GREET1.5a: Changes from GREET1.5

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Center for Transportation Research
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1.0 Introduction

The GREET model was developed to estimate fuel-cycle energy use and emissions associated with alternative transportation fuels and advanced vehicle technologies. In August 1999, the latest public version of the model — GREET1.5 — was released with a two-volume report describing its methodology, development, use, and results (Wang 1999a and 1999b). Both the GREET1.5 model and the report are available at Argonne's Transportation Technology Research and Development Center (TTRDC) web site (http://www.transportation.anl.gov/ttrdc/greet).

Since the release of GREET version 1.5, we completed a study for the U.S. Department of Energy's Office of Technology Utilization (under the Office of Transportation Technologies). That study evaluated fuel-cycle energy and emission impacts of transportation fuels produced from natural gas (NG). The final report for that study (ANL/ESD-40), entitled *A Full Fuel-Cycle Analysis of Energy and Emissions Impacts of Transportation Fuels Produced from Natural Gas* (Wang and Hann 1999), is also available on Argonne's TTRDC web site (http://www.transportation.anl.gov/ttrdc/publications/pdfs/esd-40.pdf). During revision efforts for the NG fuels study, we made revisions to GREET1.5, resulting in a new version of the model: GREET1.5a. This memorandum documents changes from GREET1.5 to GREET1.5a.

2.0 Additional Fuel Pathways and Vehicle Technologies

2.1 Flared Gas to Liquid Fuels: Liquefied Natural Gas and Liquid Hydrogen

In GREET1.5, flared gas (FG)-based pathways included FG to methanol, dimethyl ether (DME), and Fischer-Tropsch diesel (FTD). These liquid fuels can be produced in remote areas where gas distribution infrastructure is neither available nor feasible. The liquid fuels produced from gas, which is otherwise flared, can be transported over long distances (and across oceans) and used in transportation applications. Liquefied natural gas (LNG) and liquid hydrogen (LH_2), as well as methanol, DME, and FTD, can be produced from FG in remote areas and then transported to user sites. These two additional FG-based pathways were added in GREET1.5a.

2.2 Natural Gas to Fuel-Cell Fuels: Diesel, Liquefied Natural Gas, and Liquefied Petroleum Gas

GREET1.5 considered hydrogen, methanol, gasoline, ethanol, and compressed natural gas (CNG) as potential fuels for fuel-cell vehicles. The current efforts to develop a universal on-board fuel processor could make it possible to use any hydrocarbon fuels to power fuel-cell vehicles. Technologically, it is possible to reform diesel, LNG, and liquefied petroleum gas

(LPG), as well as the fuels already included in GREET1.5, to produce hydrogen onboard fuel-cell vehicles. These three fuels were added as fuel-cell vehicle fuels in GREET1.5a.

Note that GREET is a fuel-cycle model to evaluate energy and emission effects of various transportation fuels. GREET does not address the economics of the technologies, which will eventually help determine which fuels will be introduced in which vehicle propulsion systems.

3.0 Changes in Parametric Assumptions

During the revision of the NG fuels report, we conducted additional research on some of the key assumptions regarding upstream activities for NG-based fuels. On the basis of our research, we changed some of the key upstream assumptions. The changes, which have been incorporated in GREET1.5a, are described in Sections 3.1 through 3.11. For more detailed information regarding the changes, see Wang and Hann (1999).

3.1 Energy Conversion Efficiency of Natural Gas-Fired, Combined-Cycle Turbines

In GREET1.5, the energy conversion efficiency of NG-fired, combined-cycle turbines was assumed to be 55%. On the basis of new information, the efficiencies were changed to 56% for near-term and 60% for long-term technology options in GREET1.5a.

3.2 Natural Gas Compression Efficiency

In GREET1.5, an average NG compression efficiency of 95% was assumed for a combination of NG and electric compressors. This average was based on our review of some major fuel-cycle studies. In GREET1.5a, the efficiencies of NG-powered and electric compressors were calculated by means of a formula developed by Stodolsky (discussed in detail in Wang and Hann 1999). The NG compression efficiencies in the new version of GREET are 91.7% for near-term NG compressors, 92.7% for long-term NG compressors, 96.6% for near-term electric compressors, and 97% for long-term electric compressors.

3.3 Energy Efficiency of Methanol Plants

For methanol plants with commercial gas as the feedstock, we assumed in GREET1.5 energy efficiencies of 68% for near-term methanol plants that export no steam or electricity and 65% for long-term methanol plants that cogenerate 111,000 Btu of steam per million Btu of methanol produced. In GREET1.5a, for methanol plants that export no steam or electricity, the conversion efficiencies are assumed to be 67% for near-term and 70% for long-term plants. For methanol plants that export steam or electricity, a conversion efficiency of 65% and cogeneration of 111,000 Btu of steam per million Btu of methanol produced are assumed for both near- and long-term methanol plants.

For methanol plants with FG as the feedstock, GREET1.5 assumed an energy conversion efficiency of 65% with no steam or electricity export for both near- and long-term methanol plants. In GREET1.5a, the energy efficiencies are assumed to be 65% and 67%, with no steam or electricity export, for near- and long-term plants, respectively.

3.4 Energy Efficiency of Fischer-Tropsch Diesel Plants

For FTD plants with commercial gas as the feedstock, GREET1.5 assumed energy efficiencies of 54% for near-term FTD plants that export no steam or electricity and 53% for long-term plants that cogenerate 264,000 Btu of steam per million Btu of FTD produced. In GREET1.5a, for FTD plants that export no steam or electricity, we assume an energy efficiency of 57% for both near- and long-term plants. For FTD plants that export steam or electricity, we assume an efficiency of 49% and 347,000 Btu of steam cogenerated per million Btu of FTD produced for both near- and long-term plants.

