction resulting in the WTP results for this baseline fuel. LL-EtOH blends consist of CG mixed with EtOH. This results in two major fuel processes being used in conjunction resulting in the WTP results for this alternative fuel. Each major fuel process consists of many different individual processes. These individual processes are grouped into the feedstock and fuel stages which combine to form the WTP results for each fuel.

In terms of feedstock, CG and RFG rely mainly on crude oil while EtOH is produced entirely from corn. For gasoline, crude feedstock includes conventional crude oil, and oil sands products from surface mining and in situ production. The crude oil process includes estimations for recovery, transportation to U.S. refineries, and storage.

Shown in Figure 3.4.1, conventional crude oil used in U.S. refineries is transported from multiple sources including the U.S., Canada, Mexico, and other offshore countries and distributed using several different transportation modes. The transportation mode shares and distances are all considered in process estimations. The surface mining and in situ production of the oil sands recovery process both include estimations for bitumen extraction, bitumen upgrading, transportation to U.S. refineries, and storage. For ethanol, the corn farming process includes estimations for corn farming, fertilizer use, pesticide use, and corn transportation. Shown in Figure 3.4.2, corn is harvested and transported to a central destination before being transported to ethanol plants. Fertilizer and pesticide transportation and distribution (T&D) are also included in the WTP estimations.

In terms of fuel, CG and EtOH production are the main production processes. RFG is a combination of CG and EtOH blend stocks. The CG fuel stage includes estimates of CG refining, CG transportation and distribution, and CG storage. The RFG fuel stage consists of RFG gasoline blend stock and corn based EtOH processes. The RFG gasoline blend stock process includes estimates of RFG gasoline blend stock refining, RFG transportation and distribution, and RFG storage. The corn based EtOH process includes estimates of both dry and wet milling production with co-product credits. T&D activities shown in Figure 3.4.3 are consistent with both CG and RFG for the delivery of fuels from refineries to refueling stations.

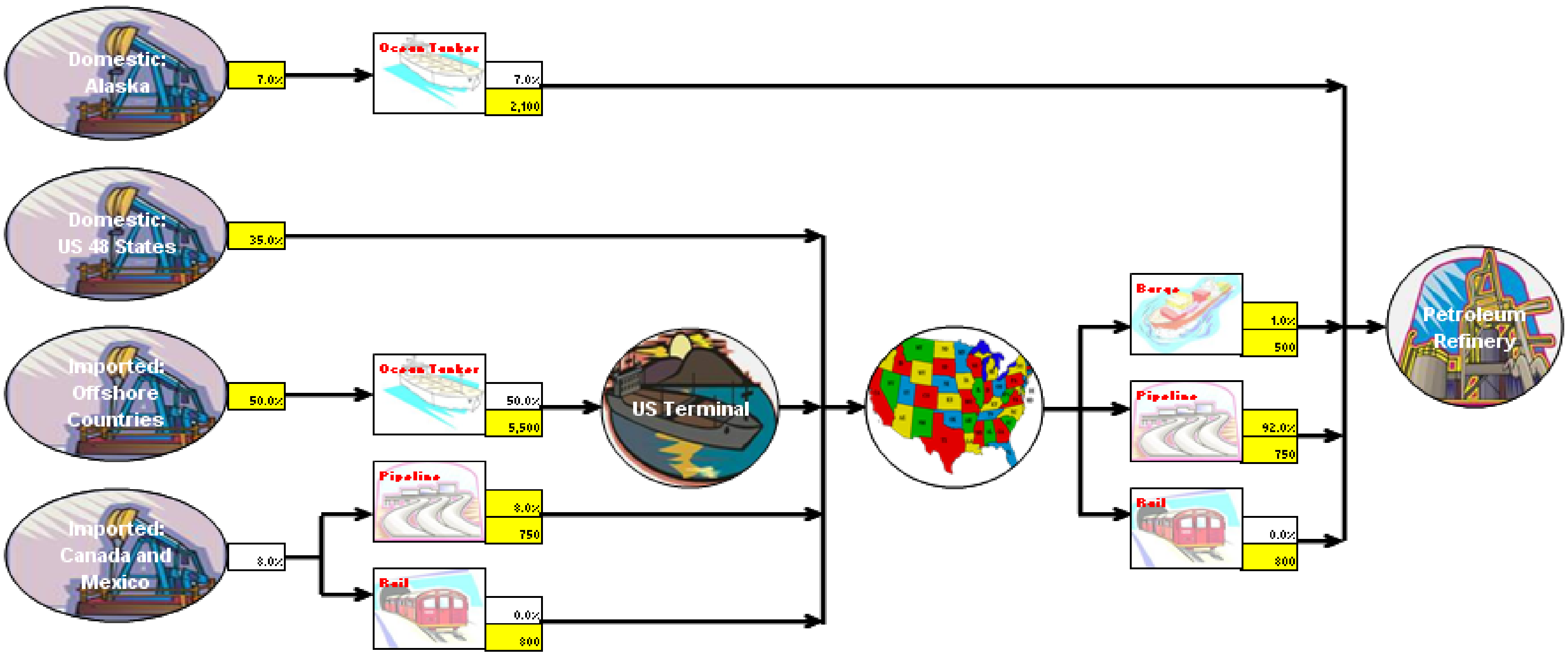


Figure 3.4.1 Transportation & distribution process diagram for conventional crude oil for use in U.S. refineries

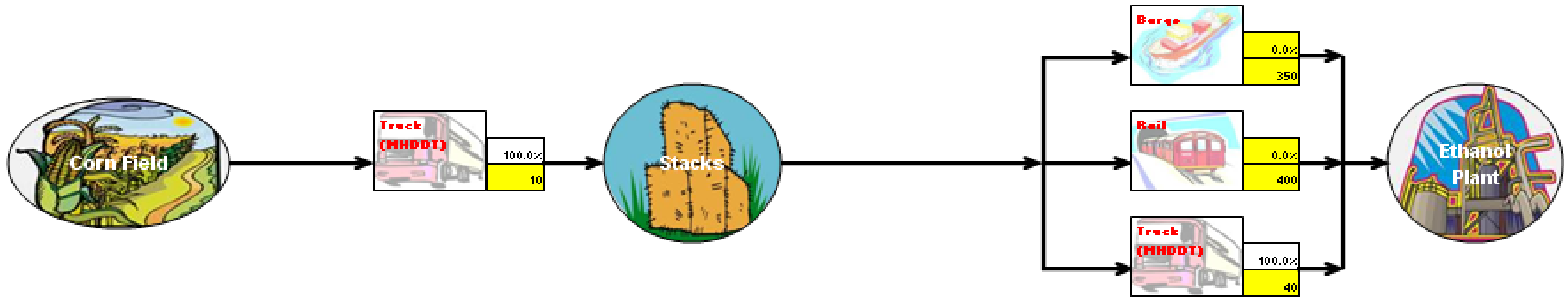


Figure 3.4.2 Transportation & distribution process diagram for U.S. corn-based ethanol for use in U.S.

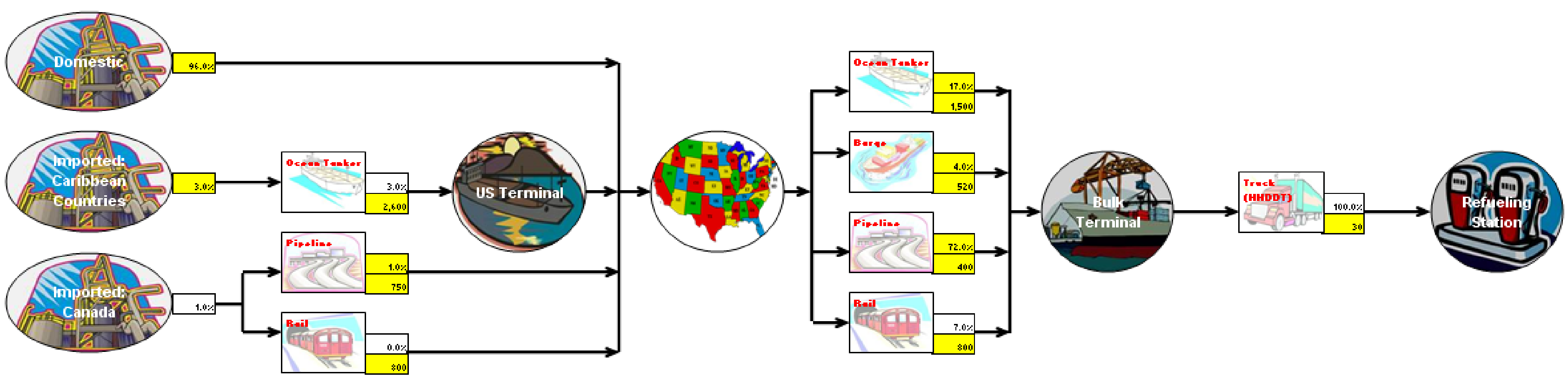


Figure 3.4.3 Transportation & distribution process diagram for U.S. conventional and reformulated gasoline

For LSD and BD20, the general LSD WTP process described here applies to BD20 as well. In this simulation, LSD holds all market shares. This results in one major fuel process being simulated for the WTP results of LSD. BD20 consists of LSD mixed with BD. This results in two major fuel processes being used in conjunction. Each major fuel process consists of many different individual processes. These individual processes are grouped into the feedstock and fuel stages which combine to form the WTP results for each fuel.

In terms of feedstock, LSD relies mainly on crude oil while BD is produced entirely from soybeans. For LSD, crude feedstock includes conventional crude oil, and oil sands products from surface mining and in situ production. These processes are the same as those described for the crude feedstock for CG and RFG above. For BD, the soybean farming process includes estimations for soybean farming, fertilizer use, herbicide use, pesticide use, and soybean transportation. Shown in Figure 3.4.4, soybeans are harvested and transported to a central destination before being transported to biodiesel plants. Fertilizer, herbicide, and pesticide T&D are also included in the WTP estimations.

In terms of fuel, LSD and BD production are the main processes. BD20 is a combination of LSD and BD blend stocks. The LSD fuel stage includes estimates of LSD refining, LSD transportation and distribution, and LSD storage. T&D activities shown in Figure 3.4.5 illustrate part of the LSD fuel stage process. The BD fuel stage includes estimates of soy oil extraction, soy oil transesterfication, BD transportation and distribution, and BD storage. BD20 consists of LSD blend stock and soybean based BD processes. T&D activities shown in Figure 3.4.6 illustrate part of the BD20 fuel stage process.

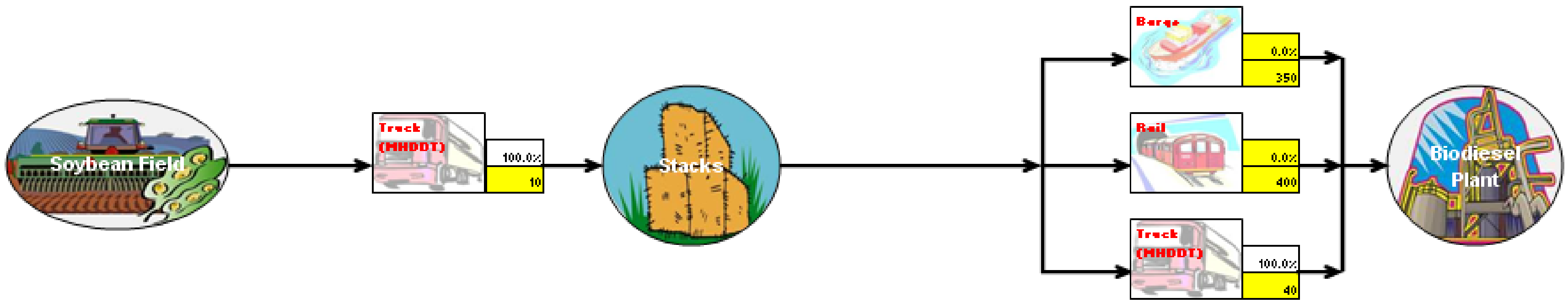


Figure 3.4.4 Transportation & distribution process diagram for U.S. soybean-based biodiesel for use in the U.S.

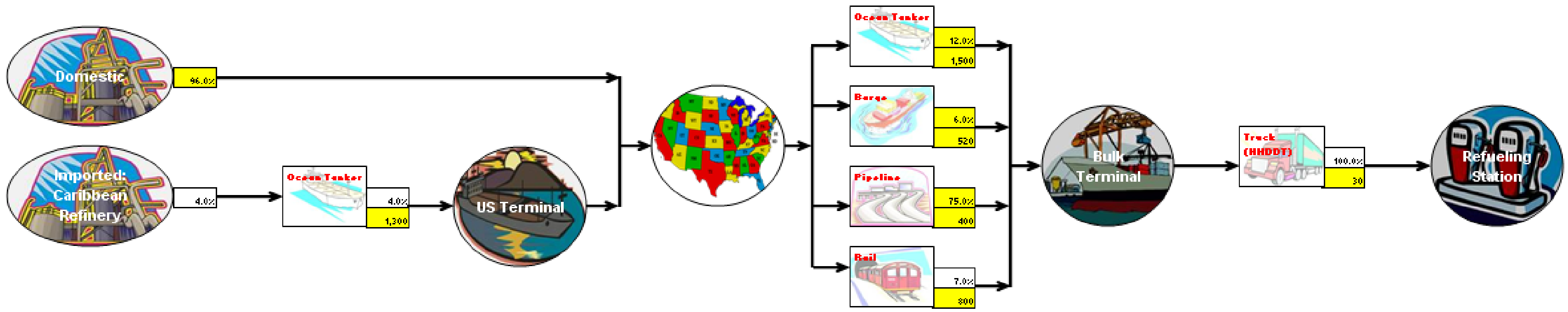


Figure 3.4.5 Transportation & distribution process diagram for U.S. LSD

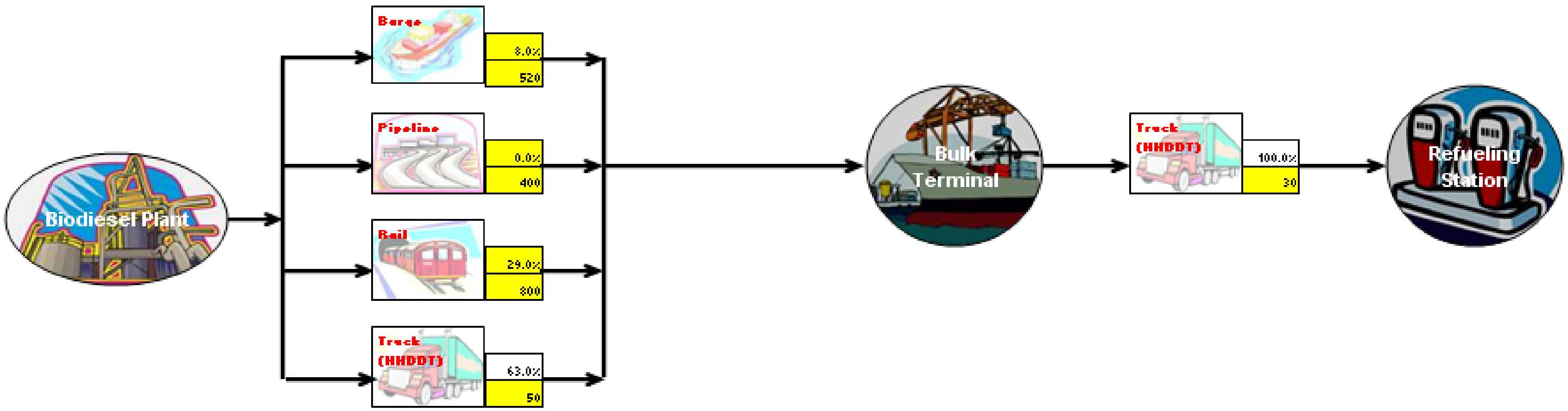


Figure 3.4.6 Transportation & distribution process diagram for biodiesel

For this case study, the WTP efficiency shown in Figure 3.4.7 indicates that it is much more energy efficient to produce LSD and baseline CG and RFG than it is to produce their corresponding alternatives. The WTP efficiency is based on the energy available at the fuel pump and the total energy consumed getting the fuel through the feedstock and fuel stages to the pump. Thus, it is dependent on total energy consumed rather than any one of the individual parts such as fossil fuels. Only looking at the efficiency may give a skewed impression about the fuels, but a higher WTP efficiency is typically desired in a fuel.

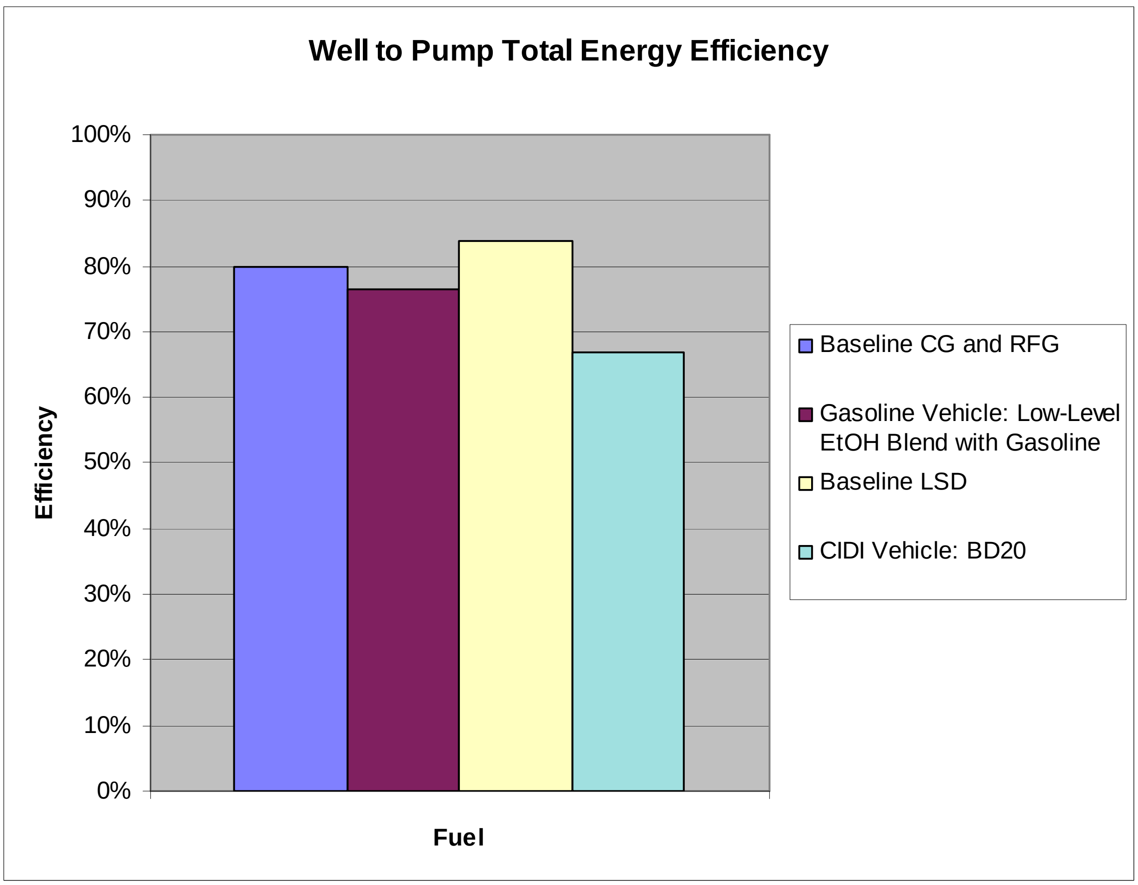


Figure 3.4.7 WTP energy efficiency for making a mmBtu of fuel available at fuel station pumps

A closer inspection of the energy consumption results shows that the amount of total energy consumption is somewhat deceptive for the alternative fuels, especially for BD20. According to the simulation results shown in Figure 3.4.8, BD20 consumes more than double the total energy than its chief competitor, LSD. The LL-EtOH blend consumes about 22% more total energy than its chief competitor, CG and RFG. In terms of fossil fuel consumption, the alternative fuels are much closer to their competitors. BD20 consumes about 11% more fossil fuels energy than LSD to deliver the same amount of energy to the pump. The LL-EtOH blend consumes about 8% more fossil fuels energy than the baseline CG and RFG. Interestingly, BD20 consumes slightly less coal and petroleum energy than its counterpart and the LL-EtOH blend consumes about 3% less petroleum energy than the baseline CG and RFG. These increases in total energy (more so for BD20) negatively impact the WTP efficiency despite some of the reductions in specific fossil fuels, namely petroleum.

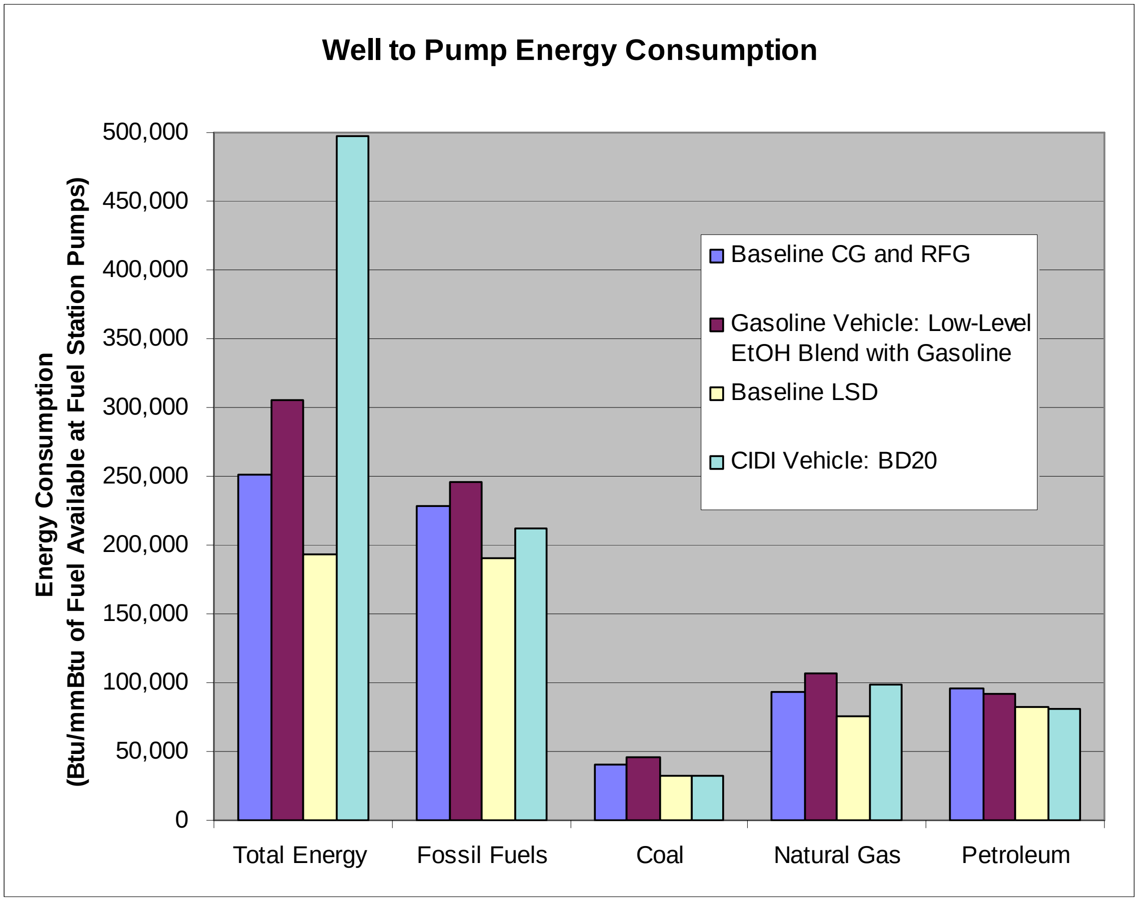


Figure 3.4.8 WTP energy consumption of for competing fuels

The difference between LL-EtOH blends with CG and the baseline CG and RFG in this case study is effectively the amount of ethanol in the fuel. CG as a base fuel does not contain ethanol. But the RFG simulated here contains ethanol as an oxygenate to boost the O_2 content to 2.3% by weight which means that the RFG contains approximately 6.3% EtOH by volume. Since the baseline fuel is considered to be a 50/50 market share of CG and RFG, the amount of ethanol relative to CG is reduced even more in the simulation of this fuel. On the other hand, the LL-EtOH blend has 10% ethanol by volume blended with CG. This energy consumption information shows that the increased ethanol requirements of a LL-EtOH blend drastically increases the total energy consumption necessary to have a mmBtu of fuel available at the pump. The effects of this difference are also apparent in the individual energy consumption categories. The shift in energy consumptions is the direct result of changes in the WTP process which increase production of ethanol and decrease the production of CG. Also, note that ethanol is less energetic per volume than CG and RFG which means that larger volumes of the LL-EtOH blend will need to be transported and distributed to make a mmBtu of fuel available at fuel station pumps. The increased volume could effect T&D energy consumption during the fuel stage.

The difference between LSD and BD20 is that BD in this case study replaces a portion of LSD with a 20% mix by volume of soy derived biodiesel. Thus, the differences in energy consumption over the categories above are directly linked to the use of biodiesel instead of LSD. A comparison of total energy consumption suggests the WTP process for producing BD is massively more energy intensive than the WTP process for producing LSD. However, the large increase in total energy consumption is not based entirely on fossil fuel consumption which means that the energy consumption can be attributed to other sources. In fact, the estimated difference in fossil fuels energy consumption for BD20 and LSD can be primarily attributed to the increased consumption of natural gas energy during the WTP process. The shift in energy consumptions is the direct result of differences in the WTP process between the two fuels which include the production of BD and a decrease in the production of LSD.

Relative GHG emissions produced during the WTP process offer another interesting view of the effects of the making these fuels available at the pump. For comparison purposes, Figure 3.4.9 includes the adjusted levels of CH_4 and N_2O relative to CO_2 using the global warming potentials from IPCC Climate Change 2007.[4] The actual estimated emissions of CH_4 and N_2O are 25 times less and 298 times less, respectively, than what is shown.

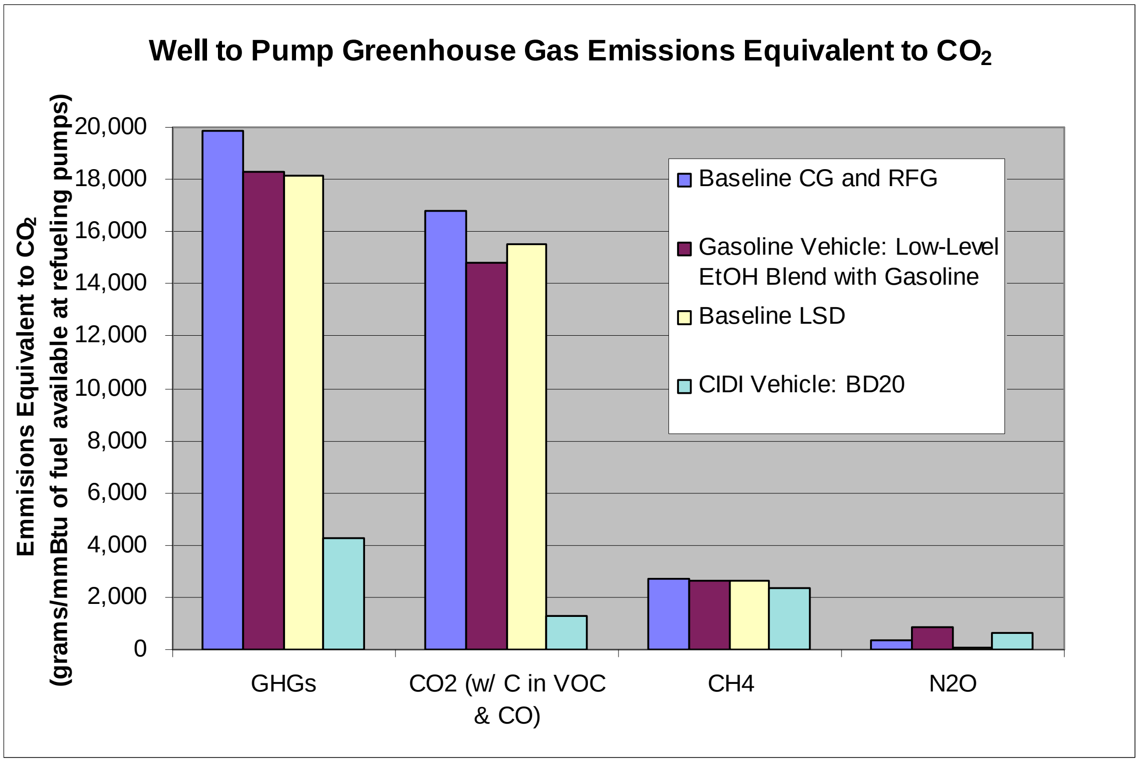


Figure 3.4.9 WTP GHG emissions relative to their respective global warming potentials for competing fuels

The impact of making BD20 available at the pumps rather than LSD on equivalent GHG emissions is very substantial. The simulation suggests that the WTP process for BD20 produces about 77% less equivalent GHG emissions than the WTP process for LSD. The primary difference between the two fuels is in the CO_2 emissions where BD20 has a distinct advantage by producing 92% less CO_2 emissions than the LSD process. This large reduction of CO_2 emissions is most likely due to carbon offsets during the growth of soybean plants as the feedstock for biodiesel. The BD20 WTP process produces about 11% less CH_4 emissions and about 9 times as much N_2O as the LSD WTP process.

Making LL-EtOH blends available at the pumps rather than CG and RFG also effects the equivalent GHG emissions. The simulation suggests that the WTP process for the LL-EtOH blend produces about 8% less equivalent GHG emissions than the WTP process for CG and RFG. The primary difference between the two fuels is in the CO_2 emissions where the LL-EtOH blend has an advantage by producing 12% less CO_2 emissions than the CG and RFG process. This reduction of CO_2 emissions is most likely due to increased carbon offsets due to additional corn growth for the extra ethanol production required by LL-EtOH blends coupled with decreased production of CG and RFG. The LL-EtOH blend WTP process produces about 2% less CH_4 emissions and about 2.5 times as much N_2O as the CG and RFG WTP process.

Principal pollutants produced during the WTP process are a major concern, especially in urban areas where the effects are compounded by increased vehicle use and increased population density. For this reason, the total emissions and the urban emissions must both be discussed. The principal pollutants considered by GREET are VOC, CO, NO_x, SOx, PM_{10}, and $PM_{2.5}$.

For WTP activities, the total VOC and urban VOC emissions estimated by GREET contradict each other in terms of conventional and alternative fuel pairings as shown in Figure 3.4.10. For gasoline blends, the availability of the LL-EtOH blend at the pump is expected to cause a 5% increase in VOC emissions compared to the baseline CG and RFG. This is approximately a 1.26 gram increase per mmBtu available. However, the same availability of LL-EtOH blend is expected to cause a 1% decrease in urban emissions of VOC compared to the baseline CG and RFG. This decrease is approximately 0.097 grams per mmBtu of fuel available. For diesel blends, the availability of the BD20 at the pump is expected to cause a 340% increase in VOC emissions compared to the baseline LSD. This is approximately an 18.7 gram increase per mmBtu available. However, the same availability of BD20 blend is expected to cause a 14% decrease in urban emissions of VOC compared to the baseline LSD. This decrease is approximately 0.406 grams per mmBtu of fuel available. While both alternative fuels are expected to produce higher total VOC emissions, the estimated emissions in urban areas are expected to be less than their conventional counterparts.

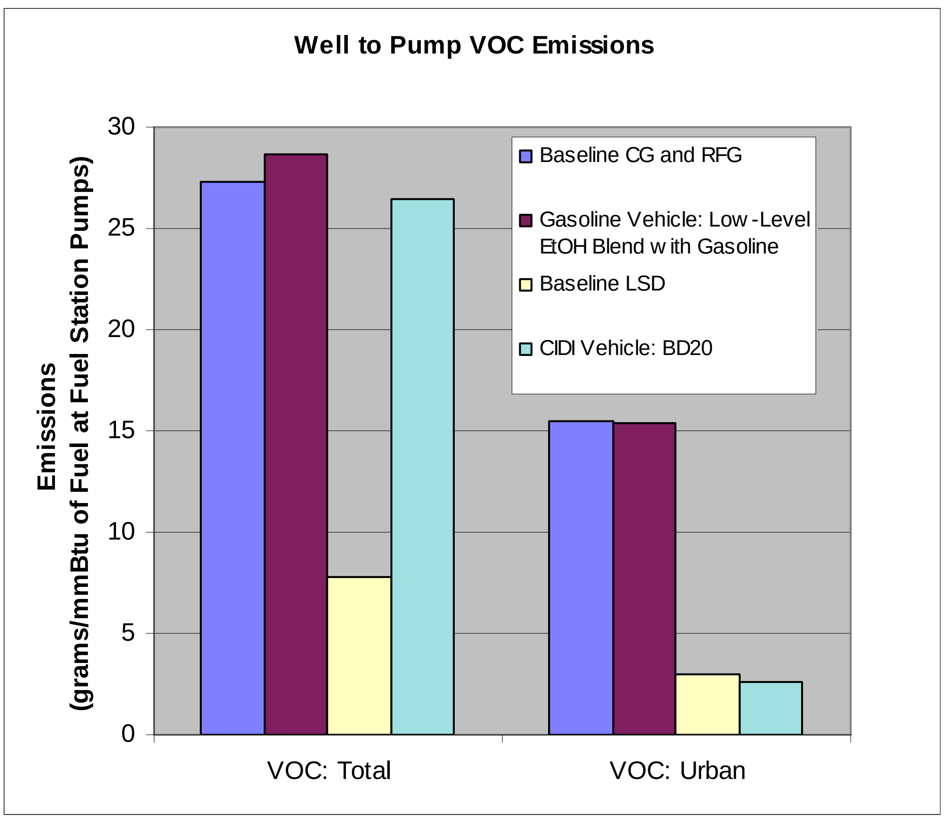


Figure 3.4.10 WTP VOC emissions for competing fuels

For WTP activities, the total CO and urban CO emissions estimated by GREET contradict each other in terms of conventional and alternative fuel pairings as shown in Figure 3.4.11. For gasoline blends, the availability of the LL-EtOH blend at the pump is expected to cause an 8% increase in CO emissions compared to the baseline CG and RFG. This is approximately a 1.10 gram increase per mmBtu available. However, the same availability of LL-EtOH blend is expected to cause a 4% decrease in urban emissions of CO compared to the baseline CG and RFG. This decrease is approximately 0.162 grams per mmBtu of fuel available. For diesel blends, the availability of the BD20 at the pump is expected to cause a 19% increase in CO emissions compared to the baseline LSD. This is approximately a 2.40 gram increase per mmBtu available. However, the same availability of BD20 blend is expected to cause a 14% decrease in urban emissions of CO compared to the baseline LSD. This decrease is approximately 0.479 grams per mmBtu of fuel available. While both alternative fuels are expected to produce higher total CO emissions, the estimated emissions in urban areas are expected to be less than their conventional counterparts.

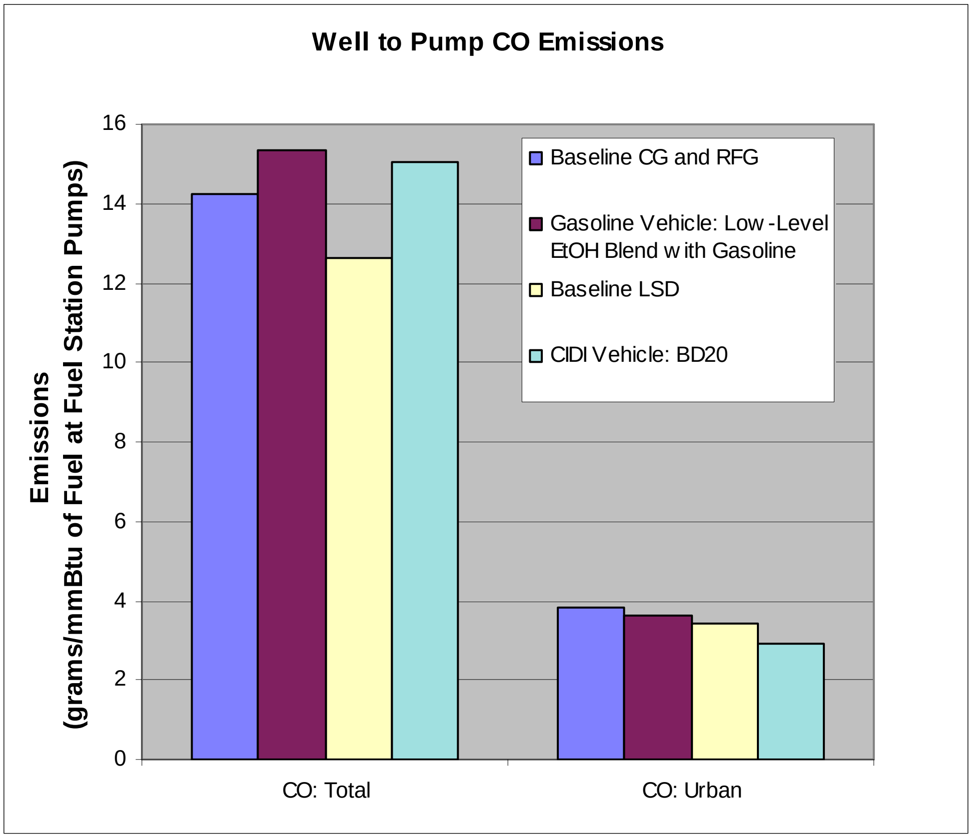


Figure 3.4.11 WTP CO emissions for competing fuels

For WTP activities, the total NO_x and urban NO_x emissions estimated by GREET contradict each other in terms of conventional and alternative fuel pairings as shown in Figure 3.4.12. For gasoline blends, the availability of the LL-EtOH blend at the pump is expected to cause a 6% increase in NO_x emissions compared to the baseline CG and RFG. This is approximately a 2.83 gram increase per mmBtu available. However, the same availability of LL-EtOH blend is expected to cause a 4% decrease in urban emissions of NO_x compared to the baseline CG and RFG. This decrease is approximately 0.382 grams per mmBtu of fuel available. For diesel blends, the availability of the BD20 at the pump is expected to cause an 8% increase in NO_x emissions compared to the baseline LSD. This is approximately a 3.41 gram increase per mmBtu available. However, the same availability of BD20 blend is expected to cause a 13% decrease in urban emissions of NO_x compared to the baseline LSD. This decrease is approximately 1.17 grams per mmBtu of fuel available. While both alternative fuels are expected to produce higher total NO_x emissions, the estimated emissions in urban areas are expected to be less than their conventional counterparts.

