ANL/ESD-40

A Full Fuel-Cycle Analysis of Energy and Emissions Impacts of Transportation Fuels Produced from Natural Gas

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CORRIGENDUM

After this report was completed, we identified several errors in calculating fuel-cycle energy use and emissions of gaseous hydrogen and liquid hydrogen. In particular, errors were involved in four hydrogen pathways:

1. For the pathway of gaseous hydrogen production in centralized plants, the produced hydrogen was supposed to be compressed with electric compressors at refueling stations (page 26). But calculations done for this report assumed use of natural gas compressors.

2. For the pathway of gaseous hydrogen production at refueling stations, the produced hydrogen was supposed to be compressed with both electric and natural gas compressors (pages 27-28). But calculations made for the report assumed use of natural gas compressors only.

3. For the pathway of liquid hydrogen production from commercial gas, power for hydrogen liquefaction was supposed to be provided by electric compressors (page 29). But calculations for this report assumed natural gas compressors.

4. For the pathway of liquid hydrogen production from flared gas, the calculation assumed natural gas compressors, rather than electric compressors (page 37).

These identified errors were corrected in GREET1.5a. Consequently, new results for these four pathways were calculated. The tables on the next three pages present correct results for these pathways. In particular, the four tables on page 2 here should replace the corresponding tables on pages 101 and 102 of the report. The four tables on page 3 here should replace the corresponding tables on pages 108 and 109. The table on page 4 here should replace the corresponding columns on pages 113 and 114 of the report.

Corrected Results for Fuel-Cell Vehicles Fueled with Hydrogen

1. Per-Mile Fuel-Cycle Energy Use and Emissions

A. The Incremental Scenario:

GH2 FCV: Central

	Feedstock	Fuel	Vehicle Operation
Total energy	105	1,134	1,671
Fossil fuels	103	988	1,671
Petroleum	7	12	0
VOC: Total	0.002	0.008	0.000
VOC: Urban	0.000	0.000	0.000
CO: Total	0.021	0.076	0.000
CO: Urban	0.000	0.003	0.000
NOx: Total	0.018	0.136	0.000
NOx: Urban	0.000	0.008	0.000
PM10: Total	0.001	0.007	0.021
PM10: Urban	0.000	0.000	0.021
SOx: Total	0.005	0.066	0.000
SOx: Urban	0.000	0.000	0.000
CH4	0.174	0.095	0.000
N2O	0.000	0.001	0.000
CO2	8	169	0
GHGs	12	171	0

GH2 FCV: Refueling Stations

	Feedstock	Fuel	Vehicle Operation
Total energy	160	1,475	1,671
Fossil fuels	158	1,344	1,671
Petroleum	8	177	0
VOC: Total	0.004	0.013	0.000
VOC: Urban	0.000	0.008	0.000
CO: Total	0.034	0.106	0.000
CO: Urban	0.001	0.086	0.000
NOx: Total	0.049	0.184	0.000
NOx: Urban	0.003	0.108	0.000
PM10: Total	0.001	0.008	0.021
PM10: Urban	0.000	0.003	0.021
SOx: Total	0.005	0.060	0.000
SOx: Urban	0.000	0.000	0.000
CH4	0.330	0.123	0.000
N2O	0.000	0.001	0.000
CO2	11	188	0
GHGs	18	191	0

LH2 FCV: NG

	Feedstock	Fuel	Vehicle Operation
Total energy	106	2,414	1,671
Fossil fuels	105	2,344	1,671
Petroleum	8	38	0
VOC: Total	0.002	0.012	0.000
VOC: Urban	0.000	0.001	0.000
CO: Total	0.022	0.099	0.000
CO: Urban	0.000	0.001	0.000
NOx: Total	0.018	0.150	0.000
NOx: Urban	0.000	0.003	0.000
PM10: Total	0.001	0.009	0.021
PM10: Urban	0.000	0.000	0.021
SOx: Total	0.005	0.008	0.000
SOx: Urban	0.000	0.000	0.000
CH4	0.177	0.062	0.000
N2O	0.000	0.002	0.000
CO2	8	240	0
GHGs	12	242	0

LH2 FCV: FG

	Feedstock	Fuel	Vehicle Operation
Total energy	0	-776	1,671
Fossil fuels	0	-794	1,671
Petroleum	0	39	0
VOC: Total	0.000	0.000	0.000
VOC: Urban	0.000	0.001	0.000
CO: Total	0.000	0.007	0.000
CO: Urban	0.000	0.001	0.000
NOx: Total	0.000	-0.019	0.000
NOx: Urban	0.000	0.003	0.000
PM10: Total	0.000	-0.004	0.021
PM10: Urban	0.000	0.000	0.021
SOx: Total	0.000	0.007	0.000
SOx: Urban	0.000	0.000	0.000
CH4	0.000	-0.106	0.000
N2O	0.000	-0.001	0.000
CO2	0	52	0
GHGs	0	50	0

B. The Leap-Forward Scenario:

	GH2 FCV: Central			GH2 FCV: Refueling Station		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	93	1,008	1,485	143	1,267	1,485
Fossil fuels	92	879	1,485	141	1,159	1,485
Petroleum	7	10	0	7	147	0
VOC: Total	0.001	0.008	0.000	0.003	0.011	0.000
VOC: Urban	0.000	0.000	0.000	0.000	0.007	0.000
CO: Total	0.019	0.068	0.000	0.030	0.092	0.000
CO: Urban	0.000	0.003	0.000	0.001	0.074	0.000
NOx: Total	0.016	0.121	0.000	0.044	0.155	0.000
NOx: Urban	0.000	0.007	0.000	0.003	0.091	0.000
PM10: Total	0.001	0.006	0.021	0.001	0.007	0.021
PM10: Urban	0.000	0.000	0.021	0.000	0.002	0.021
SOx: Total	0.004	0.059	0.000	0.005	0.050	0.000
SOx: Urban	0.000	0.000	0.000	0.000	0.000	0.000
CH4	0.155	0.084	0.000	0.293	0.104	0.000
N2O	0.000	0.001	0.000	0.000	0.001	0.000
CO2	7	150	0	10	164	0
GHGs	11	152	0	16	167	0

	LH2 FCV: NG			LH2 FCV: FG		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	95	1,841	1,485	0	-754	1,485
Fossil fuels	93	1,785	1,485	0	-769	1,485
Petroleum	7	32	0	0	34	0
VOC: Total	0.001	0.010	0.000	0.000	0.000	0.000
VOC: Urban	0.000	0.001	0.000	0.000	0.001	0.000
CO: Total	0.019	0.083	0.000	0.000	0.007	0.000
CO: Urban	0.000	0.001	0.000	0.000	0.001	0.000
NOx: Total	0.016	0.117	0.000	0.000	-0.018	0.000
NOx: Urban	0.000	0.003	0.000	0.000	0.003	0.000
PM10: Total	0.001	0.007	0.021	0.000	-0.003	0.021
PM10: Urban	0.000	0.000	0.021	0.000	0.000	0.021
SOx: Total	0.004	0.006	0.000	0.000	0.006	0.000
SOx: Urban	0.000	0.000	0.000	0.000	0.000	0.000
CH4	0.157	0.053	0.000	0.000	-0.090	0.000
N2O	0.000	0.002	0.000	0.000	-0.001	0.000
CO2	7	195	0	0	42	0
GHGs	11	197	0	0	40	0

2. Change in Per-Mile Fuel-Cycle Energy Use and Emissions: Relative to Baseline GVs Fueled with RFG

	Incremental Scenario				LEAP-Forward Scenario			
	GH2 FCV: Central	GH2 FCV: R. Station	LH2 FCV: NG	LH2 FCV: FG	GH2 FCV: Central	GH2 FCV: R. Station	LH2 FCV: NG	LH2 FCV: FG
Total energy	-50.5%	-43.8%	-28.7%	-84.8%	-56.0%	-50.8%	-41.8%	-87.6%
Fossil fuels	-52.6%	-45.6%	-29.3%	-85.0%	-57.9%	-52.2%	-42.3%	-87.7%
Petroleum	-99.6%	-96.0%	-99.0%	-99.1%	-99.6%	-96.6%	-99.1%	-99.3%
VOC: Total	-95.1%	-92.0%	-93.4%	-99.9%	-95.7%	-93.2%	-94.5%	-99.9%
VOC: Urban	-99.7%	-94.1%	-99.5%	-99.5%	-99.7%	-95.0%	-99.5%	-99.6%
CO: Total	-96.6%	-95.2%	-95.8%	-99.8%	-97.0%	-95.8%	-96.5%	-99.8%
CO: Urban	-99.9%	-96.9%	-99.9%	-99.9%	-99.9%	-97.3%	-100.0%	-100.0%
NOx: Total	-25.8%	12.8%	-18.6%	-109.2%	-34.0%	-4.0%	-35.7%	-108.8%
NOx: Urban	-84.3%	128.5%	-94.1%	-94.2%	-86.1%	93.0%	-94.8%	-94.8%
PM10: Total	-38.6%	-34.9%	-33.3%	-63.1%	-40.4%	-38.1%	-38.3%	-62.4%
PM10: Urban	-33.7%	-25.2%	-33.5%	-33.5%	-33.7%	-26.5%	-33.6%	-33.6%
SOx: Total	-17.0%	-23.9%	-85.5%	-92.0%	-26.3%	-36.7%	-88.1%	-93.4%
SOx: Urban	-98.2%	-97.7%	-99.4%	-99.4%	-98.4%	-98.1%	-99.4%	-99.5%
CH4	-62.1%	-36.1%	-66.2%	-115.0%	-66.3%	-43.9%	-70.4%	-112.7%
N2O	-96.7%	-95.1%	-91.2%	-104.3%	-97.1%	-95.8%	-93.3%	-103.9%
CO2	-59.6%	-54.7%	-43.3%	-88.1%	-64.1%	-60.3%	-53.8%	-90.4%
GHGs	-60.4%	-54.8%	-45.0%	-89.2%	-64.8%	-60.5%	-55.1%	-91.4%

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Notation

Acronyms and Abbreviations

ATR	autothermal reforming
CD	conventional diesel
CG	conventional gasoline
CH_3OH	methyl alcohol (methanol)
CH_4	methane
CI	compression ignition
CIDI	compression-ignition, direct-injection
CNG	compressed natural gas
CNGV	compressed natural gas vehicle
CO	carbon monoxide
CO_2	carbon dioxide
DI	direct injection
DME	dimethyl ether
DOE	U.S. Department of Energy
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
EV	electric vehicle
FCV	fuel-cell vehicle
FFV	flexible-fuel vehicle
FG	flared gas
FRFG2	federal phase 2 reformulated gasoline
FTD	Fischer-Tropsch diesel
GAPC	Global Alternative Propulsion Center
GH_2	gaseous hydrogen
GHG	greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GWP	global warming potential
H_2	hydrogen
H_2S	hydrogen sulfide
HEV	hybrid electric vehicle
HFCs	hydrofluorocarbons
HHV	high heating value
ICE	internal combustion engine
IPCC	Intergovernmental Panel on Climate Change
LH_2	liquid hydrogen
LHV	low heating value
LNG	liquefied natural gas
LNGV	liquefied natural gas vehicle
LPG	liquefied petroleum gas

M85	85% methanol and 15% gasoline by volume
M90	90% methanol and 10% gasoline by volume
MeOH	methanol
MTBE	methyl tertiary butyl ether
N_2O	nitrous oxide
NG	natural gas
NGL	natural gas liquid
Ni-MH	nickel metal hydride
NLEV	national low-emission vehicle
NO_x	nitrogen oxide
OPEC	Organization of Oil Exporting Countries
PFCs	perfluorinated carbons
PM_{10}	particulate matter with diameters of 10 micrometers or less
POX	partial oxidation
R&D	research and development
RFD	reformulated diesel
RFG	reformulated gasoline
RVP	Reid vapor pressure
SCR	selective catalytic reactor
SF_6	sulfur hexafluoride
SI	spark ignition
SIDI	spark-ignition, direct-injection
SMR	steam-methane reforming
SO_2	sulfur dioxide
SO_x	sulfur oxide
T&S	transportation and storage
T&S&D	fuel transportation, storage, and distribution
VOC	volatile organic compound
ZnO	zinc oxide
ZnS	zinc sulfide

Units of Measure

Btu	British thermal unit
d	day
ft^3	cubic feet
g	gram
gal	gallon
GJ	gigajoules
kWh	kilowatt hour
m^3	cubic meter
mi	mile
MJ	megajoules
mpg	miles per gallon
mpgeg	miles per gasoline-equivalent gallon
nm^3	normal cubic meter
ppm	parts per million

psi	pounds per square inch
scf	standard cubic foot
therm	100,000 Btu

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Abstract

Because of its abundance and because it offers significant energy and environmental advantages, natural gas has been promoted for use in motor vehicles. A number of transportation fuels are produced from natural gas; each is distinct in terms of upstream production activities and vehicle usage. In this study, we evaluate eight fuels produced from natural gas — compressed natural gas, liquefied natural gas, liquefied petroleum gas, methanol, hydrogen, dimethyl ether, Fischer-Tropsch diesel, and electricity — for use in five types of motor vehicles — spark-ignition vehicles, compression-ignition vehicles, hybrid electric vehicles, battery-powered electric vehicles, and fuel-cell vehicles.

Because of great uncertainties associated with advances both in fuel production and vehicle technologies, we evaluate near-term and long-term fuels and vehicle technologies separately. Furthermore, for long-term options, we establish both an “incremental technology scenario” and a “leap-forward technology scenario” to address potential technology improvements. Our study reveals that, in general, the use of natural gas-based fuels reduces energy use and emissions relative to use of petroleum-based gasoline and diesel fuel, although different natural gas-based fuels in different vehicle technologies can have significantly different energy and emissions impacts.

Section 1
Introduction

The transportation sector, a vital part of the U.S. economy, consumes a major share of the energy used in the United States and contributes a significant amount of the air pollutant emissions. As Table 1.1 shows, in 1997, the transportation sector accounted for 66% of total U.S. petroleum consumption; petroleum accounted for 39% of total U.S. energy consumption. Of the total energy consumed by the U.S. transportation sector, 97% is from petroleum. As domestic oil production in the United States declines, the amount of imported oil will continue to increase (Table 1.2). This reliance on imported oil contributes to the U.S. trade imbalance and makes the nation vulnerable to oil price shock and political instability in oil-producing regions. This issue is especially significant considering that the twelve Organization of Oil Exporting Countries (OPEC) nations control more than 77% of the world's oil reserves (Table 1.3). The United States must diversify its transportation energy sources in order to reduce our reliance on imported oil.

Table 1.4 shows U.S. greenhouse gas (GHG) emissions in 1997. The transportation sector accounts for 26% of total GHG emissions; this share may increase in the future because of a continuous increase in vehicle miles traveled. Concern about the potential climate changes caused by GHG emissions and a commitment by the government to reduce total GHG emissions will require that the United States find ways to reduce GHG emissions generated by the transportation sector.

Although the United States has made continuous improvements in urban air quality, many U.S. cities still do not comply with federal air quality standards. In 1998, 38 ozone nonattainment areas, 20 carbon monoxide (CO) nonattainment areas, and 77 nonattainment areas for particulate matter with diameters of 10 micrometers or less (PM_{10}) were identified by the U.S. Environmental Protection Agency (EPA 1998). Motor vehicles are one of the major sources of urban air pollution; in 1996, motor vehicles accounted for 79% of total CO emissions, 50% of total nitrogen oxide (NO_x) emissions, and 42% of total volatile organic compound (VOC) emissions in the United States (EPA 1997). To solve urban air pollution problems, continuing reductions in motor vehicle emissions are needed.

Various measures, including improving conventional technologies and developing new vehicle and fuel technologies, have been implemented and/or proposed to address the issues of reliance on foreign oil, GHG emissions, and criteria pollutant emissions in the transportation sector. Many of the proposed alternative transportation fuels are produced or derived from natural gas (NG). Such fuels include compressed natural gas (CNG), liquefied natural gas (LNG), liquefied petroleum gas (LPG), methanol (MeOH), Fischer-Tropsch diesel (FTD), dimethyl ether (DME), hydrogen (H_2), and electricity generated from NG. LPG and CNG have already been used in motor vehicles in the United States; the other fuels do not enjoy widespread use as transportation fuels.

Table 1.1 U.S. Energy Consumption by End-Use Sector[a,b]

Sector	1997[c]	2010[c]	2020[c]	Annual Growth Rate, 1997–2020 (%)
Residential	**10.92**	**12.00**	**13.08**	**0.8**
Petroleum	1.44	1.23	1.12	-1.2
Natural Gas	5.15	5.52	5.94	0.6
Coal	0.06	0.05	0.05	-0.5
Electricity[d]	3.66	4.57	5.31	1.6
Others[e]	0.6	0.62	0.65	0.4
Commercial	**7.63**	**8.77**	**9.37**	**0.9**
Petroleum	0.73	0.57	0.55	-1.3
Natural Gas	3.37	3.84	4.00	0.7
Coal	0.08	0.10	0.10	0.9
Electricity[d]	3.44	4.26	4.72	1.4
Industrial	**27.01**	**31.18**	**33.74**	**1.0**
Petroleum	9.33	10.81	11.49	0.9
Natural Gas	9.92	11.43	12.52	1.0
Coal	2.36	2.51	2.60	0.4
Electricity[d]	3.52	4.13	4.57	1.1
Others[e]	1.88	2.31	2.56	1.4
Transportation	**24.91**	**32.77**	**36.44**	**1.7**
Petroleum	24.10	31.33	34.68	1.6
Natural Gas	0.74	1.16	1.35	2.7
Electricity[d]	0.06	0.15	0.22	5.9
Others[e]	0.0	0.13	0.18	NA[f]
All Sectors: Delivered Energy	**70.47**	**84.72**	**92.62**	**1.2**
Petroleum	35.62	43.95	47.84	0.9
Natural Gas	19.19	21.95	23.81	0.9
Coal	2.5	2.65	2.75	0.4
Electricity[d]	10.68	13.11	14.82	1.4
Others[e]	2.48	3.06	3.40	1.4
Electricity Generation	**34.25**	**39.22**	**42.09**	**0.9**
Petroleum	0.87	0.28	0.24	-5.5
Natural Gas	3.4	6.84	9.36	4.5
Coal	18.59	21.41	23.51	1.0
Others[e]	11.39	10.69	8.99	-1.0
All Sectors: Primary Energy[g]	**94.04**	**110.83**	**119.90**	**1.1**
Petroleum	36.49	44.23	48.08	1.2
Natural Gas	22.59	28.79	33.17	1.7
Coal	21.09	24.06	26.26	1.0
Others[e]	13.87	13.75	12.39	-0.5

[a] Values are in quadrillion British thermal units (Btu) per year.

[b] From Energy Information Administration (EIA 1998a). Energy use here includes fuel use and feedstock use (such as petrochemical feedstocks).

[c] Data for 1997 are historical data; data for 2010 and 2020 are EIA projections.

[d] Electricity for the residential, commercial, industrial, and transportation sectors is energy delivered to each sector (i.e., energy loss during electricity generation is not accounted for).

[e] Others include renewable energy and nuclear energy (for electricity generation).

[f] NA = not available.

[g] Energy consumption at the primary energy level takes into account primary energy used for electricity generation (i.e., energy loss during electricity generation is accounted for).

Table 1.2 U.S. Petroleum and Natural Gas Supply[a,b]

Production/Importation	1997[c]	2010[c]	2020[c]	Annual Growth Rate, 1997–2020 (%)
Domestic Petroleum Production	13.65	11.83	10.51	-1.1
Net Imported Petroleum[d]	19.65	29.16	33.95	2.4
Domestic Natural Gas Production	19.47	24.44	28.12	1.6
Net Imported Natural Gas	2.90	4.45	5.14	2.5

[a] From EIA (1998a).

[b] Values are in quadrillion Btu per year.

[c] Data for 1997 are historical data; data for 2010 and 2020 are EIA projections.

[d] Including both crude and crude products.

Table 1.3 Oil and Natural Gas Reserves[a,b]

	Oil Reserve	Natural Gas Reserve	
Location	10^9 Barrels	10^{12} Cubic Feet (ft^3)	10^9 Oil-Equivalent Barrels[c]
North America	68.1	297.2	51.2
United States	22.5	167.2	28.8
Central and South America	74.6	221.9	38.3
Western Europe	19.0	166.5	28.7
Eastern Europe and Former USSR	61.7	1,952.0	336.6
Middle East	650.7	1,723.4	297.1
Africa	73.4	351.9	60.7
Far East and Oceania	50.2	378.5	65.3
OPEC[d]	766.9	2,213.0	381.6
World Total	**997.6**	**5,091.2**	**877.8**

[a] As of January 1, 1998.

[b] Data are from EIA (1999). Reserves are proven reserves, except in the former USSR, where values represent explored reserves.

[c] On a Btu content basis, one barrel of crude is equivalent to 5.8×10^3 ft^3 of NG.

[d] OPEC member countries include Algeria, Gabon, Indonesia, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, United Arab Emirates, and Venezuela.

Table 1.4 U.S. GHG Emissions in 1997[a,b]

Sector	CO_2[c]	CH_4[c]	N_2O[c]	HFCs, PFCs, and SF_6[c]	All GHGs
Residential Sector	286.1	NE[d]	NE	NE	286.1
Commercial Sector	237.1	NE	NE	NE	237.1
Industrial Sector	483.7	NE	NE	NE	483.7
Transportation Sector	446.5	1.4	17.5	4.5	469.9
Others	34.5	178.2[e]	91.5[f]	32.6	302.3
All Sectors	1487.9	179.6	109.0	37.1	1,813.6

[a] Values in 10^6 metric tons of carbon-equivalent GHGs.

[b] From EPA (1999).

[c] CO_2 = carbon dioxide, CH_4 = methane, N_2O = nitrous oxide, HFCs = hydrofluorocarbons, PFCs = perfluorinated carbons, and SF_6 = sulfur hexafluoride.

[d] NE = not estimated.

[e] The five largest CH_4 emission sources are landfills, enteric fermentation, NG production and distribution systems, coal mining, and manure management.

[f] The single largest N_2O source is agricultural soil management.

As Table 1.3 shows, on an energy content basis, the worldwide gas reserves are almost as large as worldwide oil reserves. Furthermore, the share of the world's gas reserves by OPEC countries is smaller than their share of the oil reserves (43% versus 77%), which makes it more difficult for OPEC countries to manipulate gas prices.

In 1997, annual worldwide oil production was 23.733 billion barrels, and annual worldwide gas production was 82.333 trillion ft^3 (equivalent to 14.195 billion barrels of oil) (American Petroleum Institute 1999). Worldwide gas production lags far behind oil production primarily because of a lack of pipelines in many parts of the world to transport the gas across long distances, and because transportation of NG across oceans in the gaseous form is impractical. Producing liquid transportation fuels from NG locally and then transporting the fuels would make use of gas stranded in remote regions practical and feasible.

Of the NG-based fuels, CNG, LNG, LPG, and MeOH are applicable to spark-ignition (SI) engine (i.e., gasoline-fueled) vehicles; FTD and DME are applicable to compression-ignition (CI) engine (i.e., diesel-fueled) vehicles; H_2, methanol, CNG, LNG, and LPG can be used in fuel-cell vehicles (FCVs); and electricity can be used in battery-powered electric vehicles (EVs). Although H_2 can also be used in SI engines, the current interest in H_2 as a transportation fuel is in FCVs. In our study, we do not include H_2 as an SI engine fuel.

Although all of these fuels are produced from NG, the energy and environmental effects of their use can differ considerably because (1) the production technologies and distribution pathways for the fuels are significantly different, and (2) the fuel economy and emissions performance associated with the vehicles powered by these fuels vary. To thoroughly examine the energy and environmental effects of these fuels, researchers must evaluate their full fuel-cycle energy and environmental effects. In this study, we use the fuel-cycle model GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) developed at

Argonne National Laboratory to estimate per-mile, fuel-cycle energy use and emissions associated with using these fuels in different vehicle propulsion systems. The information generated from this effort is helpful in evaluating the costs and benefits of various NG-based fuel pathways.

Section 2
Scope of Study

2.1 Fuel-Cycle Analysis

The *fuel cycle* for a given transportation fuel includes the following processes: energy feedstock (or primary energy) production; feedstock transportation and storage (T&S); fuel production; fuel transportation, storage, and distribution (T&S&D); and vehicle operations that involve fuel combustion or other chemical conversions (Figure 2.1). The processes that precede vehicle operations are often referred to as upstream activities; vehicle operations are referred to as downstream activities. In Figure 2.1, the processes enclosed in rectangles are production- or combustion-related activities, and those enclosed in ovals are distribution-related activities. Usually, energy use and emissions of the former are far greater than those of the latter.

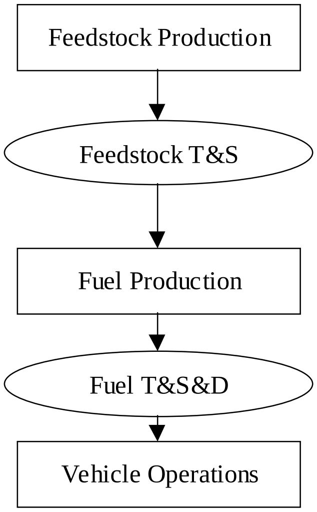

Figure 2.1 Stages of a Fuel Cycle

In 1995, Argonne began to develop a spreadsheet-based model for estimating the full fuel-cycle energy and emission impacts of alternative transportation fuels and advanced transportation technologies (Wang 1996). The intention of creating such a model was to allow researchers to readily test various parametric assumptions that affect fuel-cycle energy use and emissions. The GREET model has since been expanded and upgraded. For this study, we revised the current version, GREET 1.5 (Wang 1999a,b), into a new version, GREET 1.5a, which incorporates additional fuel cycles and vehicular technologies, revised modeling approaches for upstream fuel production activities, and new parametric assumptions. These changes are documented in this report.

GREET calculates Btu-per-mile (Btu/mi) energy use and grams-per-mile (g/mi) emissions by taking into account energy use and emissions of fuel combustion and non-combustion sources such as fuel leaks and evaporation. The model calculates total energy use (all energy sources), fossil energy use (petroleum, NG, and coal), and petroleum use. It includes emissions of three major GHGs (CO_2, CH_4, and N_2O) and five criteria pollutants (VOCs, CO, NO_x, PM_{10}, and sulfur oxide [SO_x]). Table 2.1 lists output items from the GREET model.

The three major GHGs (CO_2, CH_4, and N_2O), together with three other GHGs (HFCs, PFCs, and SF_6, which are not significantly affected by use of different transportation fuels), were specified in the 1997 Kyoto Protocol for individual countries to estimate their GHG emissions inventories. The three GHGs used in this study represent the largest percentage of

Table 2.1 Output Items from the GREET Model

Category	Output Item	Remarks
Energy (Btu/mi)	All energy sources Fossil energy (petroleum, NG, and coal) Petroleum	
Greenhouse Gases (g/mi)	CO_2 CH_4 N_2O VOC (optional) CO (optional) NO_x (optional)	GHGs are converted into CO_2-equivalent emissions with their GWPs.
Criteria Pollutants (g/mi)	VOC CO NO_x PM_{10} SO_x	These emissions are separated into total and urban emissions.

total GHG emissions (see Table 1.4), and are the ones most likely to be affected by the use of alternative transportation fuels. In this study, we combine emissions of the three GHGs with their global warming potentials (GWPs) in order to calculate CO_2-equivalent GHG emissions. Table 2.2 presents the GWPs for the three GHGs that are recommended by the Intergovernmental Panel on Climate Change (IPCC). In our analysis, we use IPCC-recommended GWPs for the 100-year time horizon. As the table shows, a researcher's choice of one set of GWPs can have significant implications in comparing emissions of the three gases generated by different alternative fuels. For example, use of NG-based fuels, especially CNG and LNG, generates a large amount of fuel-cycle CH_4 emissions. If the 20-year GWPs are used, the CH_4 contribution to CO_2-equivalent emissions for these fuels is significant. On the other hand, if the 500-year GWPs are used, the contribution of CH_4 emissions to total GHG emissions is small.