For FTD plants with FG as the feedstock, GREET1.5 assumed an energy efficiency of 52% for both near- and long-term FTD plants that export no steam or electricity. GREET1.5a assumes energy efficiencies of 55% and 57%, with no steam or electricity export, for near- and long-term FTD plants, respectively.

3.5 Energy Efficiency of Dimethyl Ether Plants

For DME plants with commercial gas as the feedstock, GREET1.5 assumed energy efficiencies of 69% for near-term plants and 68% for long-term plants that cogenerate 44,000 Btu of steam per million Btu of DME produced. In GREET1.5a, for DME plants that export no steam or electricity, we assume energy efficiencies of 69% for near-term plants and 70% for long-term plants. For DME plants that export steam or electricity, we assume an energy efficiency of 68% and cogeneration of 44,000 Btu of steam per million Btu of DME produced for both near- and long-term plants.

For DME plants with FG as the feedstock, GREET1.5 assumed an energy efficiency of 66% for both near- and long-term plants. In GREET1.5a, we assume energy efficiencies of 68% for near-term plants and 69% for long-term plants.

3.6 Energy Efficiency of Gaseous Hydrogen Production

For centralized gaseous hydrogen plants, GREET1.5 assumed energy efficiencies of 73% for near-term plants and 67% for long-term plants that cogenerate 269,000 Btu of steam per million Btu of hydrogen produced. In GREET1.5a, for gaseous hydrogen plants that export no steam or electricity, we assume an energy efficiency of 73% for both near- and long-term plants. For gaseous hydrogen plants that export steam or electricity, GREET1.5a assumes an energy efficiency of 71% and cogeneration of 169,000 Btu of steam per million Btu of hydrogen produced for both near- and long-term plants.

For gaseous hydrogen production at refueling stations, GREET1.5 assumed an energy efficiency of 65% for both near- and long-term production facilities. GREET1.5a assumes an efficiency of 70% for both near- and long-term facilities. In both GREET1.5 and GREET1.5a, we assume that steam or electricity are not coproduced during hydrogen production at refueling stations.

3.7 Energy Efficiency of Gaseous Hydrogen Compression

On the basis of our review of some major fuel-cycle studies, we assumed a compression efficiency of 92% for gaseous hydrogen compression in GREET1.5. For GREET1.5a, we calculated hydrogen compression efficiency by using a formula developed by Stodolsky (see Wang and Hann 1999). Furthermore, for the centralized hydrogen production pathway, we assume that electric compressors are used for hydrogen compression. The calculated hydrogen compression efficiency is 90% for electric compressors for both near- and long-term option simulations. For the refueling-station production pathway, we assume that both electric and NG compressors are used for hydrogen compression. For electric compressors, we use the calculated compression efficiency of 90% for both near- and long-term options. For NG compressors, we estimate compression efficiencies of 77% for the near-term and 79% for the long-term options.

3.8 Liquefaction Energy Efficiency for Liquid Hydrogen Production

GREET1.5 assumed liquefaction efficiencies of 82% for near-term and 85% for long-term liquid hydrogen production. In GREET 1.5a, on the basis of new studies, we revised the liquefaction efficiencies for commercial gas-based liquid hydrogen plants to 65% for the near-term and 70% for the long-term options. For FG-based liquid hydrogen plants, the liquefaction efficiencies are 63% for the near-term and 65% for the long-term options in GREET 1.5a.

We assume in GREET1.5a that electric compressors provide power for hydrogen liquefaction. Because liquid hydrogen is produced in large, centralized plants where NG is available, and because a large amount of electricity is required for hydrogen liquefaction, there is an economic incentive for hydrogen plant operators to produce the required electricity onsite. We assume that electricity required for hydrogen liquefaction is produced from NG with combined-cycle turbines in liquid hydrogen plants. In contrast, GREET1.5 assumed use of NG compressors to provide power for hydrogen liquefaction.

3.9 Emission Factors of Combustion Technologies

Emission Factors for NG Flaring. In GREET1.5, emission factors for NG flaring were based on limited testing results in California in the mid-1980s. During the NG fuels study, we found that the emission factors were not reasonable when compared with those of NG combustion technologies. In GREET1.5a, we made the following revisions to the emission factors for NG flaring: (1) carbon monoxide (CO) and methane (CH_4) emissions are calculated from carbon dioxide (CO_2) emissions and ratios of CO and CH_4 to CO_2 as described in Kuipers and Jarvis (1996), (2) volatile organic compound (VOC) emissions from gas flaring are from the U.S. Environmental Protection Agency's (EPA's) AP-42 document, and (3) emission factors for nitrogen oxides (NO_x), particulate matter measuring less than 10 microns (PM_{10}), and nitrous oxide (N_2O) for gas flaring are assumed to be the same as the emission factors for industrial boilers fueled with NG.

Emission Factors for Barges Fueled with Residual Oil. Emission factors for barges fueled with residual oil have been revised in GREET1.5a with information contained in EPA's updated AP-42 documentation. Emission factors in GREET1.5 were 162 (VOCs), 324 (CO), and 908 (NO_x) grams per million Btu of residual oil burned. In GREET1.5a, these emission factors have been revised sharply downward to 2.21 (VOCs), 11.2 (CO), and 180.8 (NO_x).