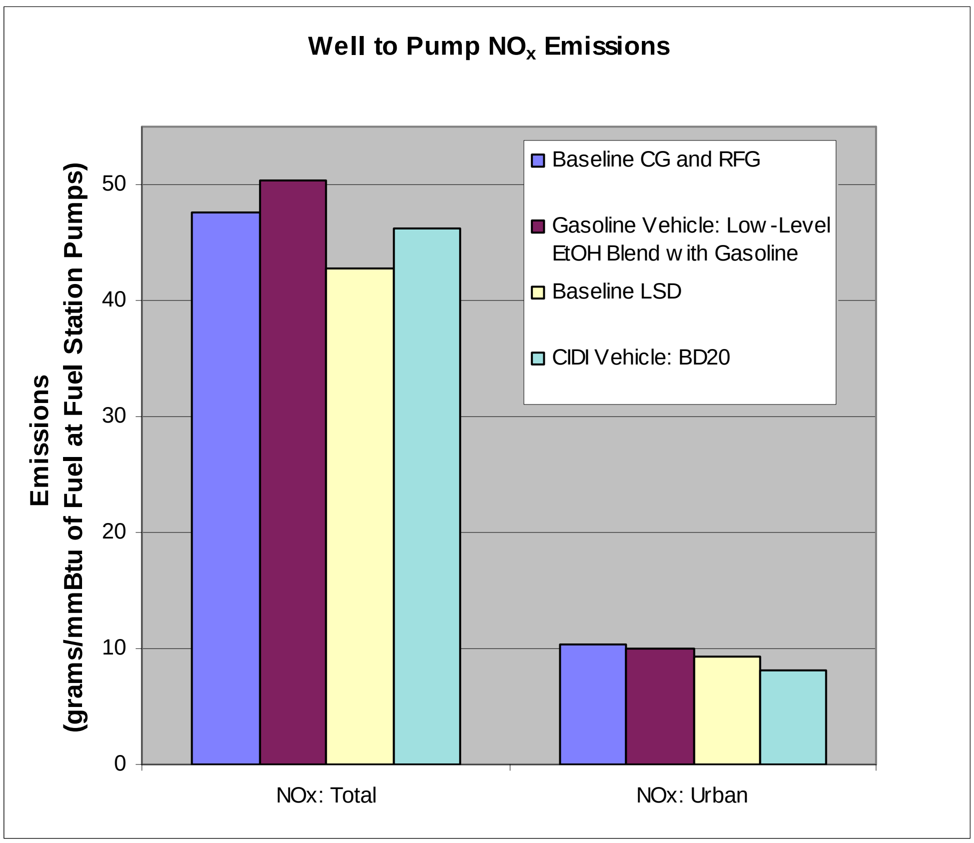


Figure 3.4.12 WTP NO_x emissions for competing fuels

For WTP activities, the total SO_x and urban SO_x emissions estimated by GREET contradict each other in terms of conventional and alternative fuel pairings as shown in Figure 3.4.13. For gasoline blends, the availability of the LL-EtOH blend at the pump is expected to cause a 10% increase in SO_x emissions compared to the baseline CG and RFG. This is approximately a 2.34 gram increase per mmBtu available. However, the same availability of LL-EtOH blend is expected to cause a 2% decrease in urban emissions of SO_x compared to the baseline CG and RFG. This decrease is approximately 0.180 grams per mmBtu of fuel available. For diesel blends, the availability of the BD20 at the pump is expected to cause a 14% increase in SO_x emissions compared to the baseline LSD. This is approximately a 2.96 gram increase per mmBtu available. However, the same availability of BD20 blend is expected to cause a 13% decrease in urban emissions of SO_x compared to the baseline LSD. This decrease is approximately 0.850 grams per mmBtu of fuel available. While both alternative fuels are expected to produce higher total SO_x emissions, the estimated emissions in urban areas are expected to be less than their conventional counterparts.

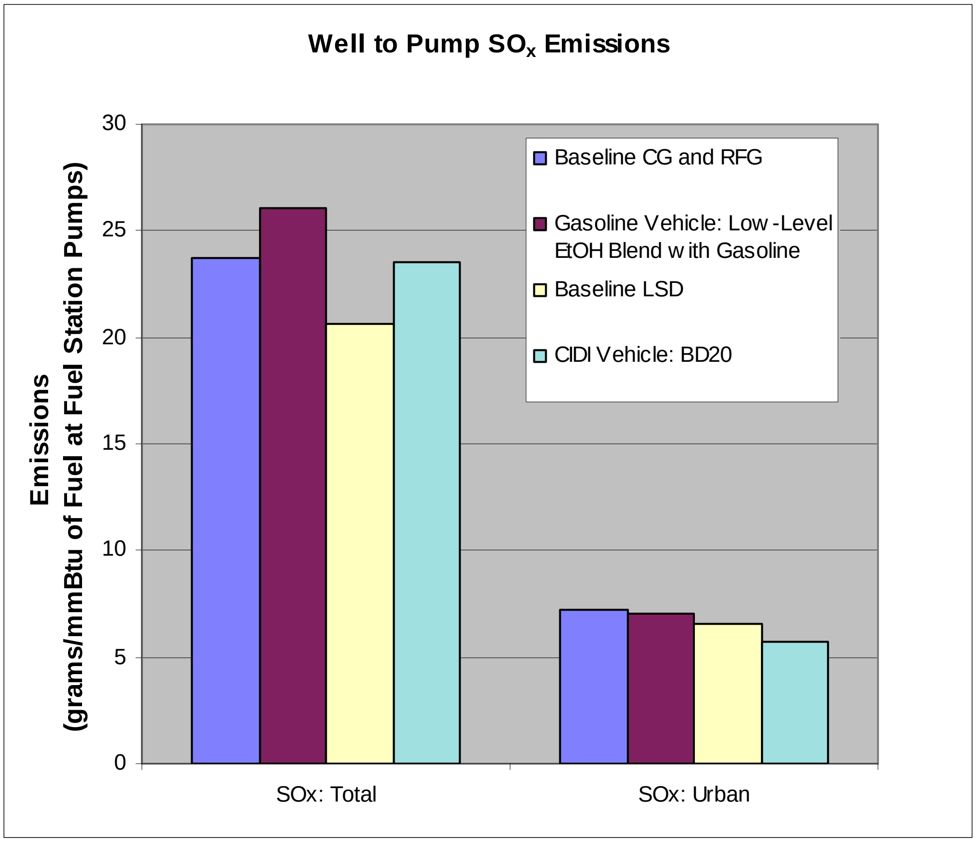


Figure 3.4.13 WTP SO_x emissions for competing fuels

For WTP activities, the total PM_{10} and urban PM_{10} emissions estimated by GREET contradict each other in terms of conventional and alternative fuel pairings as shown in Figure 3.4.14. For gasoline blends, the availability of the LL-EtOH blend at the pump is expected to cause an 18% increase in PM_{10} emissions compared to the baseline CG and RFG. This is approximately a 1.98 gram increase per mmBtu available. However, the same availability of LL-EtOH blend is expected to cause a 6% decrease in urban emissions of PM_{10} compared to the baseline CG and RFG. This decrease is approximately 0.103 grams per mmBtu of fuel available. For diesel blends, the availability of the BD20 at the pump is expected to cause a 2% increase in PM_{10}

emissions compared to the baseline LSD. This is approximately a 0.186 gram increase per mmBtu available. However, the same availability of BD20 blend is expected to cause a 17% decrease in urban emissions of PM_{10} compared to the baseline LSD. This decrease is approximately 0.267 grams per mmBtu of fuel available. While both alternative fuels are expected to produce higher total PM_{10} emissions, the estimated emissions in urban areas are expected to be less than their conventional counterparts.

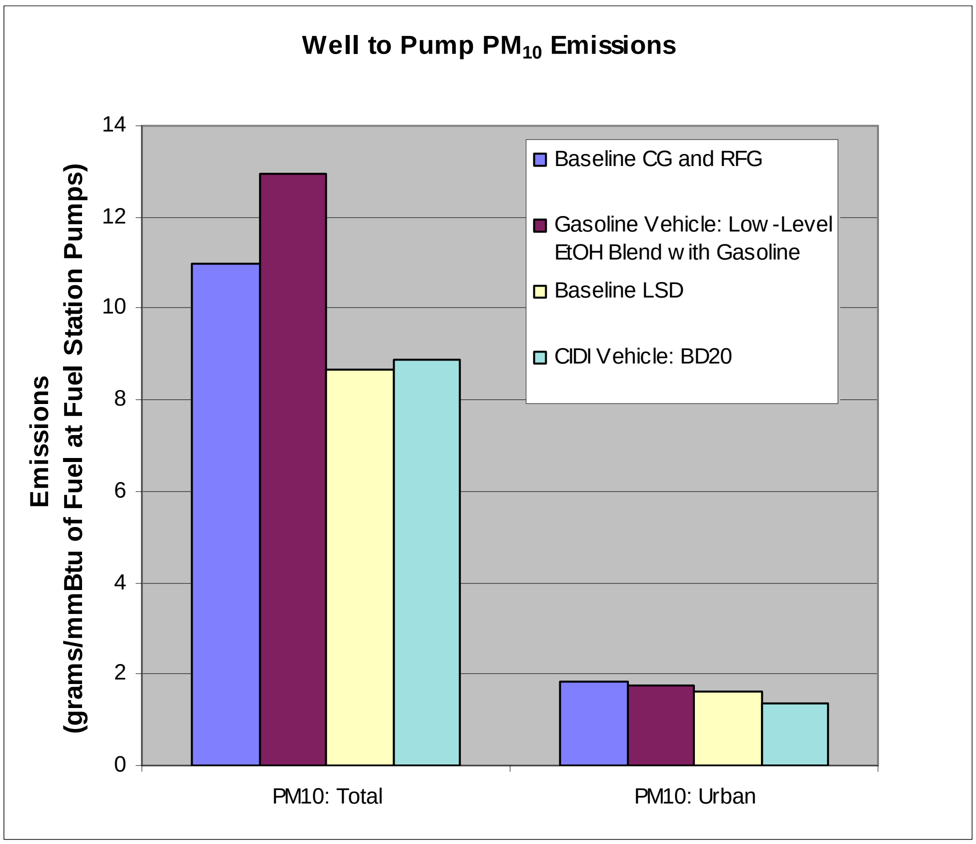


Figure 3.4.14 WTP PM_{10} emissions for competing fuels

For WTP activities, the total $PM_{2.5}$ and urban $PM_{2.5}$ emissions estimated by GREET contradict each other in terms of conventional and alternative fuel pairings as shown in Figure 3.4.15. For gasoline blends, the availability of the LL-EtOH blend at the pump is expected to cause a 14% increase in $PM_{2.5}$ emissions compared to the baseline CG and RFG. This is approximately a 0.602 gram increase per mmBtu available. However, the same availability of LL-EtOH blend is expected to cause a 6% decrease in urban emissions of $PM_{2.5}$ compared to the baseline CG and RFG. This decrease is approximately 0.059 grams per mmBtu of fuel available. For diesel blends, the availability of the BD20 at the pump is expected to cause an 8% increase in $PM_{2.5}$ emissions compared to the baseline LSD. This is approximately a 0.282 gram increase per mmBtu available. However, the same availability of BD20 blend is expected to cause a 16% decrease in urban emissions of $PM_{2.5}$ compared to the baseline LSD. This decrease is approximately 0.153 grams per mmBtu of fuel available. While both alternative fuels are expected to produce higher total $PM_{2.5}$ emissions, the estimated emissions in urban areas are expected to be less than their conventional counterparts.

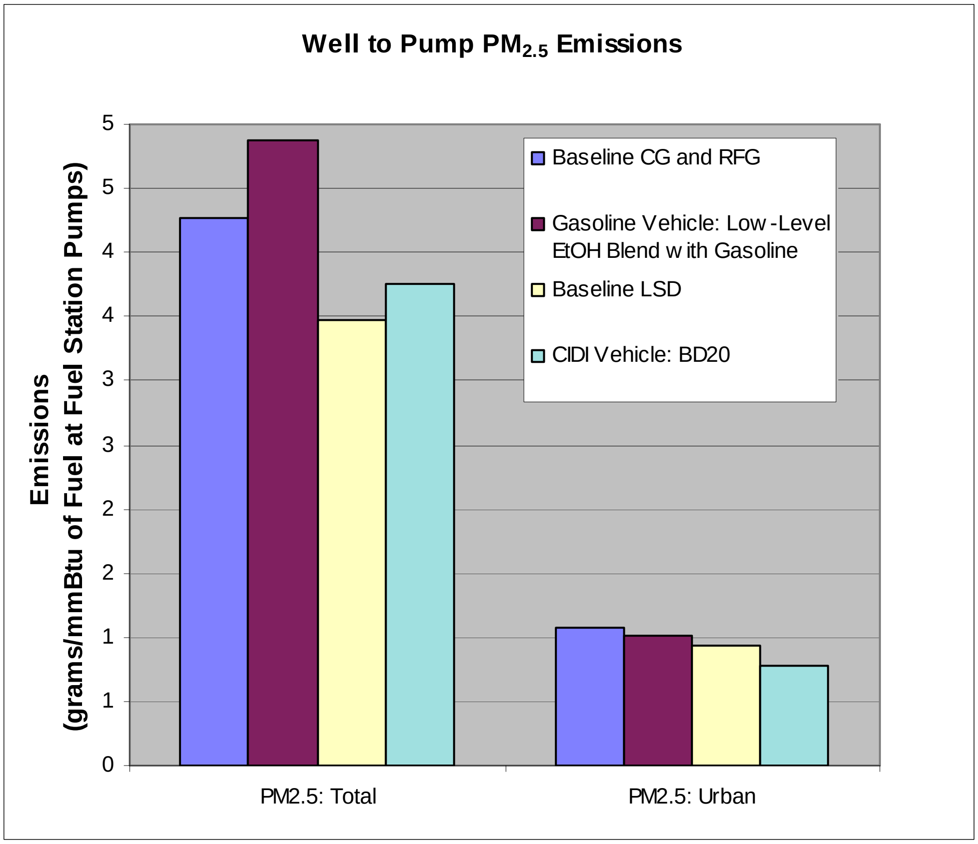


Figure 3.4.15 WTP $PM_{2.5}$ emissions for competing fuels

In its own right, the WTP results offer a way to compare fuels over the feedstock and fuel stages on a standardized basis of a mmBtu of fuel being available at the pump. In terms of CG/RFG and LL-EtOH blends, the process differences are simply in the amounts of each fuel component being produced as both fuels contain CG and EtOH. In terms of LSD and BD20, the process differences are a bit larger as a new process is included for BD production while production of LSD is decreased. For all fuels, the T&D differ and affect the results separately. Based on this information, is it fair to judge a vehicle-fuel combination? Most definitely not, considering the results do not include the vehicle operation stage, but it certainly suggests favoring a particular fuel.

Well to Wheel Results with Relative Changes

The WTW energy consumption and emissions for the operation of a vehicle-fuel combination take into account the WTP fuel results as well as vehicle operation parameters to provide results on a per mile basis for the feedstock, fuel, and vehicle operation stages. The total of all stages is used to calculate the relative changes of an item for a vehicle-fuel combination versus the baseline vehicle-fuel combination. The baseline vehicle-fuel combination in this study is the GV with SI engine fueled by CG and RFG. In this section, the energy consumption and emissions relative changes and detailed results will be compared and discussed for the simulated vehicle-fuel combinations relative to their fuel pairings and technologies.

In terms of WTW energy consumption, the WTW relative changes and results vary between vehicle-fuel combinations and categories. Using the relative changes, the tradeoffs for different fuels and vehicle technologies can be compared. An in-depth analysis of the energy consumption by stage can then be performed with the additional detailed information provided in the WTW results based on significant relative changes. The following discussion includes significant comparisons by vehicle technology, fuel technology, and vehicle-fuel combinations.

Compared to the SI vehicle technology, the SIDI vehicle technology always out-performs it with the same fuel in all energy consumption categories as shown in Table 3.4.1. This is due to the increased efficiency of the SIDI technology which operates with a 20% higher fuel economy than the SI technology. A higher fuel economy results in less fuel consumed (i.e. less energy consumed) per mile for vehicle operation. In turn, the energy consumption for the feedstock and fuel stages drops accordingly as the fuel requirements (i.e. fuel energy required to move the vehicle 1 mile) for vehicle operation drop. The result is lower energy consumption in all categories for the WTW operation of the SIDI vehicle as seen in Figure 3.4.16. This is a very good example of some of the benefits of SIDI engines versus SI engines in vehicles utilizing CG/RFG and LL-EtOH blends.

A comparison of fuels in Table 3.4.1 with respect to SIDI vehicle technology shows that LL-EtOH blend usage has the tradeoffs of increased coal and NG energy consumption for lower petroleum energy consumption when compared to CG/RFG. The increases in coal and NG energy consumption, shown in Figure 3.4.16, are due to increased consumption during the feedstock and fuel stages. The decrease in petroleum energy consumption between the two fuels is primarily attributed to lower petroleum energy consumption in the vehicle operation stage. The benefit of lower petroleum energy consumption outweighs the disadvantages of increased coal and NG energy consumption resulting in LL-EtOH blend usage having lower fossil fuel energy consumption when compared to CG/RFG in SIDI vehicles. However, LL-EtOH blend usage also has higher total energy consumption. Both vehicles use the same amount of total energy per mile for the vehicle operation stage. The difference shown in Figure 3.4.16 for total energy consumption is due to the increases during the feedstock and fuel stages related to the WTP activities for increased EtOH use and decreased CG use. This is a very good example of some of the tradeoffs that result in the use of LL-EtOH blends versus CG/RFG.

A comparison of fuels in Table 3.4.1 with respect to CIDI vehicle technology shows similar trade offs between LSD and BD20 usage. The tradeoff for the use of BD20 is effectively higher natural gas energy consumption and lower petroleum energy consumption. The decrease in petroleum energy consumption primarily occurs in the vehicle operation stage as a result of the reduction in LSD use. The increase in NG energy consumption occurs primarily in the fuel stage as a result of the BD production process. The difference in coal energy consumption between the two fuels is very small and incorporates a near offsetting small increase in the feedstock stage and small decrease in the fuel stage for BD20. As shown in Figure 3.4.16, the decrease in petroleum energy consumption outweighs the increase in natural gas consumption resulting in much lower fossil fuel consumption for CIDI vehicles using BD20 rather than LSD. However, the total energy consumption for BD20 is much higher than it is for LSD. This can be attributed to increased consumption during the fuel and feedstock stages associated with the addition of BD WTP processes and the reduction in LSD production. This is a good example of some of the tradeoffs that result in the use of BD20 versus LSD.

Table 3.4.1 WTW Energy Consumption Relative Change Results Relative to Gasoline Vehicle Fueled with Shares of Conventional Gasoline and Reformulated Gasoline

2010 (%, relative to GVs fueled with CG and RFG)	**GV: Low-Level EtOH Blend with Gasoline**	**SIDI Vehicle: CG and RFG**	**SIDI Vehicle: Low-Level EtOH Blend with Gasoline**	**CIDI Vehicle: LSD**	**CIDI Vehicle: BD20**
Total Energy	4.4%	-13.0%	-9.2%	-20.5%	-0.3%
Fossil Fuels	-2.2%	-13.0%	-14.9%	-17.9%	-29.4%
Coal	15.3%	-13.0%	0.2%	-33.7%	-33.9%
Natural Gas	15.2%	-13.0%	0.2%	-31.8%	-12.2%
Petroleum	-4.3%	-13.0%	-16.8%	-16.1%	-30.7%

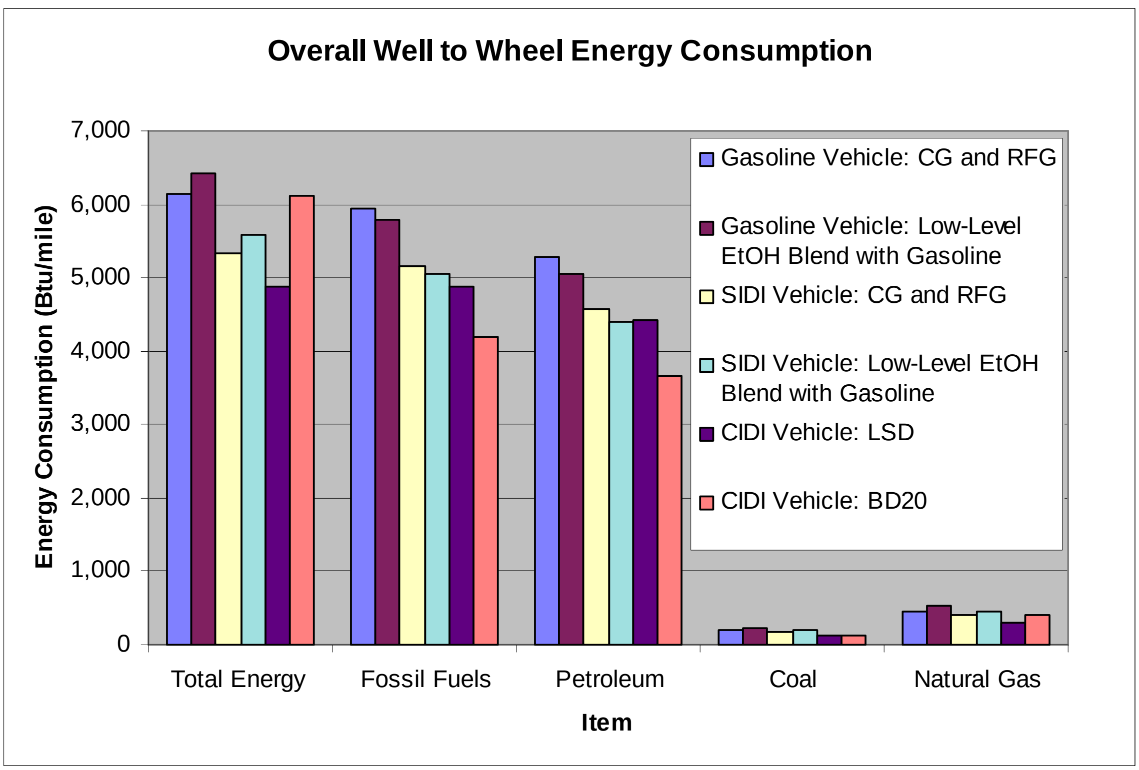


Figure 3.4.16 WTW energy consumptions for competing vehicle-fuel combinations

In terms of WTW GHG emissions, the WTW relative changes and results vary between vehicle-fuel combinations and categories. Using the relative changes, the tradeoffs for different fuels and vehicle technologies can be identified and compared. An in depth analysis of the GHG emissions by stage can then be performed with the additional detailed information provided in the WTW results based on significant relative changes. It is important to note that GREET weights the actual CO_2, CH_4, and N_2O emissions in its summation for GHGs in order to take into account the global warming potentials of each individual item. The following discussion includes significant comparisons by vehicle technology, fuel technology, and vehicle-fuel combinations.

Compared to the SI technology, the SIDI vehicle technology always out performs it for the same fuel in all GHG emission categories as shown in Table 3.4.2. All of the GHG reductions in the feedstock and fuel stage are due to the higher fuel economy and thus lower fuel requirement for the SIDI vehicles to travel a mile. While there is no change between the technologies for CH_4 and N_2O emissions during the vehicle operation stage, the amount of CO_2 produced during vehicle operation is significantly reduced in SIDI vehicles.

A comparison of fuels in Table 3.4.2 with respect to SIDI vehicle technology shows that the use of LL-EtOH blend has the tradeoffs of higher N_2O emissions for lower CO_2 and CH_4 emissions when compared to CG/RFG. The increase in weighted N_2O emissions, shown in Figure 3.4.17, is primarily due to increased emissions during the feedstock stage although it is slightly offset by a decrease in emissions during the fuel stage. Both SIDI vehicle-fuel combinations produce the same amount of N_2O during vehicle operation. The decrease in CO_2 emissions is primarily attributed to CO_2 credits for additional corn growth in the feedstock stage as well as a slight reduction in CO_2 emissions produced during the vehicle operation stage. There is also an increase in CO_2 emissions during the fuel stage for the LL-EtOH blend which effects total CO_2 emissions. The decrease in CH_4 emissions between the two fuels is primarily attributed to CH_4 emission reductions due to lower crude oil requirements and increases associated with corn farming in the feedstock stage, and reductions due to lower CG production with a small contribution from EtOH production during the fuel stage. Both SIDI vehicle-fuel combinations produce the same amount of CH_4 during vehicle operation. Overall, the SIDI vehicle fueled by LL-EtOH blend produces less of GHGs weighted by their global warming potentials than the SIDI vehicle fueled by CG/RFG.

A comparison of fuels in Table 3.4.2 with respect to CIDI vehicle technology shows that the use of BD20 has the tradeoffs of higher N_2O emissions for lower CO_2 and CH_4 emissions when compared to LSD. The increase in weighted N_2O emissions, shown in Figure 3.4.17, is due to increased emissions primarily in the feedstock stage, but also in the fuel stage. Both CIDI vehicle-fuel combinations produce about the same amount of N_2O during vehicle operation. The decrease in CO_2 emissions is primarily attributed to CO_2 credits for soybean growth in the feedstock stage which more than covers the small increases in CO_2 emissions during the fuel and vehicle operation stages due to BD production and lower LSD production. The decrease in CH_4 emissions is primarily attributed to lower crude oil requirements and increases associated with soybean farming in the feedstock stage, but there are increases due to BD production and lower LSD production during the fuel stage. Both CIDI vehicle-fuel combinations produce about the same amount of CH_4 during vehicle operation. Overall, the CIDI vehicle fueled by BD20 produces less of GHGs weighted by their global warming potentials than the CIDI vehicle fueled by LSD.

Table 3.4.2 WTW GHG Emission Relative Change Results Relative to Gasoline Vehicle Fueled with Shares of Conventional Gasoline and Reformulated Gasoline

2010 (%, relative to GVs fueled with CG and RFG)	**GV: Low-Level EtOH Blend with Gasoline**	**SIDI Vehicle: CG and RFG**	**SIDI Vehicle: Low-Level EtOH Blend with Gasoline**	**CIDI Vehicle: LSD**	**CIDI Vehicle: BD20**
CO_2 (w/ C in VOC & CO)	-2.2%	-13.0%	-15.0%	-15.8%	-28.3%
CH_4	-1.9%	-12.7%	-14.4%	-21.6%	-30.1%
N_2O	49.6%	-4.1%	39.0%	-26.0%	19.7%
GHGs	-1.7%	-12.9%	-14.4%	-16.1%	-27.8%

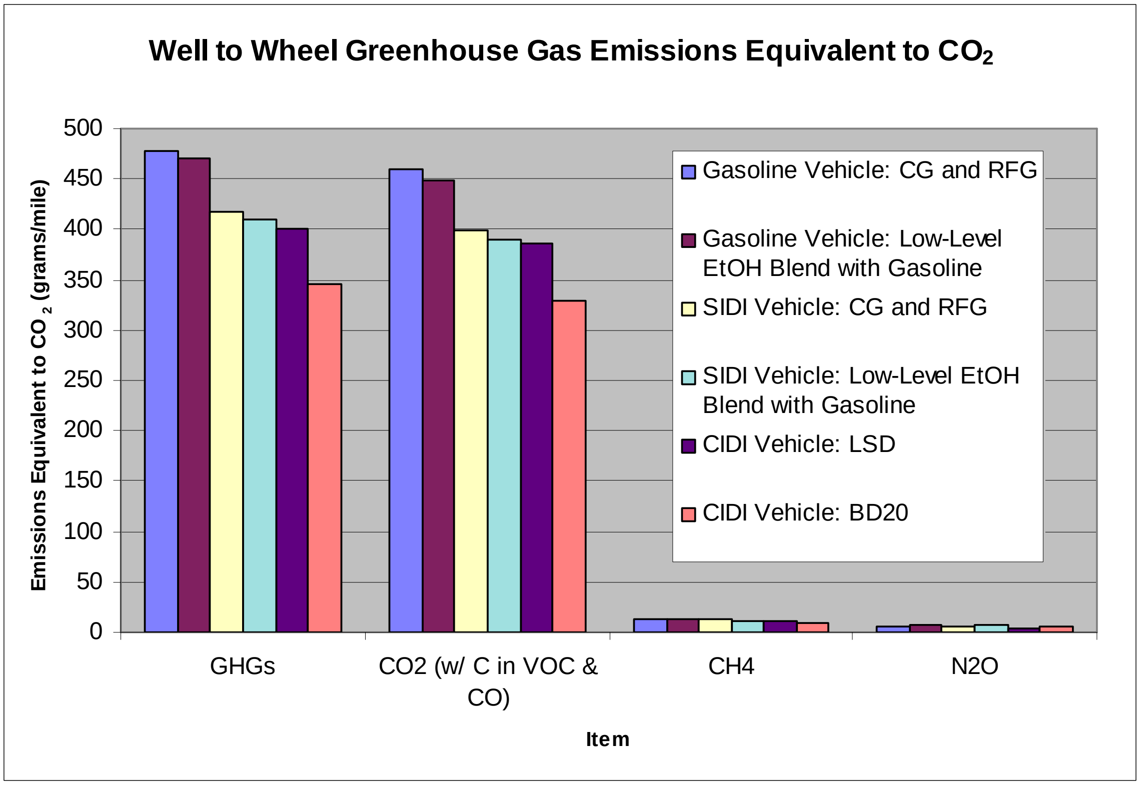


Figure 3.4.17 WTW GHG relative to CO_2 for competing vehicle-fuel combinations

In terms of WTW principal pollutants, the WTW relative changes and results vary between vehicle-fuel combinations and categories. Using the relative changes, the tradeoffs for different fuels and vehicle technologies can be identified and compared with respect to individual pollutants and the area of emission. An in depth analysis of each principal pollutant by stage and area of emission can then be performed with the additional detailed information provided in the WTW results based on significant relative changes. It is important to note that GREET assumes an urban share for individual processes in each stage in order to estimate urban emissions of principal pollutants. The following discussion includes noteworthy comparisons by vehicle technology, fuel technology, and vehicle-fuel combinations as they relate to individual principal pollutants.

A comparison of VOC emissions of SIDI technologies and SI technologies with the same fuels in Table 3.4.3 demonstrates that the SIDI technology is estimated to produce fewer total and urban VOC emissions than the SI technology with the same fuel. For both the conventional CG/RFG fuel and alternative LL-EtOH fuel, the SIDI vehicle is estimated to produce about 0.018 grams/mile less total VOC emissions for WTW operation than the SI vehicle. For the associated urban shares, the SIDI vehicle is estimated to produce about 0.010 grams/mile less urban VOC emissions than the SI vehicle with the same fuels listed above. This reduction in VOC emissions is due to reductions in the feedstock and fuel stages of WTW operations which indicate that the increase in fuel economy in SIDI vehicles and subsequent lower fuel requirements is the cause of lower VOC emissions. It is important to note that there is no appreciable difference in the VOC emissions during the vehicle operation stages between SIDI and SI vehicles for either of the selected fuels.

A comparison of fuels in Table 3.4.3 with respect to SIDI vehicle technology shows that the use of LL-EtOH blend has the tradeoffs of higher total VOC emissions for lower urban VOC emissions when compared to CG/RFG. The SIDI with LL-EtOH blend is estimated to produce 0.005 grams/mile more total VOC emissions than the SIDI with CG/RFG. With respect to the urban shares, the SIDI with CG/RFG does not produce appreciably more urban VOC emissions than the SIDI with LL-EtOH despite the differences shown in the relative changes. This is due to significant rounding in Excel which means the computed difference is less than 0.0005 grams/mile. Considerable differences between these fuels appear in the feedstock and fuel stages on account to the differences in the WTP processes outlined previously.

A comparison of fuels in Table 3.4.3 with respect to CIDI vehicle technology shows that the use of BD20 has the tradeoffs of higher total VOC emissions for lower urban VOC emissions when compared to LSD. The CIDI with BD20 is estimated to produce 0.076 grams/mile more total VOC than the CIDI with LSD. With respect to the urban shares, the CIDI with BD20 is estimated to produce 0.002 grams/mile less urban VOC emissions than the CIDI with LSD. There are no differences in the estimated total and urban VOC emissions in the vehicle operation stage for either fuel. Considerable differences between these fuels appear in the feedstock and fuel stages on account to the differences in the WTP processes outlined previously. The increase in total VOC emissions for BD20 fueled vehicles occurs primarily in the fuel stage due to the energy intensive process used to convert soy oil into BD. However, this process primarily contributes to non-urban VOC emission which is why BD20 fueled vehicles produce less urban VOC emissions.

Table 3.4.3 WTW VOC Emission Relative Change Results Relative to Gasoline Vehicle Fueled with Shares of Conventional Gasoline and Reformulated Gasoline

2010 (%, relative to GVs fueled with CG and RFG)	GV: Low-Level EtOH Blend with Gasoline	SIDI Vehicle: CG and RFG	SIDI Vehicle: Low-Level EtOH Blend with Gasoline	CIDI Vehicle: LSD	CIDI Vehicle: BD20
VOC: Total	2.0%	-5.6%	-3.9%	-61.9%	-37.6%
VOC: Urban	-0.3%	-5.3%	-5.5%	-64.4%	-65.3%

A comparison of CO emissions of SIDI technologies and SI technologies with the same fuels in Table 3.4.4 demonstrates that the SIDI technology is estimated to produce fewer total and urban CO emissions than the SI technology with the same fuel. For the conventional CG/RFG fuel, the SIDI vehicle is estimated to produce about 0.009 grams/mile less total CO emissions for WTW operation than the SI vehicle. For the alternative LL-EtOH blend, the SIDI vehicle is estimated to produce about 0.009 grams/mile less total CO emissions for WTW operation than the SI vehicle. For the associated urban shares, the SIDI vehicle is estimated to produce about 0.002 grams/mile less urban CO emissions than the SI vehicle with the same fuels listed above. This reduction in CO emissions is due to reductions in the feedstock and fuel stages of WTW operations which indicate that the increase in fuel economy in SIDI vehicles and subsequent lower fuel requirements is the cause of lower CO emissions. It is important to note that there is no appreciable difference in the CO emissions during the vehicle operation stages between SIDI and SI vehicles for either of the selected fuels.

A comparison of fuels in Table 3.4.4 with respect to SIDI vehicle technology suggests that the use of LL-EtOH blend offers no benefits for CO emissions when compared to CG/RFG. Using the WTW results, the SIDI with LL-EtOH blend is estimated to produce 0.005 grams/mile more total CO emissions than the SIDI with CG/RFG. With respect to the urban shares, the results show that the SIDI with LL-EtOH blend is estimated to produce about 0.001 grams/mile less urban CO emissions than the SIDI with CG/RFG. There are no differences in the estimated total and urban CO emissions in the vehicle operation stage for either fuel. Significant differences between these fuels appear in the feedstock and fuel stages due to the differences in the WTP processes outlined previously.

A comparison of fuels in Table 3.4.4 with respect to CIDI vehicle technology shows that the use of BD20 has the tradeoffs of higher total CO emissions for lower urban CO emissions when compared to LSD. The CIDI with BD20 is estimated to produce 0.010 grams/mile more total CO emissions than the CIDI with LSD. With respect to the urban shares, the CIDI with BD20 is estimated to produce 0.002 grams/mile less urban CO emissions than the CIDI with LSD. There are no differences in the estimated total and urban CO emissions in the vehicle operation stage for either fuel. Significant differences between these fuels appear in the feedstock and fuel stages on account to the differences in the WTP processes outlined previously. The increase in total CO emissions for BD20 fueled vehicles occurs primarily in the feedstock stage due to soybean farming. Since the soybean farming process primarily contributes to non-urban CO emission and the BD production process produces less urban CO than the LSD refining process, BD20 fueled vehicles produce slightly less urban CO emissions than LSD fueled vehicles.