Emissions of VOCs, CO, and NO_x could have global warming effects because of their contributions to ozone formation. But because there are great uncertainties associated with the formation of ozone by the three gases, IPCC did not recommend any GWPs for these three gases. Although the GREET model is designed to allow a user to consider the three as GHGs, we do not consider these three as GHGs in our study.

Table 2.2 GWPs of CO_2, CH_4, and N_2O[a]

Time Horizon	CO_2	CH_4	N_2O
20-year	1	56	280
100-year	1	21	310
500-year	1	6.5	170

[a] From IPCC (1996).

Our analysis includes estimates of both total and urban emissions of the five criteria pollutants, because the locations of these pollutants (i.e., urban vs. rural) can be as important as the amount of emissions. In the GREET model, "total emissions" are emissions occurring in all locations — from upstream stages to vehicle operations. "Urban emissions" are those occurring only within an urban area. In our study, urban areas are the metropolitan areas defined in the Energy Policy Act of 1992.

To calculate urban emissions from upstream activities, we estimate the share of these activities that takes place in urban areas versus the share that occurs outside of urban areas (in rural areas) and account for only the emissions associated with urban activities. To estimate urban emissions from vehicle operations, we assume that vehicles using NG-based fuels will be introduced to urban areas to help solve urban air pollution problems. Thus, all vehicular emissions are treated as urban emissions. Our intention is to evaluate urban emissions impacts if alternative-fueled vehicles are introduced to urban areas and are used in urban areas to replace gasoline vehicles. If researchers need to evaluate the emissions effects of introducing alternative-fueled vehicles in a region or country, they must know the market split between urban and rural areas for alternative-fueled vehicles, the split between urban and rural areas for use of urban vehicles, and the split between urban and rural areas for use of rural vehicles.

2.2 Fuel Pathways Included in This Study

This study addresses the transportation fuels that are produced from NG; petroleum-based gasoline and diesel are used as baseline fuels. Table 2.3 lists the fuel pathways included in this study. As the table shows, there are multiple pathways for producing some of the fuels. For example, H_2 can be produced in either gaseous or liquid form. Gaseous H_2 (GH_2) can be produced in large, centralized H_2 plants near NG fields (centralized production) or in refueling stations to avoid constructing expensive H_2 pipelines (decentralized production). Also note that LNG, MeOH, DME, FTD, and liquid hydrogen (LH_2) can be produced from NG or from flared gas (FG). Detailed information on fuel-cycle stages and assumptions regarding key stages for these pathways are presented in Section 3.

Table 2.3 Fuel Pathways Included in This Study

Feedstock	Fuel
Petroleum	CG RFG CD RFD
NG	CNG LNG in central plants LPG Electricity MeOH GH_2 in central plants GH_2 in refueling stations LH_2 in central plants DME FTD
FG	LNG MeOH DME FTD LH_2

Some of the fuels included in this study can be produced from energy feedstocks other than NG. For example, LPG is currently produced in petroleum refineries as well as NG processing plants. Electricity is generated from many sources including NG. Methanol may be produced from biomass or coal. Hydrogen can be produced from electricity via water electrolysis. These pathways are beyond the scope of our study, but they are included in the GREET model. Results of the fuel-cycle analyses of those other pathways (except biomass to MeOH, which GREET does not include) are presented in Wang (1999a,b).

2.3 Combinations of Fuels and Vehicle Propulsion Systems

Researchers have studied various vehicle propulsion systems and proposed many for use with alternative transportation fuels, including NG-based transportation fuels. Table 2.4 presents the potential vehicle technologies that can be fueled with NG-based fuels. These combinations of vehicle technologies and fuels are evaluated during our study. Note that there are many combinations of vehicle technologies and transportation fuels that are beyond the scope of this study.

For vehicles equipped with conventional SI engines, we include conventional gasoline (CG), reformulated gasoline (RFG), CNG, LNG, LPG, and methanol. These fuels have high octane numbers and are applicable to SI engines. Recently, interest in developing efficient, low-emission spark-ignition, direct-injection (SIDI) engine technologies has increased. SIDI technology achieves considerable gains in vehicle fuel economy relative to conventional SI technology. In our analysis, we include SIDI engines fueled with CG, RFG, and methanol. Because the two gaseous SI fuels (CNG and LNG) do not appear to offer inherent fuel economy benefits when used in SIDI engines rather than in SI engines, we do not include these fuels in our analysis for SIDI engines. LPG could be used in SIDI engines with some fuel economy benefits, but we also do not include this option.

Hybrid electric vehicles (HEVs) achieve great fuel economy gains relative to vehicles equipped with internal combustion engines (ICEs) alone. HEVs have recently gained some momentum after Toyota and Honda each introduced an HEV into the marketplace. We include HEVs equipped with SI engines, SIDI engines, and compression-ignition, direct-injection (CIDI) engines in our analysis.

We include CIDI vehicles in this study because CIDI engines help increase vehicle fuel economy substantially and because most new diesel cars and light-duty trucks are equipped with CIDI engines. In order to meet future stringent emission standards, the diesel fuel used in CIDI engines will probably have to be reformulated to reduce the levels of sulfur and aromatics. We therefore included a potential reformulated diesel (RFD), as well as conventional diesel (CD) in our study.

All of the major automakers have research and development (R&D) programs that focus on FCVs. We include FCVs fueled with H_2, methanol, gasoline, CNG, LNG, and LPG in this study. Use of methanol, gasoline, CNG, LNG, and LPG in FCVs requires on-board fuel processors that produce H_2 from these fuels. Although direct methanol FCVs are being researched, the high operation temperatures required by these fuel cells creates a major technology challenge. We do not include direct methanol FCVs in our analysis. On the other hand, many current R&D efforts focus on developing a universal fuel processor with partial oxidation technology that can produce H_2 from virtually any hydrocarbon fuel. It is conceivable, then, that all the fuels included in this study could be used in FCVs.

Table 2.4 Combinations of Fuels and Vehicle Technologies Included in This Study

Vehicle Technology	Fuels Applied to the Technology
Conventional SI Engines	CG RFG CNG LNG LPG MeOH
SIDI Engines	CG RFG MeOH
HEVs with SI Engines	CNG LNG LPG
HEVs with SIDI Engines	CG RFG MeOH
CIDI Engines	CD RFD DME FTD
HEVs with CIDI Engines	CD RFD DME FTD
FCVs	H_2 MeOH RFG[a] CNG LNG LPG
EVs	Electricity from NG

[a] Gasoline for FCVs may be different from gasoline used for ICEs. The gasoline used in FCVs must have a much lower sulfur content to avoid poisoning FCV catalysts, but FCVs do not require that the gasoline used have a high octane number or contain oxygen. On the other hand, because additional costs will be required to establish a fuel distribution system for FCV gasoline, it is possible that a common gasoline with a low sulfur content will be developed for both FCV and ICE applications. Because of a lack of data, we did not differentiate FCV RFG from ICE RFG in this study.

Electric vehicles have long been promoted for their energy and emission benefits. Our study includes EVs fueled with electricity generated from NG.

Detailed assumptions regarding fuel economy and emissions of these vehicle-fuel combinations are presented in Section 4.

Section 3
Upstream Fuel-Cycle Stages

Although all the fuels evaluated in this study are produced from NG, each goes through different upstream stages. Figure 3.1 shows the pathways and their main stages for the fuels included in this study. Some of the fuels could be produced in plants near or adjacent to NG processing plants so that NG transmission pipelines would be unnecessary. Besides NG produced for commercial use, FG associated with crude oil recovery can be used to produce liquid fuels that can then be transported over long distances to end-user sites. Because we include FG-based pathways in our study, multiple pathways exist for some of the fuels.

In this section, we discuss key assumptions regarding upstream stages for each of the pathways shown in Figure 3.1. For most fuels, because the production stage consumes more energy and generates more emissions than other upstream stages, our discussion focuses mainly on the fuel production technologies and our assumptions regarding energy efficiencies and emissions associated with the technologies. Assumptions for other upstream stages such as NG recovery, NG transmission, and fuel transportation and distribution are documented in Wang (1999a). On the basis of our research for this project, we revised some assumptions in GREET1.5 (the current version of the GREET model). The new assumptions are incorporated in the completed GREET 1.5a version. Any revisions to the GREET 1.5 assumptions are documented in this report.

3.1 Fuels Produced from Commercial Natural Gas

3.1.1 Natural Gas to Compressed Natural Gas

Figure 3.2 presents the pathway from NG to CNG. For this pathway, we assume that NG is stored onboard compressed natural gas vehicles (CNGVs) at a pressure of about 3,000 pounds per square inch (psi). In order to achieve this onboard pressure, the gas in storage tanks at CNG refueling stations probably needs to be maintained at around 3,600 psi. NG may need to be compressed initially to 4,000 psi to maintain the 3,600-psi tank pressure, primarily because the pressure drops during cooling. In our analysis, we assume compression of NG from about 15 psi to 4,000 psi at CNG refueling stations.

CNG compressors can be powered by NG-fueled reciprocating engines or electric motors. Currently, most CNG stations in the United States are equipped with electric compressors because they are reliable and because most CNG stations are small. As more CNGVs are introduced into the marketplace and larger CNG stations are built to serve them, more of the stations may be equipped with NG-fueled compressors because NG is cheaper than electricity. In our analysis, we assume that 50% of CNG stations are equipped with electric compressors and the remaining 50% with NG-fueled compressors.

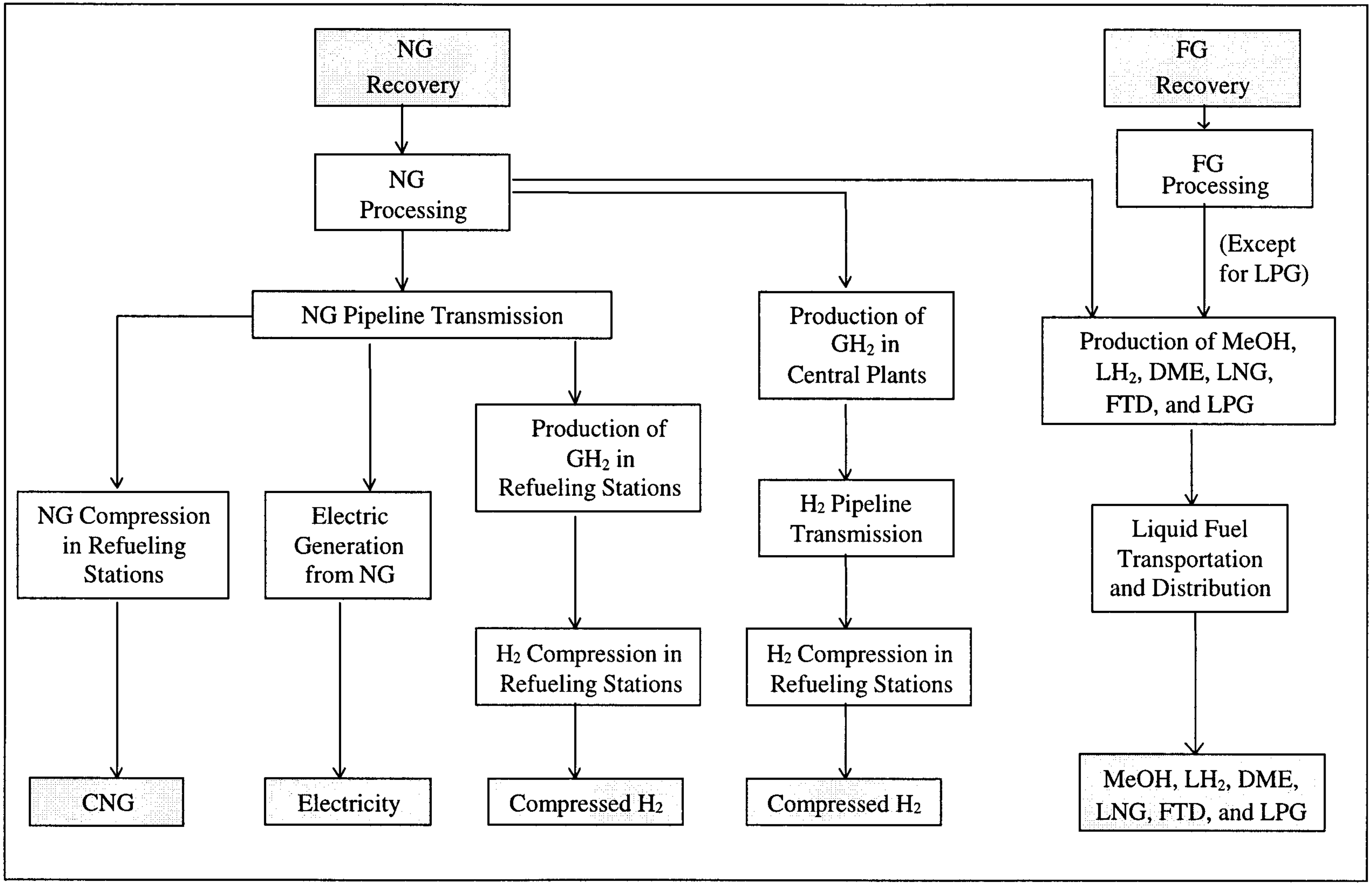

Figure 3.1 Fuel Pathways Included in This Study

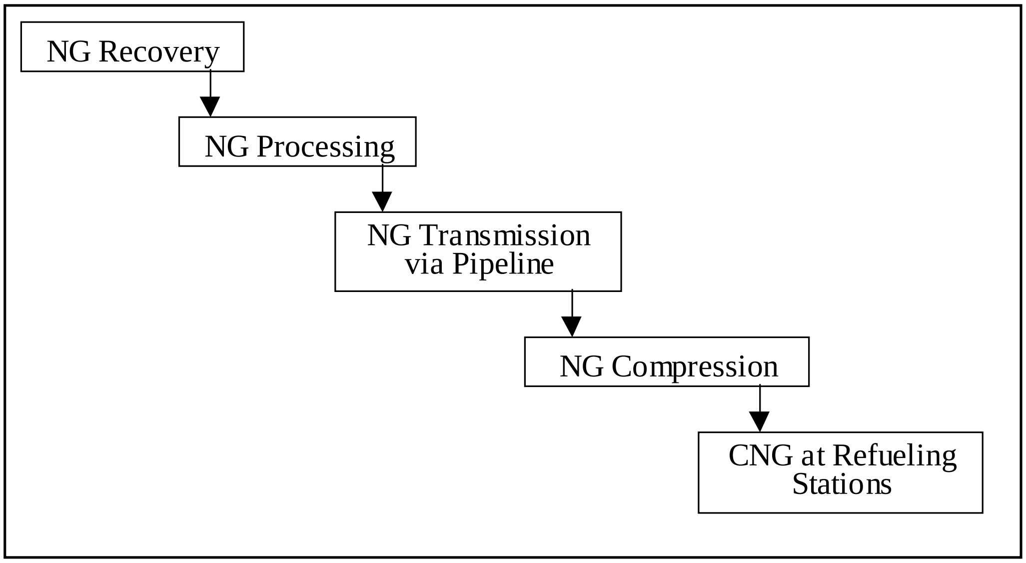

Figure 3.2 NG-to-CNG Pathway

In GREET, the energy efficiency for the NG compression stage is calculated by dividing the energy in the compressed gas by the sum of the energy in the NG feed required for compression and the amount of process fuel (NG or electricity) consumed by the compressors. The energy content of electricity and NG here is restricted to the energy contained in each fuel. That is, we do not account for energy losses during electricity generation and NG recovery and transmission in calculating NG compression efficiencies. These losses are accounted for automatically in some other parts of the GREET model.

For electric compressors, the gas industry often cites an electricity consumption of 1 kilowatt-hour (kWh) per therm (100,000 Btu) of gas compressed (American Gas Association 1989). This rate translates into a compression efficiency of 96.6% for electric compressors. Small, inefficient CNG stations, however, may have much higher electricity consumption rates. For example, the actual measured electricity consumption rate at Argonne’s CNG station has been measured at between 1.75 and 2 kWh per gasoline equivalent gallon (Livengood 1999) — a compression efficiency of 94.1–94.8%.

Stodolsky (1999) recently developed a formula to calculate CNG compression efficiency based on thermodynamic principles. To use Stodolsky’s formula, we assume a thermal energy efficiency of 35% for NG-fueled reciprocating engines (assuming also that the engines used for compressors will be operated within a narrow range of engine speed), an energy efficiency of 90% for electric motors, and a 30% loss factor for the work delivered from engines or motors to work used during NG compression. On the basis of these assumptions, we calculate a compression efficiency of 96.6% for electric compressors and 91.7% for NG compressors. We used these values for our incremental technology scenario (Section 4 describes the two scenarios used in our study). In the long term, compressor manufacturers will likely design compression systems with a lower loss factor. We assume a loss factor of 20% (rather than 30%) for our leap-forward technology scenario. Using this loss factor, we estimate compression efficiencies of 97% and 92.7% for electric and NG compressors, respectively, under the leap-forward scenario.

Use of NG compressors in CNG refueling stations will generate emissions of criteria pollutants within urban areas; most, if not all, of the stations will be located in urban areas. This effect is amplified for urban NO_x emissions. The GREET model accounts for emissions from the compressors.

3.1.2 Natural Gas to Liquefied Natural Gas

Compared with CNGVs, vehicles fueled with LNG (LNGVs) have one distinct advantage — a longer driving range per refueling. But cryogenic storage of LNG onboard a vehicle presents technical and cost challenges. Another advantage is that LNG can be transported via ocean tankers. Currently, Japan imports LNG from Southeast Asia and the Middle East; some European countries import LNG from North Africa.

Although LNG has been promoted primarily for heavy-duty vehicle applications such as buses, long-haul trucks, and locomotives because of its emissions benefits relative to diesel fuel, it can also be used in light-duty vehicles. For our study, we evaluate LNG application in light-duty vehicles.

LNG is currently produced mostly in Southeast Asia, Australia, the Middle East, and Africa. LNG produced in these regions is transported to and consumed in Europe, Japan, Korea, and the United States. We assume that LNG will be produced from remote, stranded gas at locations outside North America. LNG will be transported to the United States via ocean tankers. Here, LNG will be transported from port terminals to bulk terminals and refueling stations via rail, barges, and/or trucks (Figure 3.3).

In LNG plants, substances such as water, CO_2, sulfur, and heavier hydrocarbons that would freeze during NG liquefaction must be removed before liquefaction. The purified NG is cooled to about -260°F (at atmospheric pressure), the temperature at which NG becomes liquid. The gas is liquefied by heat exchange between the NG feed and refrigerants that vaporize during the process. NG can also be liquefied using an expansion cycle in which the gas (under high pressure) is expanded rapidly, thereby cooling it to its boiling point. Produced LNG is stored as a cryogenic liquid in insulated storage vessels at pressures of 50–150 psi. LNG can be transported in these vessels by ocean tankers, trucks, railcars, or barges.

Some researchers have proposed that LNG be produced by means of small liquefiers in refueling stations to make LNG transportation and bulk storage unnecessary and to allow domestic NG to be transported via pipeline to LNG stations. We do not include this pathway in our analysis because of a lack of data.

The largest amount of energy in LNG plants is used to power the refrigeration compressors. Energy required by the compressors can be provided by steam boilers, steam turbines, gas turbines, or electric motors. In old LNG plants, steam boilers or steam turbines with low thermal efficiencies were used. New plants are equipped with more efficient gas

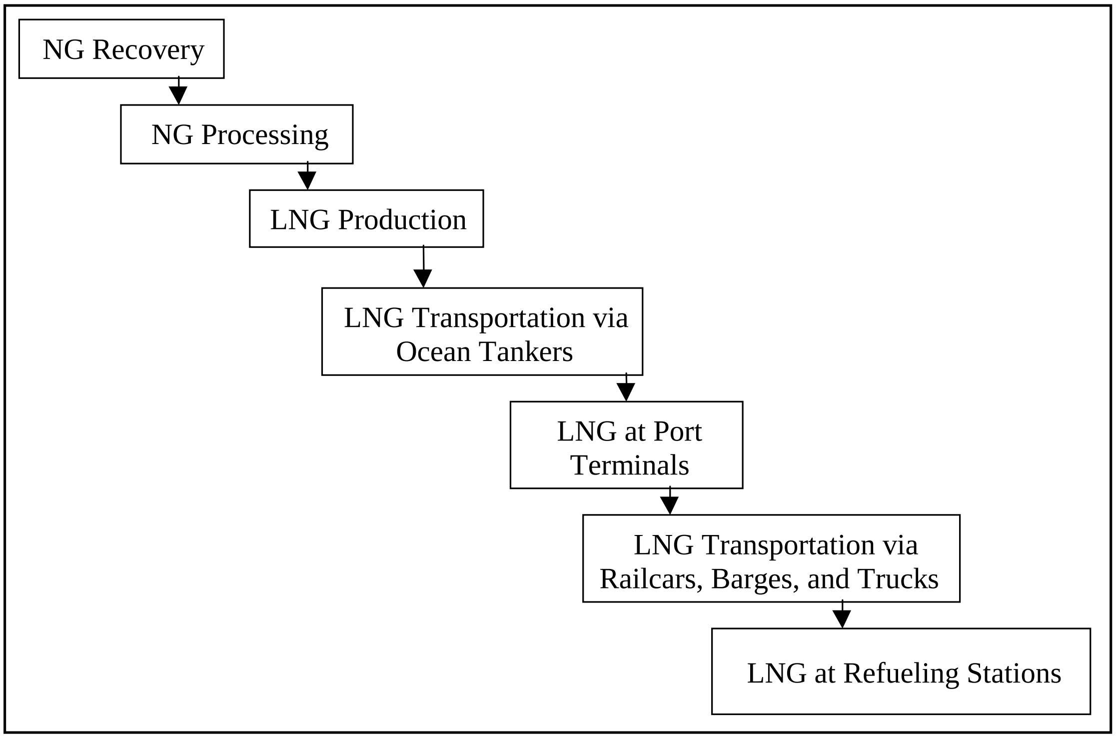

Figure 3.3 NG-to-LNG Pathway

turbines, especially combined-cycle gas turbines (either providing shaft power directly or generating electricity for use in electric motors) (Kikkawa and Nozawa 1999). We assume that new centralized LNG plants employ combined-cycle turbines that provide shaft power directly to the compressors. On the basis of information provided in Kikkawa and Aoki (1999), we assume an energy efficiency of 90% for NG liquefaction in LNG plants.

As the temperature in LNG tanks rises over time, some LNG evaporates and becomes NG. Pressure within an LNG tank can build up; this buildup is called the “boiling-off effect” and the gas generated is called “boiling-off gas.” The boiling-off effect can cause major losses of LNG during transportation and storage. The boiling-off gas in LNG plants, ocean tankers, and bulk terminals is usually collected as a fuel for combustion. We account for the collected boiling-off gas in our simulation.

3.1.3 Natural Gas to Liquefied Petroleum Gas

Raw NG from gas fields must be processed before transport via pipelines. Raw gas contains liquids (hydrocarbon liquids and water). Hydrocarbon liquids, called “natural gas liquids” (NGLs), are separated from NG for use as fuels or chemical feedstocks. The term NGLs initially referred to liquids collected from the NG stream at room temperature and atmospheric pressure. As NG processing technologies have advanced, however, low temperature and high pressure have been applied, causing some hydrocarbons that were formerly gases at room temperature and pressure to be collected as liquids.

In NG processing plants, non-hydrocarbon gases such as water, hydrogen sulfide (H_2S), and CO_2 are removed from the gas stream during a gas conditioning stage. Water is removed in a dehydrator through a chemical reaction with a solvent or through physical absorption. The gas stream then passes through a gas processing stage, where NGLs are separated from the gas. The separation involves refrigeration to lower the temperature of the gas stream; absorption of NGLs by light oil such as kerosene; adsorption of NGLs by means of activated carbon, alumina gel, or silica gel beds; or compression of the gas stream. Finally, NGLs are separated into ethane, LPG, and pentanes plus through liquid fractionation by varying the temperature and pressure of the liquid stream. The LPG produced consists primarily of propane with small amounts of butane and isobutane.

In petroleum refineries, the crude stream goes through fractionation processes during which ethane and LPG are produced. Because this study addresses NG-based fuels, we do not include that LPG pathway.

The largest producer of NGLs from gas processing operations is North America, followed by the Middle East. The yield of NGLs per unit of NG stream depends on gas composition and processing technologies. Because the production of LPG in NG processing plants involves only separation of LPG (and other NG liquids) from NG, production of LPG from NG is very efficient. We assume an energy efficiency of 96.5% for LPG production. LPG is transported via ocean tankers, pipelines, railcars, barges, and/or trucks to bulk terminals for storage and distribution. LPG is finally transported by truck to LPG refueling stations (Figure 3.4).

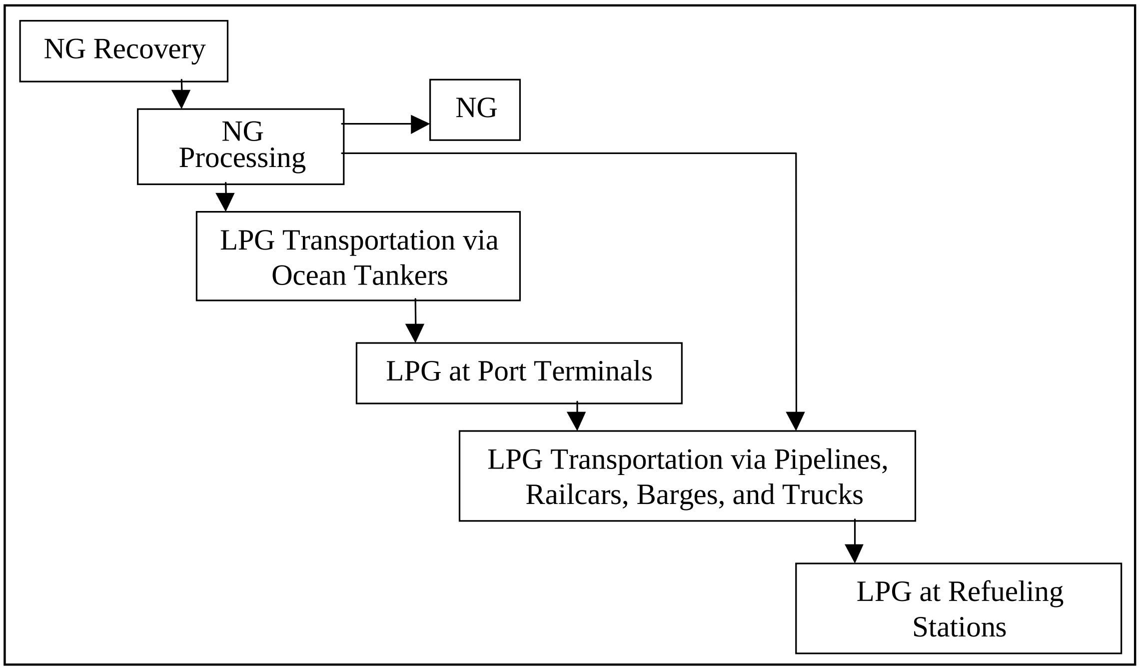

Figure 3.4 NG-to-LPG Pathway

3.1.4 Natural Gas to Electricity via Combined-Cycle Gas Turbine

About 15% of the electricity in the United States is generated from NG. That share is predicted to rise in the future. In fact, the fossil fuel power plants added to U.S. electric utility systems in recent years have been NG-fired combined-cycle plants. In the electric utility sector, combined-cycle technology refers to the combined use of hot-combustion gas turbines and steam turbines to generate electricity. The combination of the two turbine types can increase the thermal efficiency of power plants to far above that of conventional power plants using either type of turbine alone. Because of their economic and environmental superiority, NG-fired combined-cycle power plants are expected to account for a significant market share of future power generation expansion (Zink 1998a; Hansen and Smock 1996). Our analysis includes this pathway of electricity generation from NG (Figure 3.5).

A gas turbine consists of three major components: a compressor, a combustor, and a power turbine. Ambient air is drawn into the compressor and compressed up to 30 atmospheres (about 440 psi). The air is then directed to the combustor, where NG is introduced and burned. Hot combustion gases are diluted and cooled with additional air from the compressor and directed to the turbine. Energy from the hot, expanding exhaust gases is recovered in the form of shaft horsepower, which can be used to drive an external load generator for electricity generation.