NO_x Emission Factor for Steam Boilers Fueled with Hydrogen. As described in Section 2.1, we added to GREET1.5a a new pathway for producing liquid hydrogen in remote areas. Under this pathway, liquid hydrogen is assumed to be transported to the United States via ocean tankers. Because a large amount of gaseous hydrogen is produced on ocean tankers from the boiling-off effect of liquid hydrogen, it is feasible for the gaseous hydrogen generated to be collected and burned in boilers to provide power for the ocean tankers. GREET1.5a includes this assumption. Emission factors for hydrogen-fueled boilers are needed to simulate this scenario. In GREET1.5a, we assume an emission factor of 60 grams of NO_x per million Btu of hydrogen burned; this emission factor is based on emission data for hydrogen-fueled internal combustion engines, and is comparable to NO_x emission factor for NG-fired boilers.

3.10 Energy and Emission Credits of the Electricity Co-Produced in Dimethyl Ether, Fischer-Tropsch Diesel, Hydrogen, and Methanol Plants

The steam co-generated in DME, FTD, hydrogen, and methanol plants can be exported directly to nearby plants or can be used to generate electricity for export to the local electric grid. The co-generated steam is usually in the form of low-quality (i.e., low-pressure) steam. Turbines can be designed to use low-pressure steam to generate electricity. The turbines powered with low-pressure steam usually have a lower energy conversion efficiency. On the basis of discussions with boiler and turbine industry experts, in GREET1.5a we used an energy conversion efficiency of 30% for low-pressure steam turbines to estimate the amount of electricity produced from co-generated steam in these chemicals plants.

To calculate the energy and emission credits for the produced electricity, we needed to identify the type of electric power plants in which electricity generation would be displaced by the electricity co-generated in these chemical plants. Because DME, FTD, hydrogen, and methanol plants are assumed to be located in remote areas, the electricity generated from these plants would likely displace electricity from new electric power plants built to meet electricity demand. We assume that the new plants would be equipped with combined-cycle turbines fueled by NG because these types of electric power plants are expected to be built in the future in those locations.

3.11 Vehicular Emission Changes: Evaporative VOC and Exhaust CO Emissions of Long-Term Spark-Ignition Engines Fueled with CNG, LNG, and LPG

On the basis of our assessment of new data regarding vehicle emissions and fuel properties, we assume a VOC evaporative emission reduction of 95% for vehicles fueled by CNG, LNG, and LPG in GREET1.5a. In GREET1.5, the reduction was assumed to be 90%. For CO emissions, GREET1.5a assumes an emission reduction of 40%; GREET1.5 assumed a reduction of 20%.

4.0 Format Changes

To enhance user interface features of the GREET model, we made significant format changes in GREET1.5a. Major format changes are summarized in Sections 4.1 through 4.3.

4.1 A New Inputs Sheet

In GREET1.5a, a new sheet called *Inputs* was created to present key scenario control parameters and key assumptions regarding upstream and vehicle operation activities. The user can now make changes to this single sheet and then go directly to the results sheets to obtain fuel-cycle energy and emission results. In GREET1.5, key scenario control parameters and parametric assumptions were presented in many sheets that the user had to access to make the changes necessary to simulate certain fuel-cycle scenarios.

In the *Inputs* sheet, we developed four major features to provide users with the flexibility to simulate various scenarios. Each is described below.

First, a user can simply change a control parameter to simulate near- or long-term technology options. In GREET1.5, in order to simulate one or the other of the two options, the user had to access many cells and manually enter assumptions for near- or long-term technology options.

Second, we designed a control parameter for the user to choose simulations for passenger cars, light-duty trucks 1 (LDT1), or light-duty trucks 2 (LDT2). In GREET1.5, the user had to manually input baseline vehicle fuel economy and fuel economy and emission changes of alternative-fueled vehicles in order to select one vehicle type over another.

Third, we added a feature to simulate energy and emission credits of the steam co-produced by methanol, DME, gaseous hydrogen, liquid hydrogen, and FTD plants. The new feature allows the user to select “no credit,” “steam credit,” or “electricity credit” for these plants. In GREET1.5, only two options (no credit and steam credit) were available for simulation. We added the electricity credit simulation because we recognized that it may not be practical to export steam in some plant locations. Any of the three options for these chemicals plants can be readily selected in a table on the *Inputs* sheet.

Fourth, we added a feature on the *Inputs* sheet that allows the user to choose the extent to which a NG pipeline transmission and distribution system will be used to produce a given NG-based fuel. In GREET1.5a, the complete pipeline transmission and distribution system — from NG fields to NG end-user sites — is taken into account for the pathway from gas fields to compressed NG in refueling stations. For other NG-based fuels, depending on the location of fuel production plants, the user can assume the use of none or a portion of the NG pipeline transmission and distribution system for producing and distributing a given fuel. A table on the *Inputs* sheet allows the user to choose. The user’s selection of the extent of NG pipeline system use affects methane emissions considerably.

4.2 Separate Results Sheets

In GREET1.5, a single *Results* sheet was provided to present fuel-cycle energy and emission results for both near- and long-term technology options. Results for near-term options were presented in the top section of the sheet, and those for long-term options were presented in the bottom section of the sheet. Users needed to be very careful to avoid mixing up results between near- and long-term options. To help users avoid the potential mixup, we designed two separate results sheets for GREET1.5a: *Near-Term Results* for near-term options and *Long-Term Results* for long-term options. We also added a programming feature in GREET1.5a to prevent users from going to the *Long-Term Results* sheet if they have chosen to simulate near-term options in the *Inputs* sheet, or vice versa.

Similarly, the single *Graph*s sheet in GREET1.5 has been separated into two separate graph sheets: *Near-Term Graphs* and *Long-Term Graphs*.

4.3 Upstream Energy Use and Emission Results

Some users have suggested that energy use and emissions of upstream activities be presented separately from vehicle operation-related energy use and emissions. To accommodate this suggestion, in GREET1.5a we present upstream energy use and emissions for activities from feedstock recovery to fuels available at refueling stations in Btu (for energy use) and grams (for emissions) per million Btu of fuel available at refueling stations. The upstream energy and emission results are presented in the top portions of the two results sheets.