Table 3.4.4 WTW CO Emission Relative Change Results Relative to Gasoline Vehicle Fueled with Shares of Conventional Gasoline and Reformulated Gasoline

2010 (%, relative to GVs fueled with CG and RFG)	**GV: Low-Level EtOH Blend with Gasoline**	**SIDI Vehicle: CG and RFG**	**SIDI Vehicle: Low-Level EtOH Blend with Gasoline**	**CIDI Vehicle: LSD**	**CIDI Vehicle: BD20**
CO: Total	0.1%	-0.2%	-0.1%	-84.5%	-84.3%
CO: Urban	0.0%	-0.1%	-0.1%	-85.1%	-85.2%

A comparison of NO_x emissions for SIDI technologies and SI technologies with the same fuels in Table 3.4.5 demonstrates that the SIDI technology is estimated to produce fewer total and urban NO_x emissions than the SI technology with the same fuel. For the conventional CG/RFG fuel, the SIDI vehicle is estimated to produce about 0.030 grams/mile less total NO_x emissions than the SI vehicle for WTW operation. For the alternative LL-EtOH blend, the SIDI vehicle is estimated to produce about 0.032 grams/mile less total NO_x emissions than the SI vehicle for WTW operation. For the associated urban shares, the SIDI vehicle is estimated to produce about 0.007 grams/mile and 0.006 grams/mile less urban NO_x emissions than the SI vehicle with CG/RFG and LL-EtOH blend, respectively. This reduction in NO_x emissions is due to reductions in the feedstock and fuel stages of WTW operations which indicate that the increase in fuel economy in SIDI vehicles and subsequent lower fuel requirements is the cause of lower

NO_x emissions. It is important to note that there is no difference in the NO_x emissions during the vehicle operation stages between SIDI and SI vehicles for either of the selected fuels.

A comparison of fuels in Table 3.4.5 with respect to SIDI vehicle technology shows that the use of LL-EtOH blend has the tradeoffs of higher total NO_x emissions for lower urban NO_x emissions when compared to CG/RFG. The SIDI with LL-EtOH blend is estimated to produce 0.012 grams/mile more total NO_x emissions than the SIDI with CG/RFG. With respect to the urban shares, the SIDI with LL-EtOH blend is estimated to produce 0.002 grams/mile less urban NO_x emissions than the SIDI with CG/RFG. There are no differences in the estimated total and urban NO_x emissions in the vehicle operation stage for either fuel. Significant differences between these fuels appear in the feedstock and fuel stages due to the differences in the WTP processes outlined previously.

A comparison of fuels in Table 3.4.5 with respect to CIDI vehicle technology shows that the use of BD20 has the tradeoffs of higher total NO_x emissions for lower urban NO_x emissions when compared to LSD. The CIDI with BD20 is estimated to produce 0.014 grams/mile more total NO_x emissions than the CIDI with LSD. With respect to the urban shares, the CIDI with BD20 is estimated to produce 0.005 grams/mile less urban NO_x emissions than the CIDI with LSD. There are no differences in the estimated total and urban NO_x emissions in the vehicle operation stage for either fuel. Significant differences between these fuels appear in the feedstock and fuel stages on account to the differences in the WTP processes outlined previously. The increase in total NO_x emissions for BD20 fueled vehicles occurs primarily in the feedstock stage due to soybean farming. Since the soybean farming process primarily contributes to non-urban NO_x emission and the BD production process produces less urban NO_x than the LSD refining process, BD20 fueled vehicles produce slightly less urban NO_x emissions than LSD fueled vehicles.

Table 3.4.5 WTW NO_x Emission Relative Change Results Relative to Gasoline Vehicle Fueled with Shares of Conventional Gasoline and Reformulated Gasoline

2010 (%, relative to GVs fueled with CG and RFG)	**GV: Low-Level EtOH Blend with Gasoline**	**SIDI Vehicle: CG and RFG**	**SIDI Vehicle: Low-Level EtOH Blend with Gasoline**	**CIDI Vehicle: LSD**	**CIDI Vehicle: BD20**
NO_x: Total	3.7%	-8.1%	-4.9%	-15.6%	-11.9%
NO_x: Urban	-1.4%	-4.8%	-6.0%	-9.6%	-13.1%

A comparison of SO_x emissions between SIDI technologies and SI technologies with the same fuels in Table 3.4.6 demonstrates that the SIDI technology is estimated to produce fewer total and urban SO_x emissions than the SI technology with the same fuel. For the conventional CG/RFG fuel, the SIDI vehicle is estimated to produce about 0.016 grams/mile less total SO_x emissions and 0.005 grams/mile less urban SO_x emissions than the SI vehicle for WTW operation. For the alternative LL-EtOH blend, the SIDI vehicle is estimated to produce about 0.018 grams/mile less total SO_x emissions and 0.005 grams/mile less urban SO_x emissions than the SI vehicle for WTW operation. This reduction in SO_x emissions is due to increased fuel efficiency of SIDI vehicles which leads to SO_x emission reductions in all stages of WTW operations.

A comparison of fuels in Table 3.4.6 with respect to SIDI vehicle technology shows that the use of LL-EtOH blend has the tradeoffs of higher total SO_x emissions for lower urban SO_x emissions when compared to CG/RFG. The SIDI with LL-EtOH blend is estimated to produce 0.009 grams/mile more total SO_x emissions than the SIDI with CG/RFG. With respect to the urban shares, the SIDI with LL-EtOH blend is estimated to produce 0.001 grams/mile less urban SO_x emissions than the SIDI with CG/RFG. There are no appreciable differences in the estimated total and urban SO_x emissions in the vehicle operation stage for either fuel. Significant differences between these fuels appear in the feedstock and fuel stages due to the differences in the WTP processes outlined previously.

A comparison of fuels in Table 3.4.6 with respect to CIDI vehicle technology shows that the use of BD20 has the tradeoffs of higher total SO_x emissions for lower urban SO_x emissions when compared to LSD. The CIDI with BD20 is estimated to produce 0.011 grams/mile more total SO_x emissions than the CIDI with LSD. With respect to the urban shares, the CIDI with BD20 is estimated to produce 0.003 grams/mile less urban SO_x emissions than the CIDI with LSD. There are no appreciable differences in the estimated total and urban SO_x emissions in the vehicle operation stage for either fuel. Significant differences between these fuels appear in the feedstock and fuel stages on account to the differences in the WTP processes outlined previously. The increase in total SO_x emissions for BD20 fueled vehicles occurs primarily in the feedstock stage due to soybean farming (primarily fertilizer use). Since the soybean farming process primarily contributes to non-urban SO_x emission and the BD production process produces less urban SO_x than the LSD refining process, BD20 fueled vehicles produce slightly less urban SO_x emissions than LSD fueled vehicles.

Table 3.4.6 WTW SO_x Emission Relative Change Results Relative to Gasoline Vehicle Fueled with Shares of Conventional Gasoline and Reformulated Gasoline

2010 (%, relative to GVs fueled with CG and RFG)	**GV: Low-Level EtOH Blend with Gasoline**	**SIDI Vehicle: CG and RFG**	**SIDI Vehicle: Low-Level EtOH Blend with Gasoline**	**CIDI Vehicle: LSD**	**CIDI Vehicle: BD20**
SO_x: Total	9.0%	-13.0%	-5.2%	-29.4%	-19.9%
SO_x: Urban	-3.0%	-13.0%	-15.6%	-27.9%	-37.4%

A comparison of PM_{10} emissions between SIDI technologies and SI technologies with the same fuels in Table 3.4.7 demonstrates that the SIDI technology is estimated to produce fewer total and urban PM_{10} emissions than the SI technology with the same fuel. For the conventional CG/RFG fuel, the SIDI vehicle is estimated to produce about 0.007 grams/mile less total PM_{10} emissions and 0.001 grams/mile less urban PM_{10} emissions than the SI vehicle for WTW operation. For the alternative LL-EtOH blend, the SIDI vehicle is estimated to produce about 0.008 grams/mile less total PM_{10} emissions and 0.001 grams/mile less urban PM_{10} emissions than the SI vehicle for WTW operation. This reduction in PM_{10} emissions is due to increased fuel efficiency of SIDI vehicles which leads to PM_{10} emission reductions in the feedstock and fuel stages of WTW operations. Interestingly, there is no difference during the vehicle operation for PM_{10} emissions since each of the vehicles is expected to emit the same amount of PM_{10} emissions from exhaust and tire and brake wear.

A comparison of fuels in Table 3.4.7 with respect to SIDI vehicle technology shows that the use of LL-EtOH blend has the tradeoffs of higher total PM_{10} emissions for lower urban PM_{10} emissions when compared to CG/RFG. The SIDI with LL-EtOH blend is estimated to produce 0.008 grams/mile more total PM_{10} emissions than the SIDI with CG/RFG. With respect to the urban shares, the SIDI with LL-EtOH blend is estimated to produce 0.001 grams/mile less urban PM_{10} emissions than the SIDI with CG/RFG. There is no difference during the vehicle operation for PM_{10} emissions since each of the vehicles is expected to emit the same amount of PM_{10} emissions from exhaust and tire and brake wear. Significant differences between these fuels appear in the feedstock and fuel stages due to the differences in the WTP processes outlined previously.

A comparison of fuels in Table 3.4.7 with respect to CIDI vehicle technology shows that the use of BD20 has the tradeoffs of higher total PM_{10} emissions for lower urban PM_{10} emissions when compared to LSD. The CIDI with BD20 is estimated to produce 0.001 grams/mile more total PM_{10} emissions than the CIDI with LSD. With respect to the urban shares, the CIDI with BD20 is estimated to produce 0.001 grams/mile less urban PM_{10} emissions than the CIDI with LSD. There is no difference during the vehicle operation for PM_{10} emissions since each of the vehicles is expected to emit the same amount of PM_{10} emissions from exhaust and tire and brake wear. Significant differences between these fuels appear in the feedstock and fuel stages due differences in the WTP processes outlined previously. The increase in total PM_{10}

emissions for BD20 fueled vehicles occurs primarily in the feedstock stage due to soybean farming. Since the soybean farming process primarily contributes to non-urban PM_{10} emission and the BD production process produces less urban PM_{10} than the LSD refining process, BD20 fueled vehicles produce slightly less urban PM_{10} emissions than LSD fueled vehicles.

Table 3.4.7 WTW PM_{10} Emission Relative Change Results Relative to Gasoline Vehicle Fueled with Shares of Conventional Gasoline and Reformulated Gasoline

2010 (%, relative to GVs fueled with CG and RFG)	**GV: Low-Level EtOH Blend with Gasoline**	**SIDI Vehicle: CG and RFG**	**SIDI Vehicle: Low-Level EtOH Blend with Gasoline**	**CIDI Vehicle: LSD**	**CIDI Vehicle: BD20**
PM_{10}: Total	11.8%	-8.5%	1.7%	-21.3%	-20.3%
PM_{10}: Urban	-1.9%	-4.4%	-6.0%	-7.1%	-11.2%

A comparison of $PM_{2.5}$ emissions between SIDI technologies and SI technologies with the same fuels in Table 3.4.8 demonstrates that the SIDI technology is estimated to produce fewer total and urban $PM_{2.5}$ emissions than the SI technology with the same fuel. For the conventional CG/RFG fuel, the SIDI vehicle is estimated to produce about 0.003 grams/mile less total $PM_{2.5}$ emissions than the SI vehicle for WTW operation. Despite the relative change, there are no appreciable changes in urban $PM_{2.5}$ emissions due to rounding as reported by GREET. The difference between SIDI and SI vehicles with the same fuel for urban $PM_{2.5}$ emissions is less than 0.0007, but both are reported as 0.014 for each fuel. For the alternative LL-EtOH blend, the SIDI vehicle is estimated to produce about 0.003 grams/mile less total PM_{10} emissions than the SI vehicle for WTW operation. There is no significant difference in the urban $PM_{2.5}$ emissions between the two fuels. The reduction in $PM_{2.5}$ emissions is due to increased fuel efficiency of SIDI vehicles which leads to $PM_{2.5}$ emission reductions in the feedstock and fuel stages of WTW operations. Interestingly, there is no difference during the vehicle operation for $PM_{2.5}$ emissions since each of the vehicles is expected to emit the same amount of $PM_{2.5}$ emissions from exhaust and tire and brake wear.

A comparison of fuels in Table 3.4.8 with respect to SIDI vehicle technology shows that the use of LL-EtOH blend has the tradeoffs of higher total $PM_{2.5}$ emissions for lower urban $PM_{2.5}$ emissions when compared to CG/RFG. The SIDI with LL-EtOH blend is estimated to produce 0.003 grams/mile more total $PM_{2.5}$ emissions than the SIDI with CG/RFG. With respect to the urban shares, there is no significant difference between the two fuels for urban $PM_{2.5}$ emissions. There is no difference during the vehicle operation for $PM_{2.5}$ emissions since each of the vehicles is expected to emit the same amount of $PM_{2.5}$ emissions from exhaust and tire and brake wear. Significant differences between these fuels appear in the feedstock and fuel stages due to the differences in the WTP processes outlined previously.

A comparison of fuels in Table 3.4.8 with respect to CIDI vehicle technology shows that the use of BD20 has the tradeoffs of higher total $PM_{2.5}$ emissions for lower urban $PM_{2.5}$ emissions when compared to LSD. The CIDI with BD20 is estimated to produce 0.001 grams/mile more total $PM_{2.5}$ emissions than the CIDI with LSD. With respect to the urban shares, the CIDI with BD20 is estimated to produce 0.001 grams/mile less urban $PM_{2.5}$ emissions than the CIDI with LSD. There is no difference during the vehicle operation for $PM_{2.5}$ emissions since each of the vehicles is expected to emit the same amount of $PM_{2.5}$ emissions from exhaust and tire and brake wear. Significant differences between these fuels appear in the feedstock and fuel stages due differences in the WTP processes outlined previously. The increase in total $PM_{2.5}$ emissions for BD20 fueled vehicles occurs primarily in the feedstock stage due to soybean farming. Since the soybean farming process primarily contributes to non-urban $PM_{2.5}$ emission and the BD production process produces less urban $PM_{2.5}$ than the LSD refining process, BD20 fueled vehicles produce slightly less urban $PM_{2.5}$ emissions than LSD fueled vehicles.

Table 3.4.8 WTW $PM_{2.5}$ Emission Relative Change Results Relative to Gasoline Vehicle Fueled with Shares of Conventional Gasoline and Reformulated Gasoline

2010 (%, relative to GVs fueled with CG and RFG)	**GV: Low-Level EtOH Blend with Gasoline**	**SIDI Vehicle: CG and RFG**	**SIDI Vehicle: Low-Level EtOH Blend with Gasoline**	**CIDI Vehicle: LSD**	**CIDI Vehicle: BD20**
$PM_{2.5}$: Total	8.3%	-7.6%	-0.5%	-16.4%	-13.2%
$PM_{2.5}$: Urban	-2.0%	-4.7%	-6.5%	-6.1%	-10.4%

Chapter Summary and Conclusions

The following section summarizes comparisons made in this study and the conclusions drawn from them. First, the SI-SIDI vehicle comparison is summarized with a vehicle specific conclusion. The fuel comparison summaries for a SIDI vehicle and a

CIDI vehicle follow with conclusions for each comparison follow. Finally, a brief statement on future considerations for similar simulations regarding vehicle-fuel comparisons is given.

For gasoline vehicle technologies listed in this case study, the SIDI is conclusively better than SI technology with the same fuel in all categories considered by GREET. There are no tradeoffs in terms of the energy consumption and emissions considered. Based on the results of the simulation, direct injection technology should be considered a necessity for the reduction of energy consumption and emissions in the WTW process for any gasoline vehicle.

For SIDI vehicles, there are tradeoffs between the traditional CG/RFG fuel and the alternative LL-EtOH fuel. In terms of energy consumption, the traditional CG/RFG fuel consumes less total energy than the alternative LL-EtOH blend, but it consumes more fossil fuel energy than its competitor. Namely, the LL-EtOH blend has the advantage of consuming significantly less petroleum energy while consuming slightly more coal and NG energy. In terms of GHG emissions relative to CO_2, the LL-EtOH blend produces less GHG emissions than the traditional CG/RFG blend. In terms of the principal pollutants, the traditional CG/RFG has the advantage of lower total emissions than the LL-EtOH blend in all principal pollutants. However, the LL-EtOH blend does offer slight reductions in urban emissions for several of the principal pollutants. Based on the results of the simulation, neither the traditional CG/RFG fuel nor the alternative LL-EtOH blend is conclusively better than its competitor.

For CIDI vehicles, there are tradeoffs between the traditional LSD fuel and the alternative BD20 fuel. In terms of energy consumption, the traditional LSD fuel consumes less total energy than the alternative BD20 blend, but it consumes considerably more fossil fuel energy than its competitor. Namely, the BD20 blend has the advantage of consuming significantly less petroleum energy while consuming more NG energy. In terms of GHG emissions relative to CO_2, the BD20 blend produces significantly less GHG emissions than the traditional LSD blend. In terms of the principal pollutants, the traditional LSD has the advantage of lower total emissions than the BD20 blend in all categories. However, the BD20 blend does offer slight reductions in urban emissions for all of the principal pollutants. Based on the results of the simulation, neither the traditional LSD fuel nor the alternative BD20 blend is conclusively better than its competitor.

This study has effectively simulated the selected traditional and alternative fuel systems for associated well to wheel activities. As a result of this case study, the traditional and alternative vehicle-fuel combinations for SIDI and CIDI vehicles were found to have advantages in different areas. Thus, this study is inconclusive as to whether the traditional or alternative fueled vehicle is better than its counterpart based on the results of this study. However, it would be interesting to see in future studies if the advantages shown in this case study are statistically significant. Additionally, there are other factors beyond the purview of GREET that would contribute to the use of a specific vehicle-fuel combination. In the next case study, I resolve some of these factors for a specific vehicle comparison.

CHAPTER 4

VEHICLE-FUELS COMPARISON: TRADITIONAL VS. HYBRID FUEL SYSTEMS

Introduction

Given a choice between three prominent vehicle technologies, which vehicle-fuel combination is the best choice for a daily commuter in the Chattanooga area? To answer this question, this case study simulates the operation of 2009 model Escape variants in this area using assumptions and parameters relevant to 2010 for vehicles and fuels. The purpose is to evaluate the energy and emissions of the vehicles as modeled by GREET with an accompanying cost analysis to determine which vehicle would be more beneficial for a commuter. A single year will be modeled by GREET for energy consumption and emissions. The cost analysis will look at expected cost differences over an 8 year, 100,000 mile period and overall value after that period. This case study will try to determine which vehicle provides the most benefit to the consumer in terms of energy consumption, emissions, and cost with the following assumptions and parameters.

As seen in the first case study, GREETGUI allows the user to adjust first tier assumptions and parameters directly without directly changing the Excel-based model. For this case study, the GREET Excel model will be used to adjust both first and second tier assumptions and parameters. The Excel model is preferred to GREETGUI because of a problem with the assumptions and parameter selections relevant to the simulated vehicle model year. GREETGUI assumes for this case a 2005 vehicle model which causes GREET to then call up 2005 time series (TS) data for the SI GC PHEV model. Unfortunately, placeholder data was input for pre-2010 TS data. This placeholder data is not similar to researched TS data for 2010 and later. Thus, a simulation utilizing the placeholder data would not clearly indicate the estimated energy consumption and emissions for the test vehicle. This problem is bypassed using the GREET Excel model.

The 2009 Escape variants in this case study include the 2009 Ford Escape XLT FWD I4, the 2009 Ford Escape Hybrid FWD, and the 2009 Ford Escape Hybrid FWD with Miles Plus conversion by Hybrids Plus. Each variant was chosen due to similarities in terms of equipment and features to provide the best comparison between function and price. The standard gross vehicle weight rating (GVWR) for these vehicles are 4300 lbs and 4640 lbs for the Escape and Escape HEV.[10][11] The Miles Plus conversion adds another 12.4 lbs to the Escape HEV bringing the Escape PHEV GVWR up to 4652.4 lbs.[12] These vehicles are modeled respectively using the GREET 1.8c.0 Excel model for SIDI, SI GI HEV, and SI GC PHEV technologies under the LDT1 category based on their GVWR. Shown in Table 4.1.1, the estimated fuel economy of the Escape and Escape HEV follow the GREET estimations of approximately 43% city and 57% highway based on the posted city/highway fuel economy 20/28 and 34/31 mpge, respectively.[10][11][13] The fuel economy of the Escape PHEV in Charge Depleting (CD) and Charge Sustaining (CS) modes are based on fleet testing averages by Idaho National Laboratory and cosponsors using a Hybrids Plus battery and a K2 Energy Solutions battery of equivalent size. CS mode is active when the PHEV sustains an average battery charge through discharge and charge cycles. CD mode occurs when the PHEV battery's charge is depleting, thus displacing the use of gasoline in the internal combustion engine. When the battery's charge is depleted to a set percentage, then it will shift back to CS mode. The vehicles with a Hybrids Plus battery averaged 40 mpge in CD mode and 32 mpge in CS mode while the vehicles with a K2 Energy Solutions battery averaged 40 mpge in CD mode and 31 mpge in CS mode.[14][15] These fuel economies already incorporate city and highway driving habits related to fleet testing and are not adjusted. These vehicles are assumed to be fueled by a gasoline blend of 50% RFG and 50% CG as well as electricity where applicable.

Table 4.1.1 Estimated fuel economy for the Ford Escape variants.

	2009 Ford Escape XLT FWD I4	**2009 Ford Escape Hybrid FWD**	**2009 Ford Escape Hybrid FWD Miles Plus conversion**	
	Average	**Average**	**CD mode**	**CS mode**
Fuel Economy (mpge)	24.56	32.29	40.0	31.5

The electricity mix for transportation and stationary purposes models the supply from TVA as reported in their fiscal year 2009 annual report highlights since fiscal year 2010 data are not currently available. The 2009 generation by fuel source indicates that 46% generation by coal-fired, 32% generation by nuclear, 7% generation by hydro, and 2% generation by combustion turbines, diesel, and renewables.[16] The report also indicates that 13% of the power was purchased from another distributor. [16] This model assumes that the 13% purchased power has a similar breakdown in terms of generation source to the power generated by TVA. Thus, the assumption stands at 52.9% generation by coal-fired, 36.8% generation by nuclear, 8% generation by hydro, and 2.3%

generation by combustion turbines, diesel, and renewables. Further refinement of the last 2.3% assumes 0.1% generation due to residual oil, 2.0% generation due to natural gas, and 0.2% generation due to wind and solar sources. These refinements are based on the generation capabilities outlined by TVA on their website with additional information from a TVA representative. The generation due to wind and solar sources combines with hydro sources to form the "others" category for non emission sources in GREET. Table 4.1.2 contains the estimates for the electricity mix in this simulation. It is important to note that these generation numbers fluctuate from year to year. For example, 2009 generation occurred during a period of lower than average rainfall which hampered hydro production during the year and put more stress on other generation sources to cover the shortfall. For simplicity, this simulation also neglects time of day power consumption for electricity.

Table 4.1.2 Estimated Shares of Power Generation by Fuel Source for TVA in 2010

Fuel Source	**Share**
Residual Oil	0.1%
Natural Gas	2.0%
Coal	52.9%
Nuclear	36.8%
Biomass	0.0%
Others	8.2%

Procedure

The following section summarizes the procedure used to simulate the 2009 Escape variants with the GREET Excel model. The Excel model is preferred for this simulation since the 2005 parameters for the PHEV model in GREET contain placeholder values which are not comparable to researched values for 2010 and later. To achieve a more accurate simulation of the PHEV, the model changes reflect 2010 vehicles with adjustments pertaining to the 2009 Escape variants. Thus, the simulation uses 2010 model data for the modeled vehicles with pertinent updates for the 2009 vehicle data and an estimated electricity mix based on the 2009 annual report with the default 2010 assumptions and parameters. Alterations of the Excel model occur on the 'Inputs,' 'LDT1_TS,' and 'Fuel_Prod_TS' tabs. Specifically, the 'Inputs' tab will receive updates reflecting the LDT1 vehicle type and appropriate electricity mixes, the 'LDT1_TS' tab will receive updates to relevant time series (TS) tables for model year 2005 data as well as updated fuel economies, and the 'Fuel_Prod_TS' tab will receive updates to the simulation year 2010 electricity generation mixes previously mentioned in Table 4.1.2. These changes are reflected in the 'Results' tab under the three specific models relevant to this case study. The exact procedure for updating the GREET Excel model for this particular case study, including appropriate figures of the changed Excel model, is located in Appendix B.1.

Results

The results from GREET Excel model are located on the 'Results' tab in the specific cells mentioned in the step by step procedure located in Appendix B.1. An electronic copy of the results is included in the modified GREET Excel model (See 'GREET1_8c 2009 Ford Escape CS2 with TVA mix.xls') with an edited copy of the results appearing in Appendix B.2. The results listed in this section include WTP results of energy consumption and emissions for each fuel, WTW results of each vehicle-fuel combination, and modified WTW energy and emissions relative changes.

Well to Pump Results

The WTP results listed in Table 4.3.1 are pulled from their respective columns in the modified GREET Excel model. The energy consumption and emissions results listed in Table 4.3.1 pertain to the amount of energy consumed and emissions generated to make a mmBtu, or 1,000,000 Btu, of fuel available at fuel station pumps. The WTP results include only the feedstock and fuel production stages. GREET does not include double listings for the same fuels used in different vehicle types. That is, the baseline vehicle with CG and RFG corresponds to both the Escape and Escape HEV which are fueled primarily by the CG and RFG blend. The blend itself is representative of the blend detailed in the model. The GC SI PHEV model fueled by the gasoline blend and electricity is based on a ratio of blended gasoline and electricity for transportation used in the vehicle. Electricity generated by regenerative breaking in the Escape HEV and PHEV is not included in these results since it is a direct result of vehicle operation rather than WTP operations. The following section gives a brief description of the results in Table 4.3.1.

With respect to energy consumption, there are several items listed under the WTP results that offer distinct results for each simulated fuel. The total energy item represents all energy consumed to make a mmBtu of the listed fuel available at fuel station pumps and includes both fossil fuels and non-fossil fuels consumed. Thus, the total energy consumed to make a mmBtu of baseline CG and RFG blend available at the pump is

247,376 Btu as seen in Table 4.3.1. The fossil fuels item represents all fossil fuel energy consumed to make a mmBtu of fuel available at fuel station pumps and is the sum of the individual coal, natural gas, and petroleum items listed below it. For the baseline CG and RFG blend in Table 4.3.1, the coal, natural gas, and petroleum energy consumptions are 41,460 Btu, 87,194 Btu, and 94,884 Btu, respectively. Thus, the combined fossil fuel consumption is 223,538 Btu. Non fossil fuel consumption is not specifically stated but is inherently included as the difference between total energy consumed and fossil fuel energy consumed. For example, producing a mmBtu of the baseline CG and RFG blend consumes about 247,376 Btu of total energy and 223,538 Btu of fossil fuel energy as seen in Table 4.3.1. The non-fossil fuel energy consumed is thus approximately 23,838 Btu in order to make a mmBtu of CG and RFG fuel available at fuel station pumps.

The WTP efficiency is a measure of how effective it is to deliver a mmBtu of fuel to a fuel station pump and is calculated using the equation

$$E = \frac{P}{P + C}, \tag{4.1}$$

where E is the WTP efficiency (%), P is the energy delivered to the pump (i.e. a mmBtu of fuel), and C is the energy consumed to produce a mmBtu of fuel. For example, the total energy consumed for the baseline CG and RFG in Table 4.3.1 is 247,376 Btu per mmBtu available at fuel station pumps. This value corresponds to the variable C in Equation 1. The energy delivered to the pump, P, from Equation 4.1 is always 1,000,000 Btu per mmBtu available at fuel station pumps for all WTP calculations in GREET. Inputting the appropriate values into Equation 4.1, the resulting WTP efficiency is approximately 80.2% as shown in Table 4.3.1 for baseline vehicles fueled by CG and RFG.

The greenhouse gas results listed in the WTP results include CO_2 (w/ C in VOC & CO), CH_4, and N_2O. The CO_2 (w/ C in VOC & CO) results encompass estimates of direct CO_2 emissions and CO_2 emissions resulting from VOC and CO emissions based on carbon ratios of VOC, CO, and CO_2. CH_4 and N_2O items indicate the emissions of the respective substances. Each of the greenhouse gases listed above has a global warming potential relative to CO_2 assigned to it by the IPCC. For this simulation, CO_2 has the default potential value of 1, CH_4 has the default value of 25, and N_2O has the default value of 298. These values are used in conjunction with the actual emissions of CO_2 (w/ C in VOC & CO), CH_4, and N_2O to calculate the GHGs item listed in Table 4.3.1. For the baseline CG and RFG blend, 16,552 grams of CO_2 (w/ C in VOC & CO), 108.155 grams of CH_4, and 1.130 grams of N_2O are multiplied by their respective global warming potentials relative to CO_2. Thus, the approximate weighted values are 16,552 grams CO_2 (w/ C in VOC & CO), 2,703.8 grams of CH_4, and 336.7 grams of N_2O. Summing these weighted values produces the weighted estimate of 19,592 grams per mmBtu of fuel available at the pump for GHGs as shown in Table 4.3.1.

The emissions of principal pollutants for WTP activities include VOC, CO, NO_x, PM_{10}, $PM_{2.5}$, and SO_x. The total emissions for each category is listed followed by the amount of emissions released in urban areas for the same activities as shown in Table 4.3.1. The difference between the total and urban emissions is the amount of emissions released outside urban areas.

As a short reminder, WTP activities include feedstock and fuel production stages of the fuel process. Each fuel listed in the WTP results has a unique set of WTP activities which result in comparable results for energy consumption and emissions. Typically, the feedstock activities relate to the acquisition, processing, transportation and distribution (T&D), and storage of a feedstock. For example, the CG and RFG blend in this case study relies on crude feedstock that includes conventional crude oil and oil sands products from surface mining and in situ production. For conventional crude oil, energy consumption and emissions arise from recovery, transportation to U.S. refineries, and storage. For oil sands recovery via surface mining and in situ production, energy consumption and emissions arise from bitumen extraction and upgrading, transportation to U.S. refineries, and storage. Typically, the fuel production activities relate to the acquisition, processing, transportation and distribution (T&D), and storage of a fuel. For example, the CG and RFG blend in this case study relies on the production of CG and RFG. For CG, energy consumption and emissions arise from CG refining, T&D, and storage. For RFG, energy consumption and emissions arise from RFG gasoline blendstock refining, T&D, and storage as well as additive production, transportation, and storage. The WTP activities for the PHEV vehicle in this case study incorporate the same activities outlined above for the production of gasoline as well as activities related to the production of electricity for transportation. The typical WTP activities for electricity production include energy consumption and emissions from each power plant source outlined in the electricity generation mix with respect to fuel source, plant efficiencies, and transmission losses.

Table 4.3.1 Well to Pump Energy Consumption and Emissions Results for the Escape, Escape HEV, and Escape PHEV Models (Results in Btu or grams per mmBtu of fuel available at fuel station pumps)

2010	Baseline: CG and RFG	Grid-Connected SI PHEV: Gasoline and Electricity
Total Energy	247,376	398,136
WTP Efficiency	80.2%	71.5%
Fossil Fuels	223,538	337,472
Coal	41,460	174,425
Natural Gas	87,194	79,613
Petroleum	94,884	83,435
CO2 (w/ C in VOC & CO)	16,552	41,805
CH4	108.155	123.665
N2O	1.130	1.247
GHGs	19,592	45,269
VOC: Total	27.303	25.567
CO: Total	14.050	17.729
NOx: Total	47.251	69.568
PM10: Total	11.148	53.074
PM2.5: Total	4.301	14.986
SOx: Total	23.736	91.829
VOC: Urban	15.519	13.345
CO: Urban	3.750	4.094
NOx: Urban	10.335	13.211
PM10: Urban	1.835	1.874
PM2.5: Urban	1.067	1.070
SOx: Urban	7.183	17.411

Well to Wheel Results

The WTW results for this case study are pulled from their respective grids in the modified GREET Excel model. The results for energy consumption and emissions listed in Table 4.3.2 are on a per mile basis. Each item for a vehicle-fuel combination has a value for the feedstock stage, fuel production stage, and vehicle operation stage as well as a total value for the vehicle-fuel combination. Table 4.3.2 contains the results for the Ford Escape modeled by the SIDI vehicle. Table 4.3.3 contains the results for the Ford Escape HEV modeled by the GI SI HEV. Table 4.3.4 contains the results for the Ford Escape PHEV conversion modeled by the GC SI PHEV.

The WTW results shown in Table 4.3.2, Table 4.3.3, and Table 4.3.4 have the same items as the WTP results mentioned earlier in this chapter. The WTW results are on a per mile basis, and the energy consumption and emissions items are split into individual stages. The feedstock stage includes all energy and emissions from activities relating to the feedstock of the selected fuel and includes transportation and distribution (T&D) activities. The fuel production stage includes all energy and emissions from activities relating to the production of the fuel including T&D activities. The vehicle operation stage includes all energy and emissions from activities relating to use of the fuel in the vehicle during operation. The sum of the feedstock, fuel, and vehicle operation stages is listed as the total. For example, the total fossil fuels energy consumption of the SIDI vehicle in Table 4.3.2 is approximately 5,447 Btu/mile. This is the sum of the feedstock stage which consumes approximately 226 Btu/mile, the fuel production stage which consumes approximately 786 Btu/mile, and the vehicle operation stage which consumes approximately 4,434 Btu/mile.

As a reminder, there are several items listed under the WTW results that offer distinct results for each simulated fuel. With respect to energy consumption, the total energy item represents all energy consumed for the vehicle to travel one mile and includes both fossil fuels and non-fossil fuels consumed. Thus, the total energy consumed for the vehicle to travel one mile is 5,649 Btu as seen in Table 4.3.2. The fossil fuels item represents all fossil fuel energy consumed for the vehicle to travel one mile and is the sum of the individual coal, natural gas, and petroleum items listed below it. For the SIDI vehicle model in Table 4.3.2, the totals for coal, natural gas, and petroleum energy consumptions are 188 Btu/mile, 395 Btu/mile, and 4,864 Btu/mile, respectively. Thus, the combined total fossil fuel consumption is 5,447 Btu/mile. Non fossil fuel consumption is not specifically stated but is inherently included as the difference between total energy consumed and fossil fuel energy consumed. For example, the SIDI vehicle modeled in Table 4.3.2 consumes about 5,649 Btu/mile of total energy and 5,447 Btu/mile of fossil fuel energy as the result of travel. The non-fossil fuel energy consumed is thus approximately 202 Btu/mile. With respect to GHG emissions, remember that the GHGs item is a sum of the CO_2 equivalent values for CO_2 (w/ C in VOC & CO), CH_4, and N_2O. With respect to the principal pollutants (VOC, CO, NO_x, PM_{10}, $PM_{2.5}$, and SO_x) for WTW activities, the total emissions for each item is listed followed by the amount of emissions released in urban areas for the same activities. The difference between the total and urban emissions is the amount of emissions released outside urban areas.