The primary environmental concerns for combined-cycle turbines are emissions of NO_x and CO. Turbine manufacturers have been working on new designs to reduce emissions as well as improve thermal efficiency. With continuously improved material coatings and cooling technologies, the gas turbine inlet temperature has been increased to about 1,320^{o}C (2,400^{o}F), helping to considerably increase the efficiency of the combined-cycle turbine (Viswanathan

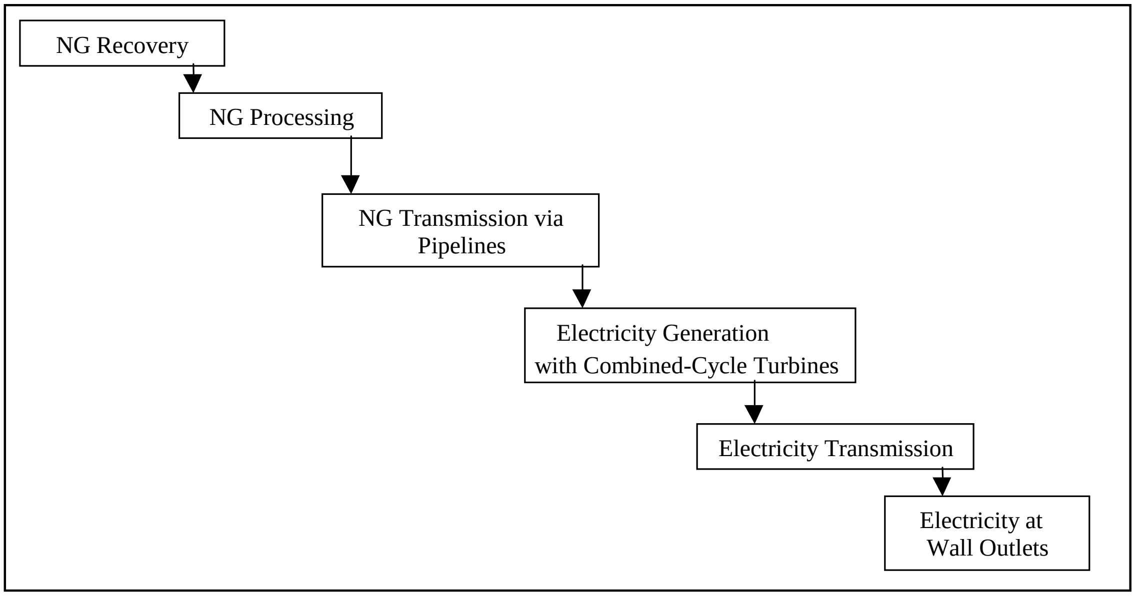

Figure 3.5 NG-to-Electricity Pathway with Combined-Cycle Turbines

et al. 1999; Esch and DeBarro 1998; Schimmoller 1998; Zink 1998b; DeMoss 1996; Kuehn 1995a,b; Smith 1994). Also, by using a lean mixture of air and fuel, staging combustion at lower temperatures, and decreasing the residence time of gases in the combustion chamber, turbine manufacturers have lowered NO_x emissions from advanced gas turbines to about 20 to 30 parts per million (ppm) without using water injection, selective catalytic reactors (SCRs), or other post-combustion control devices (Kuehn 1995a,b; Smith 1994).

More efficient combined-cycle turbines may be designed by incorporating one of these options: simple lean combustion, two-stage lean/lean combustion, and two-stage rich/lean combustion (EPA 1996). Relative to a stoichiometric mixture of fuel and air, the lean mixture helps reduce the peak and average temperature within the combustor, resulting in lower NO_x formation. The two-stage lean/lean combustion design involves two fuel-staged combustors; lean burning occurs in each. This design allows a turbine to operate with an extremely lean mixture and a stable flame that should not “blow-off” or extinguish. By contrast, the two-stage rich/lean design is essentially air-staged combustors in which the primary zone in a combustion chamber is operated under fuel-rich conditions and the secondary zone under fuel-lean conditions. The rich mixture in the primary zone produces a lower temperature (compared to a stoichiometric mixture) and high concentrations of CO and H_2 (caused by incomplete combustion). The decreased temperature, the high concentration of CO and H_2, and the decreased amount of oxygen in the rich mixture help reduce NO_x formation. Before entering the secondary combustion zone, the combustion gas from the primary zone is quenched by a large amount of air, creating a lean mixture. The combustion of the lean mixture is then completed in the secondary zone with very low NO_x emissions.

The sensible heat of the hot exhaust gas from a gas turbine can either be discarded without heat recovery (the simple cycle) or used in a heat recovery steam generator (usually a Rankine-cycle generator) to generate additional electricity (the combined cycle). Because of its low capital investment, the simple cycle is often used for small, peak-load electricity generation. The combined cycle is used for large, base-load electricity generation. The thermal efficiency of a combined cycle system with an inlet gas temperature of 2,400°F is around 56%, based on the low heating value (LHV) of NG. The efficiency goal of the U.S. Department of Energy (DOE) Advanced Turbine Systems program is 60% with an inlet gas temperature approaching 2,600°F (Schimmoller 1998). We use a generation efficiency of 56% for the incremental case and 60% for the leap-forward case in our analysis.

3.1.5 Natural Gas to Methanol Production

Methanol is used for production of methyl tertiary butyl ether (MTBE), formaldehyde, acetic acid (used in the production of plastic bottles and polyester fiber), and other products such as windshield wiper fluid, bleaches, paints, solvents, refrigerants, and disinfectants. According to the American Methanol Institute (1999), worldwide demand for methanol was about 26 million metric tons in 1998. Of that, the U.S. demand was about 8 million metric tons; production of MTBE consumed over 40% of that total in the United States. Because of concern regarding water contamination by MTBE used in gasoline, California elected to ban the use of MTBE in reformulated gasoline; the future use of MTBE in reformulated gasoline is uncertain in the rest of the United States, and therefore the future use of methanol for MTBE production in this country is uncertain.

Worldwide methanol production capacity is about 35 million metric tons. The United States has about one quarter of the total world production capacity. At present, without the use of methanol as a transportation fuel, the United States produces about three-quarters of what it consumes, with the remaining quarter imported from Canada and other countries. Worldwide, several large new methanol plants are under construction (as of the end of 1998) in Qatar, Chile, Saudi Arabia, Iran, and Trinidad, where gas is inexpensive and abundant. The trend of building new plants in such regions will likely continue. In our study, we assume that the methanol used directly as a transportation fuel in the United States will come from these regions.

Although a few methanol plants have recently been built in the United States, because of the high NG prices in this country, the economics of operating methanol plants here are not favorable. We anticipate that mega-size methanol plants will be built outside of this country, and the methanol will be transported via ocean tankers to major U.S. ports. The methanol will then be transported through pipelines to inland bulk terminals and then to refueling stations via trucks (Figure 3.6).

Methanol is produced through synthesis of a gaseous mixture of H_2, CO, and CO_2 (called syngas). Methanol can be produced from biomass, coal, heavy oil, naphtha, and other feedstocks (Rees 1997). Because the technologies required to produce methanol from NG are

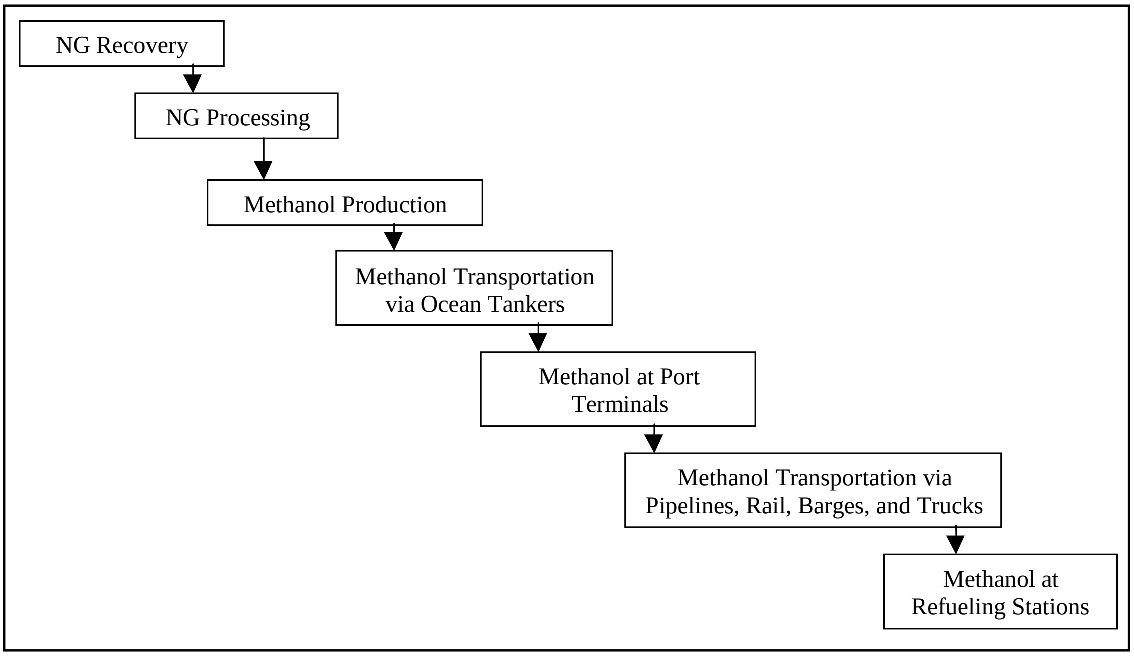

Figure 3.6 NG-to-Methanol Pathway

mature, this pathway is an economical way to produce methanol. Furthermore, steam-methane reforming (SMR) technology is widely used in existing methanol plants.

Before entering reformers, sulfur in NG must be removed because sulfur, usually in the form of H_2S, can poison the reformer catalysts. Usually, zinc oxide (ZnO) is used for desulfurization of NG, which occurs via the following reaction:

$$H_2S + ZnO \rightarrow ZnS + H_2O$$

The zinc sulfide (ZnS) produced in this way is disposed of as a solid waste. In our simulation, we assume that the sulfur in NG feed ends up as a solid waste, not as sulfur dioxide (SO_2) emissions to the air. We assume the desulfurization measure is used for plants producing methanol, H_2, DME, and FTD.

Syngas can be produced in methanol plants from NG by means of SMR. This process requires a large amount of steam and consequently consumes a large amount of energy. The syngas is then synthesized into methanol. Methanol synthesis is an exothermic reaction; a significant amount of steam can be generated during the process ($CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$). Methanol plants are generally able to generate some excess steam that can be exported to nearby plants or used for electricity generation.

The optimal mole ratio of syngas among H_2, CO, and CO_2 ($[H_2\text{-}CO_2]/[CO+CO_2]$) for methanol synthesis is between 2.05 and 2.1 (Gohna 1997). Syngas from reformers, however, has a ratio of around 2.8 and contains excess H_2. Three options are available to achieve the desired ratio: (1) burn the excess H_2 as process fuel, (2) separate and purify the excess H_2 for export to other chemical plants (such as ammonia fertilizer plants or petroleum refineries) nearby, and (3) add CO_2 to the syngas to convert some of the H_2 to CO through a shift reaction. For the third option, Stratton et al. (1982) reported that adding 6% CO_2 (by volume) to syngas could increase methanol yield by about 20%. The required CO_2 can be imported from sources outside of methanol plants. The choice among the three options depends on the availability of CO_2 and the value of H_2.

Another technology for methanol production is autothermal reforming (ATR). With ATR, the heat requirement for steam reforming is provided by combustion of a portion of the gas feed with pure oxygen inside a reforming reactor. Syngas produced from ATR tends to contain excess CO and CO_2 for methanol synthesis. H_2 could be added or some of the CO_2 could be removed to achieve the optimal mole ratio for methanol synthesis.

One recent technology development for producing syngas to achieve the desired molar ratio is to integrate a partial oxidation (POX) process using pure oxygen with the SMR process. The integrated design, sometimes referred to as “two-step reforming,” requires production of oxygen in methanol plants. The two-step reforming design is suitable for mega-size (3,000–5,000 ton/day capacity) methanol plants (Gronemann 1998; Berggren 1997; Islam and Brown 1997).

Dybkjar (1996) reported that the energy efficiency of methanol plants ranges from 65 to 70%. Islam and Brown (1997) reported a NG requirement of 34–34.8 million Btu (high heating value [HHV]) per metric ton of methanol output in methanol plants. Using an HHV of 21.7 million Btu per metric ton of methanol, we calculate an energy efficiency of 62.4–63.8% for the reported input and output numbers. Abbott (1997) reported an energy efficiency of 57.9–74.7% for compact methanol production units applicable to offshore oil recovery platforms. Berggren (1997) reported that 31.3 million Btu of NG is required to produce one metric ton of methanol, which translates into an energy efficiency of 69.3%.

Recently, Methanex, the largest methanol producer in the world, conducted an assessment of the energy efficiencies of methanol plants with four technology designs for the American Methanol Institute (Allard 1999). The table below presents the results of that assessment.

Table 3.1 Energy Efficiencies of Methanol Plants[a]

Reforming Method	Efficiency Based on LHV (percent)	Efficiency Based on HHV (percent)
Conventional Steam Reforming	62.4	63.9
Steam Reforming with CO_2 Injection	64.2	65.8
Autothermal Reforming	67.1	68.8
Two-Step Reforming	70.3	72.1

[a] From Allard (1999).

Of the four plant types, conventional SMR plants account for the majority of existing methanol plants worldwide. One out of ten of these plants may employ CO_2 injection (where CO_2 is available from other nearby chemical plants). The methanol industry believes that mega-size plants will probably use the more efficient ATR and two-step reforming technologies and that the additional capital investment in these plants will be returned by increased methanol yield (Allard 1999).

Because we are evaluating methanol as a transportation fuel for the future, we need to evaluate the types of plants that will likely be built, if methanol will be used in ICE engines and FCVs in significant amounts. While we realize that most existing methanol plants are SMR plants, we assume that future plants will rely on ATR or two-step reforming technologies that offer higher efficiencies. Because we use low heating values (LHVs) throughout our analysis, we employed efficiencies of 67% and 70% for the two cases analyzed in this study.

The majority of the total NG input in methanol plants is used as feed for syngas production; the remainder is used as process fuel. For SMR plants, Abbott (1997) reported that 78–88% of the total NG input in methanol plants is used as feed. For ATR systems, no external furnace is required, so no NG is burned as process fuel.

The split of NG between feed and fuel is used in the GREET model to calculate emissions of criteria pollutants during methanol production. In particular, the amount of NG burned and the emission factors of NG combustion are used to determine combustion emissions of NG fuel in methanol plants.

Because syngas is pressurized in reformers, fugitive emissions of CO and CO_2 may be released from reformers. But no data are available to estimate the amount of fugitive emissions. We estimate emissions from methanol plants using the process described in Section 3.1.10 (FTD production).

3.1.6 Natural Gas to Gaseous Hydrogen Produced in Centralized Plants

We assume that large-size, centralized H_2 production plants will be located near NG fields. Gaseous hydrogen will be transported through pipelines to refueling stations and compressed to 5,000–6,000 psi for fueling FCVs (Figure 3.7). Because GH_2 must be transported economically, we assume that it will be produced in North America so it can be transported via pipelines, even though NG here is much more expensive than elsewhere.

The majority of existing large-scale H_2 plants use SMR technology. The technology involves conventional, one-step steam reforming that is carried out in high-alloy tubes placed inside a large NG-fired furnace. The NG feed is normally preheated by the waste heat

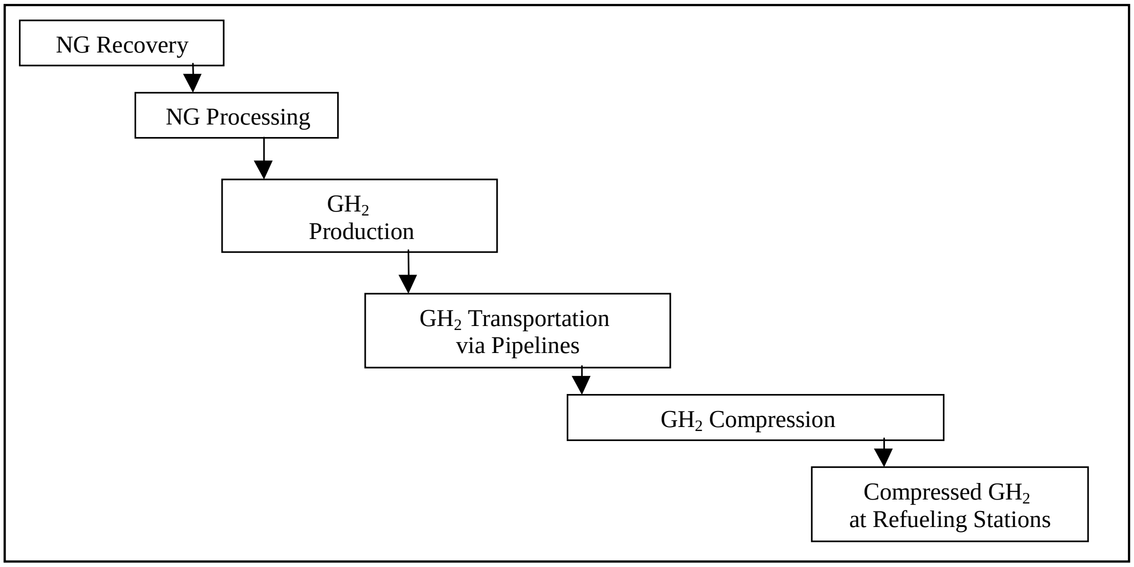

Figure 3.7 NG-to-GH_2 Pathway: Central Plant Production

from the SMR reformer, and the feed gas is processed through a bed of zinc oxide (ZnO) sorbent (see Section 3.1.5 on methanol production) to remove the sulfur (which poisons the reforming catalysts). Steam is added to the desulfurized NG feed, and the mixture of NG and steam is further preheated before entering the reformer, where CH_4 is converted into H_2, CO, and CO_2 by means of nickel-based reforming catalysts. The produced hot syngas, at a temperature of 900–930^{o}C, exits the SMR reformer and is cooled before entering the shift converter, where shift catalysts convert CO and steam to CO_2 and additional H_2. The gas from the shift converter is further cooled to ambient temperature before entering a pressure swing adsorption unit, where high-purity H_2 is produced; the remaining gas mixture is used in the SMR reformer as supplement fuel for the burners. To improve the energy efficiency of H_2 production, combustion air for the burners can be preheated by means of waste heat from the reformer's heat recovery section.

Besides conventional SMR technology, other technologies such as partial oxidation and ATR can be applied in H_2 plants. Dybkjar et al. (1998) describe several advanced steam reforming technologies for producing H_2.

An H_2 plant can generate a significant amount of steam. Some of the steam is used for processing within the plant, while the remainder can be exported to nearby chemical plants or used to generate electricity for export. Because we assume that GH_2 plants will be located in North America, these plants can be built near chemical plants to which excess steam can be exported. Some H_2 plants will likely be located far from chemical plants. In our analysis, we assume that 50% of centralized GH_2 plants will be able to export steam to nearby plants.

Table 3.2 presents energy efficiencies and steam production for different H_2 plant designs. As Sharma (1999) points out, overall plant efficiency (taking into account steam credit), is higher for H_2 plants with designs that maximize steam production than for other plants. However, if steam has low or no value, H_2 plants must be designed to maximize H_2 production. It is likely that mega-size centralized H_2 plants for producing transportation fuel will be designed for maximum H_2 production. Table 3.2 presents our assumptions for this study.

On the basis of data in Dybkjar et al. (1998), of the 1.54 million Btu of total NG input, we estimate that 1.17 million Btu feeds the SMR reformer and 0.37 million Btu fuels the burner that provides process heat. That is, the split between feed and fuel for NG input in H_2 plants is 76% and 24%. Emissions of NG fuel are calculated on the basis of the estimated amount of NG consumed as fuel (24% of total NG input) and the emission factors of NG combustion.

In H_2 plants, all the carbon in CH_4 eventually ends up as CO_2. The produced CO_2 can be sequestered into depleted oil and gas wells to limit CO_2 emissions from H_2 plants or to enhance recovery in oil fields. Some researchers maintain that injection of CO_2 into oil and gas wells helps increase oil and gas production, which could make CO_2 injection an economical way to increase oil and gas production (Blok et al. 1997; Williams and Wells 1997). However, without economic incentives or regulations, it is uncertain whether CO_2 from H_2 plants will be sequestered; we do not assume CO_2 sequestration in H_2 plants. If all CO_2 emissions from

Table 3.2 Energy Efficiencies of H_2 Plants

Plant Type	Plant Size (million scf/d[a])	Efficiency without Considering Steam Export (percent)	Efficiency Considering Steam Export (percent)	Implied Steam Production (Btu/million Btu H_2 produced)
SMR[b]	12	65	86	323,000
SMR[b]	200	71	83	169,000
SMR[c]	76	61	86	410,000
SMR[d]	76	73	82	123,000
Two-Step Reforming[b]	200	73	83	137,000
ATR[b]	200	71	82	155,000
This Study:				
H_2 Plants with Steam Export	200	71	83	169,000
H_2 Plants without Steam Export	200	73	NA[d]	0

[a] scf/d = standard cubic feet per day.

[b] From Dybkjar et al. (1998).

[c] From Sharma (1999). The design does not include pre-reformers and preheating of combustion air, and steam production is high.

[d] From Sharma (1999). The design includes pre-reformers and preheating of combustion air to increase H_2 production.

an H_2 plant are sequestered, GHG emission reductions by FCVs fueled by H_2 will increase by 27–30% relative to a case in which CO_2 emissions are not sequestered (the assumption used in this study).

We assume that more energy is needed to transport a unit of energy in H_2 than to transport a unit of energy in NG via pipelines because the energy content per volume of H_2 is only about 30% of the energy content per volume of NG. On the other hand, H_2 is much lighter than NG, so although a greater volume of H_2 must be transported to obtain a given amount of energy, energy use per volume of H_2 transported may be smaller than energy use per volume of NG transported. We assume an energy efficiency of 95% for H_2 pipeline transmission; the energy efficiency of NG pipeline transmission is assumed to be 97%.

Gaseous H_2 may need to be stored onboard FCVs at pressures above 5,000 psi, so it may need to be compressed to 6,000 psi or greater at refueling stations. We assume that electric compressors will be used to compress H_2 at the refueling stations. By using the formula developed by Stodolsky (1999), we estimate a compression efficiency of 90% for H_2 with electric compressors. The compression efficiency is defined as the energy in electricity divided by the energy in the H_2 compressed. Energy loss during electricity generation is taken into account in a different part of the GREET model. For comparison, data presented in Thomas et al. (1997) indicate a compression efficiency of 88–94% for H_2 compression using electric compressors.

Hart and Hormandinger (1998) used a compression energy use rate of 1.29 megajoules (MJ) per normal cubic meter (nm^3) of H_2 compressed to 3,300 psi, which translates into an energy efficiency of 87.3%. Using Stodolsky's formula, we calculate an energy efficiency of

79% for ICE compressors and 91% for electric compressors to compress H_2 to 3,300 psi. Hart and Hormandinger may have assumed a combination of ICE and electric compressors in their study.

3.1.7 Natural Gas to Gaseous Hydrogen Produced at Refueling Stations

The cost of developing a pipeline distribution infrastructure for GH_2 could be enormous (Wang et al. 1998). To avoid the expensive H_2 pipeline system, some researchers have proposed production of H_2 at refueling stations. This pathway, sometimes called the “decentralized production pathway,” involves transporting NG through pipelines to refueling stations, where small-scale SMR units would be used to produce GH_2. Thus, the pathway includes NG transmission and requires small-scale SMR reformers, storage tanks, and compression facilities at refueling stations (Figure 3.8).

The decentralized H_2 production pathway makes steam production and export infeasible. Centralized H_2 plants without steam production could have an energy efficiency of 73%; decentralized H_2 production at refueling stations would likely be less efficient. We assume an energy efficiency of 70% for decentralized H_2 production.

Because NG is readily available at H_2 production and refueling stations, refueling station operators may decide to use NG compressors to compress H_2 to about 6,000 psi. On the other hand, because they are more reliable, some stations could be equipped with electric compressors. We assume that 50% of the refueling stations will use NG compressors and the remainder will use electric compressors for H_2 compression. As discussed in Section 3.1.6, we

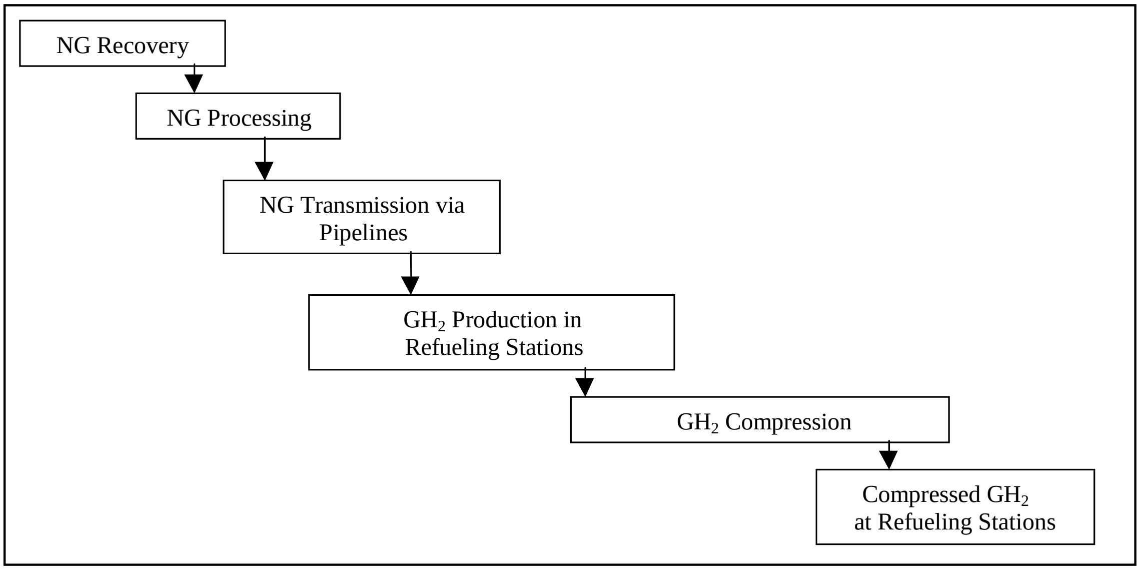

Figure 3.8 NG-to-GH_2 Pathway: Refueling Station Production

estimate a compression efficiency of 90% for electric compressors. For compressors fueled by NG, using the formula developed by Stodolsky (1999), we estimate a compression efficiency of 77% for the incremental case and 79% for the leap-forward case. For comparison, Thomas et al. (1997) reported an energy efficiency ranging from 55 to 65% for both producing and compressing H_2 in refueling stations.

3.1.8 Natural Gas to Liquid Hydrogen Produced in Centralized Plants

The GH_2 produced at centralized H_2 plants can be liquefied. LH_2 can be stored as a cryogenic liquid and transported over long distances. One advantage of using LH_2 in motor vehicles is a longer driving range per refueling than that allowed by GH_2. Two major disadvantages are: (1) liquefaction of H_2 requires a large amount of energy (resulting in fewer energy and emissions benefits), and (2) cryogenic transportation and storage of LH_2 pose technical and economic challenges.

Liquid H_2 can be transported from H_2 plants via ocean tankers, railcars, barges, and/or trucks in cryogenic vessels to bulk terminals, stored there, and then transported to refueling stations via trucks. In our study, we assume that LH_2 will be produced in regions outside of North America so that its producers can take advantage of inexpensive NG in those regions. Figure 3.9 presents the LH_2 pathway.