5.0 Programming Corrections

During the development of GREET1.5a, we identified two programming errors embedded in GREET1.5. The first was in the results sheet for calculating energy and emission changes by long-term, grid-independent, compression-ignition, direct-injection (CIDI) hybrid electric vehicles (HEVs) fueled with diesel and DME. The model drew data from the wrong cells in calculating energy and emission changes for these two options.

The other error occurred during calculation of total energy use and fossil energy use for fuels produced from FG. In GREET1.5, FG was treated as an ordinary energy source rather than a waste energy source. That is, the model accounted for energy contained in FG in calculating energy use for producing fuels from FG. Because FG is otherwise a waste product, the energy in FG should not be accounted for in calculating total energy and fossil energy use for the fuels produced from FG. Both errors are corrected in GREET1.5a.

6.0 Results

The revisions to the assumptions described in the above sections changed the fuel-cycle energy and emission results for NG-based fuels. GREET1.5a-estimated fuel-cycle energy and emission changes for NG-based fuels are presented in our NG fuels report (Wang and Hann 1999). Results from GREET1.5 are presented in the GREET1.5 report (Wang 1999a,b). A summary of the new results, taken from the NG pathway report, are presented in Tables 1 through 3. Detailed per-mile energy use and emissions for each of the fuel options are presented in the NG fuels report. For explanations of the acronyms in the three tables, readers are advised to check the acronyms and abbreviations list in the NG fuels report.

Readers are advised to use and cite the results presented in Tables 1 through 3 for the fuels and vehicle options described in this memorandum rather than the results presented in the GREET1.5 report. For the fuels and vehicle options presented in the GREET1.5 report but not in this memorandum, readers are advised to use the results presented in the GREET1.5 report. Note that in the GREET1.5 report, only one scenario was established for a given technology option. In the NG fuels report, two scenarios (an incremental and a leap-forward scenario) were established for each option. If needed, users can average the results of the two scenarios here and compare the averages with the one- scenario results provided in the GREET1.5 report.

As discussed in Sections 2.1 and 2.2, the pathways for producing LNG and liquid hydrogen from FG and the fuel-cell vehicles fueled with LNG and LPG are new in GREET1.5a. So no results are presented in the GREET1.5 report for these options. Also, the results for FTD in the GREET1.5 report were for a blend of 50% FTD and 50% petroleum diesel (by volume); the results for FTD in the NG fuels report are for FTD as a neat fuel. Consequently, no comparison among these options can be made between the GREET1.5 and GREET1.5a results.

In general, because of changes in upstream assumptions for methanol, DME, FTD, diesel fuel, gaseous hydrogen, and liquid hydrogen, emission reduction benefits (especially greenhouse gas emission reduction benefits) are smaller in GREET1.5a than in GREET1.5 for these fuels.

Table 1. Fuel-Cycle Energy and Emission Changes of Near-Term Technologies (Relative to Baseline Gasoline Vehicles Fueled with Conventional Gasoline)

	Incremental Scenario			Leap-Forward Scenario		
	Dedicated CNGV	**Dedicated LPGV**	**MeOH FFV: M85**	**Dedicated CNGV**	**Dedicated LPGV**	**MeOH FFV: M85**
Total energy	4.8%	-9.2%	22.4%	-2.6%	-13.5%	16.5%
Fossil fuels	3.1%	-9.2%	22.4%	-4.1%	-13.5%	16.5%
Petroleum	-99.4%	-98.2%	-71.3%	-99.4%	-98.3%	-72.6%
VOC: Total	-64.6%	-58.2%	-7.3%	-76.4%	-66.8%	-18.8%
VOC: Urban	-67.0%	-53.4%	-6.7%	-81.3%	-64.1%	-20.3%
CO: Total	-19.1%	-31.8%	-17.6%	-50.5%	-47.5%	-37.3%
CO: Urban	-19.5%	-31.9%	-20.1%	-51.5%	-47.9%	-40.0%
NOx: Total	32.2%	-13.5%	13.0%	21.1%	-20.9%	4.4%
NOx: Urban	28.4%	0.0%	-2.6%	16.5%	-9.7%	-12.3%
PM10: Total	-35.2%	-42.2%	-23.8%	-36.8%	-42.8%	-24.9%
PM10: Urban	-31.8%	-31.3%	-22.8%	-32.1%	-31.5%	-22.8%
SOx: Total	-31.2%	-87.1%	-59.1%	-36.0%	-87.7%	-61.1%
SOx: Urban	-96.1%	-98.1%	-72.5%	-96.4%	-98.2%	-73.8%
CH4	207.5%	6.5%	5.7%	194.8%	-1.4%	1.0%
N2O	0.5%	-1.2%	2.3%	-47.9%	-1.3%	2.0%
CO2	-13.1%	-11.3%	4.1%	-19.2%	-15.5%	-0.8%
GHGs	-6.7%	-10.6%	4.1%	-13.7%	-14.8%	-0.7%

Table 2. Fuel-Cycle Energy and Emission Changes of Long-Term Technologies (Relative to Baseline Gasoline Vehicles Fueled with RFG): the Incremental Scenario