Table 4.3.2 WTW Results for the SIDI Vehicle Model Fueled by a CG and RFG Blend Based on the 2009 Ford Escape

SIDI Vehicle: CG and RFG	**Btu/mile or grams/mile**			
Item	**Feedstock**	**Fuel**	**Vehicle Operation**	**Total**
Total Energy	236	884	4,529	5,649
Fossil Fuels	226	786	4,434	5,447
Coal	37	151	0	188
Natural Gas	136	259	0	395
Petroleum	53	377	4,434	4,864
CO2 (w/ C in VOC & CO)	15	60	348	423
CH4	0.421	0.069	0.013	0.502
N2O	0.000	0.005	0.012	0.017
GHGs	26	63	352	440
VOC: Total	0.016	0.108	0.182	0.306
CO: Total	0.030	0.034	3.448	3.512
NOx: Total	0.111	0.103	0.099	0.313
PM10: Total	0.010	0.041	0.033	0.083
PM2.5: Total	0.004	0.015	0.018	0.038
SOx: Total	0.037	0.070	0.006	0.113
VOC: Urban	0.003	0.068	0.113	0.183
CO: Urban	0.001	0.016	2.145	2.162
NOx: Urban	0.005	0.042	0.062	0.108
PM10: Urban	0.000	0.008	0.020	0.029
PM2.5: Urban	0.000	0.005	0.012	0.016
SOx: Urban	0.003	0.029	0.004	0.036

Table 4.3.3 WTW Results for the SIDI Vehicle Model Fueled by a CG and RFG Blend Based on the 2009 Ford Escape HEV

Grid-Independent SI HEV: CG and RFG	Btu/mile or grams/mile			
Item	**Feedstock**	**Fuel**	**Vehicle Operation**	**Total**
Total Energy	178	666	3,413	4,257
Fossil Fuels	170	593	3,342	4,105
Coal	28	113	0	142
Natural Gas	102	195	0	298
Petroleum	40	284	3,342	3,666
CO2 (w/ C in VOC & CO)	11	45	262	319
CH4	0.317	0.052	0.006	0.375
N2O	0.000	0.004	0.012	0.016
GHGs	19	47	266	333
VOC: Total	0.012	0.081	0.129	0.222
CO: Total	0.022	0.026	3.448	3.496
NOx: Total	0.084	0.077	0.083	0.244
PM10: Total	0.007	0.031	0.033	0.071
PM2.5: Total	0.003	0.011	0.018	0.033
SOx: Total	0.028	0.053	0.004	0.085
VOC: Urban	0.002	0.051	0.080	0.133
CO: Urban	0.001	0.012	2.145	2.157
NOx: Urban	0.004	0.032	0.052	0.087
PM10: Urban	0.000	0.006	0.020	0.027
PM2.5: Urban	0.000	0.004	0.012	0.015
SOx: Urban	0.002	0.022	0.003	0.027

Table 4.3.4 WTW Results for the SIDI Vehicle Model Fueled by a CG and RFG Blend Based on the 2009 Ford Escape PHEV Conversion

Grid-Connected SI PHEV: CG and RFG	**Btu/mile or grams/mile**			
Item	**Feedstock**	**Fuel**	**Vehicle Operation**	**Total**
Total Energy	171	1,119	3,241	4,531
Fossil Fuels	162	931	3,082	4,175
Coal	31	534	349	915
Natural Gas	87	171	13	271
Petroleum	44	226	2,719	2,990
CO2 (w/ C in VOC & CO)	11	124	213	348
CH4	0.357	0.043	0.006	0.407
N2O	0.000	0.004	0.012	0.016
GHGs	20	126	217	363
VOC: Total	0.016	0.067	0.129	0.212
CO: Total	0.021	0.037	3.448	3.505
NOx: Total	0.081	0.144	0.083	0.309
PM10: Total	0.141	0.031	0.042	0.214
PM2.5: Total	0.036	0.012	0.022	0.071
SOx: Total	0.030	0.267	0.003	0.301
VOC: Urban	0.002	0.042	0.080	0.124
CO: Urban	0.001	0.012	2.145	2.158
NOx: Urban	0.004	0.039	0.052	0.095
PM10: Urban	0.000	0.006	0.026	0.032
PM2.5: Urban	0.000	0.003	0.014	0.017
SOx: Urban	0.002	0.054	0.002	0.059

Well to Wheel Relative Change Results

The WTW relative changes are recalculations employing the same method as the GREET model using the WTW results of the SIDI model instead of the SI model as a baseline. In essence, each calculation follows the form

$$RC = \frac{AT - OT}{OT} \tag{4.2}$$

for every item and vehicle technology compared to the baseline technology where *RC* is the relative change (%), *AT* is the alternative technology item, and *OT* is the baseline technology item. In this case, the *OT* refers to the SIDI vehicle model for the Escape and the AT refers to either the Escape HEV or the Escape PHEV data from the corresponding item. For example, the total energy consumptions for Escape model (*OT*) and the Escape PHEV model (*AT*) are 4,531 Btu/mile (see Table 4.3.4) and 5,649 Btu/mile (see Table B.2), respectively. Subtracting the *OT* value, 5,649 Btu/mile, from the *AT* value, 4,531 Btu/mile, and then dividing the quantity by the *OT* value, 5,649 Btu/mile, results in a relative change of -24.6% as shown in Table 4.3.5 under the grid-independent SI HEV: CG and RFG heading for total energy. The relative changes resulting from calculations using the WTW results mentioned earlier offer a way to express the difference of individual items between an alternative vehicle and a baseline vehicle as a comparison to the size of the baseline vehicle item. Multiple relative changes based on the same baseline vehicle can be used to make comparisons between alternative vehicles. A negative relative change means that the alternative vehicle's item value is lower than the baseline vehicle's item value, and in this case study, shows that the alternate vehicle is performing better than the baseline vehicle for that particular item. A positive relative change means just the opposite. When comparing two relative changes that use the same baseline vehicle data, the alternate vehicle with the lowest relative change is the better performing vehicle between the two alternatives for that particular item.

Table 4.3.5 Relative Change (RC) Results for the Alternative Vehicle Models (AT) Relative to the Baseline Model (OT). (%, relative to 2009 Ford Escape XLT FWD I4 Fueled with CG and RFG)

Item	**Grid-Independent SI HEV: CG and RFG**	**Grid-Connected SI PHEV: CG and RFG**
Total Energy	-24.6%	-19.8%
Fossil Fuels	-24.6%	-23.3%
Coal	-24.6%	387.2%
Natural Gas	-24.6%	-31.5%
Petroleum	-24.6%	-38.5%
CO_2 (w/ C in VOC & CO)	-24.6%	-17.6%
CH_4	-25.3%	-19.1%
N_2O	-7.4%	-6.3%
GHGs	-24.5%	-17.5%
VOC: Total	-27.3%	-30.7%
CO: Total	-0.4%	-0.2%
NO_x: Total	-21.9%	-1.4%
PM_{10}: Total	-15.0%	157.7%
$PM_{2.5}$: Total	-12.6%	85.6%
SO_x: Total	-24.6%	166.0%
VOC: Urban	-27.4%	-32.7%
CO: Urban	-0.2%	-0.2%
NO_x: Urban	-19.7%	-12.8%
PM_{10}: Urban	-7.1%	13.2%
$PM_{2.5}$: Urban	-7.3%	4.8%
SO_x: Urban	-24.6%	62.5%

Discussion

Using the results of this simulation, the benefits and drawbacks can be analyzed and discussed in order to determine which advanced vehicle technology is more favorable for use in Tennessee as a daily commuter. These three vehicles rely on a gasoline blend for energy either in a primary or secondary capacity. The base model Escape relies solely on a gasoline blend as the primary source of energy. The HEV variant recovers electricity during operation through regenerative braking and expends the electricity in conjunction with a gasoline blend for energy. The PHEV variant draws electricity directly from the grid during charging and expends the stored electricity during CD mode. If there is not enough energy in the battery pack, the PHEV will switch to a gasoline blend in CS mode to supplement the charge from the battery. The PHEV variant also recovers electricity during operation in the same way as the HEV. This difference in how each of the variants operates is in essence the driving force behind the energy consumption, emissions, and costs associated with the feedstock, fuel, and operation of the vehicles. In this section, the energy consumption, emissions, and costs of each vehicle will be discussed relative to the base model with implications to other relative and important issues.

Energy Consumption

In terms of energy consumption, the requirements for WTW operation are categorized by GREET in terms of total energy and energy derived from fossil fuels. Energy sources other than fossil fuels constitute the difference between total energy and fossil fuels energy. The fossil fuels category is subdivided into groups for energy derived from coal, NG, and petroleum, individually. In this section, the WTW relative changes and per mile results for energy consumption of each of these categories is discussed.

In terms of the relative changes in energy consumption shown in Table 4.4.1, the HEV model consumes a flat 24.6% less energy than the baseline Escape in every category due to the recovery and expenditure of electricity during operation which reduces the gasoline requirements of vehicle operation. This lower energy requirement affects all WTW activities resulting in a net reduction of energy in each stage. With respect to coal and natural gas, the reductions occur only during the feedstock and fuel production stages as they are not directly consumed in the vehicle operation stage. As a reminder, the feedstock stage accounts for all activities related to the fuel feedstock, the fuel production stage accounts for all activities related to fuel production, and the vehicle operation stage accounts for the use of the fuel in the vehicle. The PHEV model consumes 19.8% less total energy with a 23.3% reduction in energy consumed from fossil fuels when compared to the baseline Escape. Interestingly, the PHEV model will consume 31.5% less NG-derived energy and 38.5% less petroleum-derived energy than the baseline Escape, but it will consume 387.2% more energy from coal sources. This dramatic increase in energy consumption from coal sources is due to coal being a major source of fuel for the electricity production mix used in the simulation.

Table 4.4.1 The estimated relative changes for 2010 WTW energy consumption

2010 WTW Energy Consumption (%, relative to 2009 Ford Escape)	2009 Ford Escape HEV (Grid-Independent SI HEV: CG and RFG)	2009 Ford Escape Miles Plus conversion (Grid-Connected SI PHEV: CG and RFG)
Coal	-24.6%	387.2%
Natural Gas	-24.6%	-31.5%
Petroleum	-24.6%	-38.5%
Fossil Fuels	-24.6%	-23.3%
Total Energy	-24.6%	-19.8%

In terms of total energy, both the advanced vehicle models consume less overall energy than the baseline model as shown in Table 4.4.2. The PHEV model reduces the total energy consumption by about 1,120 Btu/mile while the HEV model reduces the total energy consumption by about 1,390 Btu/mile. Even though the PHEV model consumes more overall energy than the HEV model, it consumes close to 172 Btu/mile less during the vehicle operation stage while consuming close to 453 Btu/mile more during the fuel production stage. Note the PHEV consumes close to 235 Btu/mile more than the baseline vehicle during the fuel production stage despite having a lower overall total energy consumption. Additionally, the PHEV model consumes about 7 Btu/mile less total energy than the HEV model during the feedstock stage. These differences are mostly due to the offset of energy from the gasoline blend to electricity from the grid. Increasing efficiencies in the production and transmission of electricity in the grid as well as charger efficiency would benefit the PHEV model and possibly make the total energy consumption more on par with the HEV model. Shown in Figure 4.4.1, the HEV is the best choice in terms of WTW total energy consumption.

Table 4.4.2 Estimated 2010 WTW Total Energy Consumption for All Stages

2010 WTW Total Energy	Btu/mile			
	Feedstock	Fuel	Vehicle Operation	Total
2009 Ford Escape	236	884	4,529	5,649
2009 Ford Escape HEV	178	666	3,413	4,257
2009 Ford Escape PHEV	171	1,119	3,241	4,531

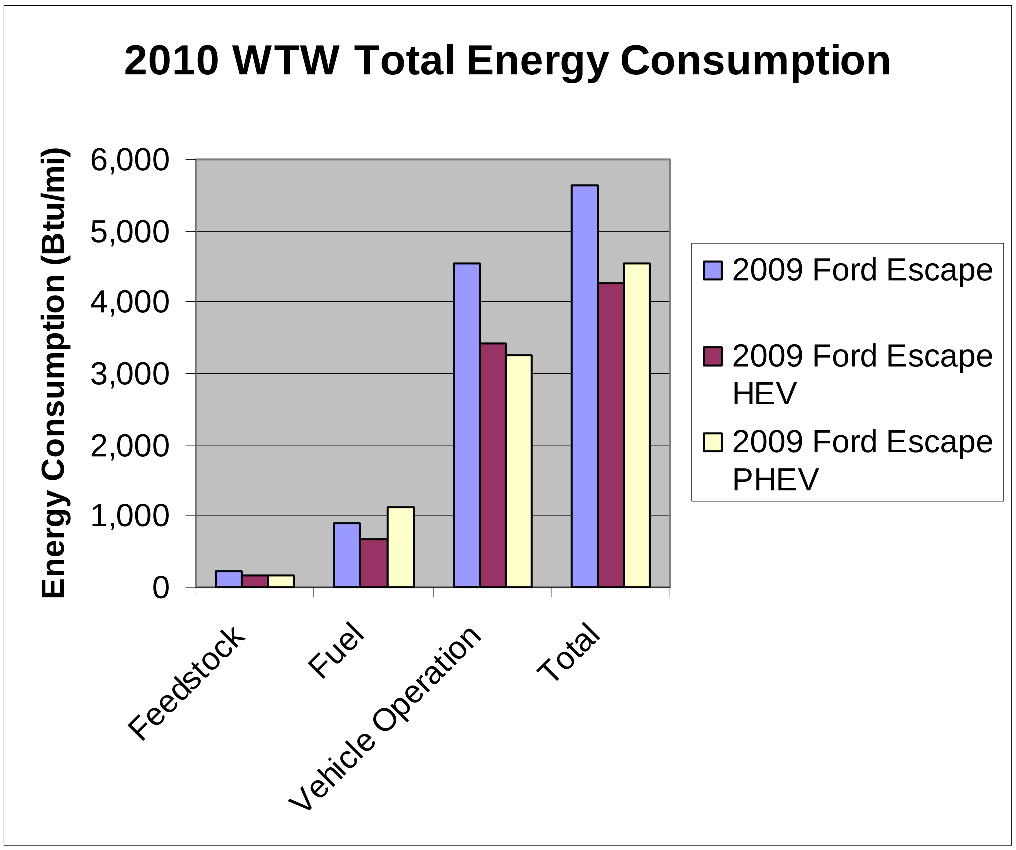


Figure 4.4.1 The estimated 2010 WTW total energy consumption by stage and in total for the baseline, HEV, and PHEV models.

In terms of fossil fuel energy, both the advanced vehicle models consume less overall energy than the baseline model as shown in Table 4.4.3. The PHEV model reduces the fossil fuel energy consumption by about 1,270 Btu/mile while the HEV model reduces the fossil fuel energy consumption by about 1,340 Btu/mile. Even though the PHEV model consumes more fossil fuel energy than the HEV model, it will consume close to 260 Btu/mile less during the vehicle operation stage while consuming close to 338 Btu/mile more during the fuel production stage. Note the PHEV will consume close to 145 Btu/mile more than the baseline vehicle during the fuel production stage despite having a lower overall fossil fuel energy consumption. Additionally, the PHEV model consumes approximately 8 Btu/mile less fossil fuel energy than the HEV model during the feedstock stage. The fossil fuel consumption includes the consumption of coal, natural gas, and petroleum sources. Increased production efficiency of electricity to the grid from these sources coupled with a production shift towards more nuclear and zero emission sources like wind, solar, and hydro power would benefit the PHEV model. Additionally, less reliance on imported fossil fuels such as petroleum and greater reliance on native fossil fuels such as coal and NG offer numerous other economic advantages which will be discussed in more detail later in this chapter. Shown in Figure 4.4.2, the HEV is the best choice in terms of WTW fossil fuel energy consumption.

Table 4.4.3 Estimated 2010 WTW Fossil Fuels Energy Consumption for All Stages

2010 WTW Fossil Fuels	Btu/mile			
	Feedstock	Fuel	Vehicle Operation	Total
2009 Ford Escape	226	786	4,434	5,447
2009 Ford Escape HEV	170	593	3,342	4,105
2009 Ford Escape PHEV	162	931	3,082	4,175

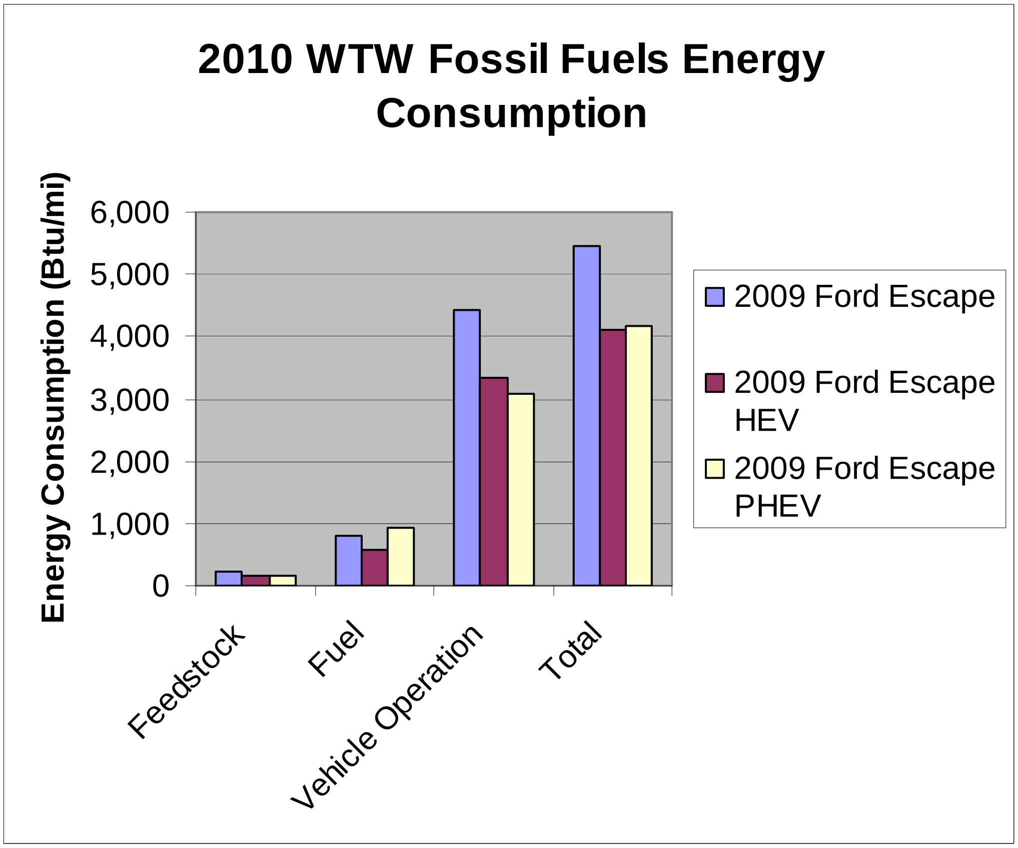


Figure 4.4.2 The estimated 2010 WTW fossil fuels energy consumption by stage and in total for the baseline, HEV, and PHEV models.

In terms of coal energy, the HEV model consumes slightly less overall energy than the baseline model while the PHEV model consumes considerably more as shown in Table 4.4.4. The PHEV model increases the coal energy consumption by about 727

Btu/mile while the HEV model reduces the coal energy consumption by about 46 Btu/mile. This increased consumption of coal energy can be attributed to coal being the source for 52.9% of the electricity production mix. Additionally, the effects of the electricity production mix trickle down through the feedstock, fuel production, and vehicle operation stages of the PHEV model. The PHEV will consume 349 Btu/mile of coal energy in the vehicle operation stage by consuming electricity from the grid while the increased generation requirement causes 534 Btu/mile to be consumed during the fuel production stage. The baseline and HEV models do not use large amounts of coal energy via electricity from the grid in the fuel production stages and, thus, consume only 151 and 113 Btu/mile respectively during the fuel production stage. Additionally, no coal energy is consumed during vehicle operation since both these models are fueled primarily by a gasoline blend. Despite the drastic differences in the fuel production and vehicle operation stages, both the advanced models require slightly less energy during the feedstock stage than the baseline model. The HEV model requires only 3 Btu/mile less coal energy than the PHEV model for the feedstock stage. Shown in Figure 4.4.3, the HEV is the best choice in terms of WTW coal energy consumption. The larger dependence on coal may yield other economic benefits for the PHEV and will be discussed further later in this chapter.

Table 4.4.4 Estimated 2010 WTW Coal Energy Consumption for All Stages

2010 WTW Coal	Btu/mile			
	Feedstock	Fuel	Vehicle Operation	Total
2009 Ford Escape	37	151	0	188
2009 Ford Escape HEV	28	113	0	142
2009 Ford Escape PHEV	31	534	349	915

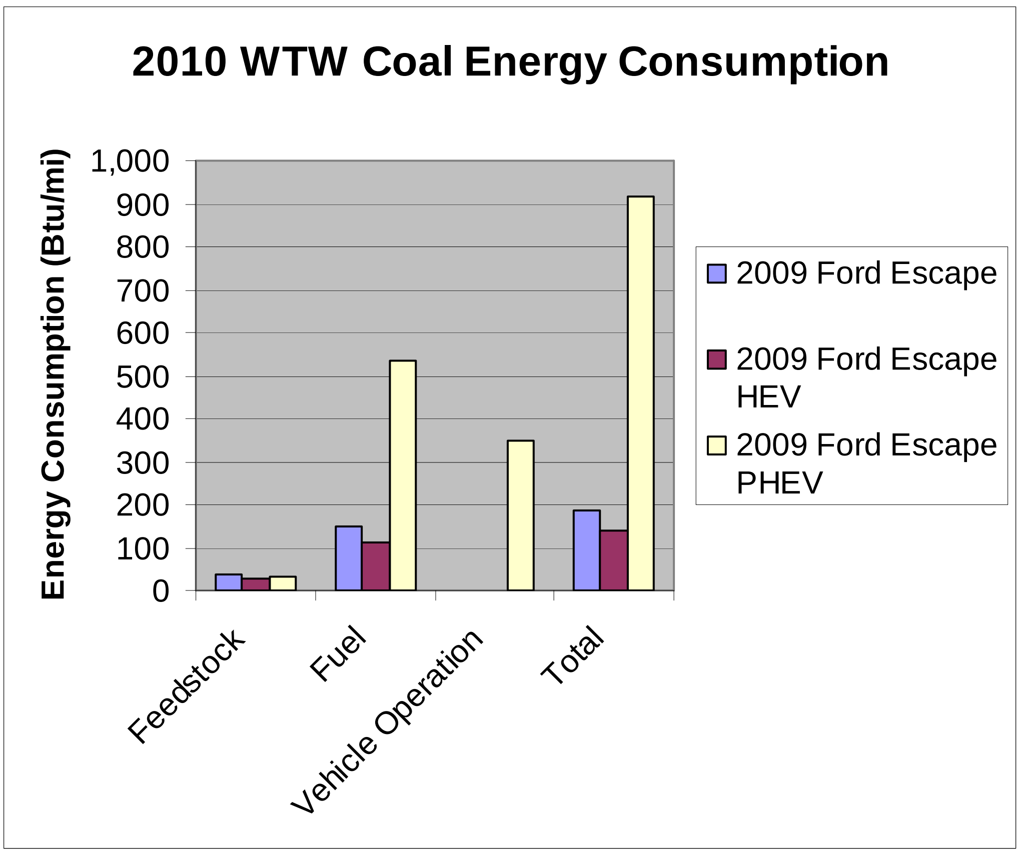


Figure 4.4.3 The estimated 2010 WTW coal energy consumption by stage and in total for the baseline, HEV, and PHEV models.

In terms of NG energy, both the advanced vehicle models consume less overall energy than the baseline model as shown in Table 4.4.5. The PHEV model decreases the NG energy consumption by about 124 Btu/mile while the HEV model reduces the coal energy consumption by about 97 Btu/mile. This decreased consumption of NG energy in the PHEV model can be attributed to NG being the source for 2.0% of the electricity production mix. In addition to the reduced dependence on gasoline, the effects on the PHEV model from NG consumption are considerable in the feedstock and fuel production stages. The PHEV model consumes 13 Btu/mile of NG energy in the vehicle operation stage by consuming electricity from the grid. During the fuel production stage, the PHEV consumes 171 Btu/mile to produce its fuels. This is 24 Btu/mile less than the HEV and 88 Btu/mile less than the baseline model. The baseline and HEV models use larger amounts of NG energy in the fuel production stages producing the gasoline blend and, thus, consume 259 and 195 Btu/mile respectively during the fuel production stage. Additionally, no NG energy is consumed during vehicle operation since both these models are fueled primarily by a gasoline blend. Both the advanced models require less energy during the feedstock stage than the baseline model, but the HEV model requires 15 Btu/mile more NG energy than the PHEV model for the feedstock stage. Shown in Figure 4.4.4, the PHEV is the best choice in terms of WTW NG energy consumption.

Table 4.4.5 Estimated 2010 WTW Natural Gas Energy Consumption for All Stages

2010 WTW Natural Gas	Btu/mile			
	Feedstock	Fuel	Vehicle Operation	Total
2009 Ford Escape	136	259	0	395
2009 Ford Escape HEV	102	195	0	298
2009 Ford Escape PHEV	87	171	13	271

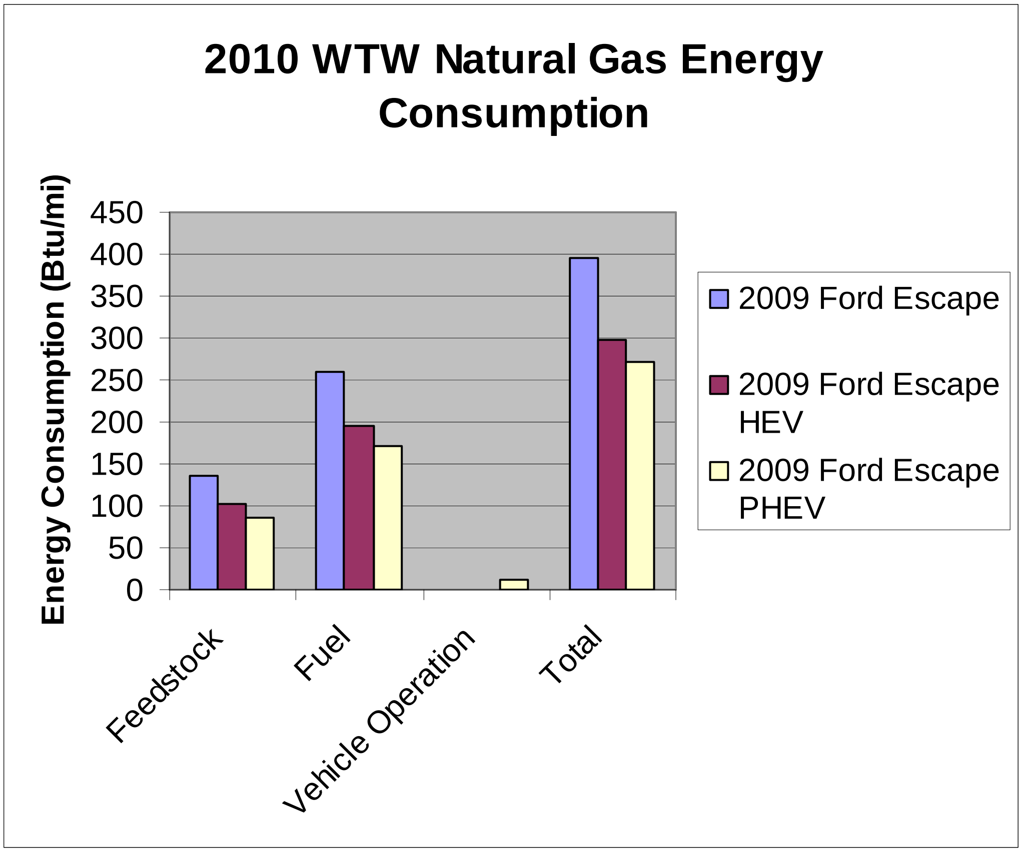


Figure 4.4.4 The estimated 2010 WTW NG energy consumption by stage and in total for the baseline, HEV, and PHEV models.

In terms of petroleum energy, both the advanced vehicle models consume less overall energy than the baseline model as shown in Table 4.4.6. The PHEV model decreases the overall petroleum energy consumption by about 1,870 Btu/mile while the HEV model reduces the overall petroleum energy consumption by about 1,190 Btu/mile. The decreased consumption of petroleum energy in the PHEV model is attributed to the consumption of electricity from the grid and a decreased dependence on gasoline as a direct fuel source. The decreased consumption of petroleum energy in the PHEV and HEV models is attributed to the consumption of electricity recovered during operation which reduces the amount of fuel required to operate each vehicle. While the PHEV and

HEV models consume 44 and 40 Btu/mile respectively during the feedstock stage and 226 and 284 Btu/mile respectively during the fuel production stage, the PHEV model has a major advantage over the HEV model by consuming about 620 Btu/mile less petroleum energy during the vehicle operation stage. Shown in Figure 4.4.5, the PHEV is the best choice in terms of WTW petroleum energy consumption.

Table 4.4.6 Estimated 2010 WTW Petroleum Energy Consumption for All Stages

2010 WTW Petroleum	Btu/mile			
	Feedstock	Fuel	Vehicle Operation	Total
2009 Ford Escape	53	377	4,434	4,864
2009 Ford Escape HEV	40	284	3,342	3,666
2009 Ford Escape PHEV	44	226	2,719	2,990

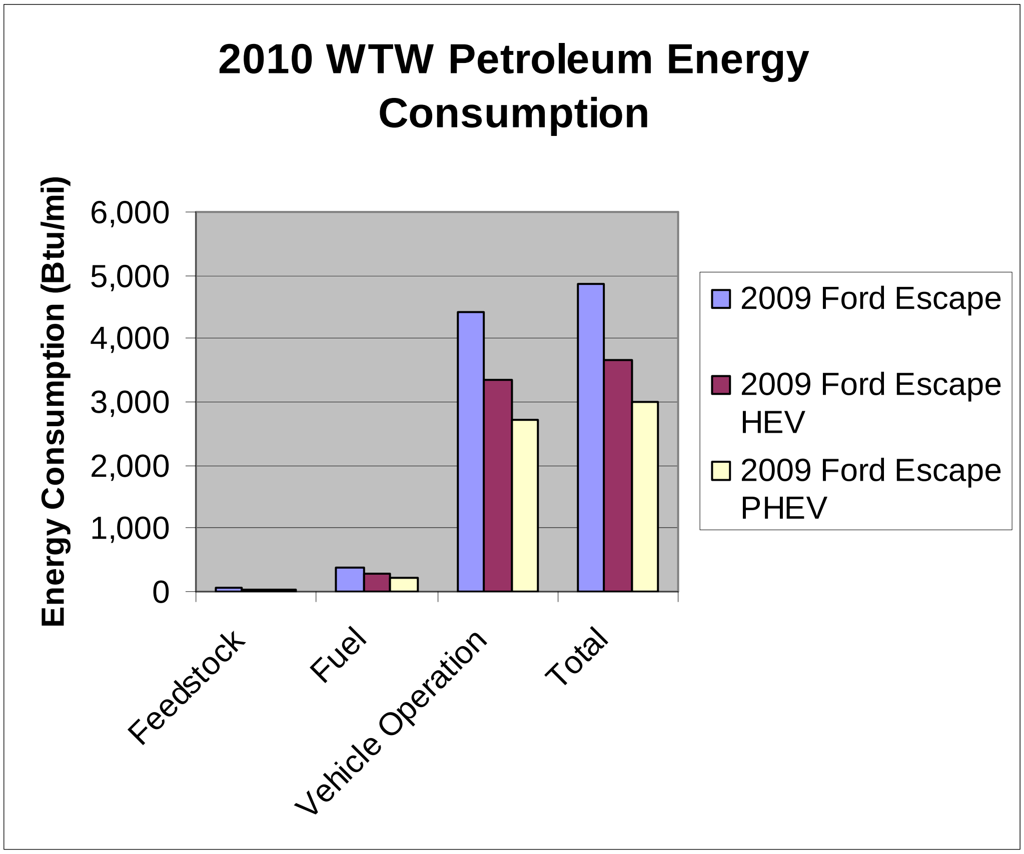


Figure 4.4.5 The estimated 2010 WTW petroleum energy consumption by stage and in total for the baseline, HEV, and PHEV models.

While the HEV model consumes the least amount of total energy and is less reliant on fossil fuel energy, the PHEV model consumes significantly less petroleum energy and significantly more coal energy. This is a possible advantage for the PHEV model since it reduces reliance on foreign oil imports, decreasing our trade deficit and improving national security, and increases reliance on coal which is fairly cheap and found in abundance within our borders. *In terms of energy consumption, the question of the day is whether or not the reduced reliance on petroleum energy outweighs the increased reliance on coal, and whether the gain from this tradeoff is greater than the gain from operating an HEV model.*

Emissions

The emissions produced from WTW operation are categorized by GREET in terms of greenhouse gases (GHGs) and the principal pollutants. The GHGs considered include CO_2 (w/ C in VOC and CO), CH_4, and N_2O emissions. As a reminder, the GHGs item includes CO_2 equivalent values of CO_2 (w/ C in VOC and CO), CH_4, and N_2O which are based on their environmental impact. This model assumes that CH_4 is 25 times as harmful as the same amount of CO_2 and N_2O is 298 times as harmful as the same amount of CO_2. The principal pollutants include VOC, CO, NO_x, PM_{10}, $PM_{2.5}$, and SO_x and are subcategorized in terms of total emissions and urban emissions. In this section, the WTW relative changes and per mile results for emissions of each of these categories is discussed.

In terms of the relative changes of GHG emissions, the HEV model produces 24.5% less weighted GHGs than the baseline Escape while the PHEV model produces only 17.5% less weighted GHGs. As shown in Table 4.4.7, this difference is also evident in the individual subcategories of GHGs. The HEV model produces 24.6% less CO_2 while the PHEV model produces only 17.6% less CO_2. The HEV model produces 25.3% less CH_4 while the PHEV model produces only 19.1% less CH_4. The HEV model produces 7.4% less N_2O while the PHEV model produces only 6.3% less N_2O.

Table 4.4.7 Estimated Relative Changes for 2010 WTW GHG Emissions

2010 WTW GHG Emissions (%, relative to 2009 Ford Escape)	**2009 Ford Escape HEV (Grid-Independent SI HEV: CG and RFG)**	**2009 Ford Escape Miles Plus conversion (Grid-Connected SI PHEV: CG and RFG)**
CO_2 (w/ C in VOC & CO)	-24.6%	-17.6%
CH_4	-25.3%	-19.1%
N_2O	-7.4%	-6.3%
GHGs	-24.5%	-17.5%

In terms of GHG emissions, both advanced vehicle models produce less weighted GHGs than the baseline model as shown in Table 4.4.8. The PHEV model produces overall 77 grams/mile less weighted GHGs while the HEV model produces overall 107 grams/mile less weighted GHGs than the baseline model. Interestingly, the PHEV model produces close to 49 grams/mile less weighted GHGs during vehicle operation than the HEV model. However, the PHEV model produces 79 grams/mile more than the HEV model and 63 grams/mile more than the baseline model during the fuel production stage. This difference is partially attributed to the large amount of emissions produced during electricity generation. There is little difference between the PHEV and HEV models for GHG production in the feedstock stage, but it is about 6 grams/mile less for both models than the baseline model. Shown in Figure 4.4.6, the HEV is the best choice in terms of WTW GHG emissions.

Table 4.4.8 Estimated 2010 WTW GHG Emissions for All Stages

2010 WTW GHG Emissions	Grams/mile			
	Feedstock	Fuel	Vehicle Operation	Total
2009 Ford Escape	26	63	352	440
2009 Ford Escape HEV	19	47	266	333
2009 Ford Escape PHEV	20	126	217	363

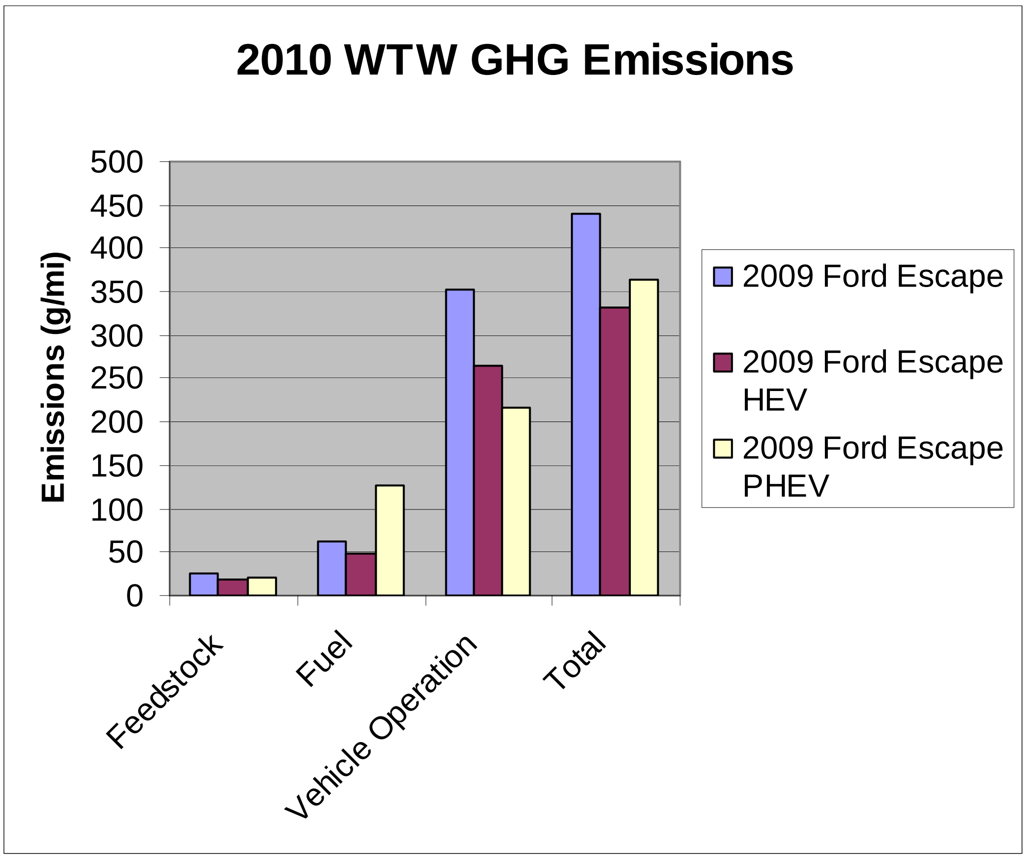


Figure 4.4.6 The estimated 2010 WTW GHG emissions by stage and in total for the baseline, HEV, and PHEV models.