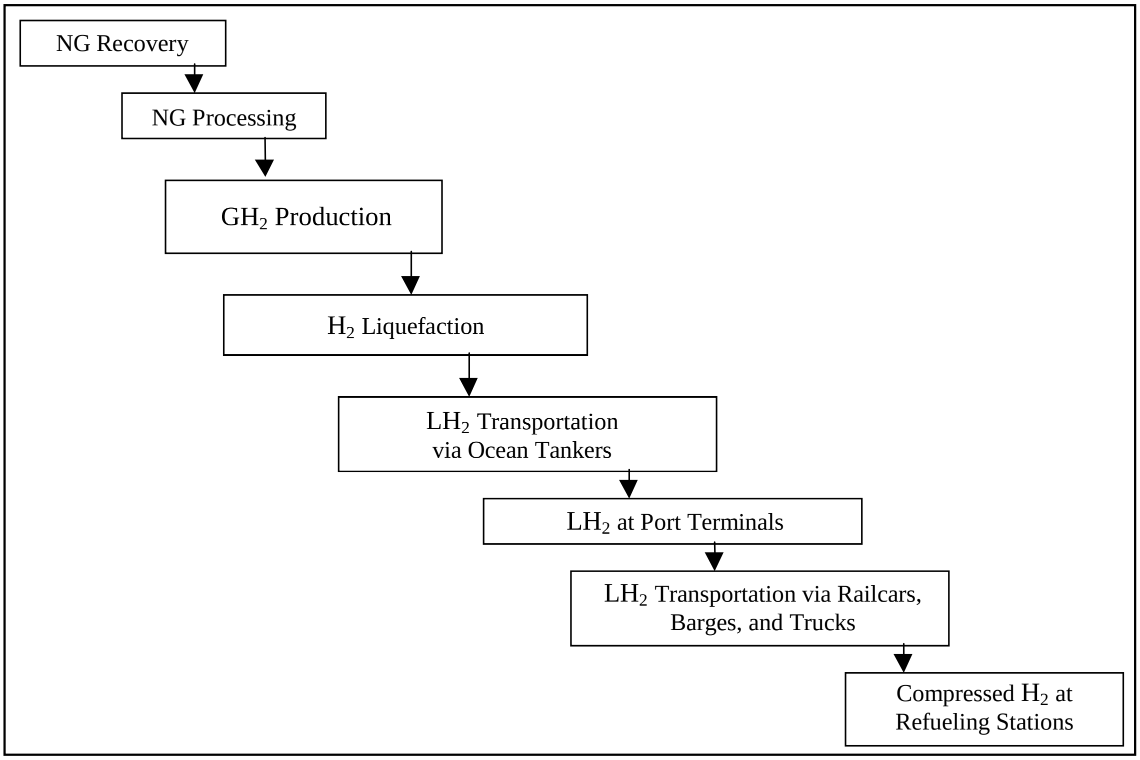

Figure 3.9 NG-to-LH_2 Pathway

We separate LH_2 production into two steps: GH_2 production and GH_2 liquefaction. For GH_2 production, we use the efficiency assumptions presented in Table 3.2. Besides the energy losses in producing GH_2, providing power to refrigeration compressors during liquefaction consumes a large amount of energy. Although energy for the compressors can be provided by steam boilers, steam turbines, gas turbines, or electric motors, most studies assume that electricity will be used for H_2 liquefaction. Because the boiling point of LH_2 is much lower that that of LNG (-253ºC vs. -163ºC), the energy required for H_2 liquefaction is much higher than that required for NG liquefaction. Wagner et al. (1998) report an energy efficiency of 70% for H_2 liquefaction. Specht et al. (1998) report an electricity consumption rate of 11 kWh per kilogram of LH_2 production for H_2 liquefaction. This translates into an energy efficiency of 67%. Thomas et al. (1997) report electricity consumption rates ranging from 9.5 to 14 kWh per kilogram of LH_2, which translates into liquefaction energy efficiencies of 58–72%. In our study, we assume an efficiency of 65% for the incremental case and 70% for the leap-forward case.

We assume that half of the LH_2 plants will generate steam and that the steam will be used in gas turbines to generate electricity for H_2 liquefaction. Because the steam generated in H_2 plants will be low in quality, we assume an energy efficiency of 30% to convert the generated steam to electricity. As shown in Table 3.2, for each million Btu of GH_2 produced, 169,000 Btu of steam could be produced, generating 14.9 kWh of electricity. On the other hand, with the assumed liquefaction efficiency of 70% under the leap-forward scenario, liquefaction of each million Btu of H_2 requires about 125.6 kWh of electricity. Thus, an additional 110.7 kWh of electricity is needed to liquefy one million Btu of H_2. We assume that the additional electricity will be generated from NG by means of combined-cycle gas turbines.

We assume that LH_2 will be transported via ocean tankers to major U.S. ports. At present, there is no across-ocean transportation of LH_2. However, it is technically feasible to transport LH_2 on ocean tankers; a Japanese research program investigated the conceptual design of a 200,000 cubic meter (m^3) tanker for cross-ocean transportation of LH_2 (Abe et al. 1998).

Because of its extremely low boiling point, LH_2 is ten times easier to evaporate than LNG (Abe et al. 1998). So the boiling-off effect for LH_2 is much greater than that for LNG. Abe et al. estimated a boiling-off rate of 0.2–0.4% per day from a proposed 200,000-m^3 ocean tanker. LH_2 will have a boiling-off rate of 2–4% during a ten-day, one-way trip. We use a boiling-off rate of 3% for ocean tankers. Abe et al. proposed that the boiling-off gas be used to power the internal combustion engines on the tanker, estimating that 20–40% of the boiling-off gas would be sufficient to power the ocean tanker. In our analysis, we assume that the boiling-off gas will be used to fuel the tankers.

The boiling-off effect continues during LH_2 storage and transportation. We assume that another 3% of LH_2 is boiled off during storage in port terminals, transportation and distribution from port terminals to refueling stations, and storage in refueling stations. We do not assume that boiling-off gas during land storage and transportation of LH_2 is used to fuel trains, barges, or trucks.

3.1.9 Natural Gas to Dimethyl Ether

DME, which has physical properties similar to those of LPG, has been proposed and tested as an alternative to diesel fuel in CI engines. Use of DME in diesel engines offers emission reduction benefits for NO_x and PM. For the NG-to-DME cycle, we assume in this study that DME is produced near gas fields in remote regions outside of North America in order to take advantage of cheap and abundant NG.

Transportation from DME plants to refueling stations is assumed to be similar to that for LPG; DME is transported across the ocean on tankers, and then transported via pipelines, railcars, barges, and/or trucks from port terminals to bulk terminals, and then to refueling stations via trucks (Figure 3.10).

DME, now used predominantly as an aerosol propellant, is produced from methanol through a dehydration process. Production involves a two-reactor process train in which methanol is first synthesized from syngas. DME is then produced by dehydration of two methanol molecules to one DME molecule. The recent development of new, dual-function catalysts allows the synthesis and dehydration to take place within a single reactor. The new one-step production approach results in an energy efficiency as high as 70%, which significantly improves the economics for large-scale DME plants (Kikkawa and Aoki 1998; Verbeek and Van der Welde 1997; Blinger et al. 1996; Hansen et al. 1995).

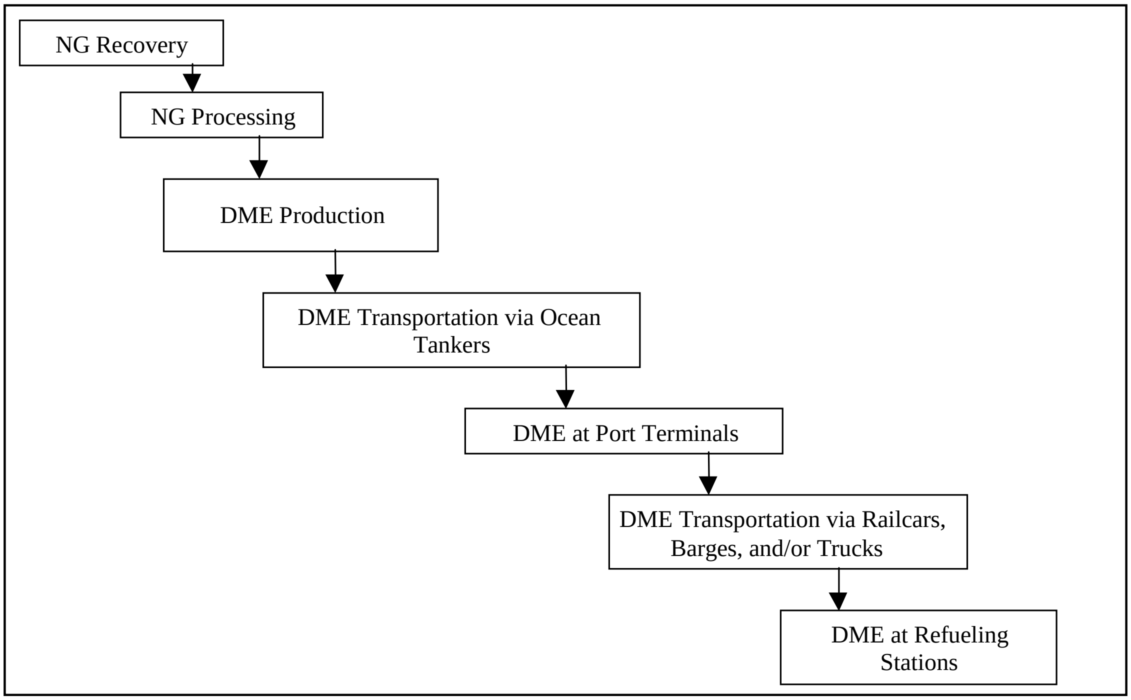

Figure 3.10 NG-to-DME Pathway

The desired mole ratio among H_2, CO, and CO_2 ($[H_2\text{-}CO_2]/[CO+CO_2]$) for DME synthesis is around 2.1. Syngas from SMR reformers, however, has a ratio of about 2.8 and contains a high concentration of H_2. To achieve the desired molar ratio for DME production, CO_2 must be added or H_2 must be removed. The ATR process (described in Section 3.1.5 for the NG-to-methanol production pathway) includes an adiabatic reactor that uses oxygen together with a much smaller amount of steam than required by SMR plants. The process produces a syngas with a ratio below 2.0. Another new technology — two-step reforming technology (also described in Section 3.1.5) — integrates an SMR reformer with a POX reformer (which uses pure oxygen to produce syngas) to achieve the desired molar ratio. The ATR and the two-step reforming technologies are reported to be particularly suitable for mega-size DME plants (5,000–10,000 ton/d capacity) (Verbeek and Van der Welde 1997; Hansen et al. 1995).

No external furnace is required with the ATR system, so no NG is burned as process fuel. Instead, a portion of the NG feed to the ATR reactor is oxidized inside the front end of the reactor to provide the heat necessary for conversion of NG to syngas. Because there is a small amount of nitrogen in the NG feed, a small amount of NO_x forms inside the ATR reactor. The NO_x is eventually emitted into the atmosphere after final product separation. However, the amount of NO_x emissions from the ATR system is less than the amount from the SMR system.

To produce one metric ton of methanol-equivalent (on the Btu basis) DME, 29.1 gigajoules (GJ) (LHV) of NG input is needed (Dybkjar 1996; Hansen et al. 1995). This value is in addition to 76 kWh of electricity coproduced per metric ton of methanol-equivalent DME. The numbers imply an energy conversion efficiency of 68.8% without considering an electricity credit.[1] If the energy (in Btu) contained in the steam that is subsequently used for electricity generation is taken into account, the efficiency is 71.7%. On the other hand, using data presented in Kikkawa and Aoki (1998), we calculate an energy efficiency of 65% for DME production without considering a steam credit. With a steam credit considered, the efficiency is increased to 66.8%. In our study, we assume energy efficiencies of 69% and 70% for the incremental and leap-forward scenarios, respectively.

DME plants can produce extra steam for export or for on-site electricity generation. However, because we assume that DME plants are located in remote regions, and because the potential amount of steam from DME plants is small (relative to the amount from H_2 or FTD plants), we do not assume coproduction of steam or electricity in DME plants.

Hansen et al. (1995) report that the CO_2 and NO_x emissions from DME plants are 440,000 and 95 grams [g] per metric ton (23,158 and 5.263 grams per million Btu) of DME, respectively. Using the above energy input data and the carbon balance method, we independently calculated CO_2 emissions of 446,000 g/metric ton of DME, which is consistent with the number reported in Hansen et al. In our analysis, we use an energy conversion efficiency of 69% for DME production under the incremental scenario and an efficiency of 70% under the leap-forward scenario.

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[1] With an LHV of 57,000 Btu/gallon (gal) and a density of 2,996 g/gal for methanol, one metric ton of methanol contains 19 million Btu of energy. One GJ is 0.9486 million Btu.

As explained above, the ATR technology does not require combustion of NG to provide the heat for DME production. So all NG input for DME production is allocated as feed. Emissions of criteria pollutants from the ATR system for DME production are estimated as described in the next section on FTD production.

3.1.10 Natural Gas to Fischer-Tropsch Diesel

The Fischer-Tropsch process produces high-quality middle distillates; it also produces naphtha and wax. Using the Fischer-Tropsch products in CI engines helps reduce NO_x and particulate emissions. The Fischer-Tropsch reaction process was used by Germany during World War II to produce diesel fuel and by South Africa during the 1980s. Currently, several major companies are actively pursuing the production of middle distillates through the Fischer-Tropsch process. Commercial Fischer-Tropsch synthesis processes are available from Sasol, Ltd., Shell International Oil Products, Exxon Corporation, Syntroleum Corporation, and Rentech, Inc. Sasol and Shell are currently producing FTD, while Exxon, Tentech, and Syntroleum have technologies to do so.

Production of FTD consists of three steps: (1) production of syngas, (2) synthesis of middle distillates, and (3) upgrading of products. At the syngas production stage, hydrocarbon feed is converted into syngas (a mixture of CO and H_2). Although SMR, POX, and ATR technologies can all be used to generate syngas, POX and ATR reformers are more suitable for syngas production in FTD plants than SMR. Before entering the reformers, NG is desulfurized through a ZnO sorbent bed (see Section 3.1.5 on methanol production). An FTD plant design analyzed by Choi et al. (1997a,b) of Bechtel Corporation employs a POX reformer and a small SMR reformer to produce syngas with the desired H_2/CO ratio of about 1.9. The oxidation reaction in the POX reformer uses pure oxygen that is produced in an oxygen plant within the FTD plant. The FTD plant designed by Syntroleum includes an ATR reformer; the oxidation reaction in the ATR reformer employs ambient air, so no oxygen plant is required (Russell 1999).

The next stage in FTD plants is the Fischer-Tropsch synthesis. Each of the companies mentioned above has a unique design for the Fischer-Tropsch synthesis reaction process. With the help of catalysts, the reaction produces a variety of hydrocarbon liquids, including middle distillates. The product mix depends on the catalyst used and the operating temperature of the reactor. For example, an operating temperature of 180–250°C helps produce predominantly middle distillates and wax; an operating temperature of 330–350°C helps produce gasoline and olefins.

Two types of catalysts, cobalt- and iron-based, can be used during the Fischer-Tropsch synthesis reaction. Iron-based catalysts cause a water gas shift reaction in addition to the synthesis reaction. The water gas shift reaction is necessary if the H_2/CO ratio of syngas is less than 2:1; such syngas is produced with feedstocks such as coal and refinery bottoms. On the other hand, for syngas produced from NG, which has the required H_2/CO ratio, cobalt-based catalysts, which do not create a water gas shift reaction, are ideal. Because sulfur compounds react with cobalt catalysts, reducing their life and performance, upstream desulfurization is necessary for cobalt-based processes. Consequently, fuels produced with cobalt-based catalysts contain virtually no sulfur.

Because the Fischer-Tropsch reaction is exothermal, the excess heat from the process can be recovered in steam. The generated steam can be exported to nearby chemical plants or used to generate electricity for export.

Table 3.3 lists the carbon and energy efficiencies of FTD plants as presented in four references. Carbon efficiency values are necessary for calculating CO_2 emissions from FTD plants because FTD plants produce hydrocarbon products ranging from C4 to above C25. Without knowing the detailed distribution of each hydrocarbon product from FTD plants, researchers cannot calculate CO_2 emissions by using the carbon balance method (carbon contained in NG feed minus carbon contained in products). In many cases, a carbon efficiency is calculated this way in individual studies. So we use carbon efficiency, as well as energy efficiency, in GREET simulations of FTD.

On the basis of the information in Table 3.3, we can assume two types of FTD plant designs. One type, the Syntroleum design reported by Russell, involves steam recovery and electricity generation. The other type is intended to maximize FTD production with virtually no steam recovery and electricity generation. This type is represented by the large plant design evaluated by Choi et al (1997a,b). In our study, we include both types.

The Syntroleum process produces two liquid products: C5-C9 naphtha (30%) and C10-C20 middle distillates (70%). Designs by other companies produce wax, middle distillates, and naphtha. The naphtha can be used as a gasoline blendstock, but its high Reid vapor pressure (RVP) presents a problem for blending it into gasoline. Research is currently under way to explore the use of naphtha in fuel cells because it contains a high concentration of H_2 (see Ahmed et al. 1999). The middle distillates from FTD plants can be used as a diesel blendstock or as neat fuels in diesel engines.

In the POX design presented by Bechtel (a POX reformer and a small SMR reformer), the split of total NG input between the POX and SMR reformers is 30 to 1. That is, about 3.2% of the total NG input goes to the SMR reformer. Furthermore, of the total NG to the SMR reformer, we assume that the split between NG as feed and NG as fuel is 76% to 24% (the same split that we developed for SMR reformers for methanol and H_2 production; see Sections 3.1.5 and 3.1.6). So, overall, only about 0.77% (3.2% × 0.24) of the total NG input is used as fuel in the Bechtel FTD design. Combustion of the 0.77% of NG input produces a small amount of criteria pollutant and GHG emissions. The Syntroleum design, using the ATR reformer, does not require combustion of NG. So all NG input is used as feed.

All NG input in FTD plants goes to the ATR reformer; none is burned directly. On the other hand, the ATR reformer generates some criteria pollutant emissions. According to Syntroleum researchers (Russell 1999), VOC emissions from FTD plants should be about equal to those from petroleum refineries (on the basis of per-unit-of-product output); CO emissions

Table 3.3 Energy and Carbon Efficiencies of FTD Production

Source	Carbon Efficiency (percent)	Energy Efficiency (percent)	Remarks
Marshall (1999)	71	55	Design evaluated by Bechtel. A POX reformer with a small SMR reformer.
	78	62	Designs by Sasol, Shell, and Exxon.
	72	57	Sytroleum technology. No oxygen, co-based catalyst, ATR reformer.
Russell (1999)	76	66	Sytroleum technology. Energy efficiency takes into account the Btu in steam.
	76	49	Sytroleum technology. Energy efficiency does not take into account the Btu in steam.
Choi et al. (1997b)	NA[a]	46	Shell design. A small plant with 100 million scf/d NG input. Energy efficiency does not take into account the Btu in exported electricity.
	NA	61	Shell design. A small plant with 100 million scf/d NG input. Energy efficiency does not take into account the Btu in exported electricity.
Choi et al. (1997a)	NA	57	Shell design. A large plant with 410 million scf/d NG input. Energy efficiency does not take into account the Btu in exported electricity.
	NA	58	Shell design. A large plant with 410 million scf/d NG input. Energy efficiency does not take into account the Btu in exported electricity.
This Study	76	66	Sytroleum design with steam recovery for electricity generation. Energy efficiency takes into account the Btu in steam.
	76	49	Sytroleum design with steam recovery for electricity generation. Energy efficiency does not take into account the Btu in steam.
	73	57	Shell design as evaluated by Bechtel. Design does not include steam or electricity export.

[a] NA = not available.

from FTD plants should be fewer than 100 tons per year for a 1,000-barrel-per-day plant; and NO_x emissions should be less than 60 tons per year. Using these values, and based on an assumed plant capacity of 85%, we estimate a CO emission rate of 58.6 g/million Btu of fuel output and a NO_x emission rate of 35.2 g/million Btu. These emission rates are based on manufacturer-suggested emissions limits. In the GREET simulation, we assume half of the estimated emissions rates.

We assume that FTD plants will be built in remote regions where inexpensive NG will be available (Figure 3.11). A large amount of steam can be recovered from FTD plants. If other chemical plants are located nearby, the recovered steam can be exported to those plants, or the steam can be used to generate electricity for export. FTD plants that will be built for producing transportation fuels will likely be large. Electricity generation from large plants for export

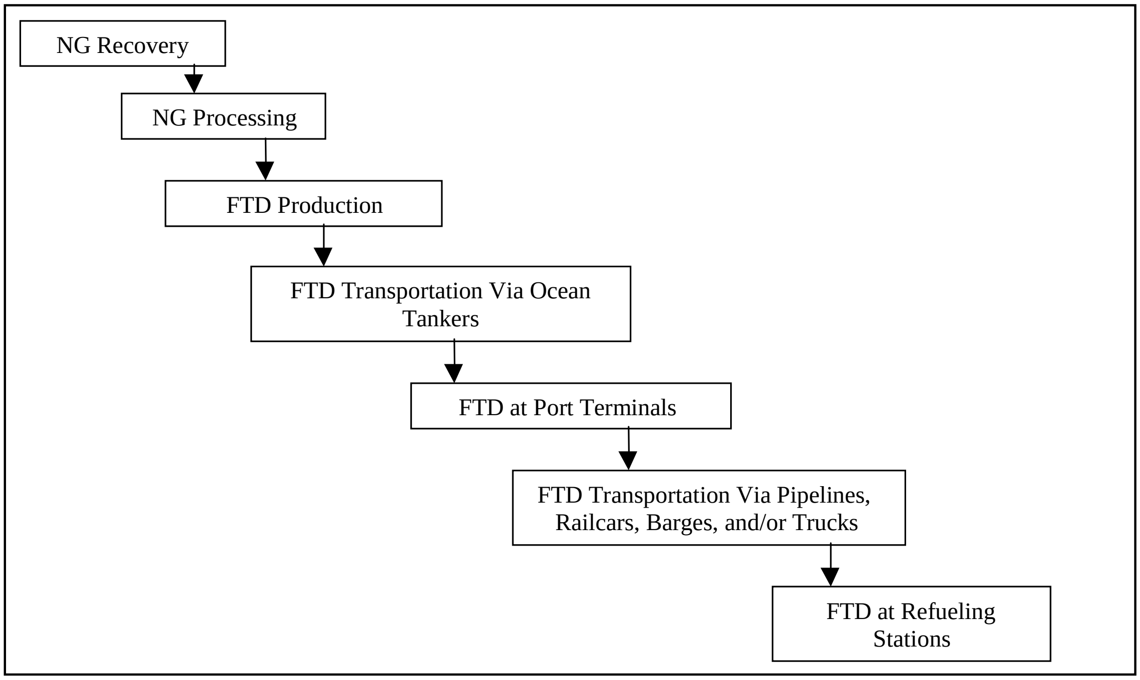

Figure 3.11 NG-to-FTD Pathway

seems more practical than steam export. We assume that the recovered steam will be used to generate electricity. Because the quality of the recovered steam will be low, we assume an energy efficiency of 30% in converting Btu in steam to Btu in electricity. We assume the electricity from FTD plants will displace electricity generated from NG-fired electric power plants equipped with a combined-cycle gas turbine.

Some FTD plants will be located in areas where electricity export will not be feasible. In this case, we assume Bechtel’s design, which has a high energy efficiency without electricity generation. In our study we assume that half of FTD plants will be the Bechtel design and half will be the Syntroleum design.

3.2 Production of Liquid Fuels from Flared Gas

Tables 3.4 and 3.5 present the amounts of NG produced and used in the United States and worldwide. In the United States, the amount of gas vented or flared represents a tiny portion of the total amount of gas produced. Vented or flared gas is usually the associated gas produced from oil fields where NG pipelines and processing infrastructure are not available to process the gas into a commercial product. Besides flaring, gas can also be vented or reinjected back into underground wells. Worldwide, about 5% of the total NG produced is flared (EIA 1998b). Some researchers suspect that the actual amount of gas flared is far greater than reported. As some countries started to impose economic penalties for gas flaring in an effort to reduce CO_2 emissions, oil companies began to look for other alternatives to dispose of or use associated gas from oil fields. One option is to build chemical plants near oil fields to produce liquid fuels

Table 3.4 NG Production and Field Usage in the United States[a]

Method	Amount (trillion ft^3)	Percent of Total Production
Gas Well Production	17.68	73.5
Oil Well Production	6.37	26.5
Total Production	**24.05**	**100**
Gas Used for Reservoir Repressuring	3.51	14.6
Gas Vented or Flared	0.27	1.1
Net Gas for Market	19.75	82.1

[a] From Oil and Gas Journal (1998); data are for 1996.

Table 3.5 Worldwide NG Production and Flaring[a]

Region	NG Reserve[b]	Annual Production[b]	Annual Flared Gas[c]	Flared Gas as Percent of Production
West Hemisphere	517.7	30.7	0.86	2.8
West Europe	170.4	9.5	0.13	1.4
East Europe	2,003.2	26.9	NA[d]	NA
Asia Pacific	320.6	7.7	0.287	3.7
Middle East	1726.1	4.7	0.914	19.4
Africa	348.6	3.0	1.637	54.6
World	**5,086.0**	**82.5**	**3.828**	**4.6**

[a] Values in trillion ft^3; data are for 1996.

[b] From Oil and Gas Journal (1998).

[c] From EIA (1998b).

[d] NA = not applicable.

from gas rather than flaring. To simulate the energy and emissions impacts of using FG for liquid fuel production, we establish cases for production of LNG, methanol, LH$_2$, DME, and FTD from FG.

Inexpensive NG feedstock is vital to allow methanol, DME, and FTD to compete with petroleum-based fuels. Production of liquid fuels from FG can overcome the NG distribution infrastructure hurdle in remote locations; such production results in huge energy and emissions benefits for produced liquid fuels because of the energy and emission credits from eliminating gas flaring.

3.2.1 Flared Gas to Liquefied Natural Gas

We assume that LNG is produced from FG outside the continental United States. LNG is transported to major U.S. ports via ocean tankers. We assume a liquefaction efficiency of 88% — 2% lower than the efficiency of LNG produced from NG.

3.2.2 Flared Gas to Methanol

We assume an energy efficiency of 65% for methanol plants using FG under the incremental scenario and 67% under the leap-forward scenario. These values are lower than the efficiency of producing methanol from NG. Because FG will be cheap, conventional SMR technology, requiring less capital investment, may be used for these plants. Some plants, though, may use ATR or the two-step technology to increase methanol production. The efficiency assumptions here reflect our belief that a combination of conventional SMR, ATR, and two-step systems will be used in these plants.

3.2.3 Flared Gas to Liquid Hydrogen

Because LH_2 can be transported long distances and across oceans, production of LH_2 from FG in remote locations is feasible. We include this pathway in our analysis. For GH_2 production, we assume an efficiency of 70% and 72% under the incremental and leap-forward scenarios, respectively. For H_2 liquefaction, we assume efficiencies of 63% and 65% for the two scenarios, respectively.

3.2.4 Flared Gas to Dimethyl Ether

For DME production from FG, we assume energy efficiencies of 68% and 69% for the incremental and leap-forward scenarios, respectively.

3.2.5 Flared Gas to Fischer-Tropsch Diesel

For FTD production from FG, we assume no electricity cogeneration in FTD plants. We assume efficiencies of 55% and 57% for the incremental and leap-forward scenarios, respectively. We use our assumptions regarding carbon efficiencies for the FTD plant design with no steam or electricity export, as presented in Table 3.3.

Section 4
Vehicle Technologies

The NG-based fuels included in this study can be used in SI engines, SIDI engines, CIDI engines, FCVs, HEVs, and EVs. Some of the combinations of fuels and vehicle propulsion systems are already in the market and others are still in the R&D stage. Because the technological status and commercial status of the technologies are different, we separate them into two groups for our analysis: near- and long-term technologies.

Table 4.1 presents the near-term technology options, which are already being used. GVs fueled with CG and CIDI diesel vehicles fueled with CD are the baseline vehicles to which we compare the vehicles fueled by NG-based fuels. Within the light-duty vehicle fleets, the diesel vehicle share is minimal. Most of the available diesel car models are equipped with CIDI engines, which have much better fuel economy than CG-powered gasoline engines. So we assume CIDI diesel vehicles, together with gasoline vehicles, as baseline vehicles. Of the three NG-based fuels, LPG is used the most often and methanol the least often. CNG is in the middle. Use of methanol vehicles was promoted until the mid-1990s. Although there are very few methanol vehicles in operation, methanol vehicle technology is readily available. We include methanol vehicles for the purpose of completeness, even though we realize that they are not being promoted at present. We assume use of M85 (85% methanol and 15% gasoline by volume) for near-term options and M90 (90% methanol and 10% gasoline by volume) for long-term options in methanol vehicles because neat methanol presents a cold start problem for engines.