	Dedi. CNGV	Dedi. LNGV: NG	Dedi. LNGV: FG	Dedi. LPGV	Dedi. M90 Vehi.: NG	Dedi. M90 Vehi.: FG	SIDI: FRFG2	SIDI: M90, NG	SIDI: M90, FG	SIDI HEV: FRFG2	SI HEV: CNG	SI HEV: LNG, NG
Total energy	-7.3%	-5.8%	-90.0%	-17.8%	12.8%	-77.7%	-20.0%	-3.3%	-82.8%	-33.3%	-31.6%	-28.8%
Fossil fuels	-8.5%	-5.2%	-90.0%	-17.5%	13.4%	-77.7%	-20.0%	-2.7%	-135.6%	-33.3%	-31.6%	-28.8%
Petroleum	-99.4%	-97.8%	-96.0%	-98.2%	-78.1%	-78.1%	-20.0%	-82.1%	-82.1%	-33.3%	-99.6%	-98.4%
VOC: Total	-62.0%	-53.4%	-58.2%	-56.1%	-14.9%	-19.8%	-10.8%	-23.8%	-28.1%	-22.1%	-63.8%	-56.7%
VOC: Urban	-54.6%	-56.1%	-56.5%	-45.3%	-11.1%	-11.1%	-7.4%	-15.8%	-15.9%	-30.0%	-55.5%	-56.6%
CO: Total	-19.6%	-17.6%	-21.7%	-21.1%	2.4%	-2.2%	-1.0%	1.3%	-2.8%	-1.6%	-20.7%	-19.2%
CO: Urban	-19.3%	-20.0%	-20.0%	-20.0%	-0.2%	-0.2%	-0.1%	-0.2%	-0.2%	-0.1%	-19.5%	-20.1%
NOx: Total	38.2%	78.1%	-20.9%	-38.2%	7.8%	-118.5%	-16.3%	-11.1%	-122.0%	-27.2%	4.4%	43.6%
NOx: Urban	121.8%	-8.3%	-13.2%	-3.7%	-17.2%	-18.7%	-5.8%	-18.3%	-19.9%	-9.6%	83.9%	-15.2%
PM10: Total	-31.8%	-29.3%	-68.5%	-38.2%	-21.3%	-62.6%	2.4%	-19.2%	-54.9%	-6.3%	-39.9%	-33.5%
PM10: Urban	-24.1%	-25.9%	-26.2%	-25.2%	-14.5%	-14.6%	11.9%	-2.1%	-2.3%	5.2%	-24.9%	-26.5%
SOx: Total	-25.9%	-76.9%	-79.2%	-71.8%	-58.7%	-61.1%	-20.0%	-75.2%	-77.8%	-33.3%	-83.3%	-83.1%
SOx: Urban	-80.4%	-98.1%	-98.4%	-91.5%	-77.9%	-78.0%	-20.0%	-80.6%	-80.6%	-33.3%	-86.0%	-98.7%
CH4	82.7%	81.6%	-7.4%	-22.9%	-14.4%	-63.0%	-18.2%	-28.6%	-71.4%	-30.3%	48.8%	47.0%
N2O	-47.9%	-47.0%	-66.1%	-1.6%	1.5%	-18.2%	-0.8%	0.4%	-17.0%	-1.4%	-49.1%	-48.3%
CO2	-24.0%	-24.6%	-93.6%	-21.1%	-6.4%	-77.3%	-20.0%	-19.8%	-82.2%	-33.4%	-44.3%	-43.0%
GHGs	-21.1%	-21.6%	-90.2%	-20.8%	-6.5%	-75.6%	-19.6%	-19.7%	-80.5%	-32.6%	-41.4%	-40.2%

	SI HEV: LNG, FG	SI HEV: LPG	SIDI HEV: M90, NG	SIDI HEV: M90, FG	CIDI: RFD	CIDI: DME, NG	CIDI: DME, FG	CIDI: FTD, NG	CIDI: FTD, FG	CIDI HEV: RFD	CIDI HEV: DME, NG	CIDI HEV: DME, FG	CIDI HEV: FTD, NG
Total energy	-92.5%	-35.1%	-36.0%	-87.4%	-27.9%	-7.3%	-94.4%	15.2%	-91.1%	-50.1%	-35.8%	-96.1%	-20.2%
Fossil fuels	-92.5%	-35.1%	-36.0%	-121.2%	-27.9%	-6.7%	-153.9%	16.0%	-150.6%	-50.1%	-35.4%	-137.3%	-19.7%
Petroleum	-97.0%	-98.6%	-87.7%	-87.7%	-16.6%	-97.7%	-97.7%	-97.2%	-97.2%	-42.3%	-98.4%	-98.4%	-98.1%
VOC: Total	-61.0%	-57.7%	-33.7%	-37.3%	-61.0%	-72.9%	-84.1%	-71.5%	-78.3%	-65.6%	-76.2%	-83.8%	-73.0%
VOC: Urban	-56.8%	-47.1%	-25.8%	-25.8%	-63.0%	-75.9%	-75.9%	-66.7%	-66.7%	-64.2%	-76.2%	-76.2%	-66.7%
CO: Total	-22.3%	-21.7%	-0.7%	-3.4%	-1.9%	0.5%	-4.1%	0.4%	-5.1%	-2.8%	-1.1%	-4.3%	-1.2%
CO: Urban	-20.1%	-20.0%	-0.2%	-0.2%	-0.1%	-0.3%	-0.3%	-0.2%	-0.3%	-0.2%	-0.3%	-0.3%	-0.3%
NOx: Total	-36.1%	-47.2%	-29.5%	-102.5%	-15.9%	-11.3%	-134.7%	-18.2%	-163.5%	-31.9%	-29.2%	-114.2%	-34.0%
NOx: Urban	-17.1%	-10.4%	-23.1%	-23.1%	41.7%	33.0%	29.1%	33.4%	29.4%	36.5%	31.8%	27.7%	32.1%
PM10: Total	-63.7%	-40.5%	-23.8%	-47.6%	-9.5%	-26.9%	-66.8%	-29.5%	-76.3%	-16.4%	-29.0%	-56.1%	-30.8%
PM10: Urban	-26.7%	-25.9%	-7.3%	-7.3%	-1.3%	-2.6%	-2.8%	-2.6%	-2.7%	-1.9%	-2.7%	-2.9%	-2.7%
SOx: Total	-84.4%	-83.5%	-76.6%	-78.0%	-22.2%	-79.7%	-82.3%	-80.7%	-81.6%	-46.1%	-86.0%	-87.7%	-86.6%
SOx: Urban	-98.8%	-93.5%	-87.6%	-87.6%	18.9%	-95.2%	-95.3%	-94.3%	-94.4%	-17.7%	-96.7%	-96.7%	-96.1%
CH4	-19.1%	-37.3%	-49.9%	-77.1%	-46.5%	-44.5%	-79.7%	-46.1%	-89.4%	-62.5%	-60.6%	-85.0%	-62.2%
N2O	-62.6%	-2.3%	-1.0%	-12.1%	-42.4%	-43.9%	-63.2%	-45.2%	-67.7%	-43.2%	-44.3%	-57.7%	-45.2%
CO2	-95.2%	-37.7%	-46.8%	-87.2%	-22.8%	-25.7%	-94.0%	-12.4%	-88.4%	-46.6%	-48.6%	-95.9%	-39.4%
GHGs	-92.1%	-37.0%	-46.0%	-85.4%	-24.0%	-26.6%	-92.9%	-14.1%	-88.0%	-47.0%	-48.9%	-94.8%	-40.2%