In terms of CO_2 emissions, both advanced vehicle models produce less overall CO_2 emissions than the baseline model as shown in Table 4.4.9. The PHEV model produces overall 75 grams/mile less CO_2 while the HEV model produces overall 104 grams/mile less CO_2 than the baseline model. During the vehicle operation stage, the PHEV model produces 49 grams/mile less CO_2 than the HEV model. However, the PHEV model produces 79 grams/mile more CO_2 than the HEV model and 64 grams/mile more CO_2 than the baseline model during the fuel production stage. The difference during these two stages is attributed to the use of less gasoline blend by the HEV and PHEV model and the use of electricity from the grid in the PHEV model. There is little difference between the PHEV and HEV models for CO_2 production in the feedstock stage, but it is about 4 grams/mile less for both advanced models than the baseline model. Shown in Figure 4.4.7, the HEV is the best choice in terms of WTW CO_2 emissions.

Table 4.4.9 Estimated 2010 WTW CO_2 Emissions for All Stages

2010 WTW CO_2 Emissions	**Grams/mile**			
	Feedstock	**Fuel**	**Vehicle Operation**	**Total**
2009 Ford Escape	15	60	348	423
2009 Ford Escape HEV	11	45	262	319
2009 Ford Escape PHEV	11	124	213	348

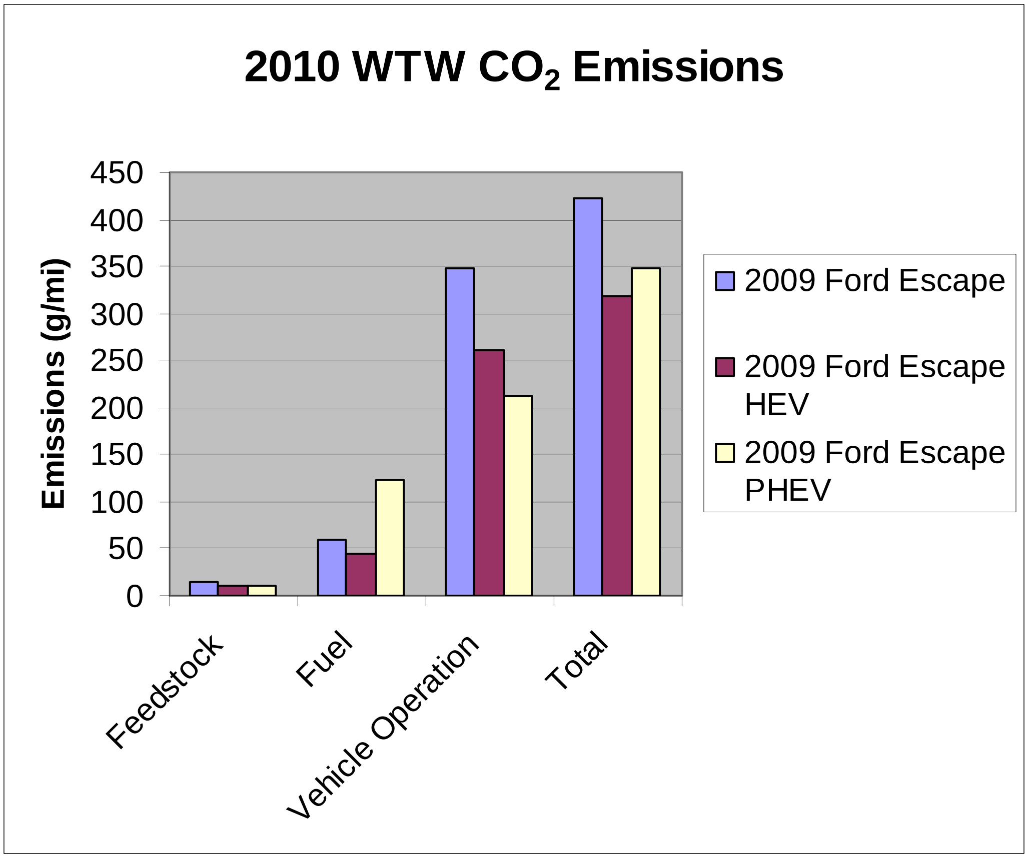


Figure 4.4.7 The estimated 2010 WTW CO_2 emissions by stage and in total for the baseline, HEV, and PHEV models.

In terms of CH_4 emissions, both advanced vehicle models produce less overall CH_4 emissions than the baseline model as shown in Table 4.4.10. The PHEV model produces overall 0.095 grams/mile less while the HEV model produces overall 0.127 grams/mile less than the baseline model. During the vehicle operation stage, the PHEV and HEV models produce about 0.007 grams/mile less CH_4 than the baseline model. Additionally, the PHEV model produces 0.009 grams/mile less CH_4 than the HEV model during the fuel production stage. During the feedstock stage, the PHEV model produces 0.040 grams/mile more than the HEV model. While the totals for CH_4 emissions seem small compared to the emissions of CO_2, their effect is estimated to be 298 times greater on the environment as a GHG. Shown in Figure 4.4.8, the HEV is the best choice in terms of WTW CH_4 emissions.

Table 4.4.10 Estimated 2010 WTW CH_4 Emissions for All Stages

2010 WTW CH_4 Emissions	Grams/mile			
	Feedstock	Fuel	Vehicle Operation	Total
2009 Ford Escape	0.421	0.069	0.013	0.502
2009 Ford Escape HEV	0.317	0.052	0.006	0.375
2009 Ford Escape PHEV	0.357	0.043	0.006	0.407

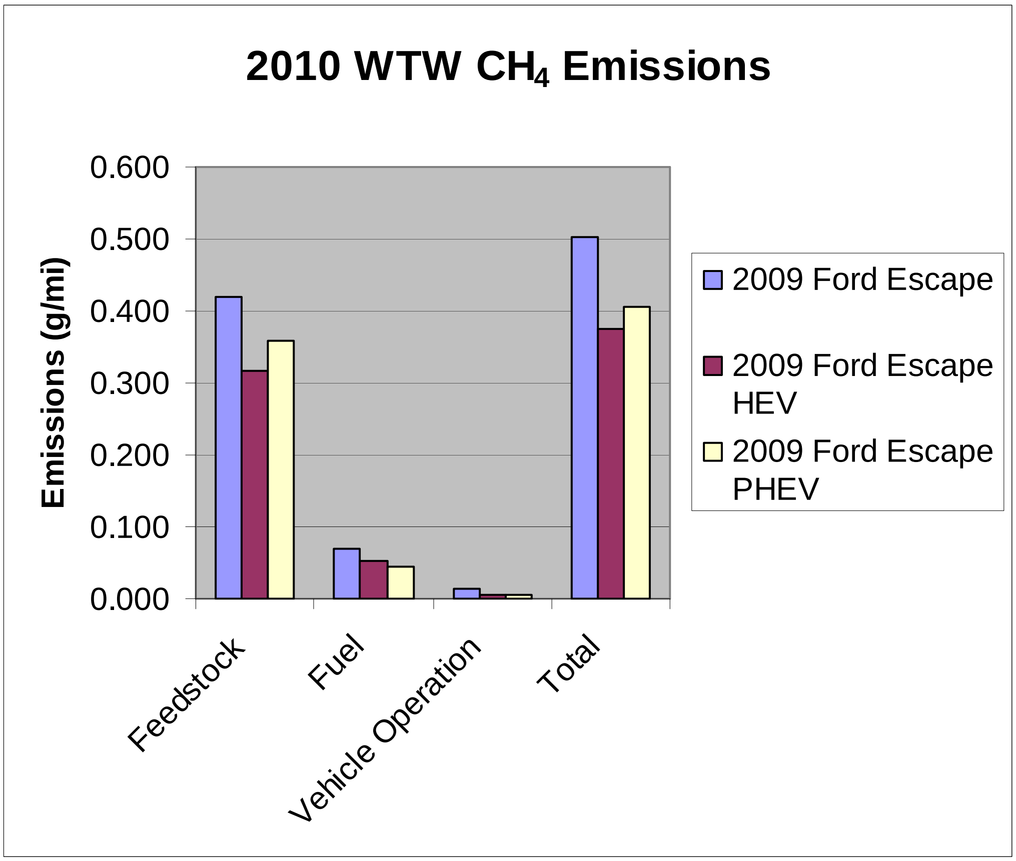


Figure 4.4.8 The estimated 2010 WTW CH_4 emissions by stage and in total for the baseline, HEV, and PHEV models.

In terms of N_2O emissions, both advanced vehicle models produce slightly less overall N_2O emissions than the baseline model as shown in Table 4.4.11. The PHEV and HEV models produce about 0.016 grams/mile overall which is only about 0.001 grams/mile less than the baseline model. During the vehicle operation stage, all models produce about 0.012 grams/mile. Additionally, the PHEV and HEV models produce 0.001 grams/mile less N_2O than the baseline model. During the feedstock stage, all models produce extremely low amounts of N_2O. While the totals for N_2O emissions seem small compared to the emissions of CO_2, their effect is estimated to be 25 times greater on the environment as a GHG. Shown in Figure 4.4.9, the HEV and PHEV offer approximately equivalent benefits in terms of WTW N_2O emissions, but the HEV has a very slight advantage over the PHEV due to rounding inefficiencies.

Table 4.4.11 Estimated 2010 WTW N_2O Emissions for All Stages

2010 WTW N_2O Emissions	**Grams/mile**			
	Feedstock	**Fuel**	**Vehicle Operation**	**Total**
2009 Ford Escape	0.000	0.005	0.012	0.017
2009 Ford Escape HEV	0.000	0.004	0.012	0.016
2009 Ford Escape PHEV	0.000	0.004	0.012	0.016

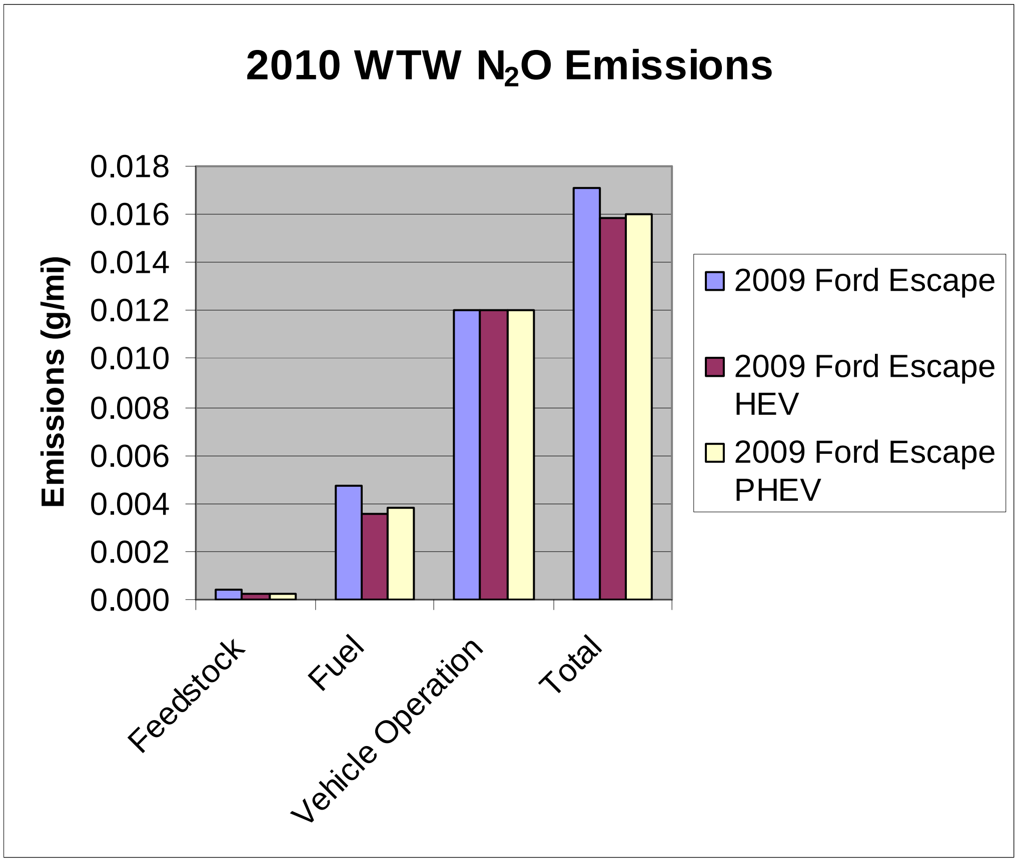


Figure 4.4.9 The estimated 2010 WTW N2O emissions by stage and in total for the baseline, HEV, and PHEV models.

In terms of the relative changes of VOC emissions, the HEV model produces in total 27.3% less VOC emissions while the PHEV model produces in total 30.7% less VOC emissions than the baseline model as shown in Table 4.4.12. In urban areas, however, these relative changes for the HEV and PHEV models increase to 27.4% less and 32.7% less, respectively. This suggests that the PHEV model may be more advantageous than the HEV model in terms of reduction of VOC emissions overall and in urban centers.

Table 4.4.12 Estimated Relative Changes for 2010 WTW VOC Emissions

2010 WTW VOC Emissions (%, relative to 2009 Ford Escape)	2009 Ford Escape HEV (Grid-Independent SI HEV: CG and RFG)	2009 Ford Escape Miles Plus conversion (Grid-Connected SI PHEV: CG and RFG)
VOC: Total	-27.3%	-30.7%
VOC: Urban	-27.4%	-32.7%

Shown in Table 4.4.13, the breakdown of total VOC emissions suggests that during the vehicle operation stage there is no discernable difference between the HEV and PHEV models. While the HEV model has lower emissions during the feedstock stage by about 0.004 grams/mile, the most notable difference occurs in the fuel production stage where the PHEV model has about 0.014 grams/mile less VOC emissions than the HEV model. Overall, the PHEV model produces about 0.010 grams/mile less and 0.094 grams/mile less VOC emissions in total than the HEV and baseline vehicles, respectively. Shown in Figure 4.4.10, the PHEV is the best choice in terms of WTW total VOC emissions.

Table 4.4.13 Estimated 2010 WTW Total VOC Emissions for All Stages

2010 WTW Total VOC Emissions	Grams/mile			
	Feedstock	Fuel	Vehicle Operation	Total
2009 Ford Escape	0.016	0.108	0.182	0.306
2009 Ford Escape HEV	0.012	0.081	0.129	0.222
2009 Ford Escape PHEV	0.016	0.067	0.129	0.212

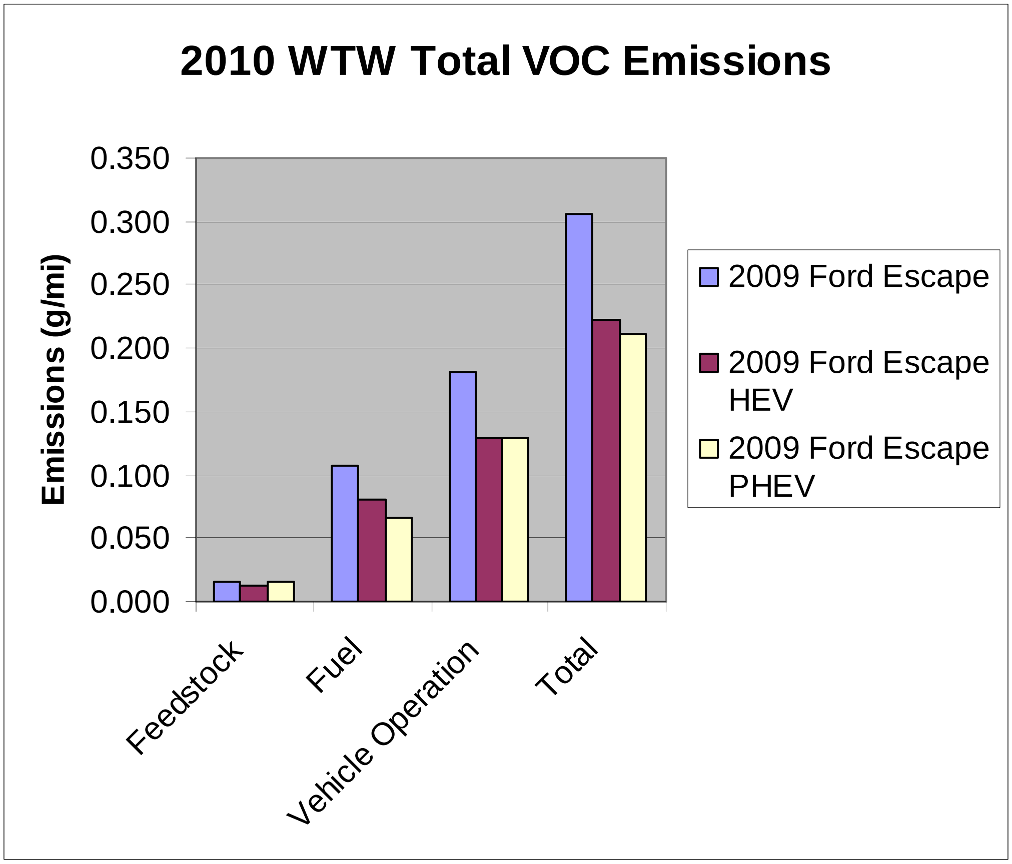


Figure 4.4.10 The estimated 2010 WTW total VOC emissions by stage and in total for the baseline, HEV, and PHEV models.

Shown in Table 4.4.14, the breakdown of urban VOC emissions is similar to that of the total VOC emissions. The HEV and PHEV models show no appreciable difference during the vehicle operation and feedstock stages. The PHEV model contributes about 0.009 grams/mile less VOC emissions to urban centers during the fuel production stage. Overall, the PHEV model produces about 0.009grams/mile less and 0.059 grams/mile less VOC emissions in urban centers than the HEV and baseline vehicles, respectively.

Shown in Figure 4.4.11, the PHEV is the best choice in terms of WTW urban VOC emissions.

Table 4.4.14 Estimated 2010 WTW Urban VOC Emissions for All Stages

2010 WTW Urban VOC Emissions	**Grams/mile**			
	Feedstock	**Fuel**	**Vehicle Operation**	**Total**
2009 Ford Escape	0.003	0.068	0.113	0.183
2009 Ford Escape HEV	0.002	0.051	0.080	0.133
2009 Ford Escape PHEV	0.002	0.042	0.080	0.124

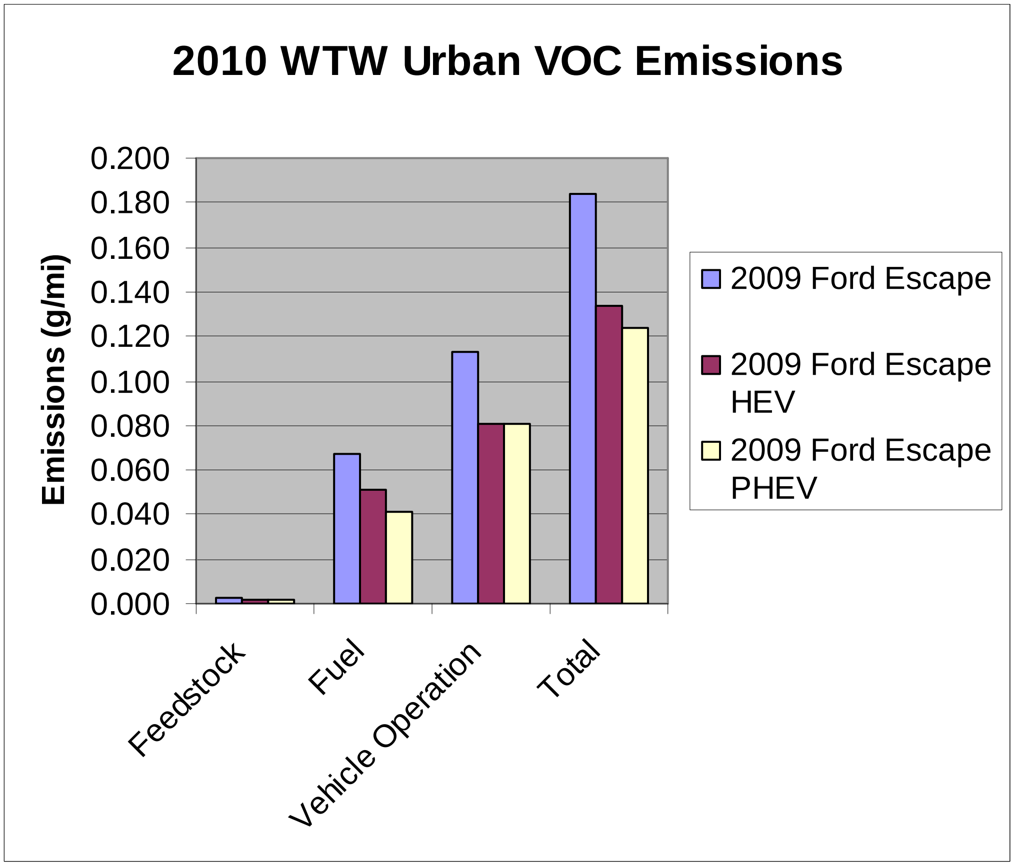


Figure 4.4.11 The estimated 2010 WTW urban VOC emissions by stage and in total for the baseline, HEV, and PHEV models.

In terms of the relative changes of CO emissions, the HEV model produces in total 0.4% less CO emissions while the PHEV model produces in total 0.2% less CO emissions than the baseline model as shown in Table 4.4.15. In urban areas, the relative changes for the HEV and PHEV models are both about 0.2% less. This suggests that the HEV model may be more advantageous than the PHEV model in terms of reduction of CO emissions overall relative to the baseline mode. However, there is no discernable difference between either model for CO emissions in urban centers relative to the baseline model.

Table 4.4.15 Estimated Relative Changes for 2010 WTW CO Emissions

2010 WTW CO Emissions (%, relative to 2009 Ford Escape)	**2009 Ford Escape HEV (Grid-Independent SI HEV: CG and RFG)**	**2009 Ford Escape Miles Plus conversion (Grid-Connected SI PHEV: CG and RFG)**
CO: Total	-0.4%	-0.2%
CO: Urban	-0.2%	-0.2%

The breakdown of total CO emissions indicates that the main differences between each of the models occur during the feedstock and fuel production stages as shown in Table 4.4.16. The HEV and PHEV models produce respectively about 0.016 grams/mile and 0.007 grams/mile less total CO than the baseline model. During the fuel production stage, the PHEV model produces about 0.003 grams/mile more than the baseline model, while the HEV model produces about 0.008 grams/mile less. Both the HEV and PHEV models contribute respectively about 0.008 grams/mile and 0.009 grams/mile less CO emissions than the baseline model. Overall, the PHEV model produces about 0.009 grams/mile more and 0.007 grams/mile less CO emissions in total than the HEV and baseline vehicles, respectively. Shown in Figure 4.4.12, the PHEV is the best choice by a small margin in terms of WTW total CO emissions.

Table 4.4.16 Estimated 2010 WTW Total CO Emissions for All Stages

2010 WTW Total CO Emissions	**Grams/mile**			
	Feedstock	**Fuel**	**Vehicle Operation**	**Total**
2009 Ford Escape	0.030	0.034	3.448	3.512
2009 Ford Escape HEV	0.022	0.026	3.448	3.496
2009 Ford Escape PHEV	0.021	0.037	3.448	3.505

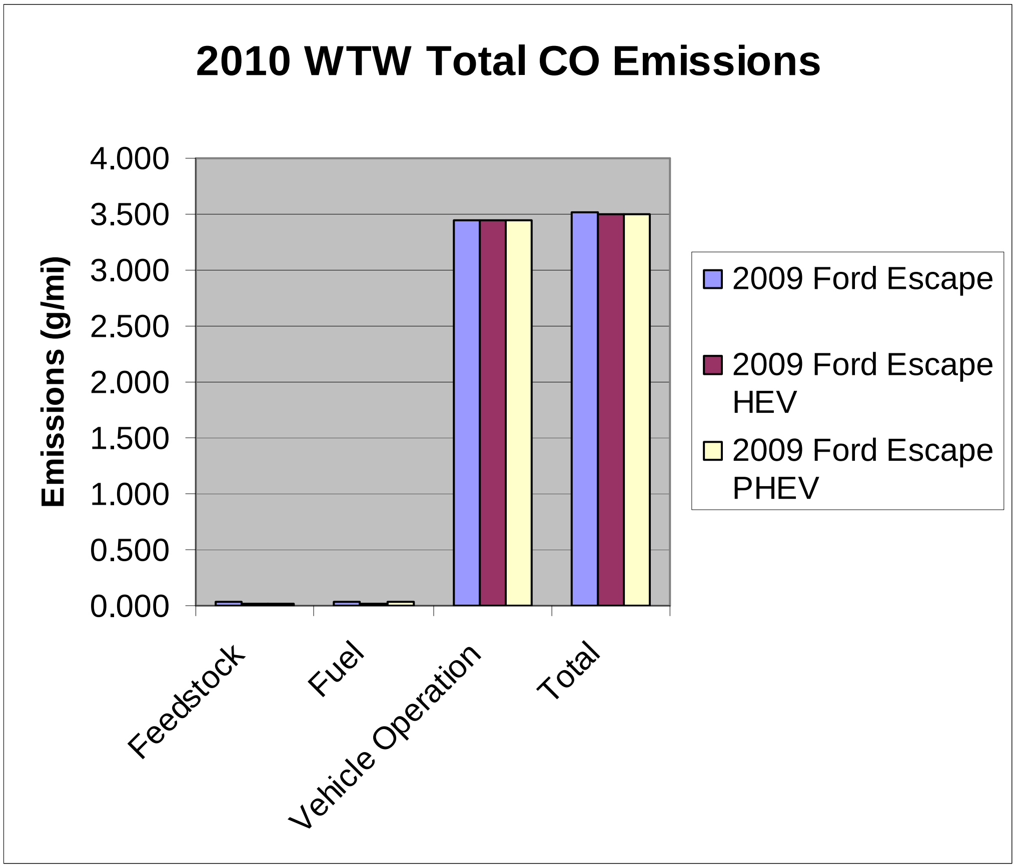


Figure 4.4.12 The estimated 2010 WTW total CO emissions by stage and in total for the baseline, HEV, and PHEV models.

The breakdown of urban CO emissions indicates that the main difference between the models occurs during the fuel production stage as shown in Table 4.4.17. Both PHEV and HEV models produce about 0.004 grams/mile less CO emissions than the baseline model in urban centers. Very small differences account for the HEV model producing slightly less overall urban CO emissions than the PHEV model. Overall, the PHEV model produces about 0.001 grams/mile more and 0.004 grams/mile less CO emissions in urban centers than the HEV and baseline vehicles, respectively. Shown in Figure 4.4.13, the PHEV is the best choice by a small margin in terms of WTW urban CO emissions.

Table 4.4.17 Estimated 2010 WTW Urban CO Emissions for All Stages

2010 WTW Urban CO Emissions	Grams/mile			
	Feedstock	Fuel	Vehicle Operation	Total
2009 Ford Escape	0.001	0.016	2.145	2.162
2009 Ford Escape HEV	0.001	0.012	2.145	2.157
2009 Ford Escape PHEV	0.001	0.012	2.145	2.158

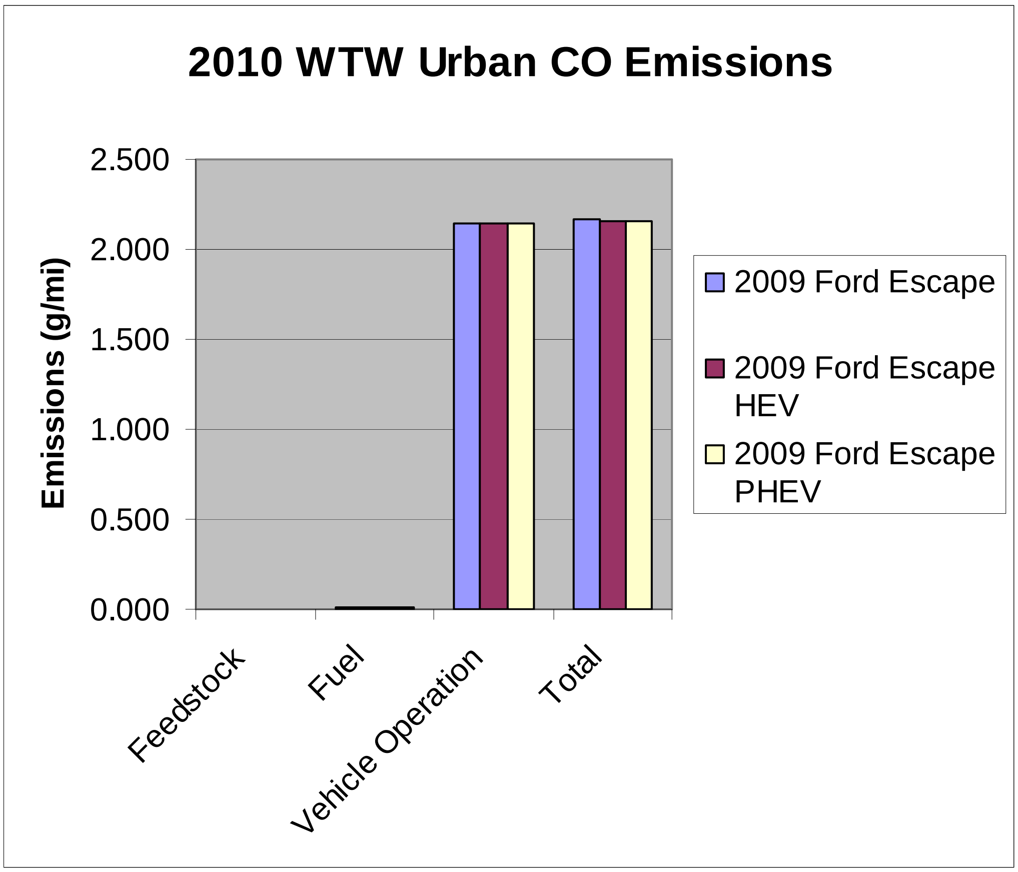


Figure 4.4.13 The estimated 2010 WTW urban CO emissions by stage and in total for the baseline, HEV, and PHEV models.

In terms of the relative changes of NO_x emissions, the HEV model produces in total about 21.9% less NO_x emissions while the PHEV model produces in total about

1.4% less NO_x emissions than the baseline model as shown in Table 4.4.18. In urban areas, the HEV model produces about 19.7% less NO_x emissions while the PHEV model produces about 12.8% less NO_x emissions. This suggests that the HEV model is more advantageous than the PHEV model in terms of reduction of NO_x emissions in total and in urban centers relative to the baseline model.

Table 4.4.18 Estimated Relative Changes for 2010 WTW NO_x Emissions

2010 WTW NO_x Emissions (%, relative to 2009 Ford Escape)	**2009 Ford Escape HEV (Grid-Independent SI HEV: CG and RFG)**	**2009 Ford Escape Miles Plus conversion (Grid-Connected SI PHEV: CG and RFG)**
NO_x: Total	-21.9%	-1.4%
NO_x: Urban	-19.7%	-12.8%

The breakdown of total NO_x indicates that the main difference between the advanced models occurs primarily during the fuel production stage as shown in Table 4.4.19. The PHEV model produces about 0.067 grams/mile more NO_x than the HEV model and about 0.031 grams/mile more NO_x than the baseline model during this stage. The PHEV model produces slightly less NO_x than the HEV model during the feedstock stage and approximately the same amount of NO_x during the vehicle operation stage. Overall, the PHEV model produces about 0.065 grams/mile more and 0.004 grams/mile less NO_x emissions in total than the HEV and baseline vehicles, respectively. Shown in Figure 4.4.14, the HEV is the best choice in terms of WTW total NO_x emissions.

Table 4.4.19 Estimated 2010 WTW Total NO_x Emissions for All Stages

2010 WTW Total NO_x Emissions	Grams/mile			
	Feedstock	Fuel	Vehicle Operation	Total
2009 Ford Escape	0.111	0.103	0.099	0.313
2009 Ford Escape HEV	0.084	0.077	0.083	0.244
2009 Ford Escape PHEV	0.081	0.144	0.083	0.309

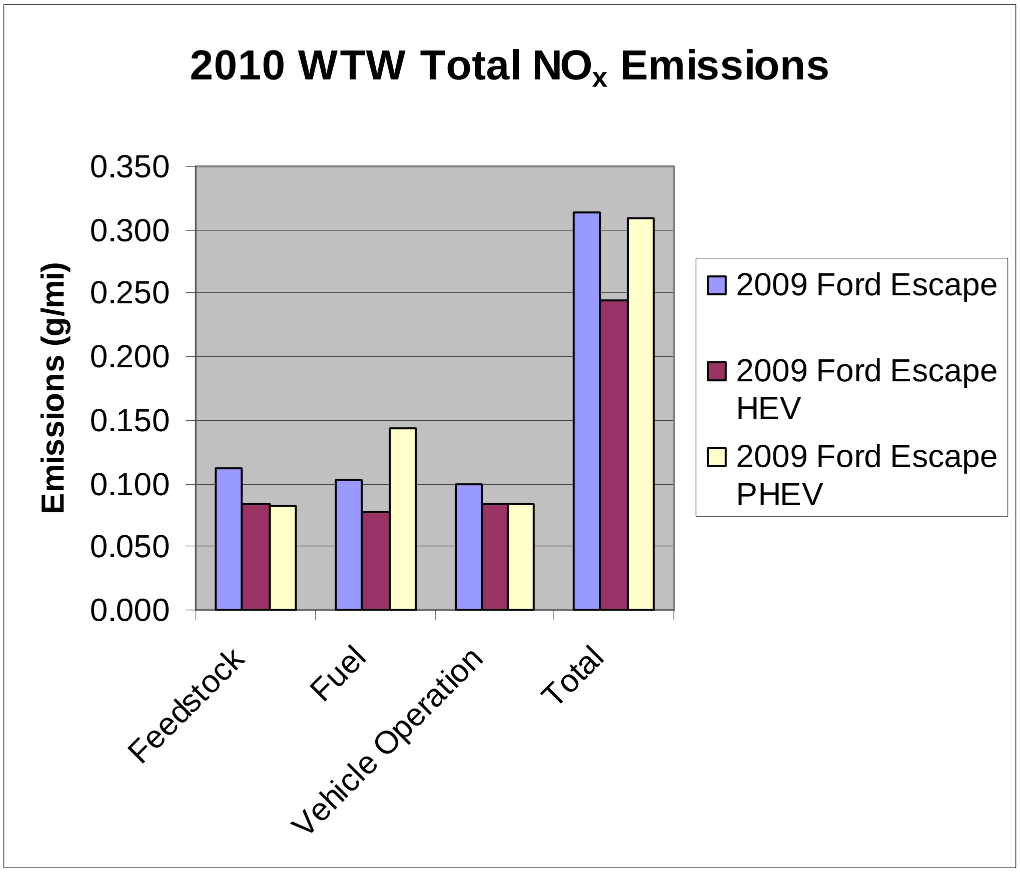


Figure 4.4.14 The estimated 2010 WTW total NO_x emissions by stage and in total for the baseline, HEV, and PHEV models.

The breakdown of urban NO_x indicates that the difference between the advanced models occurs primarily during the fuel production stage as shown in Table 4.4.20. The

PHEV model produces only about 0.007 grams/mile more than the PHEV model and about 0.003 grams/mile less than the baseline model. There is no appreciable difference between the advanced models in the feedstock and vehicle operation stages. Overall, the PHEV model produces about 0.008 grams/mile more and 0.013 grams/mile less NO_x emissions in urban centers than the HEV and baseline vehicles, respectively. Shown in Figure 4.4.15, the HEV is the best choice in terms of WTW urban NO_x emissions.