Table 4.2 presents the long-term technology options, which are either in the prototype or R&D stage. In Table 4.2, gasoline SI engines and diesel CIDI engines are our baseline engine technologies. We expect that even under a business-as-usual case, baseline technologies will be improved because of the need for better fuel economy and emission performance. The desire for improved fuel economy heightens the interest in direct injection (DI) engines for light-duty vehicle applications. We include SIDI engines and CIDI engines as long-term technology options. Because they do not offer additional fuel economy benefits, we do not include applications of gaseous fuels in DI engines. SIDI and CIDI engines can be used in stand-alone applications or in HEV applications with further improvement in vehicle fuel economy. We include both applications. Battery-powered EVs, which offer zero tailpipe emissions, can use electricity generated from NG via combined-cycle turbine plants.

Table 4.1 Near-Term Technology Options Considered in This Study

Petroleum-Based Fuels (baseline)
  SI Engines Fueled by CG
  CIDI Engines Fueled by CD

NG-Based Fuels
  SI Engines Fueled by CNG
  SI Engines Fueled by LPG
  SI Engines Fueled by M85

FCVs are promoted for their superior fuel economy and low emissions. Recently, Daimler-Chrysler announced its plan to introduce methanol-fueled FCVs by 2004. General Motors established

Table 4.2 Combinations of Fuels and Vehicle Propulsion Systems for Long-Term Technology Options[a]

	SI Engine		SI and SIDI Hybrid		CIDI Engine		CIDI Hybrid		FCVs		EVs	
Fuel	Incremental	Leap-Forward	Incremental	Leap-Forward	Incremental	Leap-Forward	Incremental	Leap-Forward	Incremental	Leap-Forward	Incremental	Leap-Forward
Petroleum RFG					▨	▨	▨	▨			▨	▨
CNG					▨	▨	▨	▨			▨	▨
LNG: NG and FG					▨	▨	▨	▨			▨	▨
LPG					▨	▨	▨	▨			▨	▨
MeOH: NG and FG					▨	▨	▨	▨			▨	▨
Petroleum RFD	▨	▨	▨	▨					▨	▨	▨	▨
DME: NG and FG	▨	▨	▨	▨					▨	▨	▨	▨
FTD: NG and FG	▨	▨	▨	▨					▨	▨	▨	▨
GH_2: Central and Stations	▨	▨	▨	▨	▨	▨	▨	▨			▨	▨
LH_2: NG and FG	▨	▨	▨	▨	▨	▨	▨	▨			▨	▨
Electricity	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		

[a] Shaded cells represent technology options that are not considered in this study.

Notes:

(1) SI engine: for RFG and methanol, the incremental scenario refers to conventional SI engines, and the leap-forward scenario refers to SIDI engines.

(2) SI and SIDI hybrid: under both the incremental and leap-forward scenarios, SI hybrid is for CNG, LNG, and LPG, and SIDI hybrid is for RFs and methanol.

(3) CIDI engine: the incremental scenario refers to existing CIDI engines, and the leap-forward scenario refers to advanced CIDI engines.

(4) CIDI hybrid: the incremental scenario refers to existing CIDI engines applied to HEVs, and the leap-forward scenario refers to advanced CIDI engines applied to HEVs.

(5) FCV: the incremental scenario refers to existing prototypes, and the leap-forward scenario refers to design goals for future FCVs.

(6) EV: the incremental scenario refers to EVs equipped with existing nickel metal hydride (Ni-MH) batteries, and the leap-forward scenario refers to EVs equipped with advanced batteries currently under development.

the Global Alternative Propulsion Center (GAPC) to conduct FCV R&D. The California Air Resources Board has established a fuel-cell partnership between the state and industries to promote FCV technologies. Industry partners include Ballard Power Systems, Inc., DaimlerChrysler, Ford Motor Company, Honda, Volkswagen, ARCO, Shell Oil U.S.A., and Texaco. Through the partnership, about 50 fuel cell passenger cars and fuel cell buses will be put on the road between 2000 and 2003. In addition to testing the FCVs, the partnership will identify fuel infrastructure issues.

In our analysis, we include FCVs fueled directly by H_2 or by other fuels using onboard fuel processors to produce H_2. We do not include other FCV technologies such as direct methanol FCVs because the challenges associated with these technologies may prevent their implementation and because it appears that R&D efforts to develop universal processors for any type of hydrocarbon fuels could be more successful and more broadly applied. In theory, any hydrocarbon fuels containing H_2 can be reformed to produce H_2 for FCVs (although reforming methanol is much easier than reforming other hydrocarbon fuels). We include gasoline, CNG, LNG, and LPG, in addition to H_2 and methanol, as FCV fuels in this study.

The long-term vehicle technology options included in our study are currently under vigorous R&D. We assume that these technologies could be introduced into the marketplace around 2010. Improvements to the technologies are subject to great uncertainties. To address these uncertainties, we establish two scenarios: an “incremental” and a “leap-forward” scenario. The incremental scenario assumes moderate improvements in fuel economy and emission performance for long-term technologies. The leap-forward scenario assumes greater fuel economy and emission advantages for these technologies. The two scenarios are intended to cover a range of vehicle fuel economy and emission performance improvements. We also assume improvements in upstream fuel production technologies for many pathways from the incremental to the leap-forward scenario (see Table 5.1).

For long-term technology evaluation, we assume that RFG and a potential RFD with low sulfur and aromatics content will be used in baseline gasoline and diesel vehicles. Use of RFG and RFD will likely be necessary for gasoline and diesel vehicles to meet the Tier 2 standards proposed by EPA.

We assume that near-term technology options will be in place between now and 2005, and long-term options will be in place around 2010. We further assume that near-term baseline technologies will meet the national low-emission vehicle (NLEV) standards adopted by EPA and automakers in 1998. We assume that long-term technologies will meet the Tier 2 emission standards proposed by EPA (see Wang 1999a).

Our analysis includes use of NG-based fuels in passenger cars. These fuels can be used in both light-duty and heavy-duty vehicles. The relative changes among the fuels for other vehicle types may be similar to those for passenger cars. Our estimated average emission rates for near- and long-term baseline vehicles are provided in Table 4.3.

Table 4.3 Fuel Economy and Emission Rates of Baseline Gasoline and Diesel Cars[a,b]

	Near-Term Baseline Vehicles		Long-Term Baseline Vehicles	
Parameter	Gasoline Car	Diesel Car	Gasoline Car	Diesel Car
Fuel Economy (in mpgeg)	22.4	30.2	24.0	36.0
Exhaust VOC	0.080	0.080	0.062	0.049
Evaporative VOC	0.127	0.000	0.063	0.000
CO	5.517	1.070	2.759	2.759
NO_x	0.275	0.600	0.036	0.063
Exhaust PM_{10}	0.012	0.100	0.010	0.010
Brake and Tire Wear PM_{10}	0.021	0.021	0.021	0.021
CH_4	0.084	0.011	0.065	0.011
N_2O	0.028	0.016	0.028	0.016

[a] Values are in miles per gasoline-equivalent gallon (mpgeg) for fuel economy and g/mi for emissions under the 55/45 combined cycle.

[b] From Wang (1999a, Table 6.4). For detailed assumptions, see that report. Note that fuel economy values are for on-road fuel economy, not laboratory-measured fuel economy.

Use of NG-based fuels offers emission reduction benefits compared with petroleum-based gasoline and diesel fuels. Researchers at the Center for Transportation Research at Argonne have been evaluating the emission reduction benefits of using alternative fuels such as NG. On the basis of these evaluations and input from other Argonne staff, we have assumed changes in fuel economy and emissions for the fuels evaluated here. Table 4.4 presents our assumed fuel economy and emission change rates.

The fuel economy and emissions changes listed in Table 4.4 for near-term SI engines fueled with CNG, LPG, and M85 are based on Argonne’s assessment of the tested fuel economy and emissions of these vehicles relative to those of GVs (Wang 1999a). For these vehicle technologies, we assume additional improvements from the near-term applications to the long-term applications. Note that emission reductions by these vehicle types (and by other vehicle types listed in the table) may appear smaller than expected because emission reductions for these vehicle types are relative to those for GVs that meet NLEV and proposed Tier 2 standards, which are already low. For the near-term options, as Table 4.4 shows, we have assumed two sets of values for fuel economy and some emission items to cover a range of potential fuel economy and emission changes for the near-term options. These two cases correspond to the incremental and leap-forward cases we established for the long-term technology options.

Many of the long-term advanced vehicle technologies (SIDI engines, CIDI engines, FCVs, and EVs) listed in the table are still in the prototype or R&D stage. Because few (if any) test results are available for these technologies, we have relied on simulations and assessments by other researchers and a mini-Delphi survey conducted for this study among Argonne experts on these technologies. For SIDI engines in stand-alone applications, we assume a fuel economy

Table 4.4 Fuel Economy and Emission Change Rates of NG-Based Fuels[a,b]

Option	Fuel Economy (mpgeg)	Exhaust VOC[c]	Evap. VOC[c]	CO	NO_x	Exhaust PM	CH_4	N_2O
Near-Term Options: Relative to NLEV Gasoline Cars Fueled with CG								
SI Engines: CNG	-7/0	-40/-80	-90	0/-40	0/-10	-95	900	0/-50
SI Engines: LPG	0/5	0/-30	-90	-15/-35	0/-10	-90	60/30	0
SI Engines: M85	0/5	0/-15	0/-15	0/-25	0/-10	-60	-50	0
Long-Term Options: Relative to Tier 2 Gasoline Cars Fueled with RFG								
SI Engines: CNG/LNG	5/10	-10	-90/-95	-20/-40	0	-80	400	-50
SI Engines: LPG	10/15	0	-90/-95	-20/-40	0	-80	10	0
SI Engines: M90	10	0	0	0	0	-40	-50	0
SIDI Engines: RFG	25	0	-10	0	0	40	0	0
SIDI Engines: M90	25	0	-10	0	0	0	-50	0
SIDI Hybrid: RFG	50/95	0	-30	0	0	20	0	0
SI Hybrid: CNG/LNG	40/80	-10	-95	-40	0	-50	400	-50
SI Hybrid: LPG	40/80	0	-95	-40	0	-50	10	0
SIDI Hybrid: M90	50/95	0	-30	0	0	-15	-50	0
FCVs: H_2	180/215	-100	-100	-100	-100	-100	-100	-100
FCVs: MeOH	110/150	-80	-60	-80	-80	-100	-80	-80
FCVs: Gasoline	75/125	-80	-30	-80	-80	-100	-80	-80
FCVs: CNG/LNG	75/125	-80	-95	-80	-80	-100	0	-80
FCVs: LPG	75/125	-80	-95	-80	-80	-100	-80	-80
EVs	250/350	-100	-100	-100	-100	-100	-100	-100
Long-Term Options: Relative to Tier 2 Diesel Cars (except fuel economy)[d]								
CIDI Engines: RFD	35/50	NN[e]	NN	NN	NN	NN	NN	NN
CIDI Engines: DME	35/50	-30	NN	0	0	0/-50	100	0
CIDI Engines: FTD	35/50	0	NN	0	0	0/-50	0	0
CIDI Hybrid: RFD	95/130	0	NN	0	0	0	0	0
CIDI Hybrid: DME	95/130	-30	NN	0	0	0/-50	100	0
CIDI Hybrid: FTD	95/130	0	NN	0	0	0/-50	0	0

[a] Values are in percent relative to fuel economy and emissions of baseline gasoline vehicles, except as noted.

[b] A negative number means a reduction; a positive number means an increase. In many cases, two values are presented. The first value represents the incremental scenario. The second value represents the leap-forward scenario.

[c] CH_4 can be volatile under certain conditions. However, VOC emissions here do not include CH_4 emissions.

[d] The changes for CIDI engines fueled with DME and FTD are relative to those for CIDI engines fueled with RFD, except for changes in fuel economy, which are relative to baseline GV fuel economy.

[e] NN = not needed.

improvement of 25% by SIDI engines over conventional gasoline engines (Stodolsky et al. 1999; results from the mini-Delphi survey at Argonne). We further assume that these vehicles will meet the proposed Tier 2 standards. Argonne's recent engine testing results (Cole et al. 1999) show that exhaust particulate emissions from SIDI engines fueled by gasoline could be higher than those of conventional SI engines fueled by gasoline. We assume a 40% increase in particulate emissions for SIDI engines fueled by gasoline. We used conventional SI engines for the incremental scenario and SIDI engines for the leap-forward scenario.

For SIDI engine applications in HEV configuration (SIDI hybrid in Table 4.4), we present assumptions for both scenarios: the smaller improvements represent the incremental scenario, and the larger improvements represent the leap-forward scenario. The 50% improvement in fuel economy by a gasoline SIDI hybrid under the incremental scenario is based on actual results from the Toyota Prius and Honda Insight and results presented in Stodolsky et al. (1999). For example, Honda's Insight has a fuel economy rating of 65 miles per gallon (mpg) under the 55/45 combined cycle, while a Geo Metro (1-liter engine, manual transmission) has a rated fuel economy of 42 mpg (EPA and DOE 1999). The Insight has a 55% better fuel economy rating than the Metro. The 95% improvement assumed in the leap-forward scenario is based on Stodolsky et al. (1999) and results published in Vyas et al. (1997).

We assume that HEVs will be operated without charging from the electric grid. Emission changes for the gasoline SIDI hybrid are assumed to be similar to those for gasoline SIDI stand-alone applications. Similarly, assumptions were made for methanol-fueled SIDI technologies (both stand-alone and hybrid applications) and for SI hybrids fueled with gaseous fuels.

For H_2 FCVs, the assumed fuel economy improvement of 180% over CG vehicles under the incremental scenario is based on an FCV modeling study conducted at Argonne (Doss et al. 1998), results in Vyas et al. (1997), and Stodolsky et al. (1999). The assumed improvement of 215% under the leap-forward scenario is from Stodolsky et al. (1999) and simulations conducted by Pentastar Electronics, Inc. (1997) and Directed Technologies, Inc. (Thomas et al. 1998; Oei et al. 1997a,b).

For FCVs fueled with RFG, fuel economy changes are based on results presented in Stodolsky et al. (1999), simulations by Directed Technologies, Inc. (Oei et al. 1997a,b; Thomas et al. 1998), and results from the mini-Delphi survey at Argonne. Emission changes are based on our assessments. For FCVs fueled with CNG, LNG, and LPG, we assume the same fuel economy changes as those for FCVs fueled with gasoline. We assume better fuel economy for methanol-fueled FCVs than for gasoline-fueled FCVs.

For EVs, fuel economy changes are based on simulations by Argonne and other organizations and potential advancements in battery technologies over time.

We assume gasoline-equivalent fuel economy changes for CIDI engines in stand-alone applications to be 35% under the incremental scenario and 50% under the leap-forward scenario. These assumptions are based on Stodolsky et al. (1999), results for the Volkswagon Passat vehicle, and results from the mini-Delphi survey at Argonne. For CIDI engines in hybrid applications, we assume a fuel economy improvement of 95% for the incremental scenario and

130% for the leap-forward scenario. These assumptions are based on Stodolsky et al. (1999) and results from the mini-Delphi survey at Argonne. Emission changes for CIDI hybrid applications are the same as those for CIDI stand-alone applications.

Vehicle emissions of SO_x and CO_2 for each vehicle type are calculated within the GREET model. SO_x emissions are calculated in GREET by assuming that all sulfur contained in a given fuel is converted into SO_2, except in FCVs; in FCVs, sulfur in a fuel is assumed to become solid waste, rather than air pollutant emissions. CO_2 emissions are calculated by using the carbon-balance approach; that is, all carbon contained in a given fuel minus carbon in VOCs, CO, and CH_4 emissions is converted into CO_2. For SO_x and CO_2 emission calculations, the sulfur and carbon contents of each fuel are needed. Table 4.5 presents the fuel specifications used in this study.

Table 4.5 Fuel Specifications

Fuel	Low Heating Value (Btu/gal)	Fuel Density (g/gal)	Carbon Weight (percent of total weight)	Sulfur Weight (ppm, by weight)
CG	115,500	2,791	85.5	200
RFG	112,300	2,795	82.9	30
CD	128,500	3,240	87.0	250
RFD	128,000	3,240	87.0	50
Methanol	57,000	2,996	37.5	0
LPG	84,000	2,000	82.0	0
LNG	72,900	1,589	74.0	0
DME	68,180	2,502	52.2	0
DMM	72,200	3,255	47.4	0
FTD	118,800	2,915	86.0	0
LH_2	30,100	263	0	0
NG	928[a]	20.5[a]	73.8	7
GH_2	274[a]	2.4[a]	0	0

[a] Values are per ft^3.

Section 5

Fuel-Cycle Energy and Emissions Results

As discussed in Section 4, we have established two scenarios for our study: an incremental technology improvement scenario and a leap-forward technology improvement scenario. We simulated the two scenarios for each technology option to cover the range of changes in energy use and emissions. Just as the assumptions regarding vehicle technologies are different for each of the two scenarios (Table 4.4), the key parameters for upstream fuel production activities also differ between the two scenarios. Table 5.1 presents upstream assumptions for each scenario.

The parametric assumptions listed in Table 5.1 are discussed in detail in Section 3. In general, we assume improvements in energy efficiencies for fuel production and processing from the incremental scenario to the leap-forward scenario. In central H_2 or FTD plants, a significant amount of steam can be coproduced with H_2 or FTD. Because we expect that GH_2 plants will be built in North America, we assume that (1) the coproduced steam can be used by nearby plants and (2) the exported steam will displace steam generation in steam boilers that have an efficiency of 80%.

Because we expect that FTD plants will be located outside of North America, we assume that (1) other plants may not be located close enough to use the steam generated by FTD plants, (2) the steam coproduced in these plants will be used to generate electricity that can be exported to the electric grid, and (3) the exported electricity will displace electricity generated by NG-fired combined-cycle turbines.

A large amount of electricity is required for H_2 liquefaction in LH_2 plants. We assume that the cogenerated steam in LH_2 plants will be used to generate electricity for use in the plant. Because the amount of electricity from the steam is far less than the amount required for H_2 liquefaction, we assume the remaining required electricity will be provided by NG-fired combined-cycle units.

Even if it is feasible to coproduce steam and electricity in H_2 and FTD plants, because of capital investment requirements and the limited infrastructure available to export steam or electricity, not all H_2 or FTD plants will be designed to coproduce steam or electricity. We assume that only 50% of GH_2 plants and FTD plants will coproduce steam or electricity for export; the remaining 50% will not.

Because flaring of gas usually occurs in remote areas where gas is cheap and abundant, there are no great incentives to install efficient fuel production technologies. So we assume lower energy efficiency to produce the same fuel from FG than from NG. On the basis of the assumptions presented in Section 4 and in Table 5.1, we calculated full fuel-cycle, per-mile energy use and emissions for each combination of fuels and vehicle technologies (see Tables 4.1 and 4.2). We then estimated per-mile energy and emissions changes of the

Table 5.1 Upstream Assumptions for the Incremental and Leap-Forward Scenarios

	Incremental Scenario		Leap-Forward Scenario	
Upstream Activity	**Energy Efficiency (percent)[a]**	**Steam Production (Btu/million Btu fuel)**	**Energy Efficiency (percent)[a]**	**Steam Production (Btu/million Btu fuel)**
NG to CNG: NG Compression				
Electric Compressors	96.6	NA[b]	97.0	NA
NG Compressors	91.7	NA	92.7	NA
NG to LNG: NG Liquefaction	90	NA	90	NA
NG to LPG: LPG Production	96.5	NA	96.5	NA
NG to electricity: Combined Cycle	56	NA	60	NA
NG to MeOH: MeOH Production	67	0	70	0
NG to GH_2: Central Plants				
Without Steam Coproduction	73	0	73	0
With Steam Coproduction	71	169,000[c]	71	169,000[c]
NG to GH_2: Refueling Stations	70	0	70	0
GH_2 Compression:				
Electric Compressors	90	NA	90	NA
NG Compressors	77	NA	79	NA
NG to LH_2:				
Without Steam Coproduction	73	0	73	0
With Steam Coproduction	71	169,000[d]	71	169,000[d]
H_2 Liquefaction	65	NA	70	NA
NG to DME: DME Production	69	0	70	0
NG to FTD: FTD Production				
Without Steam Coproduction	57	0	57	0
With Steam Coproduction	49	347,000[e]	49	347,000[e]
FG to LNG: NG Liquefaction	88	NA	88	NA
FG to MeOH: MeOH Production	65	0	67	0
FG to LH_2				
GH_2 Production	70	0	72	0
H_2 Liquefaction	63	NA	65	NA
FG to DME: DME Production	68	0	69	0
FG to FTD: FTD Production	55	0	57	0

[a] Energy efficiency here does not include Btu embedded in the steam generated from a process. In our analysis, we assume the cogenerated steam in H_2 and FTD plants will be exported to nearby plants (GH_2 plants) or be used to generate electricity for export to the electric grid (FTD plants). Energy and emissions credits for the coproduced steam or electricity are taken into account in the GREET model.

[b] NA = not applicable.

[c] Steam from GH_2 plants is assumed to be exported to nearby plants.

[d] Steam from LH_2 plants is assumed to be used to generate electricity for use during H_2 liquefaction.

[e] Steam from FTD plants is assumed to be used to generate electricity for export to the electric grid.

technology options relative to energy use and emissions of conventional SI engines fueled with CG (for near-term technology options) and with RFG (for long-term technology options). In this section, we graphically present per-mile energy use and emissions changes (Figures 5.1–5.60) and discuss key results. Per-mile energy use and emissions rates for each technology option are presented in Appendix A. Appendix B provides the energy and emissions change data used to produce the graphs.

5.1 Total Energy Use Changes

Total energy use includes energy contained in all energy sources (non-renewable and renewable). Figures 5.1 through 5.4 present per-mile changes in total energy use. The first figure presents the results for the three near-term technology options; the second for the sixteen long-term SI engine technology options; the third for the ten long-term CI engine technology options; and the fourth for the twelve long-term FCV and EV technology options. For each option, a bar in the figure represents the range of changes in total energy use. The right end of the bar shows the result for the incremental scenario; the left end shows the result for the leap-forward scenario. So the bar for each technology represents the range of energy use or emission changes for the two scenarios established in this study. This format is used for all the figures presented Section 5.

As shown in Table 4.4, use of M85 flexible-fuel vehicles (FFVs) causes a 16–22% increase in total energy use because of the large energy loss during methanol production. Use of CNG could result in increased total energy use under the incremental scenario because of the 7% fuel economy penalty we assumed for CNGVs relative to GVs under that scenario. Use of LPGVs results in about a 10% reduction in total energy use.

For the sixteen long-term SI engine technology options, the increased total energy use by dedicated M90 vehicles is again caused by a large methanol production energy loss. The greater-than-75% reduction in energy use by both M90 and LNG produced from FG is attributable to the fact that the energy contained in FG is not accounted for because the gas is flared rather than used as an energy source. Large reductions by SIDI hybrid options are attributable to the larger fuel economy gains of these vehicle technologies.

For the ten long-term CI engine options, the increased total energy use by FTD produced from NG is caused by a large energy conversion loss in FTD plants. Despite the large fuel economy gains by CIDI engines, the reductions achieved by DME produced from NG are small because of the large amount of energy lost during DME production. The huge reductions by FTD and DME produced from FG are because energy in FG feedstock is not accounted for here.

For the twelve FCV and EV options, the reductions for NG-based fuels are only moderate despite large vehicle fuel economy gains because of the energy lost during fuel production. The huge reduction by FCVs fueled by LH_2, methanol, and LNG made from FG is again because we do not account for the energy in FG feedstock.

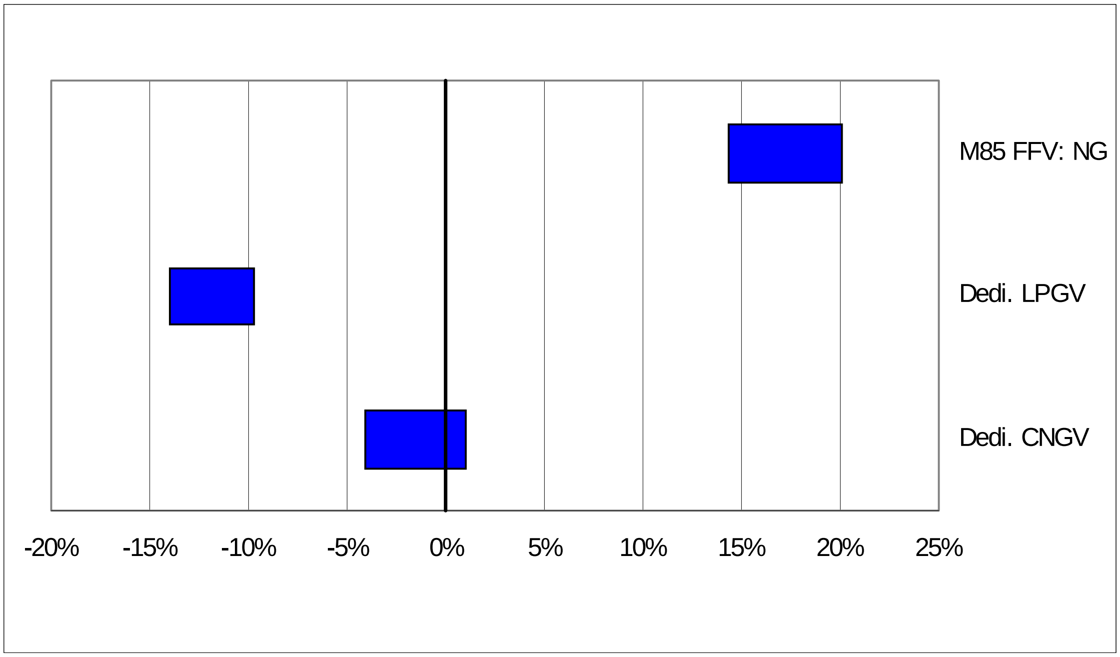

Figure 5.1 Near-Term Technologies: Total Energy Use Changes (relative to baseline GV fueled with CG)

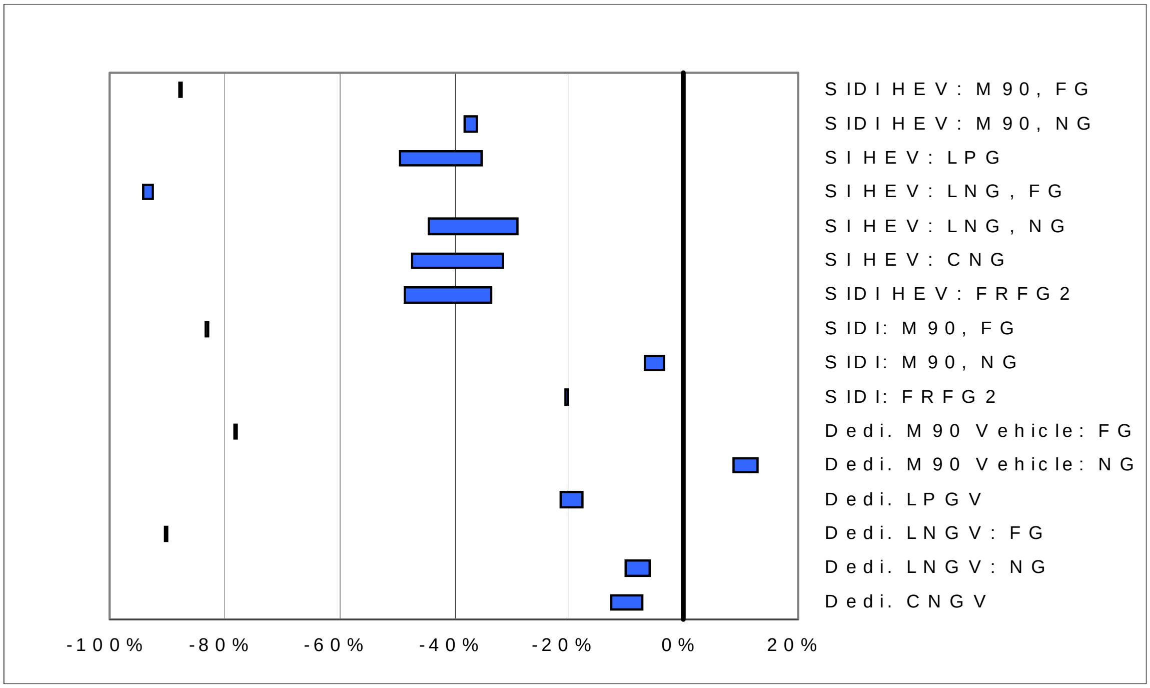

Figure 5.2 Long-Term SI Engine Technologies: Total Energy Use Changes (relative to baseline GV fueled with RFG)