	CIDI HEV: FTD, FG	EV	G.H2 FCV: Central	G.H2 FCV: R. station	L.H2 FCVs: NG	L.H2 FCVs: FG	MeOH FCV: NG	MeOH FCV: FG	RFG FCV	CNG FCV	LNG FCV: NG	LNG FCV: FG	LPG FCV
Total energy	-93.8%	-51.2%	-50.5%	-43.8%	-28.7%	-84.8%	-38.4%	-96.2%	-42.9%	-44.4%	-43.5%	-94.0%	-48.3%
Fossil fuels	-135.0%	-51.2%	-52.6%	-45.6%	-29.3%	-85.0%	-38.0%	-134.4%	-42.9%	-45.1%	-43.1%	-94.0%	-48.2%
Petroleum	-98.1%	-99.7%	-99.6%	-96.0%	-99.0%	-99.1%	-98.3%	-98.3%	-42.9%	-99.6%	-98.7%	-97.6%	-98.9%
VOC: Total	-77.5%	-95.5%	-95.1%	-92.0%	-93.4%	-99.9%	-70.1%	-73.6%	-50.2%	-87.6%	-82.5%	-85.6%	-85.6%
VOC: Urban	-66.7%	-99.3%	-99.7%	-94.1%	-99.5%	-99.5%	-73.4%	-73.4%	-53.0%	-87.5%	-88.3%	-88.6%	-84.1%
CO: Total	-5.0%	-97.9%	-96.6%	-95.2%	-95.8%	-99.8%	-76.8%	-79.8%	-78.2%	-78.4%	-77.2%	-79.7%	-79.2%
CO: Urban	-0.3%	-99.9%	-99.9%	-96.9%	-99.9%	-99.9%	-80.0%	-80.0%	-79.9%	-79.5%	-79.9%	-79.9%	-79.9%
NOx: Total	-134.1%	42.8%	-25.8%	12.8%	-18.6%	-109.2%	-47.4%	-128.4%	-49.7%	-24.1%	-0.1%	-59.9%	-68.6%
NOx: Urban	27.9%	-9.9%	-84.3%	128.5%	-94.1%	-94.2%	-82.2%	-82.3%	-69.4%	3.6%	-74.5%	-76.4%	-71.1%
PM10: Total	-62.7%	-28.6%	-38.6%	-34.9%	-33.3%	-63.1%	-45.2%	-71.2%	-35.6%	-43.7%	-42.2%	-65.3%	-47.2%
PM10: Urban	-2.9%	-28.3%	-33.7%	-25.2%	-33.5%	-33.5%	-34.0%	-34.1%	-32.6%	-31.9%	-33.0%	-33.2%	-32.5%
SOx: Total	-87.3%	-88.1%	-17.0%	-23.9%	-85.5%	-92.0%	-84.1%	-85.6%	-49.3%	-56.5%	-86.2%	-87.5%	-82.3%
SOx: Urban	-96.1%	-97.9%	-98.2%	-97.7%	-99.4%	-99.4%	-96.3%	-96.4%	-94.4%	-98.8%	-98.9%	-99.0%	-94.6%
CH4	-92.2%	-27.2%	-62.1%	-36.1%	-66.2%	-115.0%	-55.9%	-86.9%	-46.3%	-8.7%	-9.4%	-62.7%	-56.0%
N2O	-60.8%	-89.1%	-96.7%	-95.1%	-91.2%	-104.3%	-77.7%	-90.3%	-78.5%	-78.4%	-77.8%	-89.2%	-79.4%
CO2	-91.9%	-60.2%	-59.6%	-54.7%	-43.3%	-88.1%	-50.6%	-95.9%	-42.9%	-54.3%	-54.2%	-95.6%	-57.5%
GHGs	-91.3%	-59.7%	-60.4%	-54.8%	-45.0%	-89.2%	-51.3%	-95.5%	-43.7%	-53.3%	-53.2%	-94.4%	-57.9%

Table 3. Fuel-Cycle Energy and Emission Changes of Long-Term Technologies (Relative to Baseline Gasoline Vehicles Fueled with RFG): the Leap-Forward Scenario