Table 4.4.20 Estimated 2010 WTW urban NO_x emissions for All stages

2010 WTW Urban NO_x Emissions	**Grams/mile**			
	Feedstock	**Fuel**	**Vehicle Operation**	**Total**
2009 Ford Escape	0.005	0.042	0.062	0.108
2009 Ford Escape HEV	0.004	0.032	0.052	0.087
2009 Ford Escape PHEV	0.004	0.039	0.052	0.095

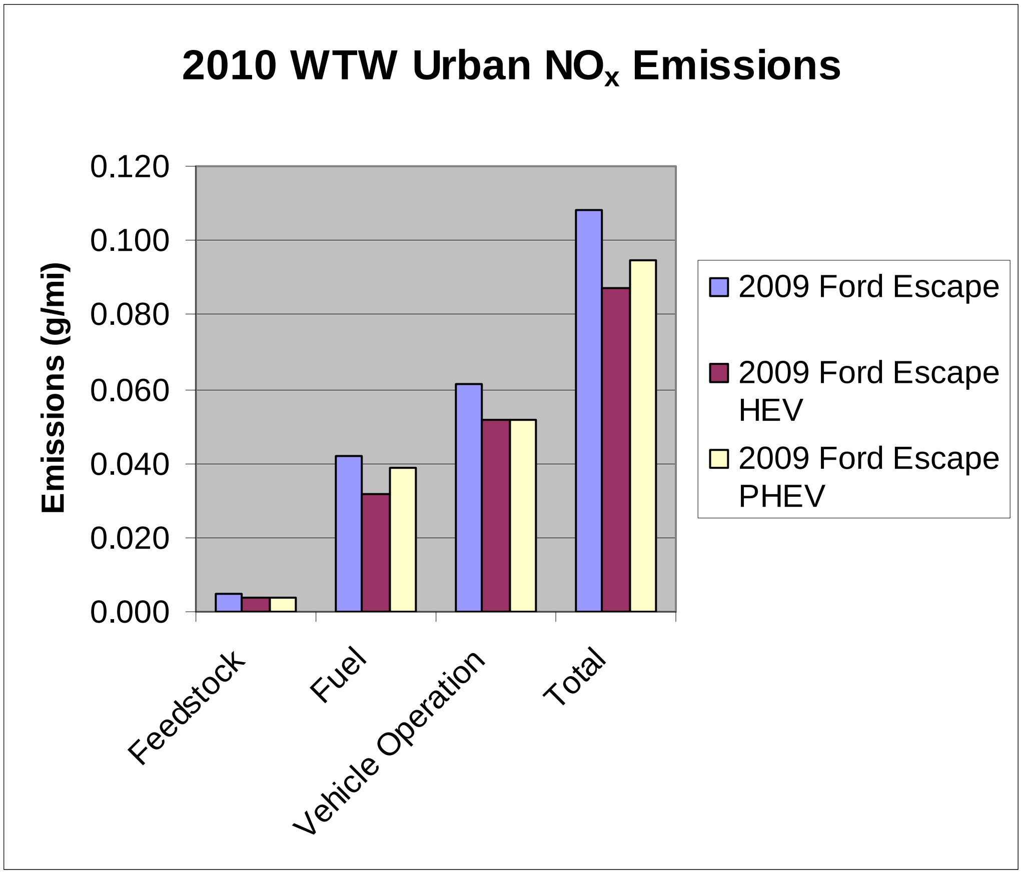


Figure 4.4.15 The estimated 2010 WTW urban NO_x emissions by stage and in total for the baseline, HEV, and PHEV models.

In terms of the relative changes of PM_{10} (particulate matter with aerodynamic diameter of 10 micrometers or less) and $PM_{2.5}$ (particulate matter with aerodynamic diameter of 2.5 micrometers or less) emissions, the HEV model produces in total about 15.0% less PM_{10} and 12.6% less $PM_{2.5}$ emissions while the PHEV model produces in total about 157.7% more PM_{10} and 85.6% more $PM_{2.5}$ emissions than the baseline model as shown in Table 4.4.21. In urban areas, the HEV model produces about 7.1% less PM_{10} and 7.3% less $PM_{2.5}$ emissions while the PHEV model produces about 13.2% more PM_{10} and 4.8% more $PM_{2.5}$ emissions than the baseline model. This indicates that the HEV model is more advantageous than the baseline model in terms of PM_{10} and $PM_{2.5}$ emissions in total and in urban centers. This also indicates that the PHEV model is more detrimental than the baseline model in terms of PM_{10} and $PM_{2.5}$ emissions.

Table 4.4.21 Estimated Relative Changes for 2010 WTW $PM_{10/2.5}$ Emissions

2010 WTW $PM_{10/2.5}$ Emissions (%, relative to 2009 Ford Escape)	**2009 Ford Escape HEV (Grid-Independent SI HEV: CG and RFG)**	**2009 Ford Escape Miles Plus conversion (Grid-Connected SI PHEV: CG and RFG)**
PM_{10}: Total	-15.0%	157.7%
PM_{10}: Urban	-7.1%	13.2%
$PM_{2.5}$: Total	-12.6%	85.6%
$PM_{2.5}$: Urban	-7.3%	4.8%

The breakdown of total PM10 emissions indicates that the primary difference between the advanced models occurs in the feedstock stage as shown in Table 4.4.22. The PHEV model produces about 0.134 grams/mile more PM10 emissions than the HEV model and about 0.131 grams/mile more than the baseline model during the feedstock stage. Additionally, the PHEV model produces about 0.009 grams/mile more PM10 emissions than the HEV and baseline models during the vehicle operation stage. During the fuel production stage, the advance models both produce about 0.010 grams/mile less PM10 emissions than the baseline model. Overall, the PHEV model produces about 0.143 grams/mile more and 0.131 grams/mile more PM10 emissions in total than the

HEV and baseline vehicles, respectively. Shown in Figure 4.4.16, the HEV is the best choice in terms of WTW total PM_{10} emissions.

Table 4.4.22 Estimated 2010 WTW Total PM_{10} Emissions for All Stages

2010 WTW Total PM_{10} Emissions	Grams/mile			
	Feedstock	Fuel	Vehicle Operation	Total
2009 Ford Escape	0.010	0.041	0.033	0.083
2009 Ford Escape HEV	0.007	0.031	0.033	0.071
2009 Ford Escape PHEV	0.141	0.031	0.042	0.214

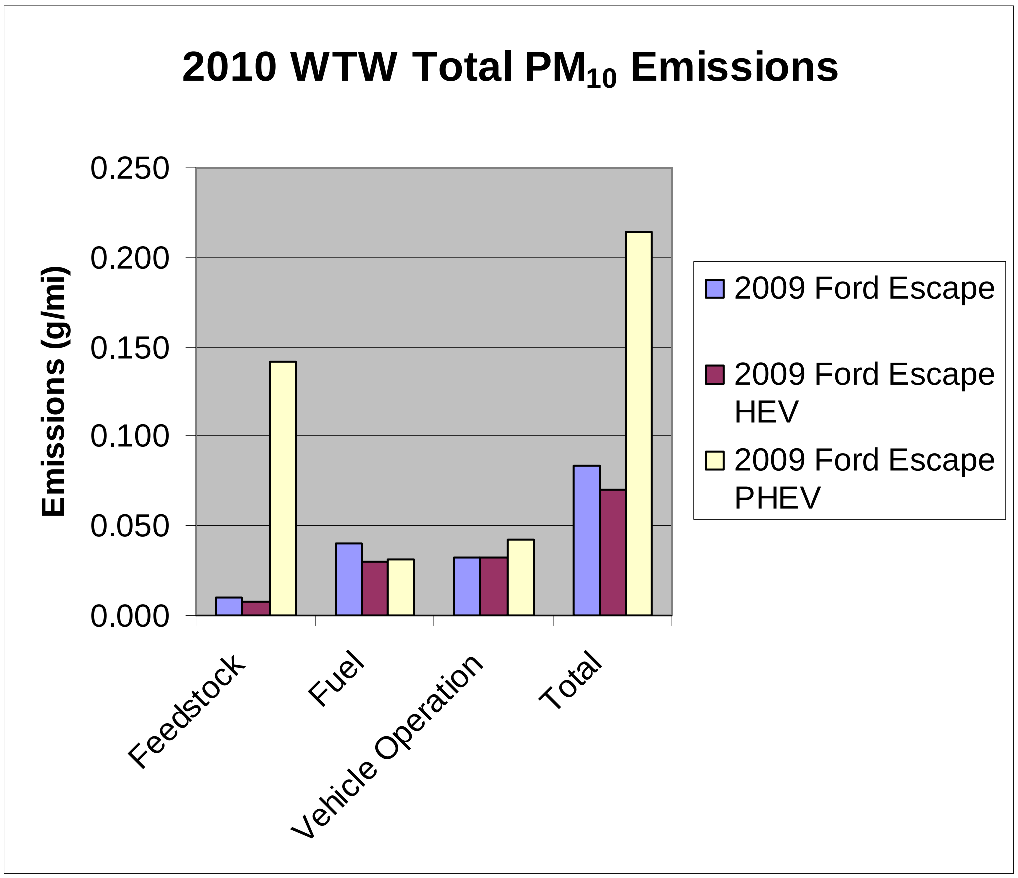


Figure 4.4.16 The estimated 2010 WTW total PM_{10} emissions by stage and in total for the baseline, HEV, and PHEV models.

The breakdown of urban PM_{10} emissions indicates that the only difference between the advanced models occurs during the vehicle operation stage as shown in Table 4.4.23. The PHEV model produces about 0.006 grams/mile more PM_{10} emissions than the HEV and baseline models during the vehicle operation stages. Both advanced models produce about 0.002 grams/mile less PM_{10} emissions than the baseline model during the fuel production stages. Overall, the PHEV model produces about 0.005 grams/mile more and 0.004 grams/mile more PM_{10} emissions in urban centers than the HEV and baseline vehicles, respectively. Note that the PM_{10} emissions produced by the PHEV model are significantly reduced in urban areas and more in line with the emissions produced by both the HEV and baseline models. Shown in Figure 4.4.17, the HEV is the best choice in terms of WTW urban PM_{10} emissions.

Table 4.4.23 Estimated 2010 WTW Urban PM_{10} Emissions for All Stages

2010 WTW Urban PM_{10} Emissions	**Grams/mile**			
	Feedstock	**Fuel**	**Vehicle Operation**	**Total**
2009 Ford Escape	0.000	0.008	0.020	0.029
2009 Ford Escape HEV	0.000	0.006	0.020	0.027
2009 Ford Escape PHEV	0.000	0.006	0.026	0.032

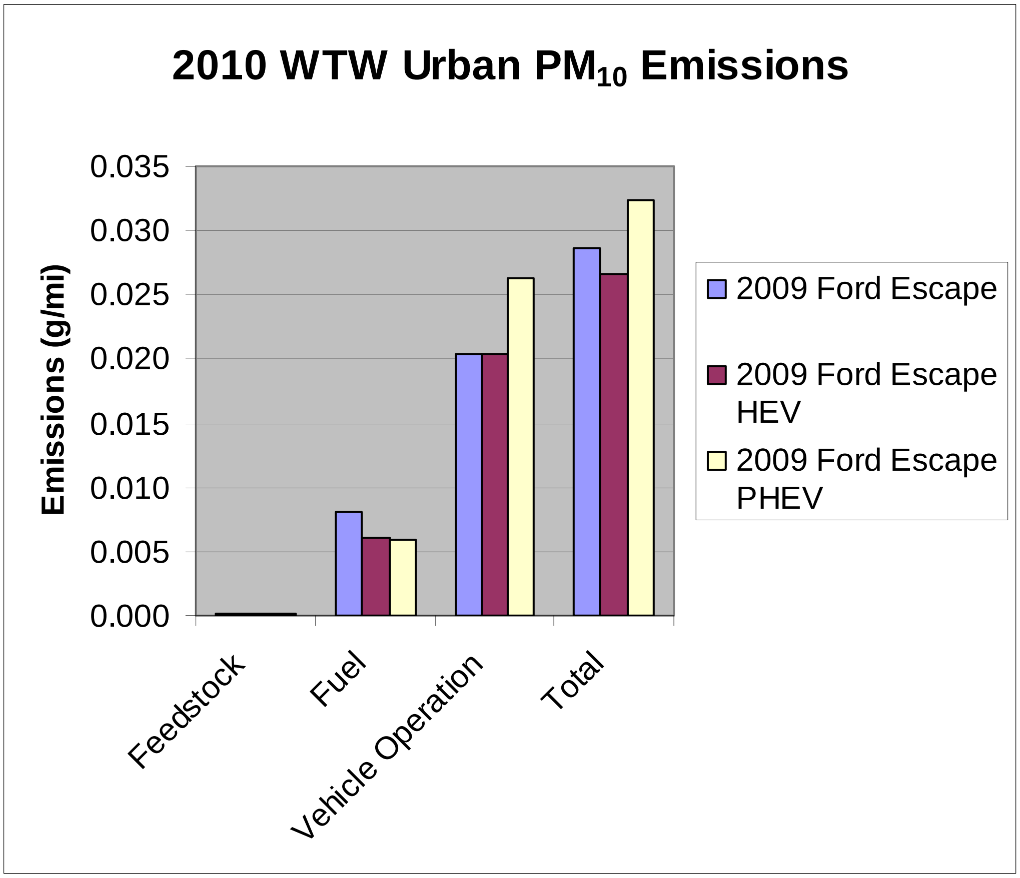


Figure 4.4.17 The estimated 2010 WTW urban PM_{10} emissions by stage and in total for the baseline, HEV, and PHEV models.

The breakdown of total $PM_{2.5}$ emissions indicates that the there are appreciable differences between the models during all stages as shown in Table 4.4.24. The most noticeable difference between the models occurs during the feedstock stage. The PHEV model produces about 0.033 grams/mile and 0.032 grams/mile more total $PM_{2.5}$ emissions than the HEV and baseline model, respectively. More subtle differences occur during the fuel production stage where the PHEV model produces only about 0.001 grams/mile more than the HEV model and about 0.003 grams/mile less than the baseline model. During the vehicle operation stage, the PHEV model produces about 0.004

grams/mile more than the HEV and baseline models. Overall, the PHEV model produces about 0.038 grams/mile more and 0.033 grams/mile more $PM_{2.5}$ emissions in total than the HEV and baseline vehicles, respectively. Shown in Figure 4.4.18, the HEV is the best choice in terms of WTW total $PM_{2.5}$ emissions.

Table 4.4.24 Estimated 2010 WTW Total $PM_{2.5}$ Emissions for All Stages

2010 WTW Total $PM_{2.5}$ Emissions	**Grams/mile**			
	Feedstock	**Fuel**	**Vehicle Operation**	**Total**
2009 Ford Escape	0.004	0.015	0.018	0.038
2009 Ford Escape HEV	0.003	0.011	0.018	0.033
2009 Ford Escape PHEV	0.036	0.012	0.022	0.071

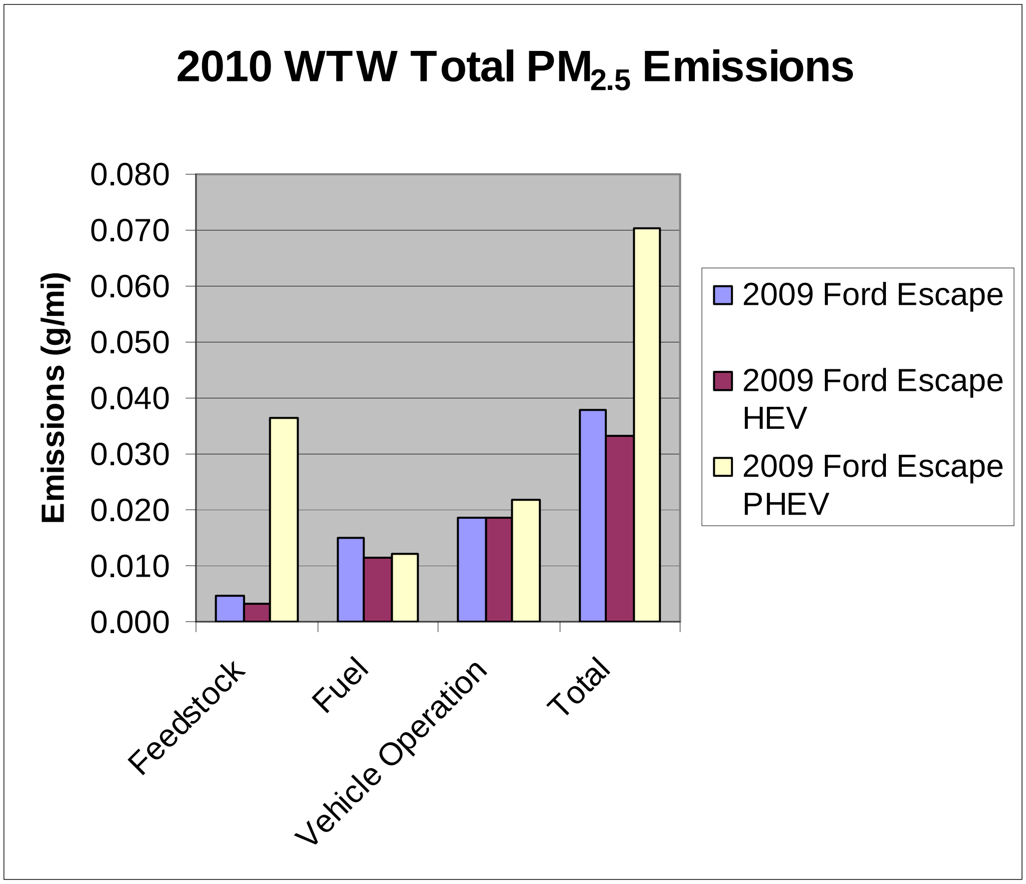


Figure 4.4.18 The estimated 2010 WTW total $PM_{2.5}$ emissions by stage and in total for the baseline, HEV, and PHEV models.

Shown in Table 4.4.25, the breakdown of urban $PM_{2.5}$ emissions indicates that there are less significant differences between the vehicle models than is seen in the total $PM_{2.5}$ emissions. During the vehicle operation stage, the PHEV model produces only about 0.002 grams/mile more than the HEV and baseline models in urban areas. During the fuel production stage, the PHEV model produces 0.001 grams/mile and 0.002 grams/mile less than the HEV and baseline models, respectively. Overall, the PHEV model produces about 0.002 grams/mile more and 0.001 grams/mile more $PM_{2.5}$

emissions in urban centers than the HEV and baseline vehicles, respectively. Shown in Figure 4.4.19, the HEV is the best choice in terms of WTW urban $PM_{2.5}$ emissions.

Table 4.4.25 Estimated 2010 WTW Urban $PM_{2.5}$ Emissions for All Stages.

2010 WTW Urban $PM_{2.5}$ Emissions	Grams/mile			
	Feedstock	Fuel	Vehicle Operation	Total
2009 Ford Escape	0.000	0.005	0.012	0.016
2009 Ford Escape HEV	0.000	0.004	0.012	0.015
2009 Ford Escape PHEV	0.000	0.003	0.014	0.017

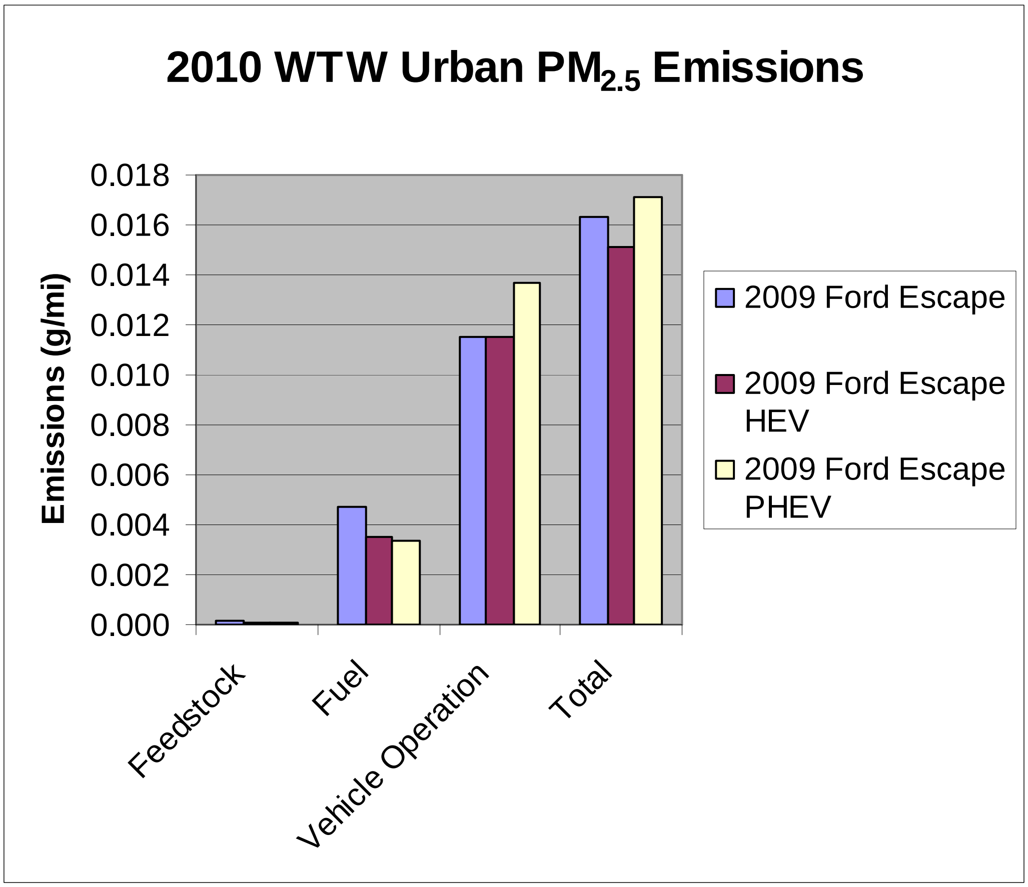


Figure 4.4.19 The estimated 2010 WTW urban $PM_{2.5}$ emissions by stage and in total for the baseline, HEV, and PHEV models.

In terms of the relative changes of SOx emissions, the HEV model produces in total about 24.6% less SOx emissions while the PHEV model produces in total about 166.0% more SOx emissions than the baseline model as shown in Table 4.4.26. In urban areas, the HEV model produces about 24.6% less SOx emissions while the PHEV model produces about 62.5% more SOx emissions than the baseline model. This indicates that the HEV model is more advantageous than the baseline model in terms of SOx emissions in total and in urban centers. This also indicates that the PHEV model is more detrimental than the baseline model in terms of SOx emissions.

Table 4.4.26 Estimated Relative Changes for 2010 WTW SO_x Emissions

2010 WTW SO_x Emissions (%, relative to 2009 Ford Escape)	**2009 Ford Escape HEV (Grid-Independent SI HEV: CG and RFG)**	**2009 Ford Escape Miles Plus conversion (Grid-Connected SI PHEV: CG and RFG)**
SO_x: Total	-24.6%	166.0%
SO_x: Total	-24.6%	62.5%

The breakdown of total SO_x emissions indicates that the primary difference between the models occurs during the fuel production stage as shown in Table 4.4.27. The PHEV model produces about 0.214 grams/mile more SO_x emissions than the HEV model and about 0.197 grams/mile more than the baseline model during the fuel production stage. During the feedstock stage, the PHEV model produces about 0.002 grams/mile more than the HEV model and about 0.007 grams/mile less than the baseline model. During the vehicle operation stage, the PHEV model produces about 0.001 grams/mile less and 0.003 grams/mile less than the HEV and baseline model, respectively. Overall, the PHEV model produces about 0.216 grams/mile more and 0.188 grams/mile more SO_x emissions in total than the HEV and baseline vehicles, respectively. Shown in Figure 4.4.20, the HEV is the best choice in terms of WTW total SO_x emissions.

Table 4.4.27 Estimated 2010 WTW Total SO_x Emissions for All Stages

2010 WTW Total SO_x Emissions	Grams/mile			
	Feedstock	Fuel	Vehicle Operation	Total
2009 Ford Escape	0.037	0.070	0.006	0.113
2009 Ford Escape HEV	0.028	0.053	0.004	0.085
2009 Ford Escape PHEV	0.030	0.267	0.003	0.301

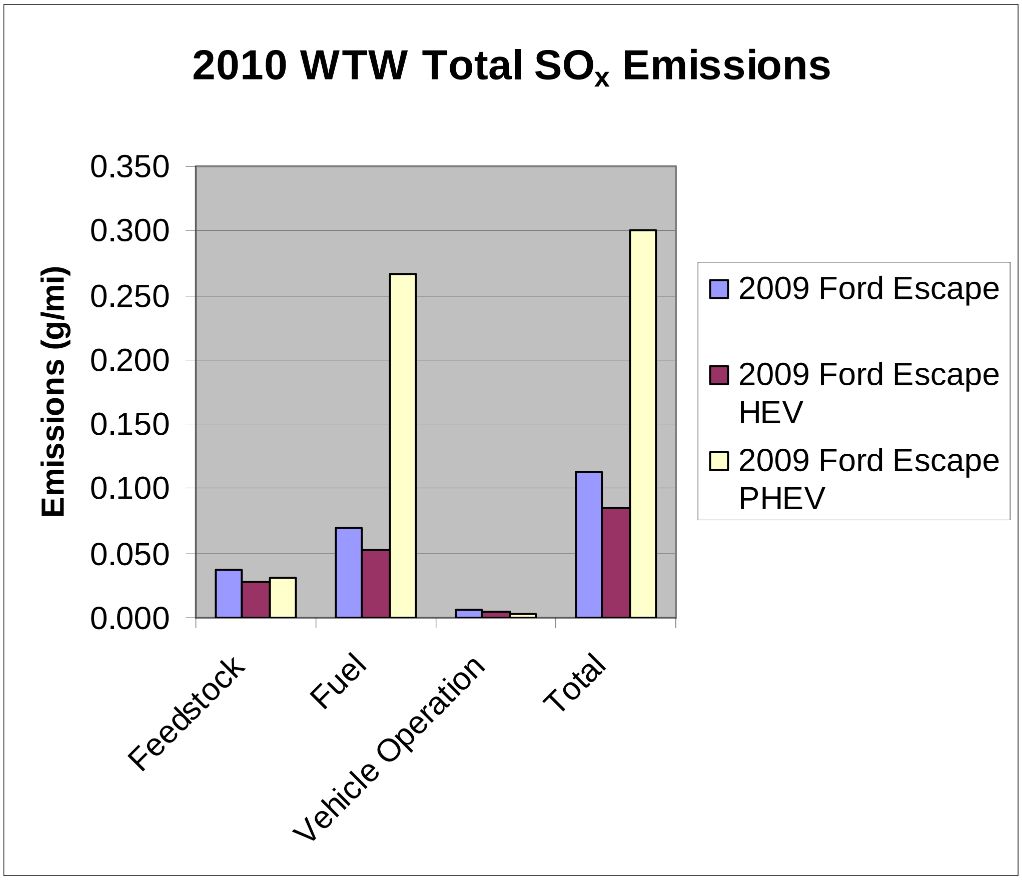


Figure 4.4.20 The estimated 2010 WTW total SO_x emissions by stage and in total for the baseline, HEV, and PHEV models.

The breakdown of urban SO_x emissions indicates that the primary difference between the models occurs during the fuel production stage as shown in Table 4.4.28. The PHEV model produces about 0.032 grams/mile more SO_x emissions than the HEV model and about 0.025 grams/mile more than the baseline model during the fuel production stage. During the feedstock stage, the PHEV and HEV models produce about 0.001 grams/mile less than the baseline model. During the vehicle operation stage, the PHEV model produces about 0.001 grams/mile less and 0.002 grams/mile less than the HEV and baseline model, respectively. Overall, the PHEV model produces about 0.032

grams/mile more and 0.023 grams/mile more SO_x emissions in urban centers than the HEV and baseline vehicles, respectively. Shown in Figure 4.4.21, the HEV is the best choice in terms of WTW urban SO_x emissions.

Table 4.4.28 Estimated 2010 WTW Urban SO_x Emissions for All Stages

2010 WTW Urban SO_x Emissions	Grams/mile			
	Feedstock	Fuel	Vehicle Operation	Total
2009 Ford Escape	0.003	0.029	0.004	0.036
2009 Ford Escape HEV	0.002	0.022	0.003	0.027
2009 Ford Escape PHEV	0.002	0.054	0.002	0.059

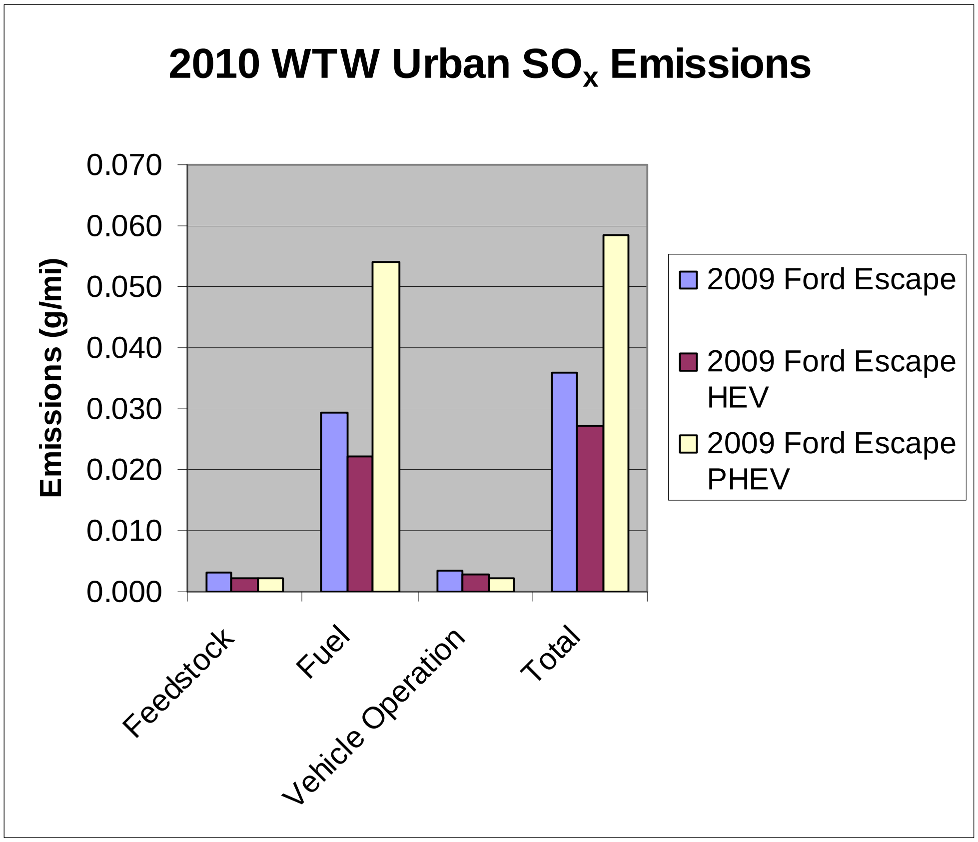


Figure 4.4.21 The estimated 2010 WTW urban SO_x emissions by stage and in total for the baseline, HEV, and PHEV models.

It is important to look at both the total emissions in each category as well as the urban emissions. The effect of urban emissions is often compounded by the amount of vehicles operating in such a close area. The total emissions allow us to gauge the effectiveness of a vehicle-fuel combination. Over all the emissions categories, the HEV model always performs better than the baseline model. Considerable improvements are indicated in all categories with the exception of CO production. The PHEV model, however, has both advantages and disadvantages compared to the baseline model. Significant improvements are indicated in all GHG categories, all VOC emissions, and urban NO_x emissions. Modest improvements are indicated in CO emissions and total NO_x emissions. Disadvantages to the PHEV model include significant increased production of PM_{10}, $PM_{2.5}$, and SO_x emissions. It seems that, due to this emissions analysis, that the HEV model is superior. However, if the electricity generation mixes shift away from coal to cleaner forms of electricity production in the future, this conclusion could change.

Cost Analysis

Cost analysis is often used to evaluate the desirability of a given decision by weighing the costs associated with one decision with the costs associated with an alternative decision. In this case, the alternative would be the purchase of an Escape HEV or Escape PHEV rather than a conventional Escape. In this case study, a simplified cost analysis building on the commonly perceived costs associated with the purchase and operation of a vehicle is used to determine the most practical choice for a daily commuting vehicle between the three options. The consumer is assumed to have funds ample enough to purchase and maintain the most expensive option. Any unused funds will be rolled into savings and earn interest over the allotted time. The vehicles are assumed to operate for an 8 year period with 100,000 miles driven. The costs considered in this analysis include vehicle purchase price, infrastructure costs, fuel costs, depreciated vehicle value, and interest earned on capital and fuel savings. Changes in interest rates and fuel costs will also be considered in the purchase decision.

Consumers are more likely to base their purchase decisions on the cost of a vehicle more than any other factor mentioned in this discussion. Each Escape variant contains a near identical package of additional features and functions in order to measure the primary differences in cost between each vehicle technology. The MSRP of a 2009 Ford Escape XLT FWD is $23,455.[11] The MSRP of a 2009 Ford Escape Hybrid FWD is $29,645.[10] The cost of the Miles Plus conversion by Hybrids Plus (Now known as EETrex) is approximately $24,000. According to EETrex, this high cost includes developmental costs incurred during the development of their Li-ion battery system and is only intended for the few promotional fleet models produced thus far. The cost of the battery is approximately a quarter of this cost, or $6,000. With this in mind, the retail price of a conversion is estimated to be approximately $10,000 which is in the range of costs for other similar conversions performed by other companies. Thus, the estimated full cost of the 2009 Ford Escape Hybrid FWD with Miles Plus conversion is approximately $39,645.

Taxes along with vehicle registration and document fees are often paid in addition to the MSRP of a vehicle. These fees will vary state to state. Assuming the vehicle purchase is made in Tennessee and the vehicle registration and document fees are the same between the Escape and HEV, only the tax on the buying price will differ between the two vehicles. In Tennessee, the maximum sales tax is 9.75% which is applied to the MSRP in this case. For the Escape, the maximum sales tax is approximately $2,290 to the purchase price. For the HEV, the maximum sales tax is approximately $2,890. For the PHEV, the maximum sales tax for the vehicle purchase and conversion is approximately $3,870.

Tax credits for hybrid vehicles have been implemented to encourage consumers to buy consciously. However, many of these federal tax credits were available only for a limited time. For example, the available credit for newly purchased 2009 HEV models was originally $3,000.[17] As of 1/4/10, the credit gradually reduced over time from $3,000 if purchased before 4/1/09 to $1,500 if purchased on 4/1/09 and on or before 9/30/09 and $750 if purchased on 10/1/09 and on or before 3/31/10.[18] Currently this federal tax credit has been phased out. Another example of federal tax credits was recently implemented in the American Recovery and Reinvestment Act of 2009. This credit is equal to 10% of the cost of converting a vehicle to a qualified plug-in electric drive motor vehicle that is placed in service after 2/17/09. The maximum credit is $4,000 and the credit will be applicable through 2011. For more information on hybrid tax credits, search the IRS website. State tax credits for hybrid vehicles have also been implemented in some states. For example, an income tax credit of 10% with a maximum of $2,500 is available for a car conversion to use an “alternative fuel” including electricity in the state of Georgia.[20] For the purpose of this simplified CBA, no state tax credits are implemented since this case study involves a purchase decision in Tennessee which does not currently have any tax credits. Additionally, the only federal tax credit implemented here is the conversion kit credit for 10% of the conversion cost since this is the only active program at this time.

The Escape and Escape HEV have the benefit of not requiring additional infrastructure. The PHEV variant will require additional infrastructure depending on the scenario in which they will be charged. A charger and possibly a new meter if time of use (TOU) charging rates apply are the main necessities. Assuming a residential charging scenario, the total costs for the infrastructure for a Level 1 charging station are estimated to be approximately $900.[22] This includes labor, material, and permit infrastructure costs associated with a Level 1 residential charging scheme that includes a charge cord and residential circuit installation (20A branch circuit, 120VAC/1-Phase). Other charging schemes for residential and commercial charging systems can cost between $800 and $2,200 per charger depending on the charger type and quantity installed. Associated costs can be expected to increase if PHEV technology becomes the prevalent technology due to upgrades to the grid which will pass on their costs to the consumer.

By combining all direct costs associated with a purchase, a principal amount of savings is determined for each purchase decision. Shown in Table 4.4.29, all costs associated with a purchase decision yield principal savings that accrue interest over an 8 year period. Included in the capital cost of the vehicles is the MSRP and applicable conversion cost. The maximum Tennessee state sales tax of 9.75% is applied to the capital cost of the vehicle. Tax credits and extra infrastructure costs associated with the vehicles are applied to the capital cost and sales tax to obtain the total cost or the purchase. The maximum total cost of any purchase decision is approximately $43,400 and is associated with the purchase of a Ford Escape PHEV. Thus, a decision to purchase a Ford Escape PHEV would amount to no principal savings. A decision to purchase a Ford Escape HEV would save the consumer a principal amount of approximately \$10,900. A decision to purchase a Ford Escape would save the consumer a principal amount of approximately \$17,700. These principal savings will grow over 8 years using the compound interest formula

$$A = P(1+i)^t , \tag{4.3}$$

where A is the amount after time t, P is the principal amount, i is the annual interest rate, and t is the time in years. Assuming a flat interest rate of 2% compounded annually over 8 years, a purchase of the Ford Escape would net approximately \$20,700 in savings while a purchase of the Ford Escape HEV would net approximately \$12,700 in savings. If instead the interest rate shifted to a flat 4% annually, a purchase of the Ford Escape would net approximately \$24,200 in savings while a purchase of the Ford Escape HEV would net approximately \$14,900 in savings. If instead the interest rate shifted to a flat 8% annually, a purchase of the Ford Escape would net approximately \$32,700 in savings while a purchase of the Ford Escape HEV would net approximately \$20,100 in savings.