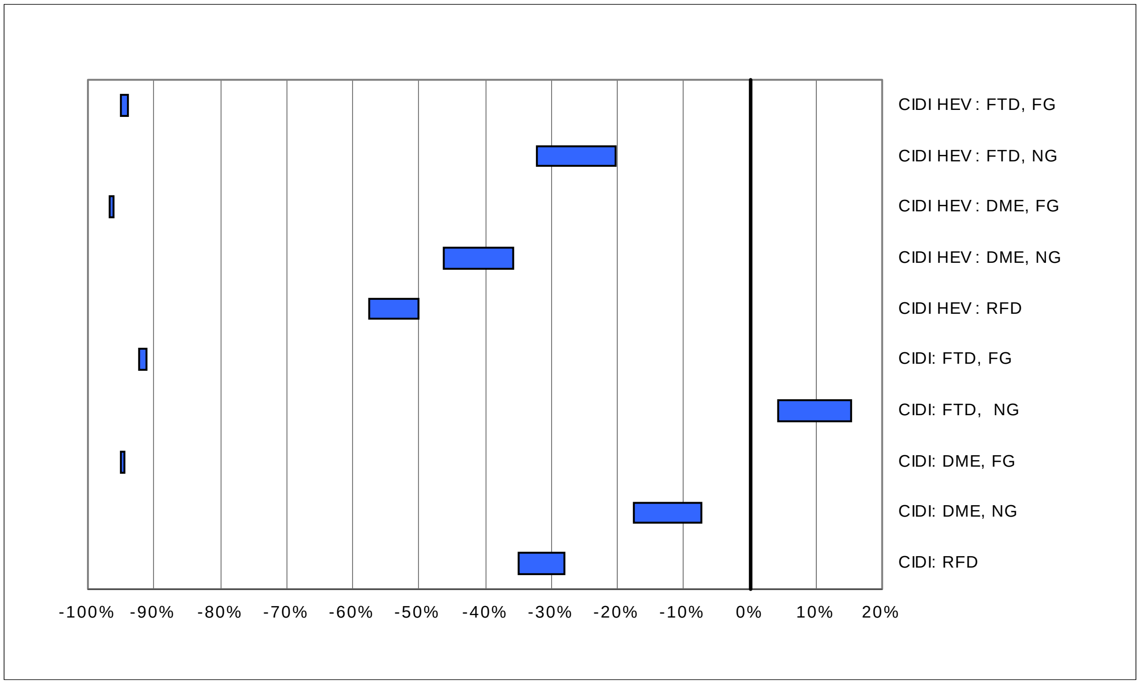

Figure 5.3 Long-Term CI Engine Technologies: Total Energy Use Changes (relative to baseline GV fueled with RFG)

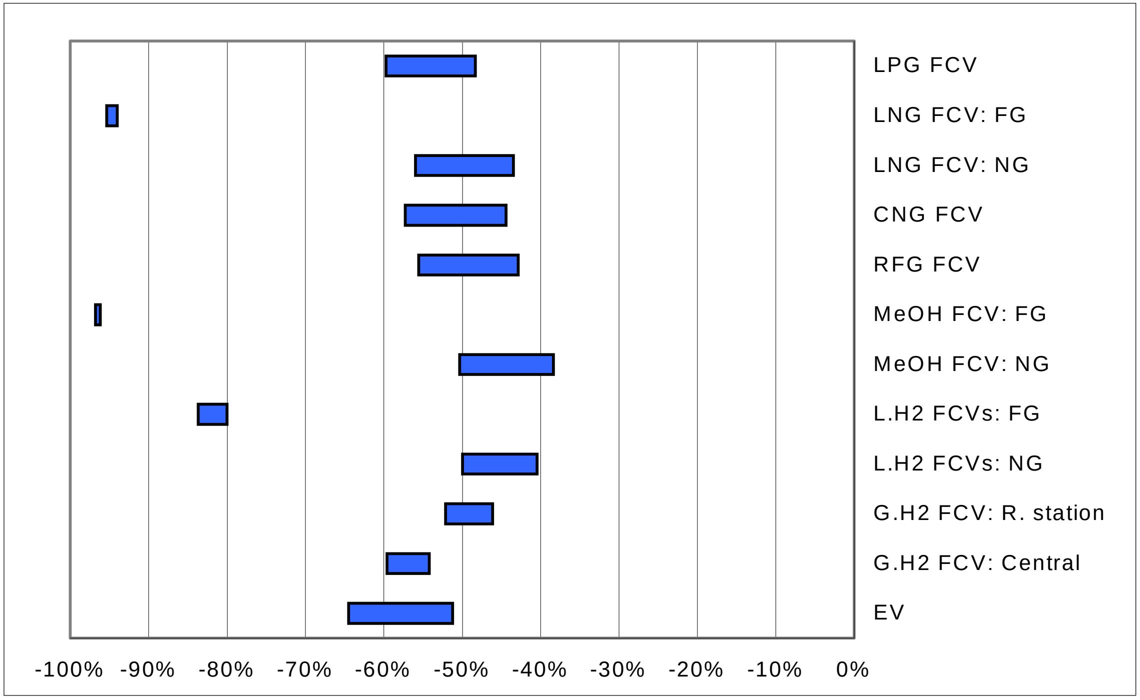

Figure 5.4 Long-Term EV and FCV Technologies: Total Energy Use Changes (relative to baseline GV fueled with RFG)

5.2 Fossil Energy Use

Figures 5.5 through 5.8 present changes in fossil energy use by technology option. Fossil energy use includes use of petroleum, NG, and coal. Changes in fossil energy use are similar to changes in total energy use. Because FG is not treated as a fossil energy source, use of methanol, LH_2, LNG, DME, and FTD produced from FG results in huge reductions in fossil energy use.

5.3 Petroleum Use

Figures 5.9 through 5.12 show changes in petroleum use. All fuel options except M85, M90, gasoline, and petroleum diesel achieve a nearly 100% reduction in petroleum use. Use of M85 and M90 in conventional SI engines and SIDI engines results in lower reductions because the fuels contain 15% and 10% gasoline, respectively. Small, but positive, reductions by vehicle technologies using RFG or RFD are attributable to improved vehicle fuel economy.

5.4 Greenhouse Gas Emissions

Figures 5.13 through 5.16 present CO_2-equivalent emissions of the three GHGs (CO_2, CH_4, and N_2O), which are weighted together with GWP factors. For the three near-term options, the use of M85 results in small increases in GHG emissions because production of methanol generates a large amount of CO_2 emissions and because improvements in fuel economy for M85 FFVs are limited (0–5% increase relative to baseline GVs). On the other hand, use of CNGVs and LPGVs results in 10–15% reductions in GHG emissions.

For the long-term SI engine options, GHG emission reductions vary significantly among fuels and vehicle technologies. Dedicated M90 vehicles fueled with methanol produced from NG achieve the smallest reductions because of the large amount of CO_2 emissions released during methanol production. CNGVs, LNGVs, LPGVs, and SIDI engine technologies fueled by RFG and M90 achieve 20–25% reductions. Reductions for the first three options are attributable to upstream reductions and moderate fuel economy improvements. The reductions for the two SIDI options are attributable to significant improvements in fuel economy (25% better than baseline GVs). GHG emission reductions for HEV options increase to 35–55% because of the large improvements in vehicle fuel economy. Use of LNG and M90 produced from FG helps increase GHG emission reductions to above 80% because CO_2 emissions from gas flaring during production of these fuels are eliminated. The eliminated CO_2 emissions are credited to the FG-based fuel options.

For the ten CIDI engine options, use of FTD produced from NG achieves small GHG emission reductions. In fact, GHG emissions for FTD are higher than those for RFD because of a large energy loss (and consequently a large amount of CO_2 emissions) during FTD production. GHG emission reductions for DME, on the other hand, are comparable to those for RFD. Overall, use of CIDI engine technologies fueled with petroleum diesel, FTD, and DME results in large GHG emission reductions. Use of FTD and DME produced from FG results in greater than 90% reductions in GHG emissions because of CO_2 emission credits from elimination of gas flaring.

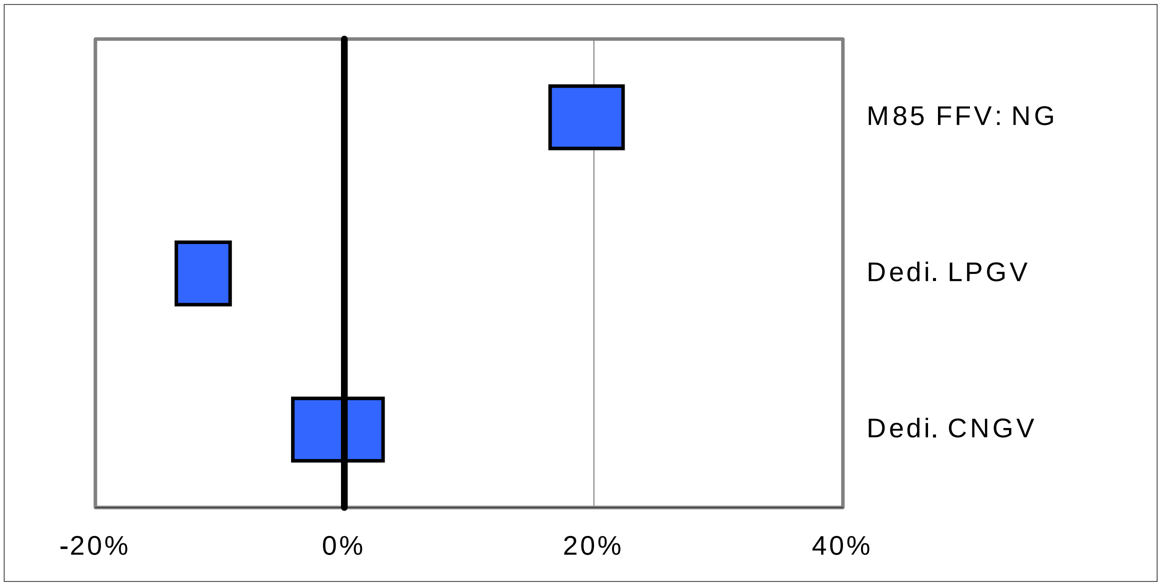

Figure 5.5 Near-Term Technologies: Fossil Fuel Use Changes (relative to baseline GV fueled with CG)

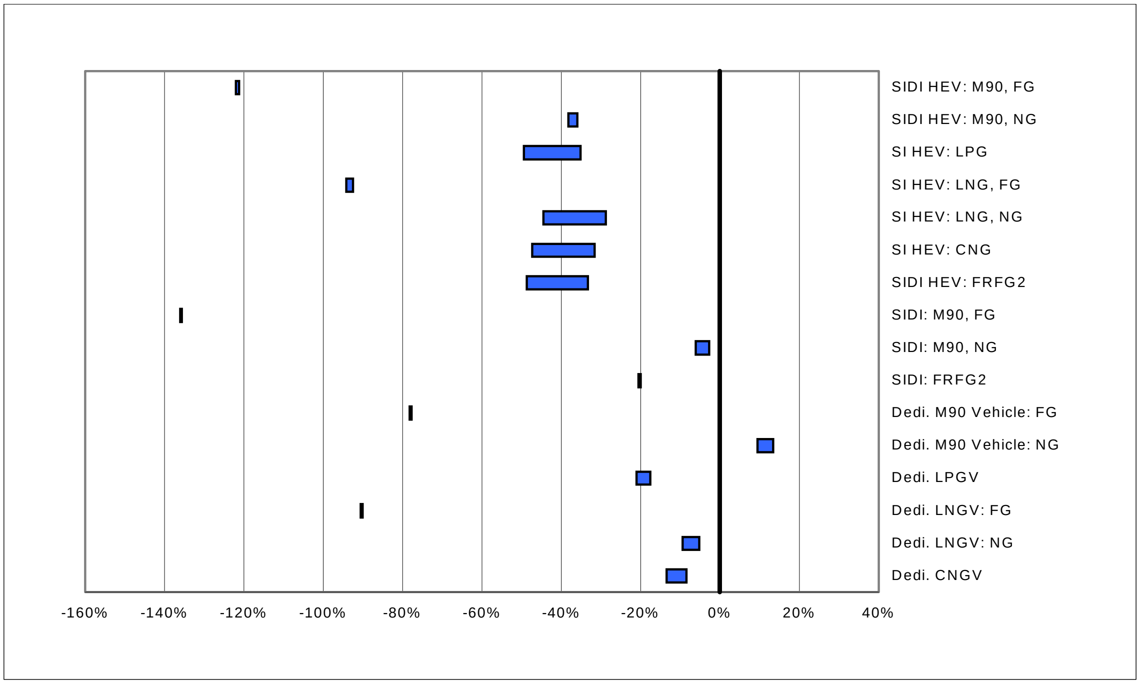

Figure 5.6 Long-Term SI Engine Technologies: Fossil Fuel Use Changes (relative to baseline GV fueled with RFG)

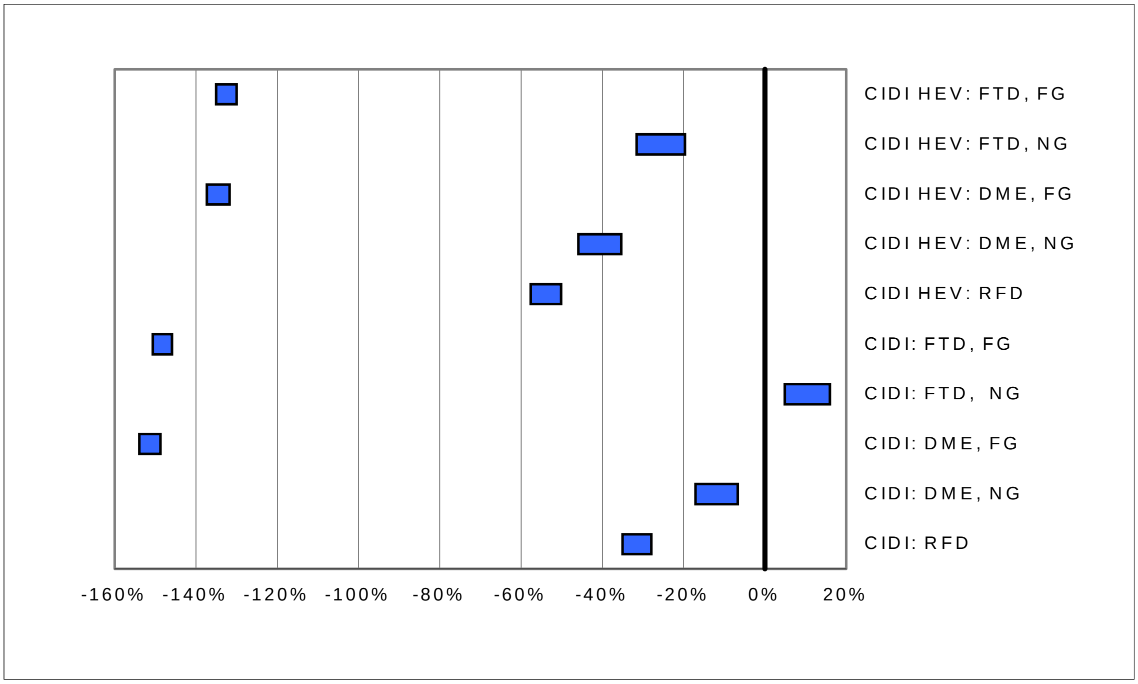

Figure 5.7 Long-Term CI Engine Technologies: Fossil Fuel Use Changes (relative to baseline GV fueled with RFG)

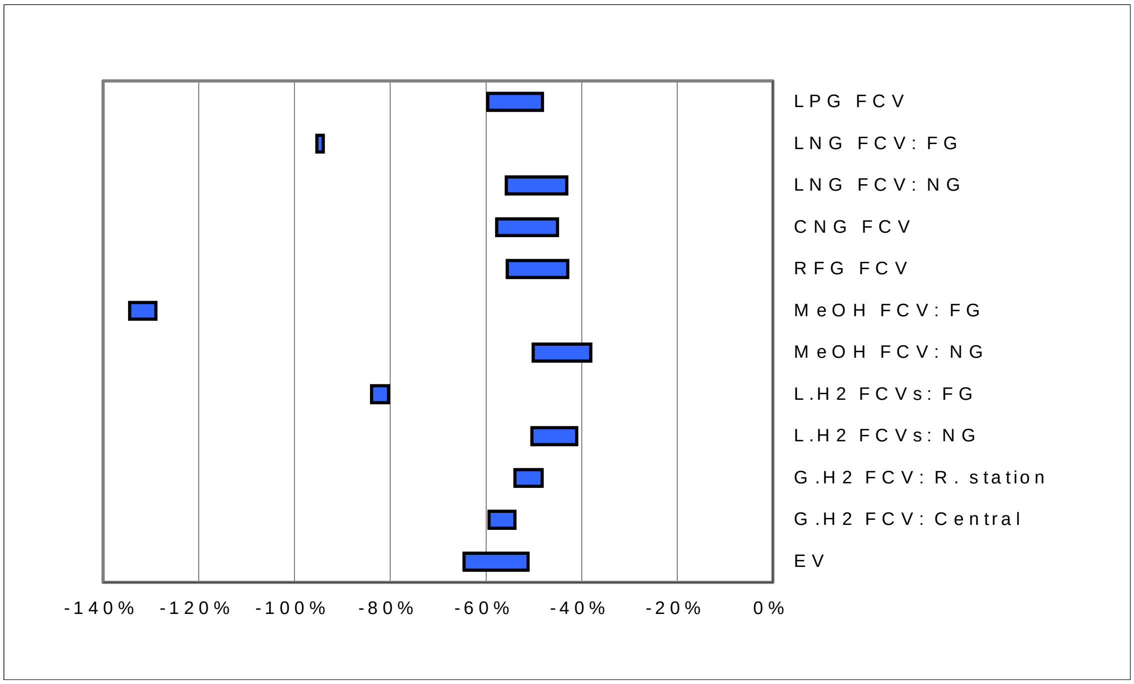

Figure 5.8 Long-Term EV and FCV Technologies: Fossil Fuel Use Changes (relative to baseline GV fueled with RFG)

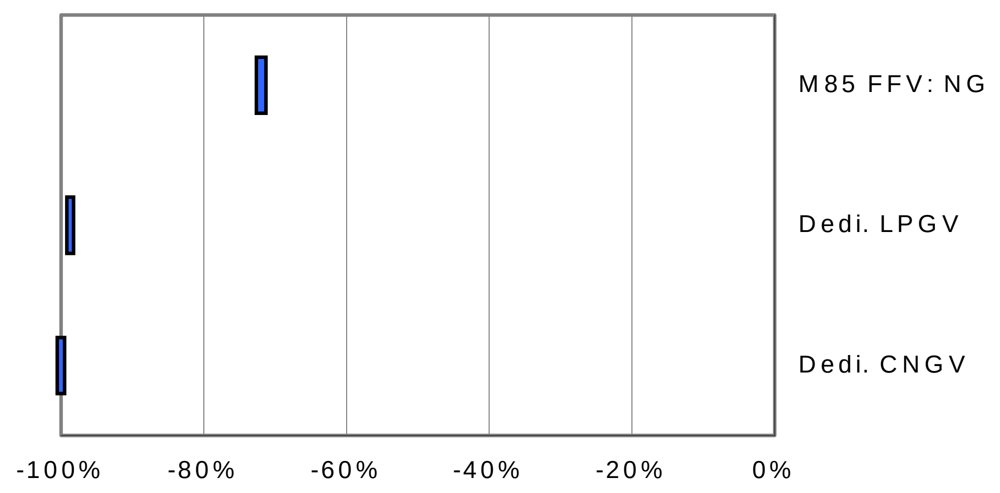

Figure 5.9 Near-Term Technologies: Petroleum Use Changes (relative to baseline GV fueled with CG)

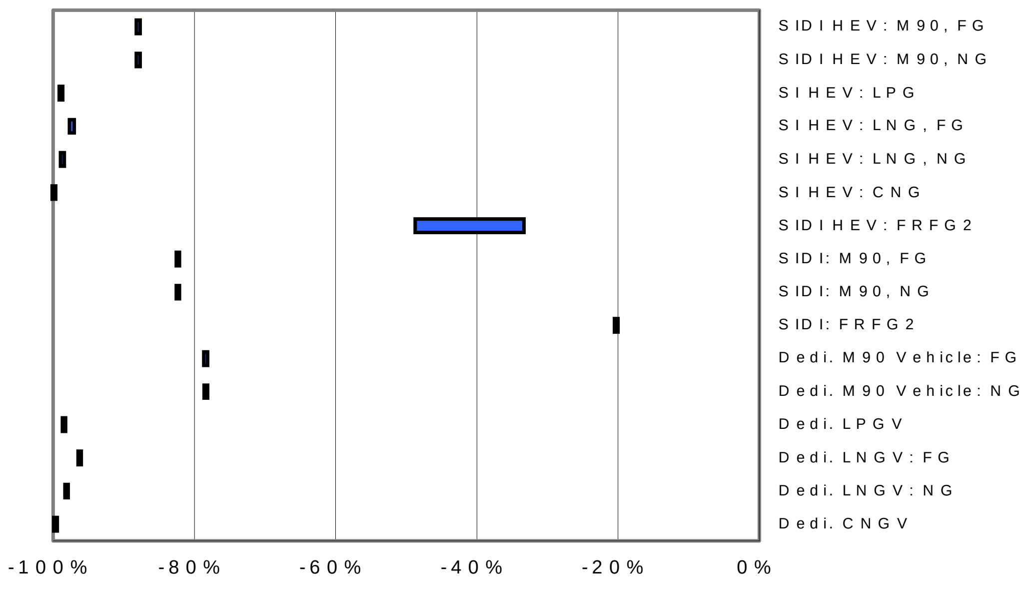

Figure 5.10 Long-Term SI Engine Technologies: Petroleum Use Changes (relative to baseline GV fueled with RFG)

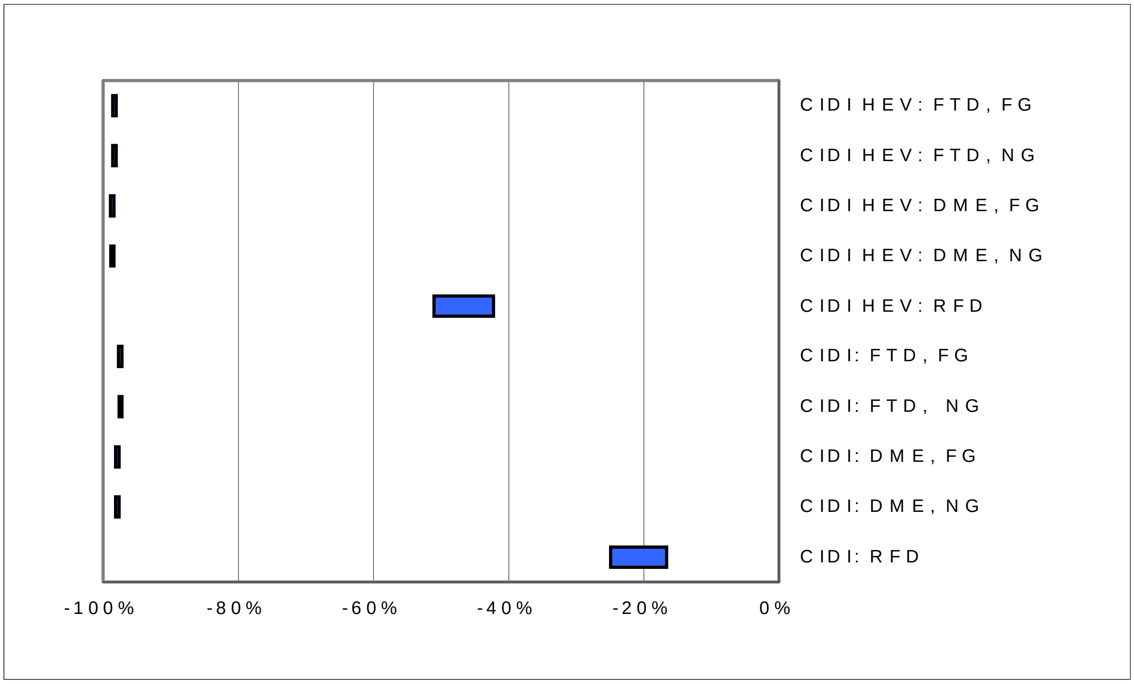

Figure 5.11 Long-Term CI Engine Technologies: Petroleum Use Changes (relative to baseline GV fueled with RFG)

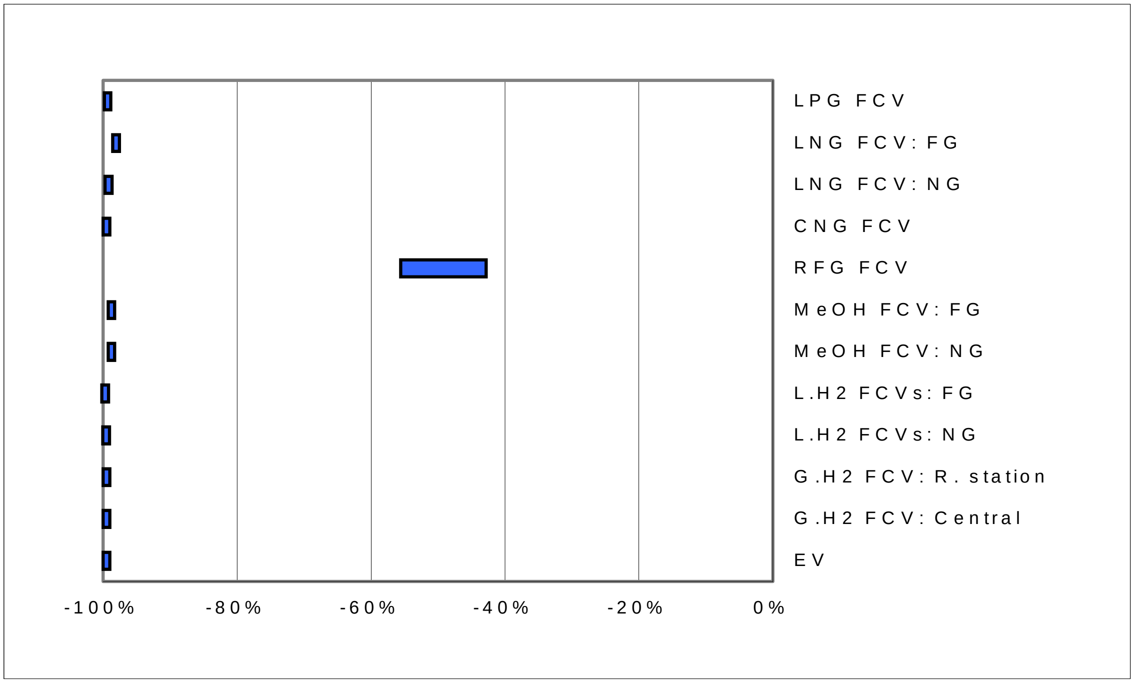

Figure 5.12 Long-Term EV and FCV Technologies: Petroleum Use Changes (relative to baseline GV fueled with RFG)