	Dedi. CNGV	Dedi. LNGV: NG	Dedi. LNGV: FG	Dedi. LPGV	Dedi. M90 Vehi.: NG	Dedi. M90 Vehi.: FG	SIDI: FRFG2	SIDI: M90, NG	SIDI: M90, FG	SIDI HEV: FRFG2	SI HEV: CNG	SI HEV: LNG, NG	SI HEV: LNG, FG
Total energy	-12.6%	-9.9%	-90.5%	-21.2%	8.9%	-77.7%	-20.0%	-6.7%	-82.8%	-48.7%	-47.4%	-44.5%	-94.2%
Fossil fuels	-13.5%	-9.4%	-90.5%	-21.0%	9.4%	-77.7%	-20.0%	-6.1%	-135.7%	-48.7%	-47.4%	-44.5%	-94.2%
Petroleum	-99.4%	-97.9%	-96.1%	-98.3%	-78.1%	-78.1%	-20.0%	-82.1%	-82.1%	-48.7%	-99.7%	-98.7%	-97.6%
VOC: Total	-64.3%	-55.7%	-60.3%	-58.1%	-14.9%	-19.8%	-10.8%	-23.9%	-28.1%	-28.1%	-66.9%	-61.1%	-64.5%
VOC: Urban	-57.3%	-58.3%	-58.7%	-47.8%	-11.1%	-11.1%	-7.4%	-15.9%	-15.9%	-32.4%	-58.4%	-59.0%	-59.2%
CO: Total	-39.0%	-36.9%	-40.9%	-40.2%	2.4%	-2.2%	-1.0%	1.2%	-2.8%	-2.4%	-40.5%	-39.3%	-41.7%
CO: Urban	-39.4%	-40.0%	-40.0%	-39.9%	-0.2%	-0.2%	-0.1%	-0.2%	-0.2%	-0.1%	-39.7%	-40.0%	-40.1%
NOx: Total	25.9%	71.0%	-23.4%	-40.1%	6.9%	-118.8%	-16.3%	-11.9%	-122.2%	-39.8%	-18.4%	16.3%	-46.0%
NOx: Urban	99.2%	-9.1%	-13.7%	-4.7%	-17.2%	-18.6%	-5.7%	-18.3%	-19.8%	-13.9%	49.1%	-18.0%	-19.5%
PM10: Total	-34.0%	-30.3%	-67.6%	-38.8%	-21.6%	-62.6%	2.4%	-19.5%	-54.9%	-11.2%	-42.4%	-37.0%	-60.6%
PM10: Urban	-24.7%	-26.0%	-26.3%	-25.3%	-14.5%	-14.6%	11.9%	-2.1%	-2.3%	4.7%	-25.9%	-26.9%	-27.0%
SOx: Total	-36.1%	-78.0%	-80.2%	-73.0%	-59.0%	-61.1%	-20.0%	-75.5%	-77.8%	-48.7%	-87.2%	-86.9%	-87.9%
SOx: Urban	-81.5%	-98.2%	-98.5%	-91.8%	-77.9%	-78.0%	-20.0%	-80.6%	-80.6%	-48.7%	-89.2%	-99.0%	-99.1%
CH4	75.0%	75.6%	-9.4%	-25.8%	-14.9%	-63.0%	-18.2%	-29.1%	-71.4%	-44.3%	24.9%	24.7%	-26.8%
N2O	-48.4%	-47.2%	-65.4%	-1.7%	1.4%	-18.2%	-0.8%	0.3%	-17.0%	-2.0%	-49.9%	-49.1%	-60.2%
CO2	-28.4%	-27.9%	-93.9%	-24.4%	-9.2%	-77.3%	-20.0%	-22.4%	-82.1%	-48.8%	-57.2%	-55.6%	-96.4%
GHGs	-25.5%	-24.9%	-90.6%	-24.0%	-9.2%	-75.6%	-19.6%	-22.1%	-80.5%	-47.7%	-54.4%	-52.8%	-93.4%