Table 4.4.29 Direct Costs and Savings Associated with the Purchase of an Escape, Escape HEV, and Escape PHEV

	2009 Ford Escape XLT FWD I4	2009 Ford Escape Hybrid FWD	2009 Ford Escape Hybrid FWD Miles Plus conversion
MSRP:	$ 23,455	$ 29,645	$ 29,645
Estimated Total Conversion cost:	$ -	$ -	$ 10,000
Capital Cost:	$ 23,455	$ 29,645	$ 39,645
Sales Tax (9.75%):	$ 2,287	$ 2,890	$ 3,865
Tax Credit:	$ -	$ -	$ (1,000)
Infrastructure Cost:	$ -	$ -	$ 900
Total Cost:	$ 25,742	$ 32,535	$ 43,410
Principal Savings:	$ 17,669	$ 10,875	$ -
Value of Purchase Savings with 2% Compound Interest After 8 Years:	$ 20,701	$ 12,742	$ -
Value of Purchase Savings with 4% Compound Interest After 8 Years:	$ 24,181	$ 14,883	$ -
Value of Purchase Savings with 8% Compound Interest After 8 Years:	$ 32,703	$ 20,129	$ -
Maximum total cost:			$ 43,410

The cost of fuel is another consideration for consumers when purchasing a vehicle, but this is often hard to account for due to the variability of fuel prices. In this cost analysis, a stable fuel cost is considered for 8 years of driving 100,000 miles with fuel usage consistent with the models above. Assuming a cost of $3 per gallon of the gasoline blend and $0.097 per kWh of electricity, the approximate cost of fuel is calculated for all variants. The Escape is estimated to spend approximately $11,800 on the gasoline blend. The HEV is estimated to spend approximately $8,920 on the gasoline blend. The PHEV is estimated to spend approximately $8,630 on the gasoline blend and electricity from the grid.

The fuel costs of associated with each vehicle technology are considered here to be the fixed periodic costs of vehicle operation. In this analysis, the consumer is assumed to save the difference between the most expensive fuel and fuel cost associated with the chosen vehicle every year. The fuel savings are deposited at the beginning of the next year and will earn interest annually. In Table 4.4.30, these yearly savings will compound to a total savings value for each vehicle technology after 8 years using the formula

$$A = \sum_{n=0}^{7} P(1+i)^{n} \ , \tag{4.4}$$

where *A* is the amount accrued, *P* is the annual principle, *i* is the interest rate, and *n* is the number of periods. The Escape will not contribute to the consumer's fuel savings as it has the most expensive fuel cost. Assuming a flat interest rate of 2% compounded annually with each periodic savings, the fuel costs for a Ford Escape HEV would net approximately $3,130 in savings while the fuel costs for the Ford Escape PHEV would net approximately $3,500 in savings. If the interest rate shifted to a flat 4% annually, the fuel costs for a Ford Escape HEV would net approximately $3,360 in savings while the fuel costs for the Ford Escape PHEV would net approximately $3,760 in savings. If the interest rate shifted to a flat 8% annually, the fuel costs for a Ford Escape HEV would net approximately $3,880 in savings while the fuel costs for the Ford Escape PHEV would net approximately $4,340 in savings.

Table 4.4.30 Estimated Annual Costs and Savings Associated with Purchasing Fuel for an Escape, Escape HEV, and Escape PHEV over an 8 Year Period

	2009 Ford Escape XLT FWD I4	**2009 Ford Escape Hybrid FWD**	**2009 Ford Escape Hybrid FWD Miles Plus conversion**
Gasoline blend:	$ 11,830	$ 8,915	$ 7,231
Electricity:	$ -	$ -	$ 1,333
Fuel Costs:	$ 11,830	$ 8,915	$ 8,564
Fuel Savings:	$ -	$ 2,914	$ 3,266
Fuel Savings Per Year:	$ -	$ 364	$ 408
Value of Fuel Savings with 2% Compound Interest On Periodic Investments After 8 Years:	$ -	$ 3,127	$ 3,504
Value of Fuel Savings with 4% Compound Interest On Periodic Investments After 8 Years:	$ -	$ 3,357	$ 3,761
Value of Fuel Savings with 8% Compound Interest On Periodic Investments After 8 Years:	$ -	$ 3,875	$ 4,342
Maximum Total Fuel Cost:	$ 11,830		

Depreciation of the vehicle is also taken into account using the MSRP and conversion cost of each vehicle. The value of each vehicle after 8 years still contributes to the overall worth of the consumer. As shown in Table 4.4.31, the Escape is estimated to have a depreciated value of approximately $6,120.[23] The Escape HEV is estimated to have a depreciated value of approximately $7,730.[23] Since the Escape PHEV is a conversion of the HEV model it is difficult to determine how much if any value is added to the car by the conversion. In this case study, the depreciation values for the PHEV does not include any part of the after market conversion cost. The Escape PHEV is estimated to have the same depreciated value as the Escape HEV.

Table 4.4.31 Estimated Vehicle Values Associated with Depreciation over an 8 Year Period

	2009 Ford Escape XLT FWD I4	2009 Ford Escape Hybrid FWD	2009 Ford Escape Hybrid FWD Miles Plus conversion
Value After 1 Year:	$ 17,591	$ 22,234	$ 22,234
Value After 2 Years:	$ 15,480	$ 19,566	$ 19,566
Value After 3 Years:	$ 13,623	$ 17,218	$ 17,218
Value After 4 Years:	$ 11,715	$ 14,807	$ 14,807
Value After 5 Years:	$ 9,958	$ 12,586	$ 12,586
Value After 6 Years:	$ 8,464	$ 10,698	$ 10,698
Value After 7 Years:	$ 7,195	$ 9,094	$ 9,094
Value After 8 Years:	$ 6,116	$ 7,730	$ 7,730

Insurance rates are another periodic cost to consider when purchasing a vehicle. Some insurance companies such as Travelers Insurance claim to extend a discount of 10% to customers if they are insuring a hybrid vehicle. However, most of these discounts have fine print associated with them such as “a discount of up to 10 percent applies only to certain coverages” and “the discount may not be available in all states and is subject to individual eligibility.”[24] It seems that these types of discounts are a simple marketing gimmick and have no real value. After talking with several agents of various insurance companies including Allstate and State Farm, it appears that the algorithms used to determine rates for all coverage types are dependent on many more factors than simply the cost of the vehicle and type. Thus, the rates can vary from person to person despite driving the exact same vehicle. According to a State Farm representative, customers should expect to pay more for comprehensive and collision coverages of hybrids since the initial rates are often based on the MSRP of the vehicle as well as replacement part costs. Additionally, the current expected costs between the HEV and PHEV in this study would not vary according to State Farm’s coverage since the conversion was done by a third party and the initial rates are determined using the MSRP for the vehicle. This would change if the PHEV models were produced directly by Ford. Other coverages vary in price between companies in large part due to a multitude of factors including age, driving history, credit history, job, and location. Because of this variability and the different coverages available for different policies, it is not practical to ascertain a difference between coverage for each of the vehicles especially since none of the insurance companies mentioned here publish their algorithms for determining insurance rates.

During vehicle operation, routine maintenance and repairs will be required by all of the vehicles. In this simplified CBA, these costs are assumed to be approximately equivalent between all three vehicle technologies. This assumption, however, is most likely going to be generous to the Escape as the Escape HEV and PHEV models will most likely require less maintenance due to transmission and engine differences. There is very little information on routine maintenance of the Escape HEV and PHEV since they are fairly new technologies. For this analysis, no appreciable gain or loss is estimated for routine maintenance and repairs.

Compiling the overall savings and value of a purchase decision in relation to the alternatives allows for a basis of comparison between the possible purchases. Shown in Table 4.4.32, the estimated values of the three purchase decisions assuming 2% interest indicate that the Ford Escape will offer the highest total value after 8 years with an approximate value of $26,800. The Ford Escape HEV is the next best alternative and will cost approximately $3,200 more than the Ford Escape. The Ford Escape PHEV is the worst alternative and will cost approximately $15,600 more than the Ford Escape and approximately $12,400 more than the Ford Escape HEV.

Table 4.4.32 Estimated Values of Purchase Decisions after an 8 Year Period with 2% Interest

	2009 Ford Escape XLT FWD I4	**2009 Ford Escape Hybrid FWD**	**2009 Ford Escape Hybrid FWD Miles Plus conversion**
Value of Purchase Savings with 2% Compound Interest After 8 Years:	$ 20,701	$ 12,742	$ -
Value of Fuel Savings with 2% Compound Interest On Periodic Investments After 8 Years:	$ -	$ 3,127	$ 3,504
Depreciated Value After 8 Years:	$ 6,116	$ 7,730	$ 7,730
Total value after 8 years:	$ 26,817	$ 23,598	$ 11,233

Shown in Table 4.4.33, the Ford Escape will still offer the highest total value after 8 years if the interest rate increased to 4% with an approximate value of $30,300. The Ford Escape HEV is still the next best alternative and will cost approximately $4,300 more than the Ford Escape. The Ford Escape PHEV is the worst alternative and will cost approximately $18,800 more than the Ford Escape and approximately $14,500 more than the Ford Escape HEV.

Table 4.4.33 Estimated Values of Purchase Decisions after an 8 Year Period with 4% Interest

	2009 Ford Escape XLT FWD I4	**2009 Ford Escape Hybrid FWD**	**2009 Ford Escape Hybrid FWD Miles Plus conversion**
Value of Purchase Savings with 4% Compound Interest After 8 Years:	$ 24,181	$ 14,883	$ -
Value of Fuel Savings with 4% Compound Interest On Periodic Investments After 8 Years:	$ -	$ 3,357	$ 3,761
Depreciated Value After 8 Years:	$ 6,116	$ 7,730	$ 7,730
Total value after 8 years:	$ 30,296	$ 25,969	$ 11,491

Shown in Table 4.4.34, the Ford Escape will still offer the highest total value after 8 years if the interest rate increased to 8% with an approximate value of $38,800. The Ford Escape HEV is still the next best alternative and will cost approximately $7,100 more than the Ford Escape. The Ford Escape PHEV is the worst alternative and will cost approximately $26,700 more than the Ford Escape and approximately $19,600 more than the Ford Escape HEV.

Table 4.4.34 Estimated Values of Purchase Decisions after an 8 Year Period with 8% Interest

	2009 Ford Escape XLT FWD I4	2009 Ford Escape Hybrid FWD	2009 Ford Escape Hybrid FWD Miles Plus conversion
Value of Purchase Savings with 8% Compound Interest After 8 Years:	$ 32,703	$ 20,129	$ -
Value of Fuel Savings with 8% Compound Interest On Periodic Investments After 8 Years:	$ -	$ 3,875	$ 4,342
Depreciated Value After 8 Years:	$ 6,116	$ 7,730	$ 7,730
Total value after 8 years:	$ 38,819	$ 31,733	$ 12,072

If the price of gas rises to a stable $4 per gallon of gasoline from the previous estimations of a stable $3 per gallon of gasoline with 2% interest on savings, then the value of the purchase decision after 8 years changes too. With higher gasoline prices, the fuel savings per year for the hybrid vehicles increases which results in a shift in the total value of the purchase decision. Shown in Table 4.4.35, the Ford Escape will still offer the highest total value after 8 years if the fuel price is increased to $4 per gallon of gasoline with an approximate value of $20,700. The Ford Escape HEV is still the next best alternative, but the cost shrinks to approximately $2,200 more than the Ford Escape. This cost is down approximately $1,000 from the cost difference under a stable fuel cost of $3 per gallon. The Ford Escape PHEV is the worst alternative, but the cost shrinks to approximately $13,900 more than the Ford Escape and approximately $11,800 more than the Ford Escape HEV. This cost is down approximately $1,600 with respect to the Ford

Escape and $600 with respect to the Ford HEV from the cost difference under a stable fuel cost of $3 per gallon.

Table 4.4.35 Estimated Values of Purchase Decisions after an 8 Year Period with 2% Interest and a $4 per Gallon of Gasoline

	2009 Ford Escape XLT FWD I4	**2009 Ford Escape Hybrid FWD**	**2009 Ford Escape Hybrid FWD Miles Plus conversion**
Value of Purchase Savings with 2% Compound Interest After 8 Years:	$ 20,701	$ 12,742	$ -
Value of Fuel Savings with 2% Compound Interest On Periodic Investments After 8 Years:	$ -	$ 4,169	$ 5,148
Depreciated Value After 8 Years:	$ 6,116	$ 7,730	$ 7,730
Total value after 8 years:	$ 26,817	$ 24,640	$ 12,878

From the standpoint of a simple cost analysis, the best possible choice for a consumer is the choice that will have the highest value after 8 years. If the fuel costs are assumed to be stable at $3 per gallon, an increase in interest rates will not affect the purchase decision of the consumer as shown in Figure 4.4.22, and the purchase of a Ford Escape will be the best decision. However, if the cost of gasoline were to increase to a stable $6.09 per gallon over 8 years, the change in fuel cost would start to effect the purchase decision at 2% interest as seen in Figure 4.4.23. At this point the Ford Escape Hybrid would be on par with the Ford Escape in terms of value after 8 years. It would take the cost of gasoline increasing to an unlikely $23.50 per gallon over 8 years to put the Escape PHEV on par with the Escape Hybrid at 2% interest as seen in Figure 4.4.24. Changes in electricity costs would alter the value of the Escape PHEV, but would not affect the purchase decisions as drastically as a change in the cost of gasoline. In Table 4.4.36, the break-even prices for gasoline between the alternative vehicles and the Ford Escape suggest that an increase in gas prices can affect the purchase decision at the considered interest rates.

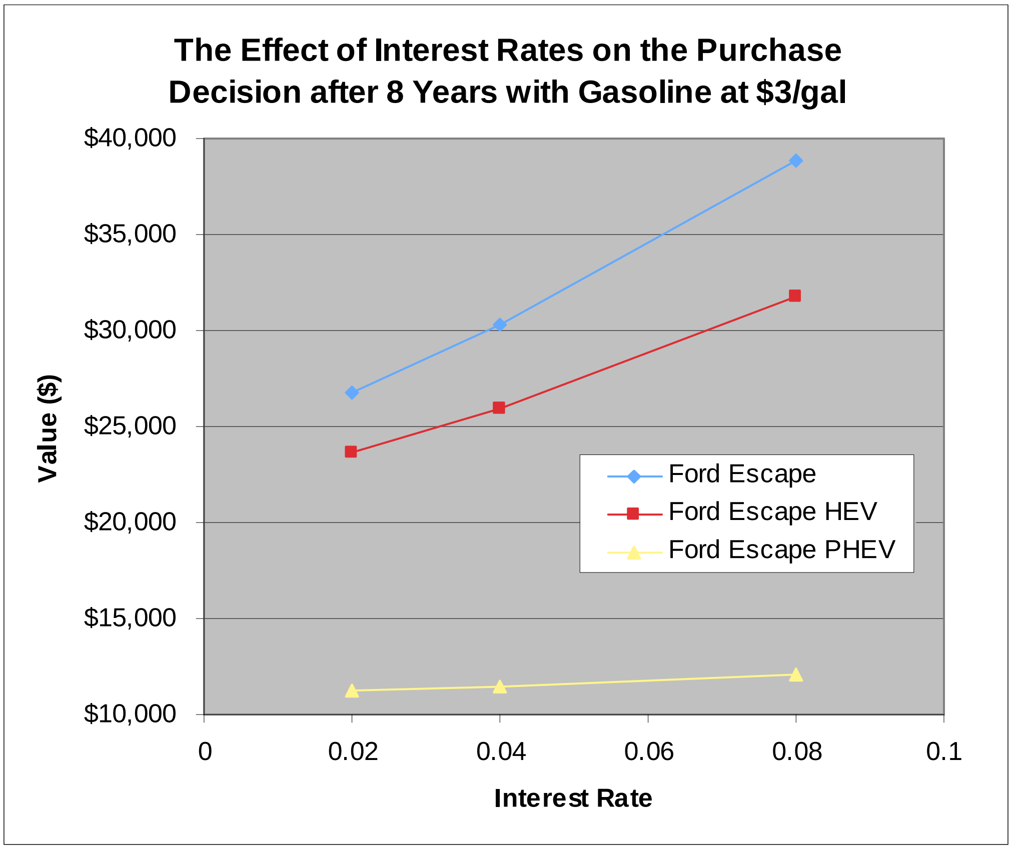


Figure 4.4.22 The effect of interest rates on the value of a purchase decision after 8 years assuming stable fuel costs of \$3/gal of gasoline blend and \$0.097/KWh.

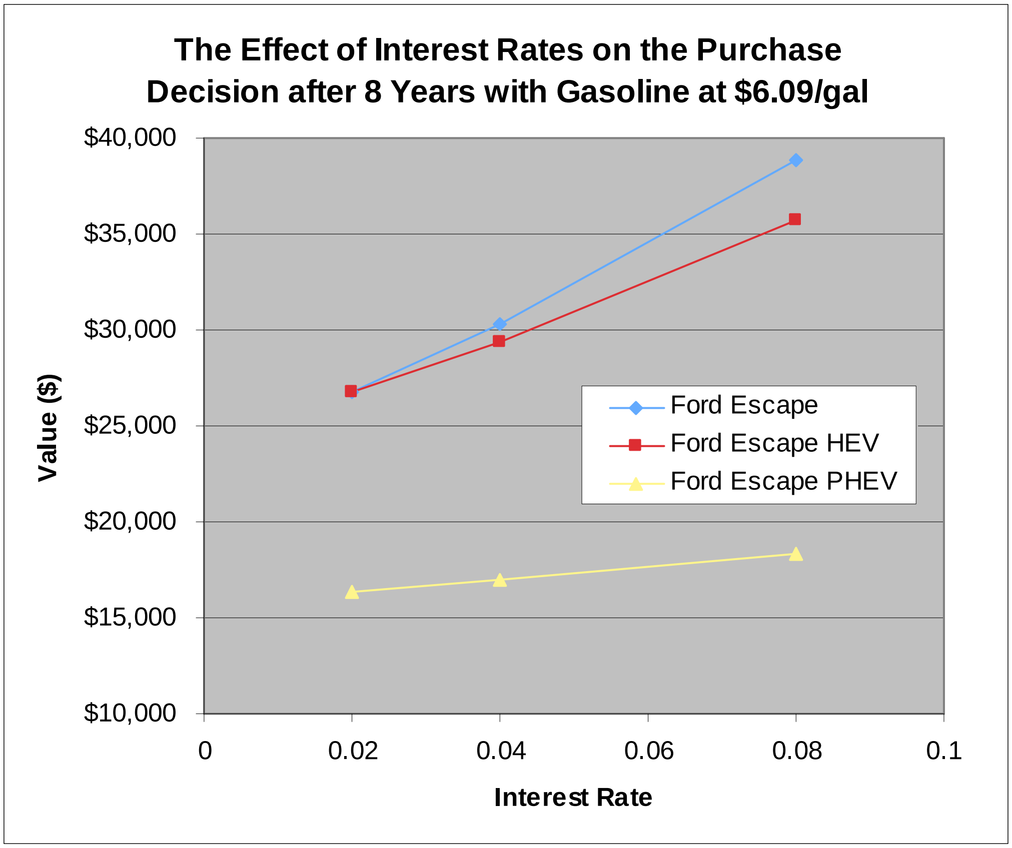


Figure 4.4.23 The effect of interest rates on the value of a purchase decision after 8 years assuming stable fuel costs of $6.09/gal of gasoline blend and $0.097/KWh.

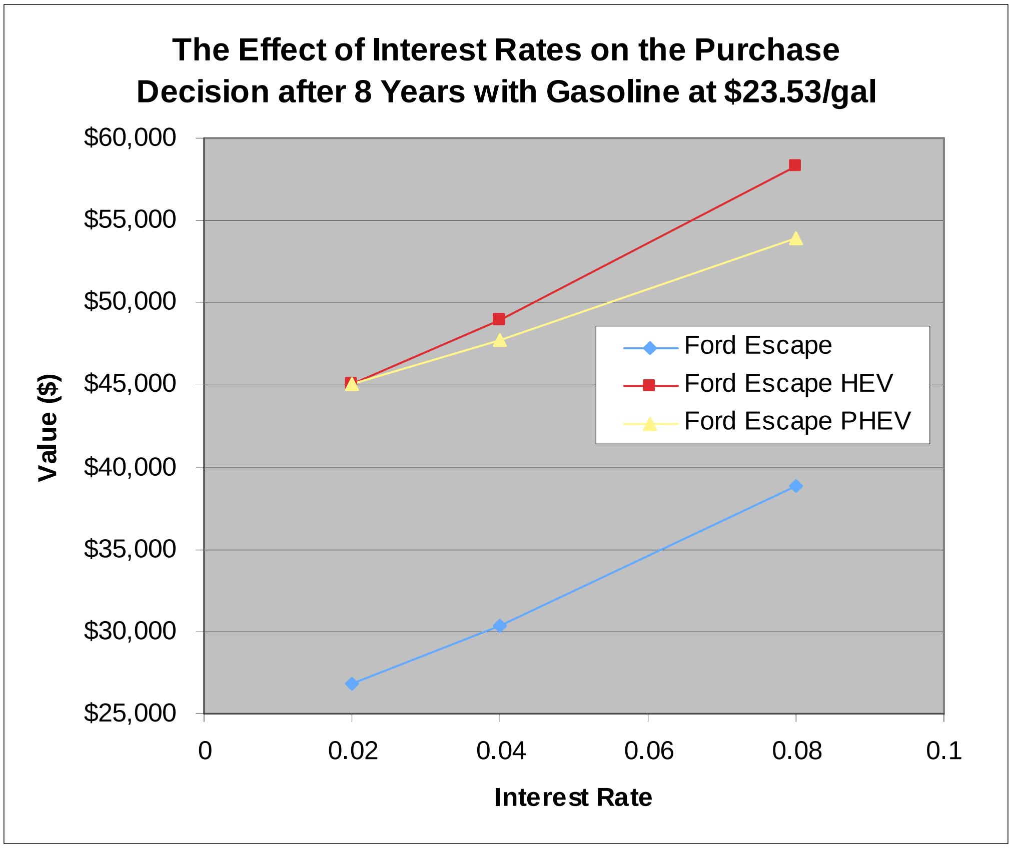


Figure 4.4.24 The effect of interest rates on the value of a purchase decision after 8 years assuming stable fuel costs of $23.53/gal of gasoline blend and $0.097/KWh.

Table 4.4.36 Break-Even Gasoline Prices with Electricity Costs of $0.097/KWh for the 2009 Ford Escape XLT FWB I4

	2009 Ford Escape Hybrid FWD	2009 Ford Escape Hybrid FWD Miles Plus conversion
2% Interest Rate	$ 6.09	$ 12.48
4% Interest Rate	$ 6.87	$ 13.66
8% Interest Rate	$ 8.49	$ 16.13

The cost analysis of a purchase decision depends on many variables. The direct costs such as vehicle purchase price, infrastructure costs, fuel costs, and depreciated vehicle value are often the easiest to asses. Changes in interest rates and fuel costs can sway the outcome of the analysis. Considering the stable fuel costs of $3/gallon of blended gasoline and $0.097/KWh as well as the flat annual interest rate of 2%, the best purchase decision a consumer could make in terms of value after 8 years is the purchase of the traditional Ford Escape. The Ford Escape Hybrid is the next best alternative for the consumer and will cost approximately $3,200 more than the Ford Escape. The Ford Escape Hybrid with Hybrids Plus conversion is the worst alternative for the consumer and will cost approximately $14,800 more than the Ford Escape and approximately $11,600 more than the Ford Escape HEV.

Other Benefits

Each of the alternative purchase decisions mentioned in this case study carry with it benefits that are not always considered by the consumer when purchasing a vehicle. Other than the stated costs, benefits that the consumer may not necessarily be aware of include health, welfare, ecological, and other economic benefits. These benefits don't have an inherent monetary value, but are still usually considered in a standard cost-benefit analysis by estimating their worth. Due to the large scale and highly variable nature of these benefits, they will be mentioned, but no direct cost to the consumer is estimated due to accuracy issues. The cost analysis above does not include monetary estimations of these benefits. If the value of the benefits associated with a purchase decision outweigh the cost differences stated previously, then that purchase decision may actually be better for the consumer.

Health Benefits

The health benefits of choosing an Escape HEV or PHEV over the conventional Escape are directly linked to cleaner air due to the reduction of certain emissions during the WTW operation of the vehicle. These emissions include the principal pollutants VOCs, CO, NOx, SOx, PM_{10}, and $PM_{2.5}$. Also, included is ground level ozone, one of the products of emissions and sunlight in the photochemical smog reaction.

According to the EPA, CO causes harmful health effects by reducing oxygen delivery to the body's organs and tissues and can lead to harmful cardiovascular and central nervous system effects. Cardiovascular effects from low level exposure include chest pain and reduced ability to exercise. Central nervous system effects by CO at high levels include vision problems, reduced ability to work or learn, reduced manual dexterity, and difficulty performing complex tasks.[25] At extremely high levels, CO is poisonous and can cause death. An Escape HEV or PHEV would reduce CO emissions during the WTW operation of the vehicle increasing the benefit to the health of the population.

NO_x can trigger a variety of health problems for susceptible individuals such as children, asthmatics, and the elderly. According to the EPA, short-term exposures can cause adverse respiratory effects including airway inflammation in healthy people and increased respiratory symptoms in people with asthma.[26] An Escape HEV or PHEV would reduce NO_x emissions during the overall operation of the vehicle increasing the benefit to the health of the population.

SO_x can trigger a variety of health problems for susceptible individuals such as children, asthmatics, and the elderly. According to the EPA, short-term exposures to SO_x may cause an array of adverse respiratory effects including bronchoconstriction and increased asthma symptoms in healthy people.[27] An Escape HEV would reduce SO_x emissions during the overall operation of the vehicle increasing the benefit to the health of the population.

PM_{10} and $PM_{2.5}$ emissions can get deep into the lungs and cause serious health problems including respiratory irritation, coughing, difficulty breathing, decreased lung function, aggravated asthma, development of chronic bronchitis, irregular heartbeat, heart attack, and premature death in people with heart or lung disease. According to the EPA, people with heart or lung diseases, children and older adults are the most likely to be affected by particle pollution exposure. [28] An Escape HEV would reduce PM_{10} and $PM_{2.5}$ emissions during the overall operation of the vehicle increasing the benefit to the health of the population.

The photochemical smog reaction of primarily VOCs, CO, NO_x, and sunlight produces ground-level ozone. According to the EPA, ground-level ozone triggers a variety of minor health problems including chest pain, coughing, throat irritation, and congestion, and cause major health problems such as bronchitis, emphysema, and asthma. Ground-level ozone exposure also reduces lung function, inflames the linings of the lungs, and may permanently scar lung tissue after repeated exposure.[29] An Escape HEV or PHEV would reduce VOCs, CO, and NO_x emissions during the WTW operation of the vehicle which would lead to a decrease in ground-level ozone thereby increasing the benefit to the health of the population.

Exposure to any of the aforementioned emissions can potentially lead to hospitalization. These emissions are compounded in urban areas by the increased number of vehicles operating in a small area. Additionally, these emissions can shift to non-urban areas with reasonable winds spreading their effects.

Environmental Benefits

Environmental benefits of choosing an Escape HEV or PHEV over the conventional Escape include reductions in certain GHG and principal pollutant emissions. Most of these environmental benefits are directly linked to emission reduction during the operation of the vehicle, but some still occur during the feedstock and fuel stages. GHGs include CO_2, CH_4, and N_2O. Principal pollutants include VOC, CO, NO_x, SO_x, PM_{10}, and $PM_{2.5}$.

GHGs negatively impact the environment by increasing the effects of global warming. Reduction of these GHGs produced during the WTW operation of a HEV or PHEV will reduce the impact caused by global warming. This benefit is associated with both the Escape HEV and PHEV to varying degrees.

VOCs, CO, and NO_x are key contributors to photo chemical smog and ground level ozone which adversely effect plants and ecosystems. According to the EPA, these effects include interfering with the ability of sensitive plants to produce and store food, damaging the leaves of trees and other plants, reducing forest growth, and potentially impacting the species diversity in ecosystems. Reduction of VOCs, CO, and NO_x as well as photochemical smog and ozone may benefit the ecological health of wildlife.[29] This benefit is associated with both the Escape HEV and PHEV to varying degrees.

Particulate matter causes environmental damage when the particles are carried long distances by the wind and settle on the ground or water according to the EPA. This can cause lakes and streams to become more acidic, alter the nutrient balance in coastal waters and large river basins, deplete nutrients in soils, damage sensitive forests and farm crops, and affect the diversity of ecosystems.[28] Reduction of particulate matter in the case of the Escape HEV may reduce the environmental damage of particulate matter. This benefit is associated with the Escape HEV.

Welfare Benefits

The welfare benefits of choosing an Escape HEV over the conventional Escape are directly linked to the reduction of particulate matter. Particulate matter causes visibility reduction and aesthetic damage. Fine particles such as $PM_{2.5}$ are the major cause of haze in parts of the United States, including many of our treasured national parks, wilderness areas, and tourist attractions.[28] For example, haze in the Chattanooga area hinders tourist's ability to view of all seven states from atop Lookout Mountain at Rock City. This view is one of the attractions key promotions. Also, particle pollution stains and damages stone and other materials, including culturally important objects such as statues, monuments, and buildings.[28] For example, many of the civil war monuments and statues in the U.S. are outdoors and vulnerable to aesthetic damage by particulate matter. A reduction of all particulate matter produced by the WTW operation of an

Escape HEV would lessen the impact on visibility and lessen aesthetic damage thereby benefiting the welfare of the general public.

Other welfare benefits of choosing an Escape HEV or PHEV over the conventional Escape are indirectly linked to the reduction of VOCs and NO_x which contribute to ground-level ozone produced by the photochemical smog reaction. Ground-level ozone damages plant matter and negatively impacts the appearance of vegetation in urban areas, national parks, and recreation areas.[29] A reduction of all VOCs and NO_x produced by the WTW operation of an Escape HEV or PHEV may cause less of an impact on vegetation than a conventional Escape thereby benefiting the welfare of the general public.

Other Economic Benefits

Apart from the obvious economic benefits for the consumer are the national economic benefits that would be felt with the movement toward more efficient alternate fuel vehicles like the hybrids. In recent years, the U.S. dependence on foreign oil has grown into an issue of national security since much of the oil used in the U.S. is imported from unstable countries or countries that are at odds with the U.S. According to the Institute for the Analysis of Global Security, the economy is subject to occasional supply disruptions, price hikes, and loss of wealth due to the instability of the foreign oil suppliers.[31] For example, a report for the DoE in 2000 estimated that the costs to the U.S. economy of the oil market upheavals of the 30 years prior to the report could be in the vicinity of $7 trillion (1998 valued dollar).[30] With other developing countries increasing their demand for oil each year, the costs are expected to only increase. Vehicle technologies like the HEV and PHEV mentioned here can reduce the stress on the U.S. economy by reducing the U.S. demand for oil. A reduced U.S. demand suggests that the U.S. would be less reliant on foreign oil from politically unstable countries and countries at odds with the U.S thus improving national security. Additionally, increased PHEV use would put more emphasis on native resources like coal for electricity production and would further reduce the need to import oil.

Chapter Conclusion

Given a choice between purchasing Ford Escape, Ford Escape Hybrid, and Ford Escape Hybrid with Hybrids Plus conversion as a daily commuter in the TVA operational area in 2010, a consumer will most likely purchase the vehicle that offers the highest value over the expected life of the vehicle. For an 8 year, 100,000 mile period, a cost analysis suggests that the consumer should buy the conventional Ford Escape. The emissions results generated by GREET suggest that a Ford Escape Hybrid will produce lower emissions in more categories than the other vehicles. The energy consumption results generated by GREET suggest that the Ford Escape Hybrid will consume the least energy in more categories than the other vehicles. Thus, the number of additional benefits associated with the purchase of the Ford Escape Hybrid seems to outweigh those associated with the Ford Escape Hybrid with Hybrids Plus Conversion. Categorically, the Ford Escape Hybrid seems like the best overall choice. This holds true for the entire study if and only if an accurate accounting for the monetary value of the benefits associated with purchasing the Escape Hybrid outweighs the extra cost of the purchase.

In my opinion, there are several ways to make the alternative vehicle technologies more attractive to consumers. An accurate cost-benefit analysis could show that the Escape Hybrid offers a value on par with or better than the conventional Escape. A renewal of tax credits on the federal and state levels could bring the purchase price of the Escape Hybrid more in line with the price of a conventional Escape. Better and cheaper battery technologies could help both the hybrid models compete with the conventional Escape in terms of cost. An increased demand for cheap hybrids could force Ford to increase production to capture a higher market share. The production of a PHEV model by Ford rather than a third party conversion company will decrease the costs of purchasing a PHEV. Implementation of smart grid technologies and off peak pricing would also increase the desirability of PHEVs. Realistically, a lot more things would have to swing in favor of the Escape PHEV to make it more viable than the Escape Hybrid in the near future.

CHAPTER 5

CONCLUSION

From the comparisons in this manuscript, alternative and hybrid vehicle-fuel combinations have been shown to offer several advantages over traditional systems. In some cases, these advantages do not necessarily indicate that one particular combination is better than another. Instead, they highlight key trade offs for the use of the alternative rather than the traditional vehicle fuel combination.

Several conclusions are drawn from comparisons between modeled alternative and traditionally fueled vehicles. First, the use of direct injection technology in spark ignition gasoline vehicles reduced considerably the energy consumption and emissions due to all WTW activities. Second, the use of a LL-EtOH blend as an alternative fuel to a CG and RFG market share blend in a SIDI vehicle showed several advantageous WTW results, especially in petroleum energy consumption and GHG emissions which were shown to be reduced by 4.3% and 1.7% respectively for WTW activities. However, the use of a LL-EtOH blend cannot be shown to be conclusively better than the CG and RFG market share blend in SIDI vehicles due to total pollutant emissions. Third, the use of the use of a BD20 blend as an alternative fuel to LSD in a CIDI vehicle showed several advantageous WTW results, especially in petroleum energy consumption and GHG emissions which were shown to be reduced by 17.4% and 14.0% respectively for WTW activities. However, the use of a BD20 blend cannot be shown to be conclusively better than LSD in CIDI vehicles due to total pollutant emissions.

Several conclusions are drawn from comparisons between modeled hybrid and traditionally fueled Ford Escapes for purchase and use in Tennessee. First, the use of a HEV as an alternative to the traditional Escape fueled by a CG and RFG market share blend showed advantageous WTW results in nearly all categories, especially petroleum energy consumption and GHG emission, which were shown to be reduced by 24.6% and 24.5% respectively. Additionally, all total and urban emissions for the HEV were appreciably reduced when compared to the traditional Escape. After an 8 year period with stable fuel cost of $3 per gallon of gas, a current decision to purchase Escape HEV was approximately $3,200 less in the value of savings than a decision to purchase a traditional Escape. It seems that, due to this analysis, the Escape HEV must be declared superior to the traditional Escape with considerations to the benefits of the vehicle. Second, the use of a PHEV as an alternative to the traditional Escape fueled by a CG and RFG market share blend showed several advantageous WTW results, especially petroleum energy consumption and GHG emission, which were shown to be reduced by 38.5% and 17.5% respectively. Due to the electricity generation mix which includes close to a 50% share of coal-fired power plants, the total and urban emission of particulate matter and SO_x is considerably increased compared to the traditional Escape. Coupled with an extremely lower value of savings after an 8 year period than the Escape, a decision to purchase Escape PHEV is not appropriate given the current market conditions and electricity generation mixes. In the future, if capital costs drop due to mass production by the original equipment manufacturer and electricity generation shifts from coal to cleaner sources of energy then the purchase decision may be reassessed in favor of the Escape PHEV, but right now, it is not the best purchase decision a consumer could make.

The effects of different vehicle-fuel combinations in this thesis are reliant on several things. First, an understanding of the GREET fuel cycle model software and the related key assumptions and parameters of different vehicle-fuel combinations is crucial to effectively using the GREET software. Second, realistic simulations of vehicle-fuel combinations that accurately depict real world scenarios must be created and the resulting information analyzed and compared to other relevant alternatives. Third, other factors, such as a variety of costs and benefits not included in the GREET simulation, but undoubtedly effecting the purchase of a real vehicle, must be considered in tandem to the results of the simulations in a comparison with other relevant alternatives. While the results obtained from these simulations and studies may not concussively point to a single, specific vehicle-fuel combination as a best option, it does point out the advantages and disadvantages of each simulated vehicle in a broader manner than just vehicle operation. This greater understanding of the effect each vehicle will have on our world will hopefully influence people to make more informed decisions in the future and hopefully bring the use of cleaner, more efficient transportation into the mainstream.

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APPENDIX A

VEHICLE-FUELS COMPARISON: TRADITIONAL VS. ALTERNATIVE FUEL SYSTEMS

APPENDIX A.1

Procedure

The following section outlines the procedure used to simulate the vehicle-fuel combinations stipulated in Chapter 3 using GREET 1.8c.0. The GREETGUI is preferred for this simulation due to its ease of use and streamlined modeling. GREETGUI also offers access to first tier assumptions and parameters which can be tweaked to simulate slightly different situations for vehicle-fuel combinations.

First, open GREETGUI following the instructions in Section 2.4.1. Follow the on screen instructions as outlined until you reach the main menu (See Fig. 2.4.4). Start a new session and input a file name. For this case study, the base reference file name is "PC CS1."

From the Scenario and Fuel Pathway Selections window (See Fig. 2.4.7), the selected simulated year is set to 2010 with gasoline and diesel selected in the petroleum pathway group (See Fig 2.4.8), low level blend (5-15% by volume with gasoline and diesel) selected in the bio-ethanol pathway group (See Fig 2.4.10), and the biodiesel pathway. No stochastic simulations are selected for the simulation. The selected vehicle type is PC.