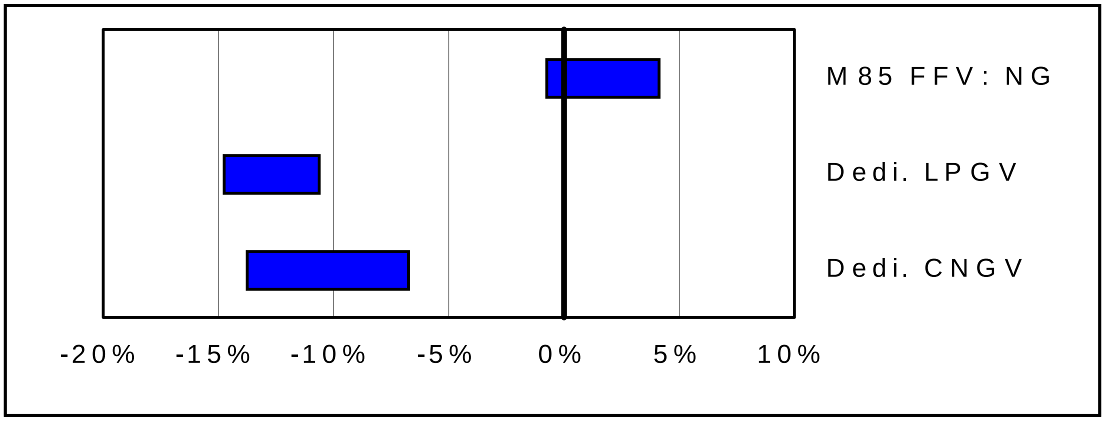

Figure 5.13 Near-Term Technologies: GHG Emission Changes (relative to baseline GV fueled with CG)

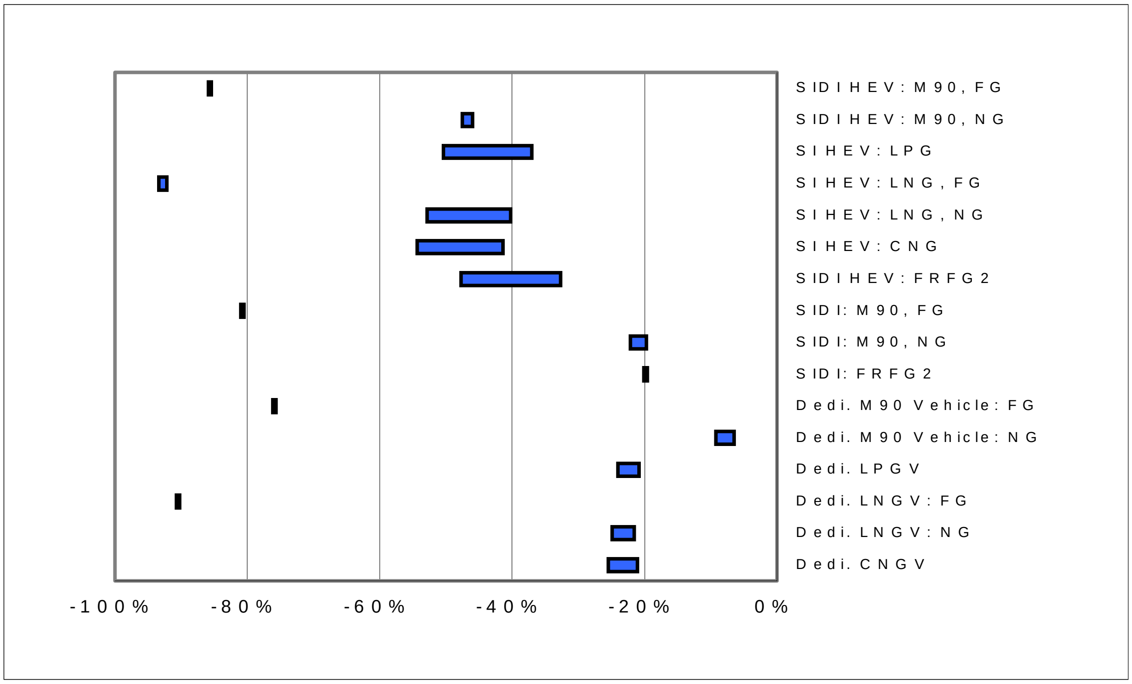

Figure 5.14 Long-Term SI Engine Technologies: GHG Emission Changes (relative to baseline GV fueled with RFG)

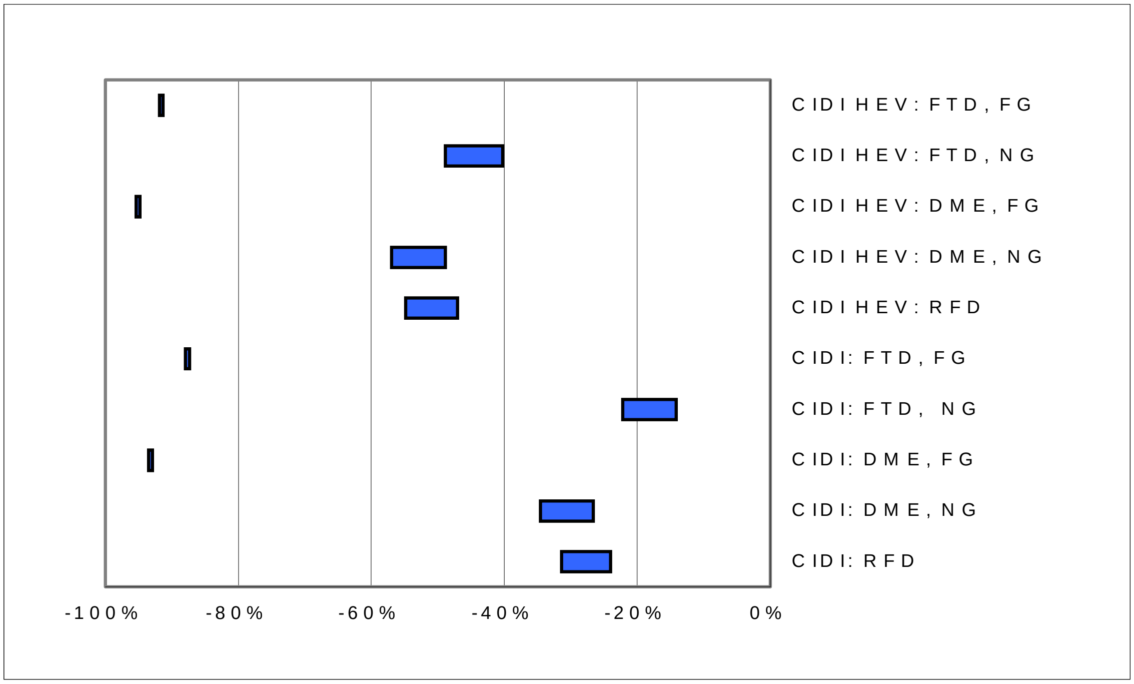

Figure 5.15 Long-Term CI Engine Technologies: GHG Emission Changes (relative to baseline GV fueled with RFG)

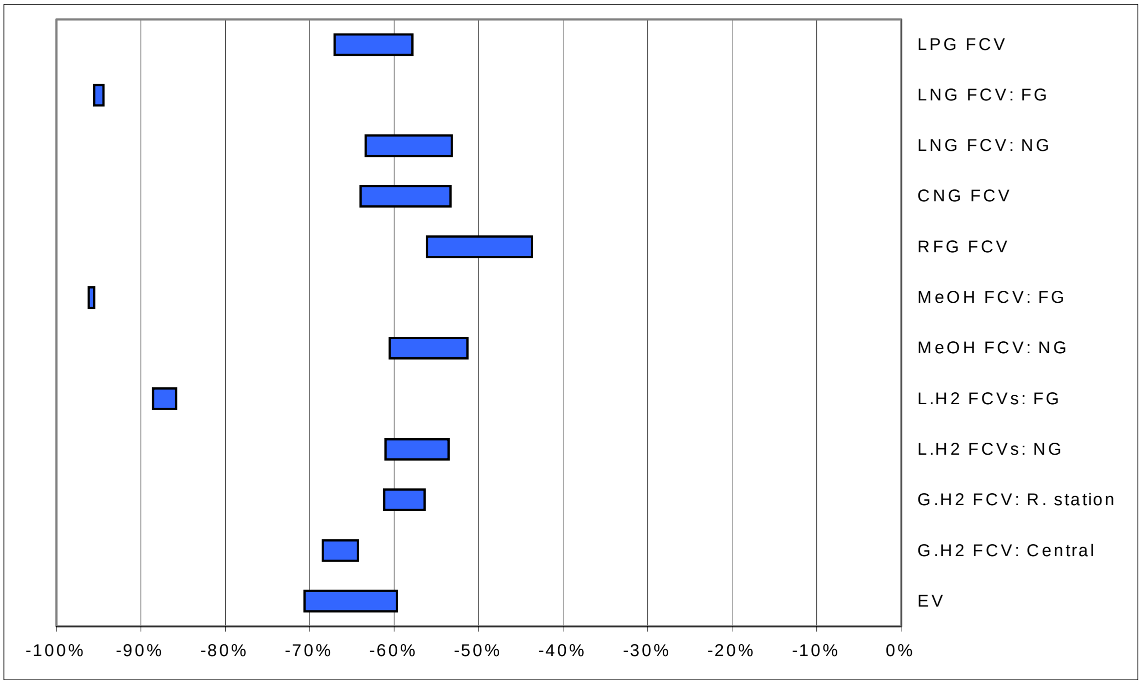

Figure 5.16 Long-Term EV and FCV Technologies: GHG Emission Changes (relative to baseline GV fueled with RFG)

For the FCV and EV options, use of EVs fueled with electricity generated by NG-fired combined-cycle turbines results in 60–70% reductions in GHG emissions because of the high energy conversion efficiency of combined-cycle turbine technology and the very high fuel economy of EVs. Use of FCVs fueled by GH_2, LH_2, methanol, CNG, LNG, and LPG results in 50–65% reductions in GHG emissions. Gasoline FCVs achieve 45–55% reductions. Use of FCVs powered by LH_2, methanol, and LNG from FG reduces GHG emissions by 85–95%.

5.5 CO_2 Emissions

Figures 5.17 through 5.20 show changes in emissions of CO_2 only. The patterns of CO_2 emission changes are similar to those of GHG emission changes. Because high CH_4 emissions are associated with NG-based pathways, emissions of GHGs are higher than emissions of CO_2 for NG-based fuels. Consequently, CO_2 emission reductions for NG-based pathways are a little larger than GHG emission reductions. Excluding CH_4 emissions from GHG emission calculations results in incorrectly high GHG emission reductions for NG-based fuels. Reductions in CO_2 emissions are presented here to demonstrate this finding; CO_2 emission results should not be used in comparing the GHG emissions associated with NG-based fuels and those associated with petroleum fuels.

5.6 Total VOC Emissions

Figures 5.21 through 5.24 present changes in total VOC emissions for each technology option. Total emissions for the five criteria pollutants (VOCs, CO, NO_x, PM_{10}, and SO_x) are emissions occurring in all stages and at all locations throughout a fuel cycle. In contrast, urban emissions for the five criteria pollutants are those occurring only within an urban area. Separating emissions for the five criteria pollutants by location is important because these pollutants are local or regional air pollution concerns. Researchers need to identify the location, as well as the amount, of these pollutants.

Urban emissions are estimated over the fuel cycle by considering the locations of upstream facilities (e.g., production facilities, distribution infrastructure, and refueling stations). In our analysis, we assume that fuel production facilities (e.g., methanol and H_2 plants) are generally located outside of urban areas. As stated in Section 3, many fuel production facilities are assumed to be located outside of North America. We also assume that a portion of the very last stage of distribution infrastructure (fuel distribution from bulk terminals to refueling stations), refueling at stations, and vehicle operations occur within urban areas. So our urban emission estimates are for a case in which new vehicle technologies are introduced into urban areas to help solve urban air pollution problems. Of course, new vehicle technologies will certainly be introduced in both urban and non-urban areas, but the non-urban case is not studied here for urban emissions estimates.

For the three near-term options, use of M85 offers only small reductions in total VOC emissions because it does not significantly reduce either tailpipe or vehicle evaporative emissions. The reductions achieved by CNG and LPG are more significant because these fuels almost eliminate evaporative emissions from the vehicles.

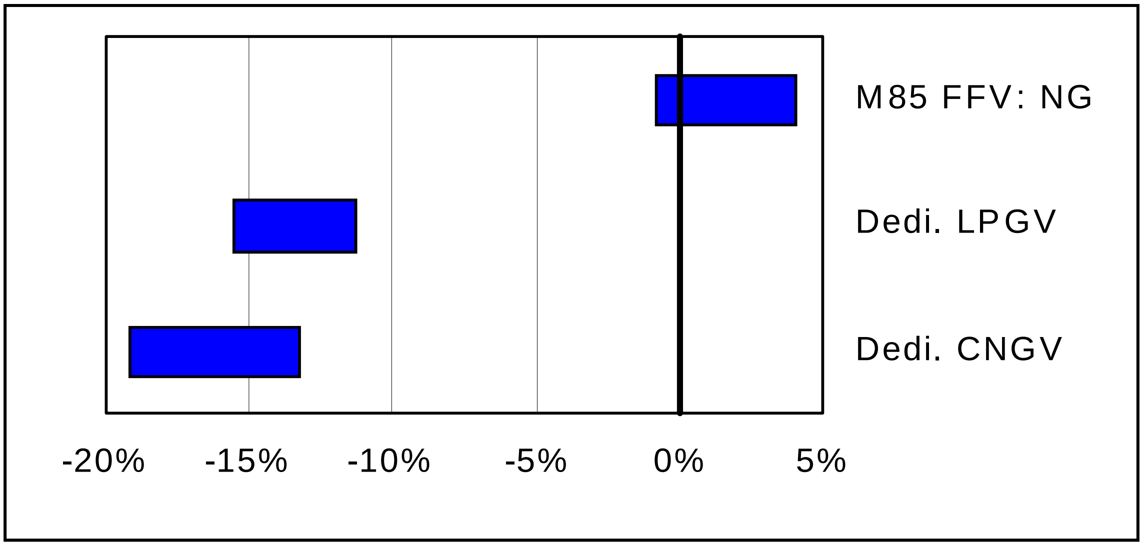

Figure 5.17 Near-Term Technologies: CO_2 Emission Changes (relative to baseline GV fueled with CG)

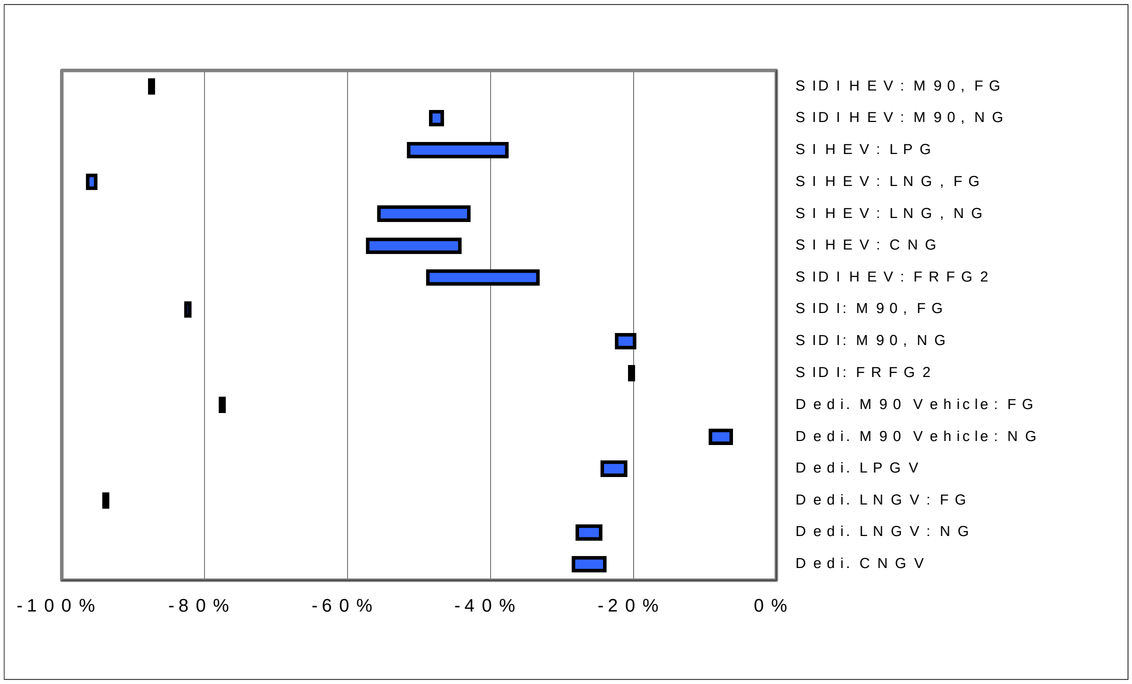

Figure 5.18 Long-Term SI Engine Technologies: CO_2 Emission Changes (relative to baseline GV fueled with RFG)

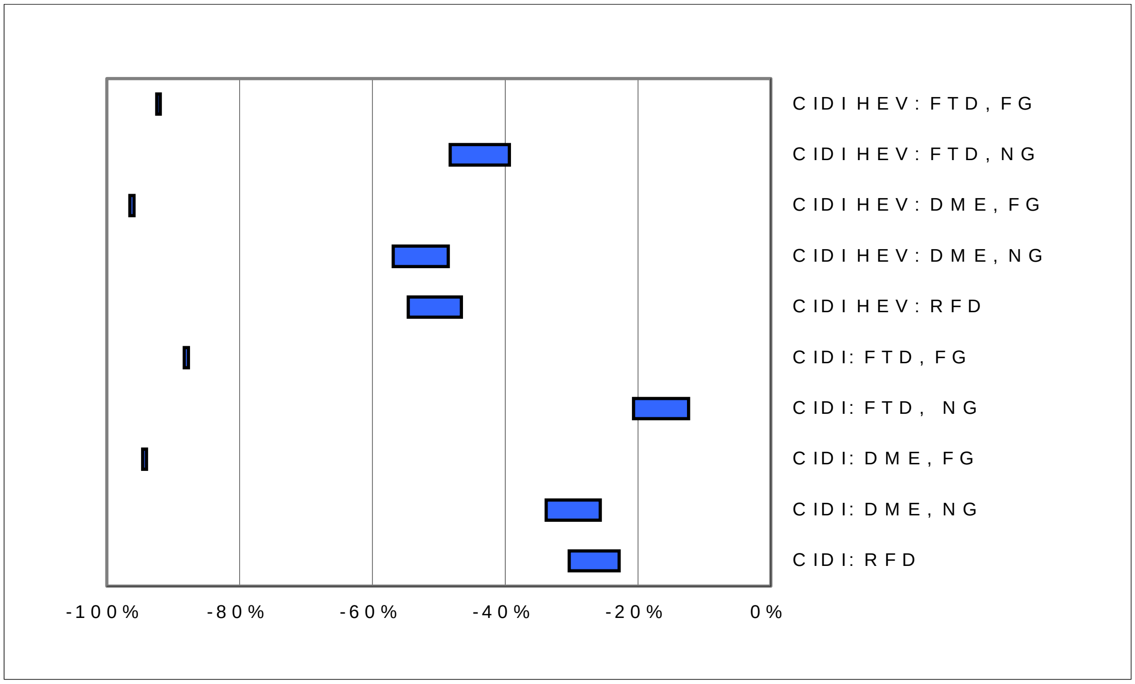

Figure 5.19 Long-Term CI Engine Technologies: CO_2 Emission Changes (relative to baseline GV fueled with CG)

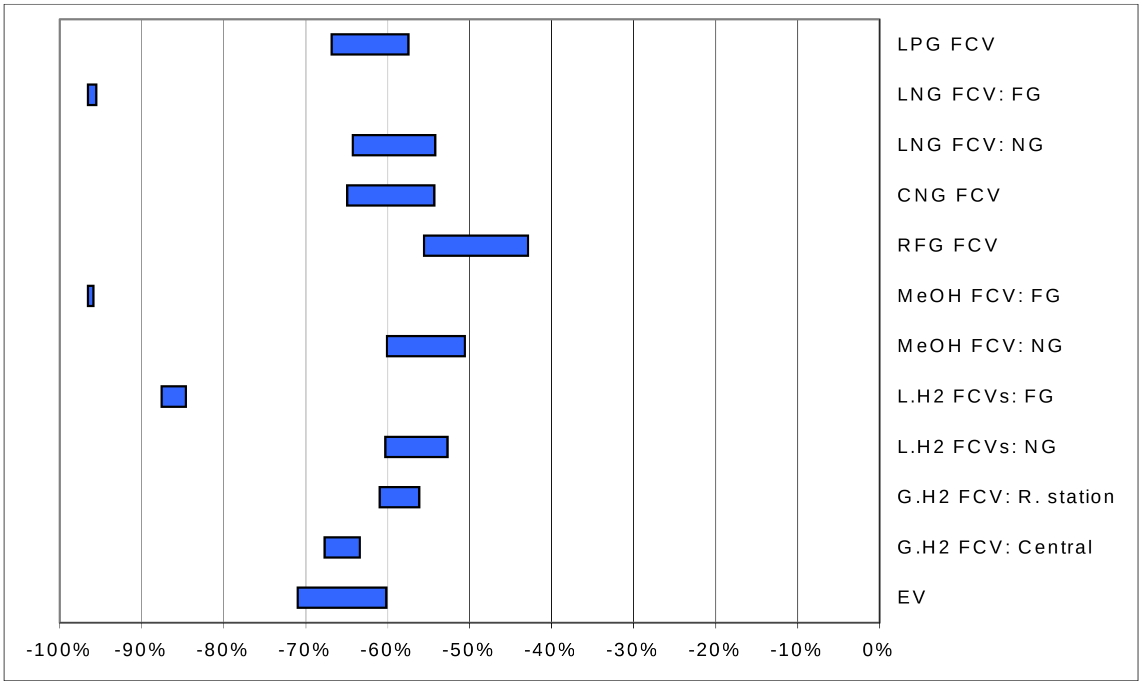

Figure 5.20 Long-Term EV and FCV Technologies: CO_2 Emission Changes (relative to baseline GV fueled with RFG)

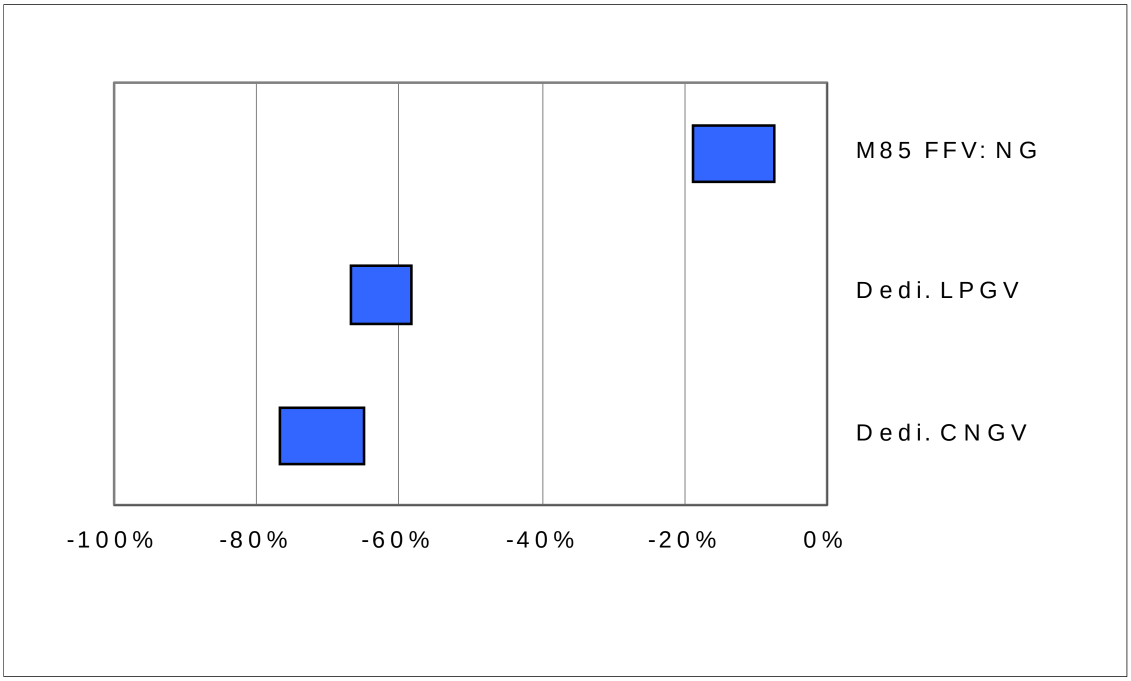

Figure 5.21 Near-Term Technologies: Total VOC Emission Changes (relative to baseline GV fueled with CG)

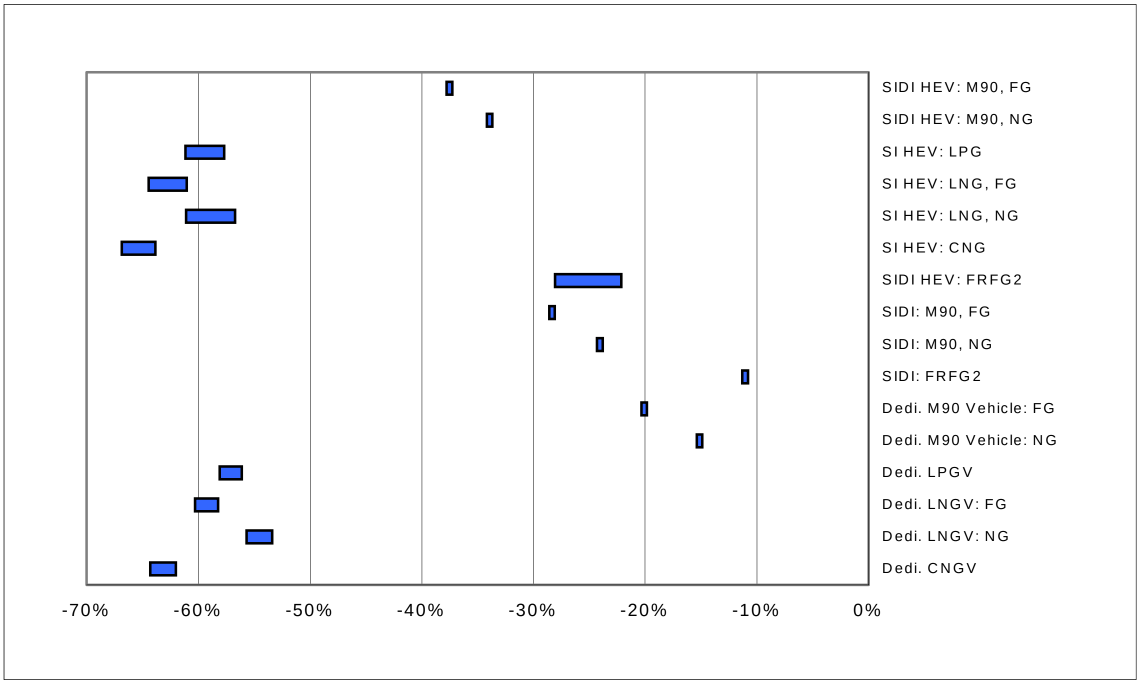

Figure 5.22 Long-Term SI Engine Technologies: Total VOC Emission Changes (relative to baseline GV fueled with RFG)

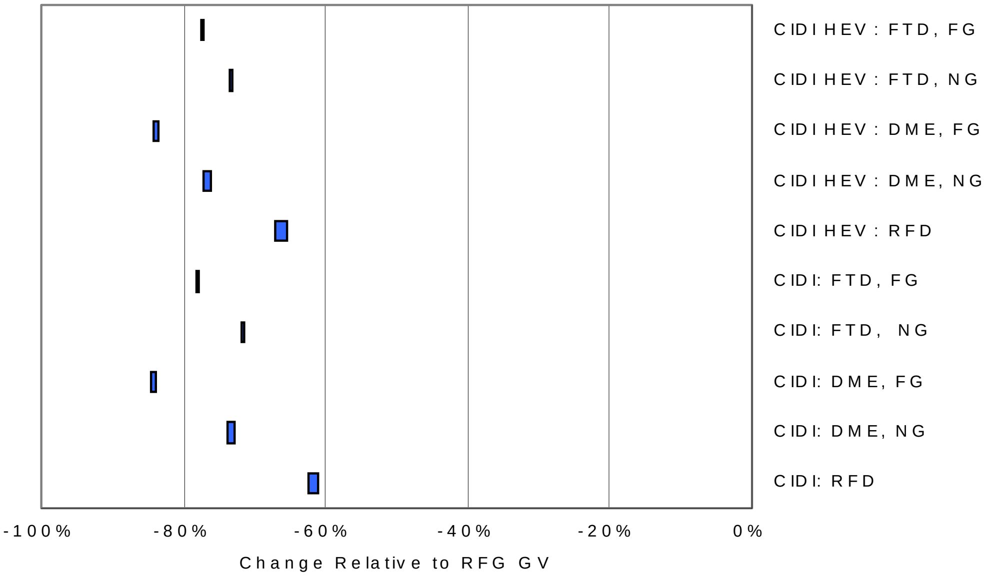

Figure 5.23 Long-Term CI Engine Technologies: Total VOC Emission Changes (relative to baseline GV fueled with RFG)

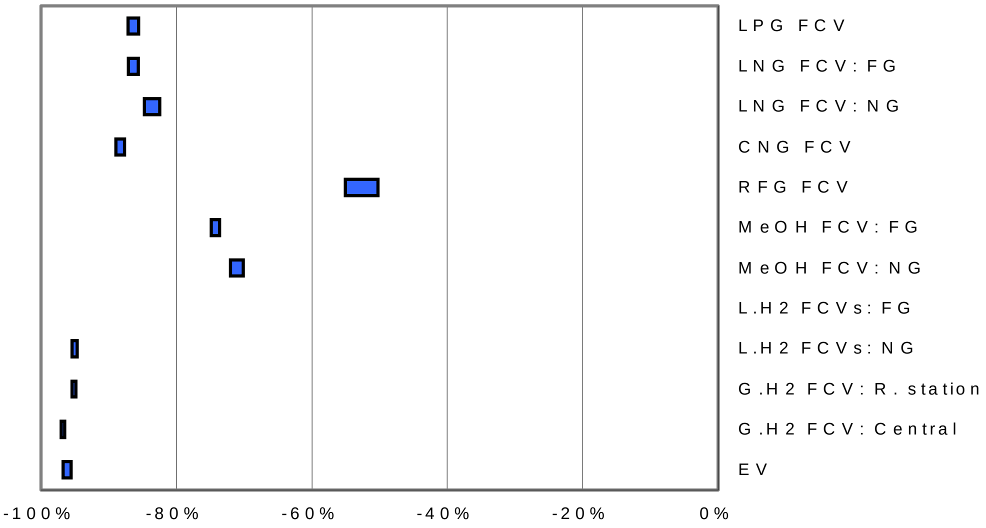

Figure 5.24 Long-Term EV and FCV Technologies: Total VOC Emission Changes (relative to baseline GV fueled with RFG)

For the long-term SI engine options, use of M90 in conventional SI engines, SIDI engines, and SIDI HEVs offers only moderate reductions in total VOCs. Use of RFG in SIDI engines and SIDI HEVs also offers only moderate reductions (attributable to improved fuel economy relative to conventional GVs) because these vehicle technologies still release a significant amount of evaporative emissions. VOC emission reductions achieved by using CNG, LNG, and LPG are higher than those associated with other technology options because these vehicles almost eliminate evaporative emissions.