	SI HEV: LPG	SIDI HEV: M90, NG	SIDI HEV: M90, FG	CIDI: RFD	CIDI: DME, NG	CIDI: DME, FG	CIDI: FTD, NG	CIDI: FTD, FG	CIDI HEV: RFD	CIDI HEV: DME, NG	CIDI HEV: DME, FG	CIDI HEV: FTD, NG	CIDI HEV: FTD, FG
Total energy	-49.5%	-38.1%	-87.4%	-35.0%	-17.6%	-95.0%	4.2%	-92.2%	-57.6%	-46.3%	-96.7%	-32.0%	-94.9%
Fossil fuels	-49.5%	-38.1%	-121.3%	-35.0%	-17.1%	-148.7%	4.9%	-145.9%	-57.6%	-45.9%	-131.8%	-31.6%	-129.9%
Petroleum	-98.9%	-87.7%	-87.7%	-25.0%	-97.9%	-97.9%	-97.5%	-97.5%	-51.1%	-98.6%	-98.6%	-98.4%	-98.4%
VOC: Total	-61.2%	-33.7%	-37.3%	-62.5%	-74.0%	-83.9%	-71.9%	-77.8%	-67.1%	-77.3%	-83.6%	-73.5%	-77.1%
VOC: Urban	-50.7%	-25.8%	-25.8%	-63.4%	-76.0%	-76.0%	-66.7%	-66.7%	-64.6%	-76.3%	-76.3%	-66.8%	-66.8%
CO: Total	-41.2%	-0.8%	-3.4%	-2.2%	0.0%	-4.1%	-0.1%	-4.9%	-3.1%	-1.7%	-4.3%	-1.8%	-4.9%
CO: Urban	-40.0%	-0.2%	-0.2%	-0.1%	-0.3%	-0.3%	-0.3%	-0.3%	-0.2%	-0.3%	-0.3%	-0.3%	-0.3%
NOx: Total	-54.8%	-29.8%	-102.6%	-20.9%	-17.0%	-126.7%	-22.8%	-149.3%	-37.2%	-35.3%	-106.2%	-39.0%	-121.0%
NOx: Urban	-14.3%	-23.0%	-22.9%	40.3%	32.7%	29.0%	33.0%	29.3%	35.0%	31.5%	27.6%	31.7%	27.8%
PM10: Total	-42.5%	-23.9%	-47.6%	-11.7%	-38.2%	-73.8%	-40.4%	-81.2%	-18.7%	-40.4%	-63.0%	-41.8%	-67.9%
PM10: Urban	-26.4%	-7.3%	-7.3%	-1.5%	-18.3%	-18.4%	-18.3%	-18.4%	-2.1%	-18.4%	-18.5%	-18.4%	-18.5%
SOx: Total	-87.2%	-76.7%	-78.0%	-29.9%	-81.8%	-84.0%	-82.5%	-83.4%	-54.3%	-88.1%	-89.6%	-88.6%	-89.1%
SOx: Urban	-94.9%	-87.6%	-87.6%	7.0%	-95.7%	-95.8%	-94.9%	-95.0%	-30.2%	-97.2%	-97.2%	-96.7%	-96.7%
CH4	-49.0%	-50.1%	-77.1%	-51.7%	-49.7%	-81.0%	-51.3%	-88.9%	-67.9%	-66.1%	-86.5%	-67.7%	-92.2%
N2O	-2.7%	-1.0%	-12.0%	-42.6%	-44.0%	-61.2%	-45.1%	-64.7%	-43.5%	-44.4%	-55.6%	-45.1%	-57.9%
CO2	-51.4%	-48.4%	-87.2%	-30.4%	-33.8%	-94.6%	-20.7%	-87.7%	-54.6%	-56.9%	-96.5%	-48.3%	-92.0%
GHGs	-50.4%	-47.5%	-85.4%	-31.3%	-34.5%	-93.5%	-22.2%	-87.3%	-54.8%	-56.9%	-95.4%	-48.9%	-91.3%

	EV	G.H2 FCV: Central	G.H2 FCV: R. station	L.H2 FCVs: NG	L.H2 FCVs: FG	MeOH FCV: NG	MeOH FCV: FG	RFG FCV	CNG FCV	LNG FCV: NG	LNG FCV: FG	LPG FCV
Total energy	-64.5%	-56.0%	-50.8%	-41.8%	-87.6%	-50.4%	-96.8%	-55.6%	-57.3%	-56.0%	-95.4%	-59.7%
Fossil fuels	-64.5%	-57.9%	-52.2%	-42.3%	-87.7%	-50.1%	-129.0%	-55.6%	-57.7%	-55.7%	-95.4%	-59.6%
Petroleum	-99.8%	-99.6%	-96.6%	-99.1%	-99.3%	-98.6%	-98.5%	-55.6%	-99.7%	-99.0%	-98.1%	-99.1%
VOC: Total	-96.8%	-95.7%	-93.2%	-94.5%	-99.9%	-72.0%	-74.9%	-55.1%	-88.9%	-84.7%	-87.1%	-87.1%
VOC: Urban	-99.5%	-99.7%	-95.0%	-99.5%	-99.6%	-73.6%	-73.6%	-54.9%	-88.1%	-88.6%	-88.8%	-85.3%
CO: Total	-98.4%	-97.0%	-95.8%	-96.5%	-99.8%	-77.5%	-80.0%	-78.8%	-79.0%	-78.1%	-80.0%	-79.6%
CO: Urban	-99.9%	-99.9%	-97.3%	-100.0%	-100.0%	-80.0%	-80.0%	-79.9%	-79.7%	-80.0%	-80.0%	-79.9%
NOx: Total	4.2%	-34.0%	-4.0%	-35.7%	-108.8%	-55.8%	-123.4%	-60.1%	-43.5%	-21.4%	-67.9%	-74.8%
NOx: Urban	-34.4%	-86.1%	93.0%	-94.8%	-94.8%	-82.7%	-82.9%	-73.0%	-23.9%	-76.9%	-78.4%	-74.2%
PM10: Total	-35.4%	-40.4%	-38.1%	-38.3%	-62.4%	-47.0%	-68.4%	-39.7%	-46.9%	-45.1%	-62.7%	-48.9%
PM10: Urban	-30.0%	-33.7%	-26.5%	-33.6%	-33.6%	-34.0%	-34.1%	-33.0%	-32.6%	-33.3%	-33.5%	-32.9%
SOx: Total	-91.4%	-26.3%	-36.7%	-88.1%	-93.4%	-86.8%	-87.9%	-60.5%	-69.5%	-89.2%	-90.3%	-86.2%
SOx: Urban	-98.5%	-98.4%	-98.1%	-99.4%	-99.5%	-96.9%	-97.0%	-95.7%	-99.2%	-99.1%	-99.3%	-95.8%
CH4	-47.0%	-66.3%	-43.9%	-70.4%	-112.7%	-63.0%	-88.7%	-57.8%	-27.7%	-27.4%	-68.9%	-65.4%
N2O	-92.1%	-97.1%	-95.8%	-93.3%	-103.9%	-78.3%	-88.8%	-79.0%	-79.0%	-78.5%	-87.4%	-79.7%
CO2	-71.0%	-64.1%	-60.3%	-53.8%	-90.4%	-60.1%	-96.6%	-55.6%	-64.9%	-64.3%	-96.6%	-66.9%
GHGs	-70.6%	-64.8%	-60.5%	-55.1%	-91.4%	-60.5%	-96.2%	-56.1%	-64.0%	-63.4%	-95.5%	-67.1%

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