From the Market Shares Options window (See Fig. 2.4.12), GREET Default Market Shares is selected for each available market. From the Gasoline and Diesel Fuel Types and Shares window (See Fig 2.4.13), the RFG% and CG% for 2010 should both read 50.0%. RFG is CG with an oxygenate, usually ethanol, added to raise the oxygen content (by weight in this case) of a fuel to some minimum limit. Many refueling stations now guarantee that the gasoline they sell is blended with no more than 10% ethanol by volume. However, they don't guarantee that they use an oxygenate all the time. The market shares reflect the estimated use of each type of gasoline during the course of the 2010 model year in the U.S. The diesel fuel was left at the default 100.0% LSD for the simulated year. From the Ethanol Feedstock Shares window (See Fig. 2.4.20), corn remained at the default of 100.0% of the feedstock market. Although strides are being made to improve production from other sources, corn is estimated by GREET to be the U.S.'s only reliable source of ethanol in 2010.

The Petroleum Pathway Options window contains the CG, RFG, and LSD fuel tabs. On the CG tab (See Fig. 2.4.22), the sulfur level remains at the default 25.5 ppm. On the RFG tab (See Fig. 2.4.21), the sulfur level remains at the default 25.5 ppm and the O_2 content (by weight) remains at 2.3%. EtOH remains selected as the oxygenate and corn holds 100% of the market shares The vehicle technologies selected in the RFG tab and reflected in the CG tab include SI engine and SIDI engine. From the LSD tab (See Fig. 2.4.24), the sulfur level remains at 11.0 ppm, and the location for use remains defaulted to the U.S. The vehicle technology selected for LSD is CIDI engine.

The Biofuels Pathway Options window contains the ethanol, electricity, and biodiesel tabs. On the ethanol tab (See Fig. 2.4.33), corn ethanol options remain at their default values. DMP holds an 87.5% market share while WMP holds a 12.5% market share. The share of process fuels for DMP remain at 80.0% and 20.0% for NG and coal while the share of process fuels for WMP remain at 60.0% and 40.0% for NG and coal. Vehicle technology for low-level blend with gasoline included SI engine and SIDI engine. No vehicle technology for low-level blend with diesel is selected. Note that not selecting a vehicle technology for a particular fuel causes a warning window to open after completing the biofuels pathway options. Simply continue on past the window after completing inputs for the entire window. On the electricity tab (See Fig. 2.4.35), the marginal generation mix for transportation use and the average generation mix for stationary use remains defaulted to U.S. mix. The U.S. mix contains 1.1% residual oil, 18.3% NG, 50.4% coal, 20.0% nuclear power, 0.7% biomass, and 9.5% others. Advanced power plant tech shares remain at default settings with NG turbine combined-process technology at 44.0%, NG turbine simple-process technology shares at 36.0%, and advanced coal and advanced biomass technology shares both at 0.0%. Under nuclear plants for electricity generation, both LWR and HTGR plants technology shares remain at 25.0% and 75.0% for gas diffusion and centrifuge technologies, respectively. Biomass power plant feedstock shares remain at default values with woody biomass holding 100.0% market share over herbaceous biomass. NGCC electricity by default is displaced by electricity co-generated in natural gas-based fuel production plants. The U.S. Mix by default is displaced by electricity co-generated in coal-based fuel production plants and biomass-based fuel production plants. On the biodiesel tab (See Fig. 2.4.36), the CIDI engine is the only vehicle technology selected.

In the Simulation Options for Alternative Fuel Blends window (See Fig.2.4.41), ethanol, biodiesel, gasoline, and diesel options remain at the default values. For blending with gasoline, 10.0% ethanol content by volume is defaulted. For blending with diesel, 20.0% biodiesel by volume is defaulted. For the ethanol (low-level blend), 100.0% CG is defaulted for blending. For the biodiesel, 100.0% LSD is defaulted for blending. After finishing the inputs, proceed to parametric assumptions options and select 'Use GREET default assumption estimates.'

On the Fuel Production Assumptions window (See Fig. 2.4.44), the default values for the base year 2010 are used for the petroleum, ethanol, and electricity tabs. Crude recovery efficiency is assumed to be 98.0%. CG refining efficiency is assumed to be 87.7%. LSD refining efficiency is assumed to be 89.3%. CO_2 emission from landuse change by corn farming was assumed to be 195.0 g/bushel. Corn farming energy use is assumed to be 12,635 btu/bushel. Ethanol production energy use by dry mills is assumed to be 36,000 btu/gallon. Ethanol production energy use by wet mills is assumed to be 45,950 btu/gallon. Residual oil utility boiler efficiency is assumed to be 34.8%. NG utility boiler efficiency is assumed to be 34.8%. NG simple process turbine efficiency is assumed to be 33.1%. NG combined process turbine efficiency is assumed to be 53.0%. Coal utility boiler efficiency is assumed to be 34.1%. Electricity transmission and distribution loss is assumed to be 8.0%. Energy intensity in HTGR reactors is assumed to be 8.704 MWh/g of U-235. Energy intensity in LWR reactors is assumed to be 6.926 MWh/g of U-235. Electricity use of uranium enrichment in gaseous diffusion plants for LWR electricity generation is assumed to be 2,400 kWh/SWU. Electricity use of uranium enrichment in centrifuge plants for LWR electricity generation is assumed to be 50.00 kWh/SWU. Electricity use of uranium enrichment in gaseous diffusion plants for HTGR electricity generation is assumed to be 2,400 kWh/SWU. Electricity use of uranium enrichment in centrifuge plants for HTGR electricity generation is assumed to be 50.00 kWh/SWU.

On the Vehicle Operation Assumptions window (See Fig. 2.4.46 and 2.4.47), the Baseline Vehicles (Model Year 2005) and Alternative-Fueled and Advanced Vehicles (Model Year 2005) keep the default values. The listed baseline vehicles include SI vehicle: CG and RFG, and CIDI vehicle: CD and LSD. Default values for the baseline vehicles are tabulated in Appendix A.1. The alternative-fueled and advanced vehicles include: CIDI vehicle: CD and LSD, SI vehicle: EtOH Low-level, SIDI vehicle: CG and RFG, SIDI vehicle: EtOH, CIDI vehicle: BD. Default values for the alternative-fueled and advanced vehicles are tabulated in Appendix A.1. After the vehicle operation assumptions, update the parametric assumptions for all years

At this point, GREETGUI updates the parametric assumptions, runs the simulation, and compiles the results. The resulting input and output files save using the input file name and appropriate appendices. For this case study, the results are saved as PC CS1In.xls, and PC CS1Out.xls. Additionally, a GREET assumption file for the simulation is saved under the simulation name.

APPENDIX A.2

VEHICLE ASSUMPTIONS

Table A.1 Baseline Vehicle Operation Parameters

Items	SI Vehicle: CG and RFG	CIDI Vehicle: CD and LSD
Gasoline Equivalent MPG	23.40	28.08
Exhaust VOC	0.122	0.088
Evaporative VOC	0.058	0.000
CO	3.745	0.539
NO_x	0.141	0.141
Exhaust PM_{10}	0.0081	0.009
Brake and Tire Wear PM_{10}	0.0205	0.0205
Exhaust $PM_{2.5}$	0.0075	0.0084
Brake and Tire Wear $PM_{2.5}$	0.0073	0.0073
CH_4	0.0146	0.0026
N_2O	0.012	0.012

Table A.2 Advanced and Alternative Fueled Vehicle Operation Parameters

Items	CIDI Vehicle: CD and LSD	SI Vehicle: EtOH Low-Level	SIDI Vehicle: CG and RFG
Gasoline Equivalent MPG	120.0%	100.0%	115.0%
Exhaust VOC		100.0%	100.0%
Evaporative VOC		100.0%	100.0%
CO		100.0%	100.0%
NO_x		100.0%	100.0%
Exhaust PM_{10}		100.0%	100.0%
Brake and Tire Wear PM_{10}		100.0%	100.0%
Exhaust $PM_{2.5}$		100.0%	100.0%
Brake and Tire Wear $PM_{2.5}$		100.0%	100.0%
CH_4		100.0%	100.0%
N_2O		100.0%	100.0%

Table A.3 Advanced and Alternative Fueled Vehicle Operation Parameters

Items	SIDI Vehicle: EtOH Low-Level	CIDI Vehicle: BD
Gasoline Equivalent MPG	115.0%	120.0%
Exhaust VOC	100.0%	100.0%
Evaporative VOC	100.0%	0.0%
CO	100.0%	100.0%
NO_x	100.0%	100.0%
Exhaust PM_{10}	100.0%	100.0%
Brake and Tire Wear PM_{10}	100.0%	100.0%
Exhaust $PM_{2.5}$	100.0%	100.0%
Brake and Tire Wear $PM_{2.5}$	100.0%	100.0%
CH_4	100.0%	100.0%
N_2O	100.0%	100.0%

APPENDIX A.3

RESULTS

Table A.4 Well to Pump Energy Consumption and Emissions for the SIDI Vehicle Fueled with CG and RFG

Item	Btu/mile or grams/mile			
	Feedstock	Fuel	Vehicle Operation	Total
Total Energy	228	842	4,268	5,338
Fossil Fuels	221	755	4,179	5,155
Coal	33	139	0	173
Natural Gas	137	259	0	397
Petroleum	51	356	4,179	4,586
CO_2 (w/ C in VOC & CO)	15	57	328	399
CH_4	0.397	0.067	0.015	0.479
N_2O	0.000	0.004	0.012	0.017
GHGs	25	60	332	416
VOC: Total	0.015	0.102	0.180	0.297
CO: Total	0.028	0.033	3.745	3.806
NO_x: Total	0.105	0.098	0.141	0.344
PM_{10}: Total	0.009	0.038	0.029	0.076
$PM_{2.5}$: Total	0.004	0.014	0.015	0.033
SO_x: Total	0.035	0.066	0.005	0.107
VOC: Urban	0.002	0.064	0.112	0.178
CO: Urban	0.001	0.015	2.329	2.346
NO_x: Urban	0.005	0.040	0.088	0.132
PM_{10}: Urban	0.000	0.008	0.018	0.026
$PM_{2.5}$: Urban	0.000	0.004	0.009	0.014
SO_x: Urban	0.003	0.028	0.003	0.034

Table A.5 Well to Pump Energy Consumption and Emissions for the SI Vehicle Fueled with a LL-EtOH Blend

	Btu/mile or grams/mile			
Item	Feedstock	Fuel	Vehicle Operation	Total
Total Energy	291	1,210	4,908	6,409
Fossil Fuels	282	927	4,591	5,800
Coal	43	186	0	229
Natural Gas	167	358	0	526
Petroleum	71	383	4,591	5,045
CO_2 (w/ C in VOC & CO)	2	70	376	449
CH_4	0.432	0.092	0.015	0.538
N_2O	0.013	0.001	0.012	0.026
GHGs	17	73	380	470
VOC: Total	0.017	0.123	0.180	0.320
CO: Total	0.037	0.038	3.745	3.820
NO_x: Total	0.133	0.114	0.141	0.388
PM_{10}: Total	0.012	0.052	0.029	0.092
$PM_{2.5}$: Total	0.006	0.018	0.015	0.039
SO_x: Total	0.049	0.079	0.006	0.134
VOC: Urban	0.003	0.073	0.112	0.188
CO: Urban	0.001	0.016	2.329	2.347
NO_x: Urban	0.005	0.044	0.088	0.137
PM_{10}: Urban	0.000	0.008	0.018	0.026
$PM_{2.5}$: Urban	0.000	0.005	0.009	0.014
SO_x: Urban	0.004	0.031	0.004	0.038

Table A.6 Well to Pump Energy Consumption and Emissions for the SIDI Vehicle Fueled with a LL-EtOH Blend

	Btu/mile or grams/mile			
Item	**Feedstock**	**Fuel**	**Vehicle Operation**	**Total**
Total Energy	253	1,052	4,268	5,573
Fossil Fuels	245	806	3,992	5,043
Coal	37	162	0	199
Natural Gas	146	312	0	457
Petroleum	62	333	3,992	4,387
CO_2 (w/ C in VOC & CO)	2	61	327	390
CH_4	0.375	0.080	0.015	0.470
N_2O	0.012	0.001	0.012	0.024
GHGs	15	63	331	410
VOC: Total	0.015	0.107	0.180	0.302
CO: Total	0.032	0.033	3.745	3.810
NO_x: Total	0.116	0.099	0.141	0.356
PM_{10}: Total	0.010	0.045	0.029	0.084
$PM_{2.5}$: Total	0.005	0.016	0.015	0.036
SO_x: Total	0.043	0.068	0.005	0.116
VOC: Urban	0.002	0.063	0.112	0.178
CO: Urban	0.001	0.014	2.329	2.345
NO_x: Urban	0.005	0.038	0.088	0.131
PM_{10}: Urban	0.000	0.007	0.018	0.025
$PM_{2.5}$: Urban	0.000	0.004	0.009	0.014
SO_x: Urban	0.003	0.027	0.003	0.033

Table A.7 Well to Pump Energy Consumption and Emissions for the CIDI Vehicle Fueled with LSD

Item	Btu/mile or grams/mile			
	Feedstock	Fuel	Vehicle Operation	Total
Total Energy	219	574	4,090	4,882
Fossil Fuels	212	566	4,090	4,868
Coal	32	100	0	132
Natural Gas	132	180	0	311
Petroleum	49	287	4,090	4,425
CO_2 (w/ C in VOC & CO)	20	43	323	387
CH_4	0.380	0.047	0.003	0.430
N_2O	0.000	0.001	0.012	0.013
GHGs	30	44	327	401
VOC: Total	0.014	0.017	0.088	0.120
CO: Total	0.027	0.025	0.539	0.591
NO_x: Total	0.101	0.074	0.141	0.316
PM_{10}: Total	0.009	0.027	0.030	0.065
$PM_{2.5}$: Total	0.004	0.010	0.016	0.030
SO_x: Total	0.034	0.051	0.002	0.087
VOC: Urban	0.002	0.010	0.055	0.067
CO: Urban	0.001	0.013	0.335	0.349
NO_x: Urban	0.004	0.033	0.088	0.125
PM_{10}: Urban	0.000	0.006	0.018	0.025
$PM_{2.5}$: Urban	0.000	0.004	0.010	0.014
SO_x: Urban	0.003	0.024	0.001	0.028

Table A.8 Well to Pump Energy Consumption and Emissions for the CIDI Vehicle Fueled with BD20

	Btu/mile or grams/mile			
Item	**Feedstock**	**Fuel**	**Vehicle Operation**	**Total**
Total Energy	254	1,777	4,090	6,121
Fossil Fuels	247	618	3,323	4,188
Coal	34	97	0	131
Natural Gas	125	276	0	401
Petroleum	87	246	3,323	3,656
CO_2 (w/ C in VOC & CO)	-39	44	324	329
CH_4	0.317	0.063	0.003	0.383
N_2O	0.008	0.001	0.012	0.021
GHGs	-29	46	328	345
VOC: Total	0.015	0.093	0.088	0.196
CO: Total	0.037	0.025	0.539	0.600
NO_x: Total	0.113	0.076	0.141	0.330
PM_{10}: Total	0.011	0.025	0.030	0.066
$PM_{2.5}$: Total	0.006	0.010	0.016	0.031
SO_x: Total	0.049	0.048	0.002	0.098
VOC: Urban	0.002	0.008	0.055	0.065
CO: Urban	0.001	0.011	0.335	0.347
NO_x: Urban	0.004	0.029	0.088	0.121
PM_{10}: Urban	0.000	0.005	0.018	0.024
$PM_{2.5}$: Urban	0.000	0.003	0.010	0.013
SO_x: Urban	0.003	0.020	0.001	0.025

APPENDIX B

VEHICLE-FUELS COMPARISON: TRADITIONAL VS. HYBRID FUEL SYSTEMS

APPENDIX B.1

PROCEDURE

The following section outlines the procedure used to simulate the 2009 Escapes with the GREET Excel model. The Excel model is preferred for this simulation since the 2005 parameters for the PHEV model in GREET contained placeholder values which are not comparable to researched values for 2010 and later. To achieve a more accurate simulation of the PHEV, the model changes reflect 2010 vehicles with adjustments pertaining to the 2009 Escape variants. Thus, the simulation uses 2010 model data for the modeled vehicles with pertinent updates for the 2009 vehicle data and an estimated electricity mix based on the 2009 annual report with the default 2010 assumptions and parameters. Previous experience with GREETGUI will benefit the user when navigating the GREET model and a basic understanding of Excel notation is required for the following instructions.

First, close all open Excel files. To begin modifying the Excel model, open "GREET1_8c_0.xls" contained in the 'GREET1.8' folder. Enable macros in order for the model to function properly. Immediately, save the file under a new name to prevent accidental alteration of the original file. The following changes will need to be made on the 'Inputs,' 'LDT1_TS,' and 'Fuel_Prod_TS' tabs to update the Excel model for this case study.

On the 'Inputs' tab, the vehicle type and electricity options will be selected using the drop down selection tools under each option heading. In cell B13, set the cell to a value of 2 as shown in Figure B.1. This value corresponds to the selection of LDT1 as the vehicle type. In cells C354:355, set each cell to a value of 4 as shown in Figure B.2. The value in each cell corresponds to the selection of a user defined electricity generation mix for transportation and stationary use which will be altered later in a separate tab.

	A	B	C
12	**2. Selection of Vehicle Types for Simulation**		
13		2	1 -- Passenger Cars
14			2 -- Light-Duty Trucks 1
15			3 -- Light-Duty Trucks 2

Figure B.1 Selection of vehicle types for simulation in GREET Excel model. Selection of a value of 2 in cell B13 in the 'Inputs' tab of the GREET Excel model sets the vehicle type to LDT1 for the Ford Escape Case Study.

	A	B	C
353	**9.2.a) Selection of Electricity Generation Mix for Transportation Use**		
354		Mix for transportation use	4
355		Mix for stationary use	4

Figure B.2 Selection of electricity generation mix for transportation use in GREET Excel model. The selection of a value of 4 in cells C354 and C355 in the 'Inputs' tab of the GREET Excel model sets the electricity generation mixes to a user defined mix for the Ford Escape Case Study.

	A	B	C	D	E	F	G	H	I	J	K	L	M
10			19.00	0.115	0.067	3.448	0.099	0.0122	0.0205	0.0112	0.0073	0.0126	0.012
11		**Model Year**	**MPG**	**VOC (Exhaust)**	**VOC (Evap.)**	**CO**	**NOx**	**PM10 (Exhaust)**	**PM10 (TBW)**	**PM2.5 (Exhaust)**	**PM2.5 (TBW)**	**CH4**	**N2O**
12		1990	16.60	1.114	0.545	19.585	1.507	0.0187	0.0205	0.0177	0.0073	0.1141	0.111
13		1995	16.20	0.668	0.426	10.802	0.996	0.0145	0.0205	0.0133	0.0073	0.0714	0.082
14		2000	16.30	0.203	0.112	6.485	0.520	0.0132	0.0205	0.0120	0.0073	0.0273	0.012
15		2005	19.00	0.115	0.067	3.448	0.099	0.0122	0.0205	0.0112	0.0073	0.0126	0.012
16		**2010**	**19.00**	**0.115**	**0.067**	**3.448**	**0.099**	**0.0122**	**0.0205**	**0.0112**	**0.0073**	**0.0126**	**0.012**
17		2015	20.40	0.115	0.067	3.437	0.099	0.0122	0.0205	0.0112	0.0073	0.0125	0.012
18		2020	22.50	0.112	0.067	3.410	0.100	0.0122	0.0205	0.0112	0.0073	0.0122	0.012

Figure B.3 LDT1 TS table in GREET Excel model. The updated 2005 model year of the LDT1 baseline TS in the 'LDT1_TS' tab reflects the data from model year 2010. Above the TS table in yellow, the data to be used by the simulation is called out of the TS table from model year 2005.

Since GREET will pull data out of time series (TS) tables located in the 'LDT1_TS' tab, the following changes will need to be made in order to have the proper data called into the simulation calculations. Note, the changes to the TS tables will only effect simulations using the LDT1 category selection and the selected vehicle technologies. To update the gasoline LDT1 baseline TS, copy cells C16:M16 and paste the data into cells C15:M15 as shown in Figure B.3. The following updates should result in similar tables with the same data for 2005 and 2010 model years. To update the GC SI PHEV CS mode TS, copy cells C493:M493 and paste the data into cells C492:M492. Then, copy cells S493:AD493 and paste the data into cells S492:AD492 followed by updating cell C492 by returning the existing formula. To update the GC SI PHEV CD mode TS, copy cells D479:M479 and paste the data into cells D478:M478. Then, copy cells S479:AD479 and paste the data into cells S478:AD478. Next, copy cells AG479:AR479 and paste the data into cells AG478:AR478. Then, copy the cells AV479:BB479 and paste the data into AV478:BB478, and copy the exact formula (do not copy the cell, or it will change the formula when pasted) from AU479, BC479, BD479, BE479, BF479 to row 478 in their corresponding columns and update each cell if necessary. Update cell C478 to complete the CD mode changes. To change the EV TS, copy cell C940 and paste the data into cell C939. The tab should automatically update all pertinent cells when you leave the tab. To check that the cells updated, check the yellow cell block above each updated table (See Fig. 4.2.3 as an example) for the new 2005 placeholder data. To update the fuel economy for each vehicle based on the standard vehicle data, the 2005 and 2010 MPG cells for each TS table must be amended. First, update cells C215:216 for the SIDI vehicle fueled with CG and RFG with the formula

‘=25.36/19.00’ to change the relative MPG to ~133.5% of the baseline vehicle as show in Figure B.4. The following fuel economy changes will result in a spreadsheet similar to Figure B.4. Next, update cells C359:360 with the formula ‘=33.65/19.00’ to change the relative MPG to ~177.1% of the baseline vehicle. Then, update cells C478:479 with the formula ‘=40/19.00’ to change the relative MPG to ~210.5% of the baseline vehicle. Finally, update cells C492:493 with the formula ‘=31.5/19.00’ to change the relative MPG to ~165.8% of the baseline vehicle.

	A	B	C
215		2005	133.5%
216		**2010**	**133.5%**

Figure B.4 Fuel economy of a LDT1 TS table in GREET Excel model. The updated 2005 and 2010 model year fuel economy of the LDT1 baseline TS in the ‘LDT1_TS’ tab reflects the expected fuel economy of the SIDI vehicle fueled by CG and RDF as a percentage of the expected fuel economy of the baseline vehicle.

Since this simulation models the Chattanooga area which is serviced by TVA for electricity generation, the table containing the user defined electricity generation mix for transportation and stationary located on the ‘Fuel_Prod_TS’ tab will require several updates. The changes correspond to the data in Table 4.1.2 for the 2010 model. First, change cell AZ345 to 0.1%. Second, change cell BA345 to 2.0%. Then, change cell BB345 to 52.9%. Next, change cell BC345 to 36.8%. Finally, change cell BD345 to 0.0%, and update cell BD345. Check that BD345 contains a value of 8.2%. The resulting table for the “User Defined Mix: Transportation Use” electricity generation should have the same 2010 data as Figure B.5. The “User Defined Mix: Stationary Use” will also need to be updated by copying the updated cells AZ345:BE345 and pasting them into

BH345:BM345. The resulting row should now contain identical data to the row shown in Figure B.5.

	AY	AZ	BA	BB	BC	BD	BE
345	2010	0.1%	2.0%	52.9%	36.8%	0.0%	8.2%

Figure B.5 User defined electricity generation mix for transportation use TS table in the GREET Excel model. The 2010 simulation year user defined electricity generation mix for transportation use reflects the expected percentage generation from TVA by major fuel source. The fuel sources are categorized as residual oil, NG, coal, nuclear, biomass, and others, respectively.

At this point, the GREET model will update the appropriate vehicle models when the ‘Results’ tab is selected. In the first section labeled “Well-to-pump Energy Consumption and Emissions,” relevant data are located in column B for the baseline, SIDI, and GI SI HEV, in column Q for the GC SI PHEV, and in column AL for the pure EV. An example of the WTP energy consumption and emissions for the SIDI vehicle is shown in Figure B.6. In the second section labeled “Well-to-wheels Energy Consumption and Emissions,” relevant data are located under the headings located at A29 for the baseline gasoline vehicle fueled by CG and RFG, at A379 for an SIDI vehicle fueled by CG and RFG, at A679 for a GI SI HEV fueled by CG and RFG, at A929 for a GC SI PHEV fueled by CG, RFG, and electricity from the grid, and at A1429 for an EV. An example of the WTW energy consumption and emissions for the SIDI vehicle is shown in Figure B.7. Other results should match the values found in the following results section.

	A	B
3		Baseline CG and RFG
4	Total Energy	247,376
5	WTP Efficiency	80.2%
6	Fossil Fuels	223,538
7	Coal	41,460
8	Natural Gas	87,194
9	Petroleum	94,884
10	CO2 (w/ C in VOC & CO)	16,552
11	CH4	108.155
12	N2O	1.130
13	GHGs	19,592
14	VOC: Total	27.303
15	CO: Total	14.050
16	NOx: Total	47.251
17	PM10: Total	11.148
18	PM2.5: Total	4.301
19	SOx: Total	23.736
20	VOC: Urban	15.519
21	CO: Urban	3.750
22	NOx: Urban	10.335
23	PM10: Urban	1.835
24	PM2.5: Urban	1.067
25	SOx: Urban	7.183
26		

Figure B.6 The WTP energy consumption and emissions results table located on the 'Results' tab for the baseline CG and RFG fuels reflect energy consumption categories, WTP efficienciy, and emissions for the simulated fuel in 2010.

	A	B	C	D	E	F	G	H
379	**SIDI Vehicle: CG and RFG**							
380		**Btu/mile or grams/mile**				**Percentage of each stage**		
381	**Item**	**Feedstock**	**Fuel**	**Vehicle Operation**	**Total**	**Feedstock**	**Fuel**	**Vehicle Operation**
382	Total Energy	236	884	4,529	5,649	4.2%	15.6%	80.2%
383	Fossil Fuels	226	786	4,434	5,447	4.1%	14.4%	81.4%
384	Coal	37	151	0	188	19.8%	80.2%	0.0%
385	Natural Gas	136	259	0	395	34.3%	65.7%	0.0%
386	Petroleum	53	377	4,434	4,864	1.1%	7.7%	91.2%
387	CO2 (w/ C in VOC & CO)	15	60	348	423	3.6%	14.2%	82.3%
388	CH4	0.421	0.069	0.013	0.502	83.8%	13.7%	2.5%
389	N2O	0.000	0.005	0.012	0.017	2.2%	27.7%	70.1%
390	GHGs	26	63	352	440	5.8%	14.3%	79.9%
391	VOC: Total	0.016	0.108	0.182	0.306	5.2%	35.2%	59.5%
392	CO: Total	0.030	0.034	3.448	3.512	0.8%	1.0%	98.2%
393	NOx: Total	0.111	0.103	0.099	0.313	35.5%	32.8%	31.6%
394	PM10: Total	0.010	0.041	0.033	0.083	11.8%	48.9%	39.3%
395	PM2.5: Total	0.004	0.015	0.018	0.038	11.8%	39.5%	48.7%
396	SOx: Total	0.037	0.070	0.006	0.113	33.1%	61.9%	5.0%
397	VOC: Urban	0.003	0.068	0.113	0.183	1.4%	36.9%	61.7%
398	CO: Urban	0.001	0.016	2.145	2.162	0.1%	0.7%	99.2%
399	NOx: Urban	0.005	0.042	0.062	0.108	4.4%	38.8%	56.8%
400	PM10: Urban	0.000	0.008	0.020	0.029	0.7%	28.3%	71.0%
401	PM2.5: Urban	0.000	0.005	0.012	0.016	0.8%	28.8%	70.4%
402	SOx: Urban	0.003	0.029	0.004	0.036	8.5%	81.7%	9.8%
403								

Figure B.7 The WTW energy consumption and emissions results table located on the 'Results' tab for the SIDI vehicle fueled by CG and RFG includes a breakdown of each category by stage as well as a percentage breakdown of each stage.

APPENDIX B.2

RESULTS

Table B.1 Well to Pump Energy Consumption and Emissions for the Escape, Escape HEV, and Escape PHEV Models

2010	**Baseline: CG and RFG**	**Grid-Connected SI PHEV: Gasoline and Electricity**
Total Energy	247,376	398,136
WTP Efficiency	80.2%	71.5%
Fossil Fuels	223,538	337,472
Coal	41,460	174,425
Natural Gas	87,194	79,613
Petroleum	94,884	83,435
CO_2 (w/ C in VOC & CO)	16,552	41,805
CH_4	108.155	123.665
N_2O	1.130	1.247
GHGs	19,592	45,269
VOC: Total	27.303	25.567
CO: Total	14.050	17.729
NO_x: Total	47.251	69.568
PM_{10}: Total	11.148	53.074
$PM_{2.5}$: Total	4.301	14.986
SO_x: Total	23.736	91.829
VOC: Urban	15.519	13.345
CO: Urban	3.750	4.094
NO_x: Urban	10.335	13.211
PM_{10}: Urban	1.835	1.874
$PM_{2.5}$: Urban	1.067	1.070
SO_x: Urban	7.183	17.411

Table B.2 Well to Wheel Energy Consumption and Emissions for the Escape Model

SIDI Vehicle: CG and RFG	**Btu/mile or grams/mile**				**Percentage of each stage**		
Item	**Feedstock**	**Fuel**	**Vehicle Operation**	**Total**	**Feedstock**	**Fuel**	**Vehicle Operation**
Total Energy	236	884	4,529	5,649	4.2%	15.6%	80.2%
Fossil Fuels	226	786	4,434	5,447	4.1%	14.4%	81.4%
Coal	37	151	0	188	19.8%	80.2%	0.0%
Natural Gas	136	259	0	395	34.3%	65.7%	0.0%
Petroleum	53	377	4,434	4,864	1.1%	7.7%	91.2%
CO2 (w/ C in VOC & CO)	15	60	348	423	3.6%	14.2%	82.3%
CH4	0.421	0.069	0.013	0.502	83.8%	13.7%	2.5%
N2O	0.000	0.005	0.012	0.017	2.2%	27.7%	70.1%
GHGs	26	63	352	440	5.8%	14.3%	79.9%
VOC: Total	0.016	0.108	0.182	0.306	5.2%	35.2%	59.5%
CO: Total	0.030	0.034	3.448	3.512	0.8%	1.0%	98.2%
NOx: Total	0.111	0.103	0.099	0.313	35.5%	32.8%	31.6%
PM10: Total	0.010	0.041	0.033	0.083	11.8%	48.9%	39.3%
PM2.5: Total	0.004	0.015	0.018	0.038	11.8%	39.5%	48.7%
SOx: Total	0.037	0.070	0.006	0.113	33.1%	61.9%	5.0%
VOC: Urban	0.003	0.068	0.113	0.183	1.4%	36.9%	61.7%
CO: Urban	0.001	0.016	2.145	2.162	0.1%	0.7%	99.2%
NOx: Urban	0.005	0.042	0.062	0.108	4.4%	38.8%	56.8%
PM10: Urban	0.000	0.008	0.020	0.029	0.7%	28.3%	71.0%
PM2.5: Urban	0.000	0.005	0.012	0.016	0.8%	28.8%	70.4%
SOx: Urban	0.003	0.029	0.004	0.036	8.5%	81.7%	9.8%

Table B.3 Well to Wheel Energy Consumption and Emissions for the Escape HEV Model

Grid-Independent SI HEV: CG and RFG	**Btu/mile or grams/mile**				**Percentage of each stage**		
Item	**Feedstock**	**Fuel**	**Vehicle Operation**	**Total**	**Feedstock**	**Fuel**	**Vehicle Operation**
Total Energy	178	666	3,413	4,257	4.2%	15.6%	80.2%
Fossil Fuels	170	593	3,342	4,105	4.1%	14.4%	81.4%
Coal	28	113	0	142	19.8%	80.2%	0.0%
Natural Gas	102	195	0	298	34.3%	65.7%	0.0%
Petroleum	40	284	3,342	3,666	1.1%	7.7%	91.2%
CO2 (w/ C in VOC & CO)	11	45	262	319	3.6%	14.2%	82.3%
CH4	0.317	0.052	0.006	0.375	84.6%	13.9%	1.6%
N2O	0.000	0.004	0.012	0.016	1.8%	22.5%	75.7%
GHGs	19	47	266	333	5.8%	14.3%	79.9%
VOC: Total	0.012	0.081	0.129	0.222	5.4%	36.5%	58.1%
CO: Total	0.022	0.026	3.448	3.496	0.6%	0.7%	98.6%
NOx: Total	0.084	0.077	0.083	0.244	34.3%	31.7%	34.0%
PM10: Total	0.007	0.031	0.033	0.071	10.4%	43.4%	46.2%
PM2.5: Total	0.003	0.011	0.018	0.033	10.1%	34.1%	55.8%
SOx: Total	0.028	0.053	0.004	0.085	33.1%	61.9%	5.0%
VOC: Urban	0.002	0.051	0.080	0.133	1.5%	38.3%	60.3%
CO: Urban	0.001	0.012	2.145	2.157	0.0%	0.6%	99.4%
NOx: Urban	0.004	0.032	0.052	0.087	4.1%	36.5%	59.5%
PM10: Urban	0.000	0.006	0.020	0.027	0.6%	23.0%	76.5%
PM2.5: Urban	0.000	0.004	0.012	0.015	0.7%	23.4%	76.0%
SOx: Urban	0.002	0.022	0.003	0.027	8.5%	81.7%	9.8%

Table B.4 Well to Wheel Energy Consumption and Emissions for the Escape PHEV Model

Grid-Connected SI PHEV: CG and RFG	**Btu/mile or grams/mile**				**Percentage of each stage**		
Item	**Feedstock**	**Fuel**	**Vehicle Operation**	**Total**	**Feedstock**	**Fuel**	**Vehicle Operation**
Total Energy	171	1,119	3,241	4,531	3.8%	24.7%	71.5%
Fossil Fuels	162	931	3,082	4,175	3.9%	22.3%	73.8%
Coal	31	534	349	915	3.4%	58.4%	38.2%
Natural Gas	87	171	13	271	32.0%	63.3%	4.7%
Petroleum	44	226	2,719	2,990	1.5%	7.6%	91.0%
CO2 (w/ C in VOC & CO)	11	124	213	348	3.3%	35.6%	61.1%
CH4	0.357	0.043	0.006	0.407	87.9%	10.6%	1.5%
N2O	0.000	0.004	0.012	0.016	1.6%	23.5%	74.8%
GHGs	20	126	217	363	5.6%	34.8%	59.6%
VOC: Total	0.016	0.067	0.129	0.212	7.6%	31.5%	60.9%
CO: Total	0.021	0.037	3.448	3.505	0.6%	1.0%	98.4%
NOx: Total	0.081	0.144	0.083	0.309	26.4%	46.7%	26.9%
PM10: Total	0.141	0.031	0.042	0.214	65.9%	14.3%	19.8%
PM2.5: Total	0.036	0.012	0.022	0.071	51.7%	17.2%	31.1%
SOx: Total	0.030	0.267	0.003	0.301	10.1%	88.7%	1.2%
VOC: Urban	0.002	0.042	0.080	0.124	1.4%	33.6%	65.0%
CO: Urban	0.001	0.012	2.145	2.158	0.0%	0.6%	99.4%
NOx: Urban	0.004	0.039	0.052	0.095	4.0%	41.3%	54.7%
PM10: Urban	0.000	0.006	0.026	0.032	0.5%	18.2%	81.3%
PM2.5: Urban	0.000	0.003	0.014	0.017	0.6%	19.6%	79.7%
SOx: Urban	0.002	0.054	0.002	0.059	3.9%	92.4%	3.7%

Table B.5 Well to Wheel Energy Consumption and Emissions Relative Change Results for the Escape, Escape HEV, and Escape PHEV Models

2010	**Grid-Independent SI HEV: CG and RFG**	**Grid-Connected SI PHEV: CG and RFG**
Total Energy	-24.6%	-19.8%
Fossil Fuels	-24.6%	-23.3%
Coal	-24.6%	387.2%
Natural Gas	-24.6%	-31.5%
Petroleum	-24.6%	-38.5%
CO_2 (w/ C in VOC & CO)	-24.6%	-17.6%
CH_4	-25.3%	-19.1%
N_2O	-7.4%	-6.3%
GHGs	-24.5%	-17.5%
VOC: Total	-27.3%	-30.7%
CO: Total	-0.4%	-0.2%
NO_x: Total	-21.9%	-1.4%
PM_{10}: Total	-15.0%	157.7%
$PM_{2.5}$: Total	-12.6%	85.6%
SO_x: Total	-24.6%	166.0%
VOC: Urban	-27.4%	-32.7%
CO: Urban	-0.2%	-0.2%
NO_x: Urban	-19.7%	-12.8%
PM_{10}: Urban	-7.1%	13.2%
$PM_{2.5}$: Urban	-7.3%	4.8%
SO_x: Urban	-24.6%	62.5%