All of the long-term CIDI engine options offer significant VOC emission reductions because CIDI engines have high fuel economy and zero evaporative emissions.

FCVs and EVs offer large VOC emissions reductions; reductions by EVs and FCVs fueled with GH_2 and LH_2 are greater than 95%. These vehicles generate no onboard VOC evaporative emissions. Gasoline- and methanol-fueled FCVs vehicles have relatively smaller VOC reductions because of the large amount of VOCs released during methanol production.

5.7 Urban VOC Emissions

Figures 5.25 through 5.28 show changes in urban VOC emissions. The patterns for urban VOC emissions are similar to those for total VOC emissions, which implies that vehicular VOC emissions, especially those from baseline vehicles, are the dominant source of VOC emissions.

5.8 Total CO Emissions

Figures 5.29 through 5.32 present changes in total CO emissions for each of the technology options. For the three near-term options, the range of emission reductions by CNGVs is about 20–50%. The range is wide because of the range of the assumptions regarding tailpipe CO emission reductions by CNGVs between the incremental scenario (20% reduction) and the leap-forward scenario (40% reduction). Reductions by LPGVs range from about 30% to more than 45%, and reductions by M85 FFVs from less than 20% to more than 35%.

For the sixteen long-term SI engine options, vehicles fueled with M90 and RFG show little change in CO emissions. SI engine vehicles fueled with CNG, LNG, and LPG achieve about 20–40% emission reductions because of lower tailpipe CO emissions from these vehicle types. Emission reductions by SI HEVs fueled with CNG, LNG, and LPG are around 40%.

For the ten long-term CI engine options, total CO emissions remain virtually the same as those for baseline GVs because we assume the same emissions for baseline GVs and CIDI engine technologies for the long-term technologies (see Tables 4.3 and 4.4) and because tailpipe CO emissions are the predominant source of CO emissions.

EVs and FCVs achieve 80–100% reductions in total CO emissions because these technologies eliminate the tailpipe emissions associated with conventional GVs. The 80% reductions by hydrocarbon fuels (around 80%) are lower than those by EVs and H_2 FCVs because of CO emissions during onboard fuel processing.

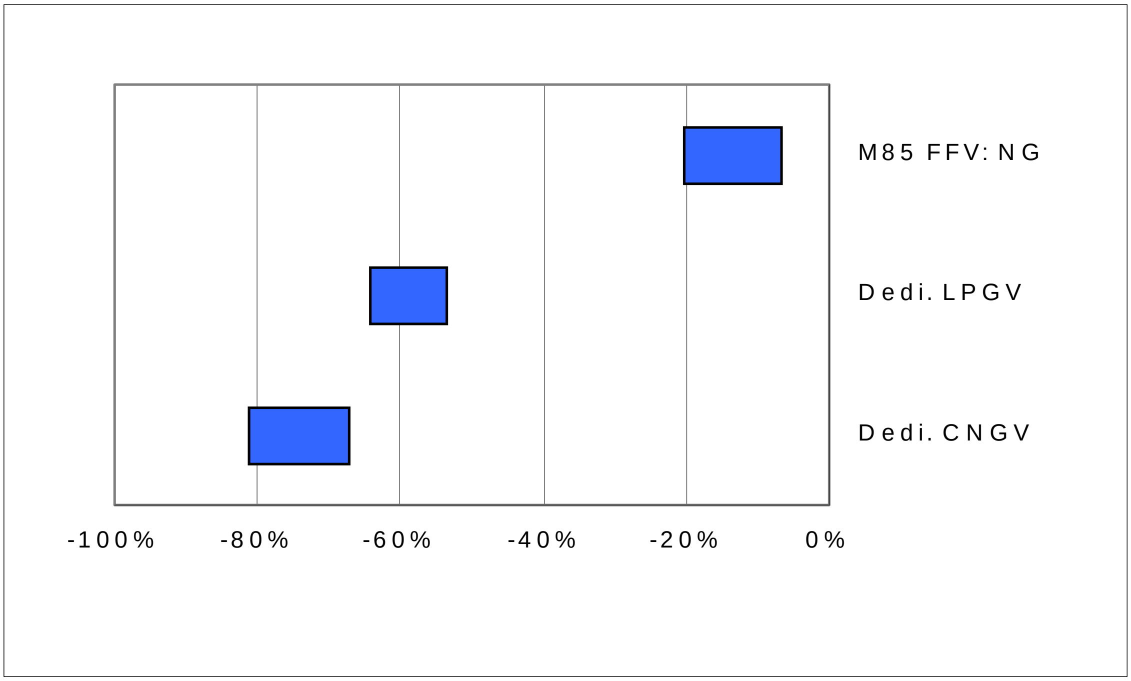

Figure 5.25 Near-Term Technologies: Urban VOC Emission Changes (relative to GV fueled with CG)

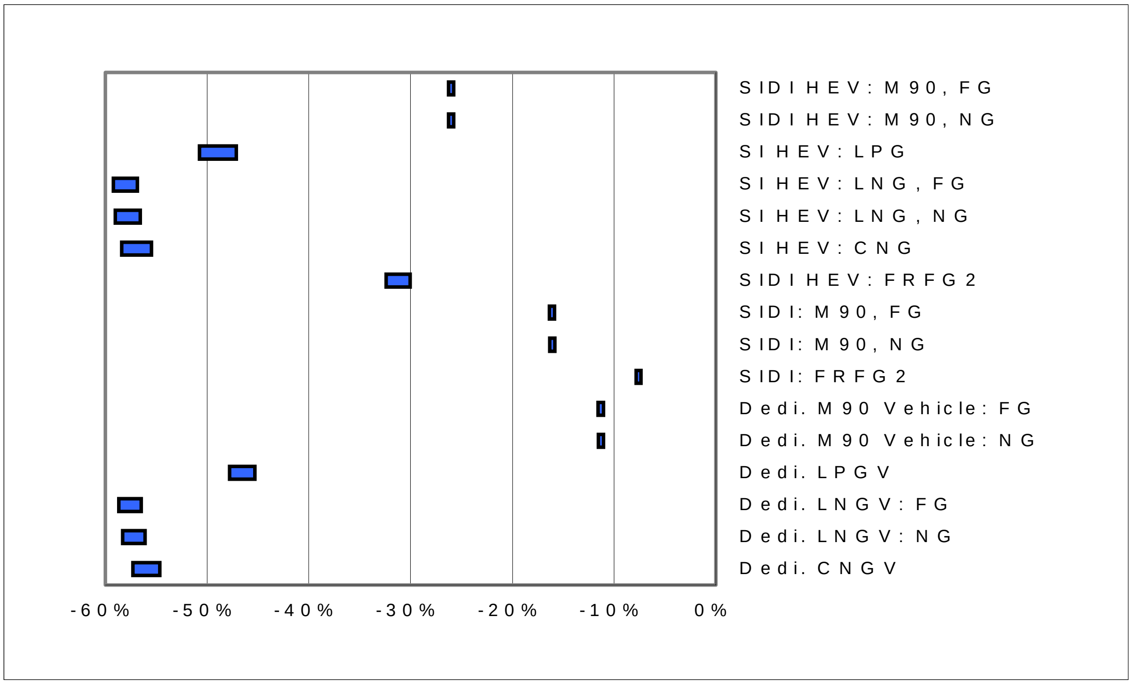

Figure 5.26 Long-Term SI Engine Technologies: Urban VOC Emission Changes (relative to baseline GV fueled with RFG)

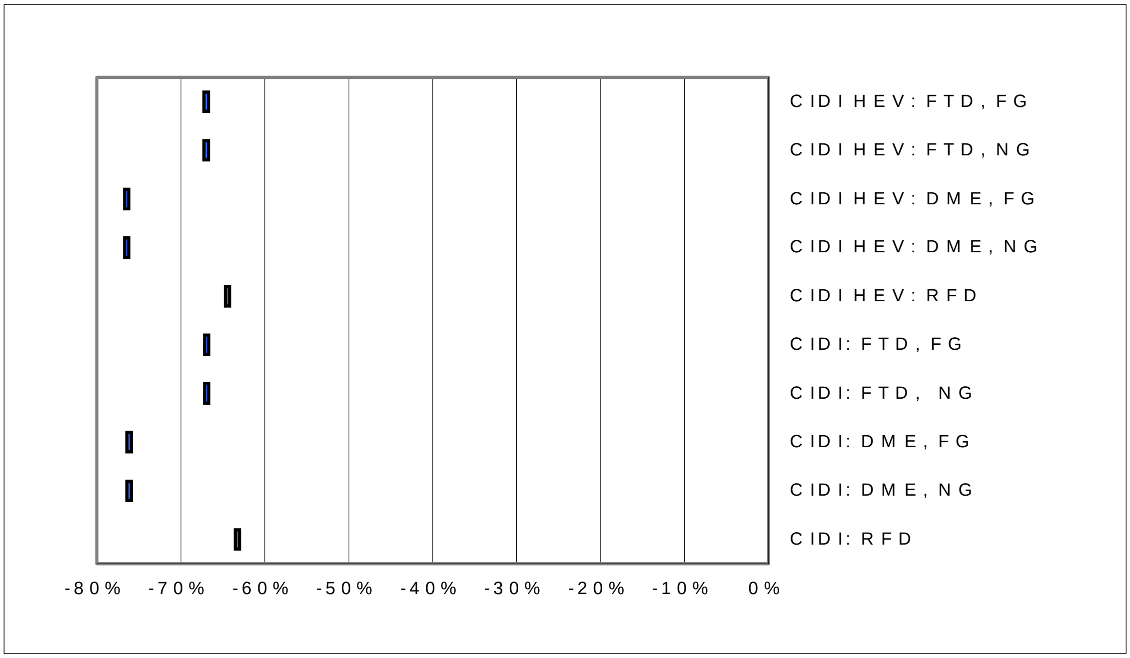

Figure 5.27 Long-Term CI Engine Technologies: Urban VOC Emission Changes (relative to baseline GV fueled with RFG)

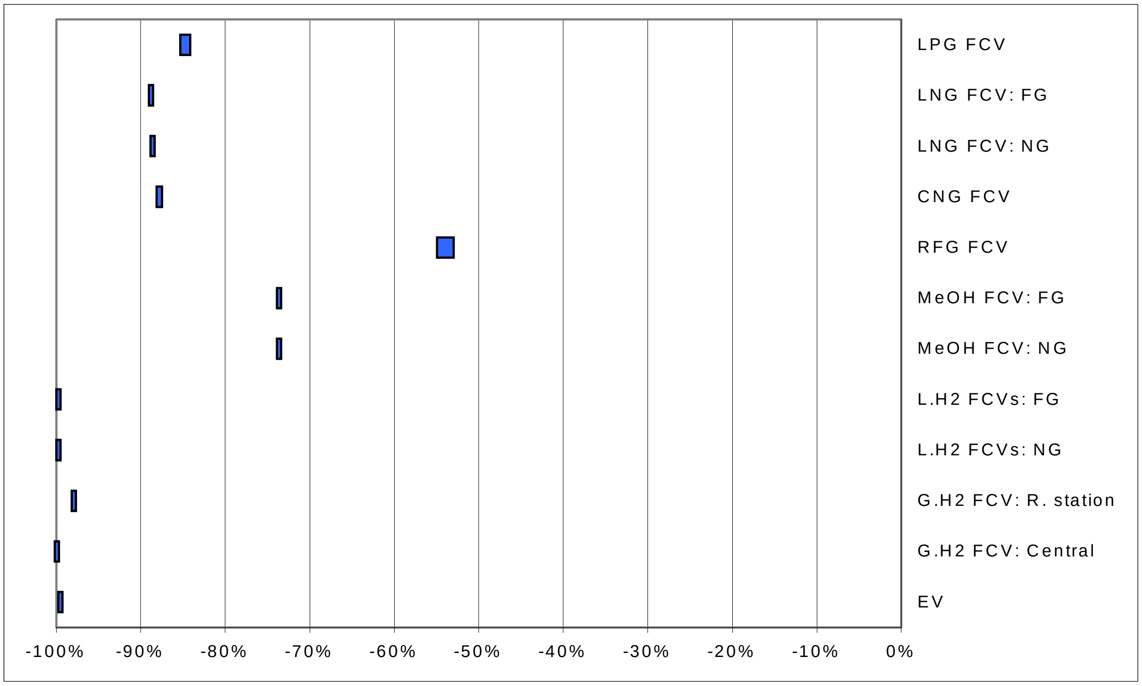

Figure 5.28 Long-Term EV and FCV Technologies: Urban VOC Emission Changes (relative to baseline GV fueled with RFG)

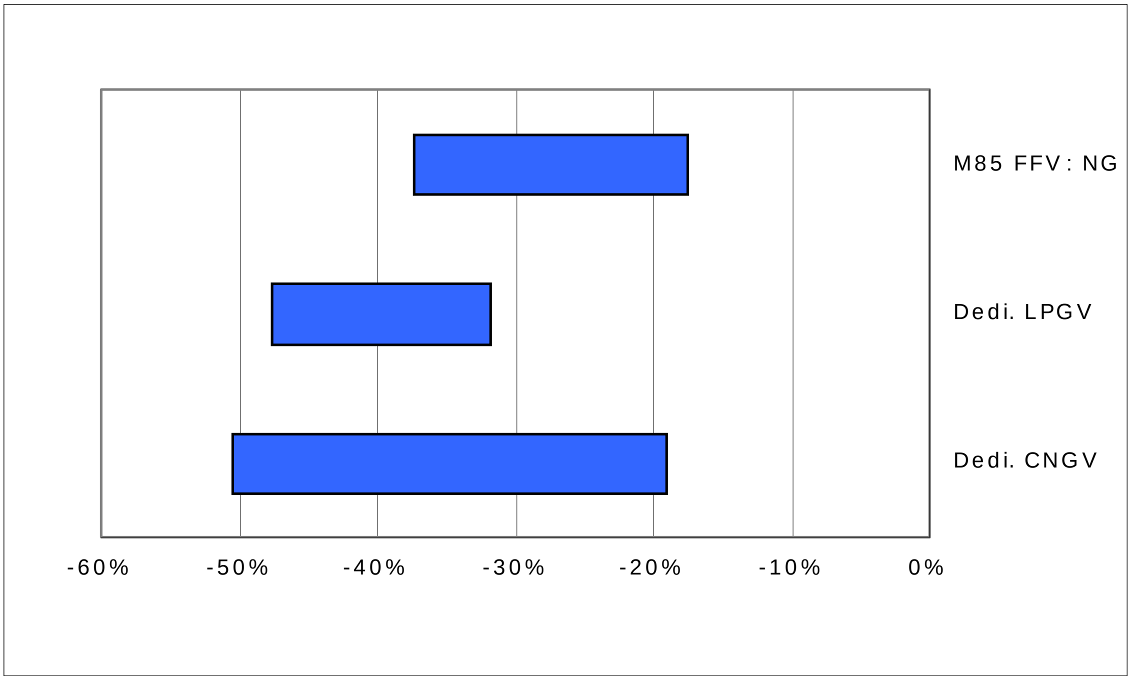

Figure 5.29 Near-Term Technologies: Total CO Emission Changes (relative to baseline GV fueled with CG)

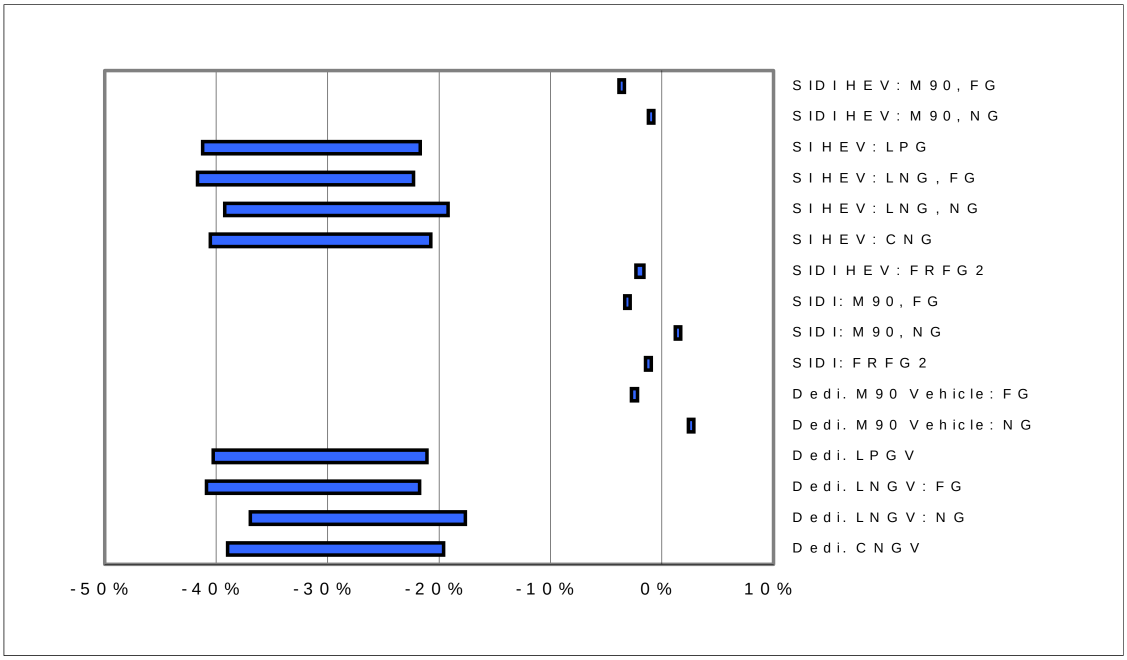

Figure 5.30 Long-Term SI Engine Technologies: Total CO Emission Changes (relative to baseline GV fueled with RFG)

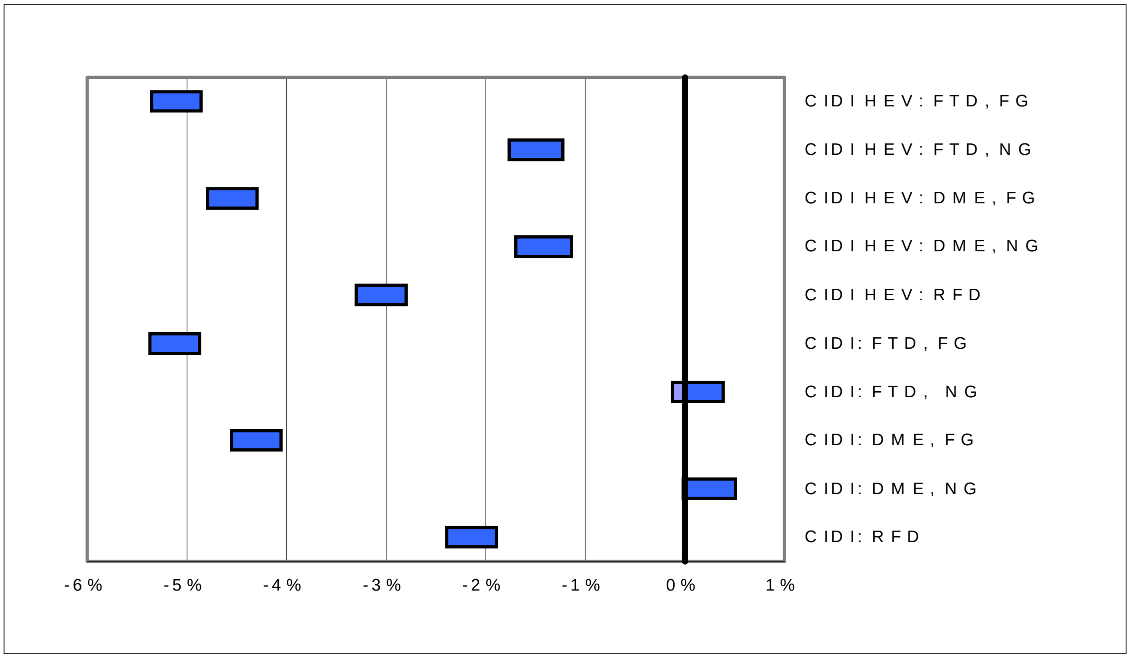

Figure 5.31 Long-Term CI Engine Technologies: Total CO Emission Changes (relative to baseline GV fueled with RFG)

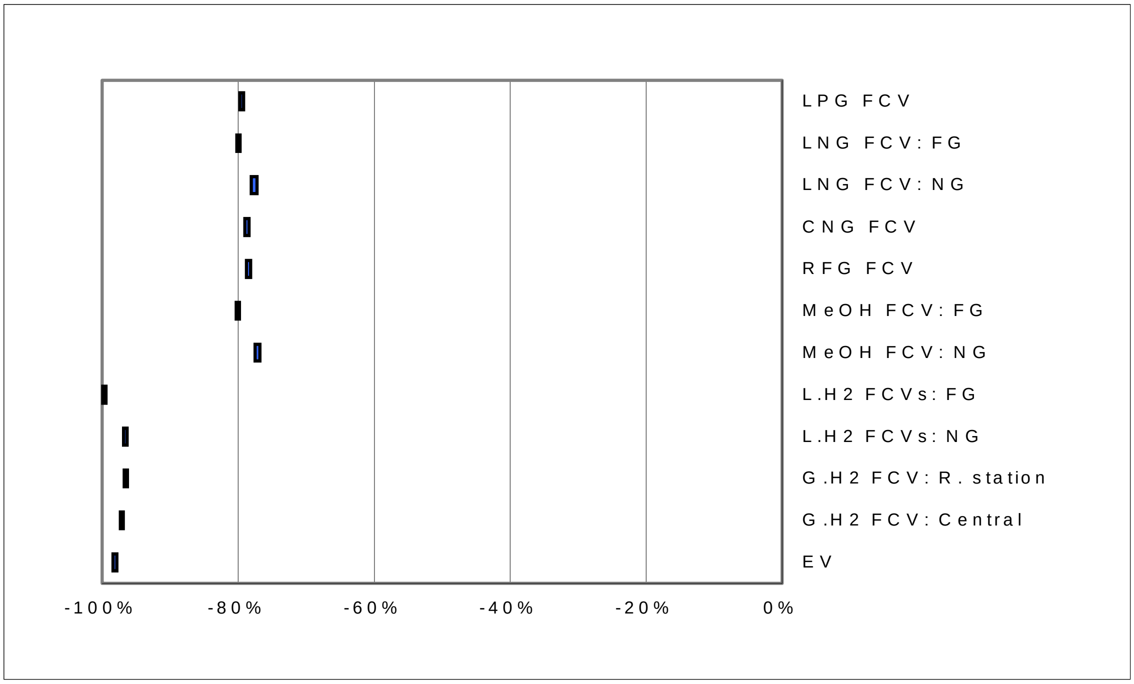

Figure 5.32 Long-Term EV and FCV Technologies: Total CO Emission Changes (relative to baseline GV fueled with RFG)

5.9 Urban CO Emissions

Figures 5.33 through 5.36 show changes in urban CO emissions that are similar to total CO emission changes because vehicular CO emissions, which occur in urban areas, account for the majority of the total fuel-cycle CO emissions.

5.10 Total NO_x Emissions

Figures 5.37 through 5.40 present changes in total NO_x emissions. For the three near-term options, total NO_x emissions from CNGVs and M85 FFVs are a little higher than those from baseline GVs. The higher NO_x emissions for CNGVs are attributable to NO_x emissions during NG compression in refueling stations. The higher emissions for M85 FFVs are caused by NO_x emissions in methanol plants.

For the sixteen long-term SI engine options, the increase in NO_x emissions caused by use of LNG is attributable to NO_x emissions associated with electricity used for NG liquefaction. The increase caused by dedicated CNGVs is primarily attributable to NO_x emissions associated with use of NG compressors at refueling stations. The increase by M90 vehicles is attributable to NO_x emissions from methanol production. Moderate reductions are achieved by LPGVs, SIDI engine vehicles, and SIDI engine HEVs. The reduction by LPG is caused by lower upstream emissions; the reduction by SIDI technologies is caused by reduced per-mile upstream emissions. Use of FG-based methanol results in a greater than 100% reduction in total NO_x emissions because the NO_x emissions associated with gas flaring are eliminated.

All of the CI engine options reduce total NO_x emissions because of lower upstream NO_x emissions. FG-based DME and FTD achieve greater than 100% reductions because their use eliminates NO_x emissions from gas flaring.

For the FCV and EV options, use of EVs increases total NO_x emissions because combined-cycle NG power plants produce a large amount of NO_x emissions. LNG FCVs offer smaller reductions than other options because significant NO_x emissions are released during generation of the large amount of electricity required for NG liquefaction. Reductions by FCVs fueled with H_2 produced at refueling stations and those fueled with CNG are small because significant NO_x emissions are generated during production of GH_2 and during NG compression. The large reduction by FCVs fueled with FG-based methanol and LH_2 is caused by elimination of NO_x emissions from gas flaring.

5.11 Urban NO_x Emissions

Figures 5.41 through 5.44 show changes in urban NO_x emissions. For the three near-term technology options, CNGVs have higher urban NO_x emissions than baseline GVs because of NO_x emissions from NG-powered compressors in refueling stations. We assume that half of NG refueling stations will be equipped with NG compressors and the other half with electric compressors. Emissions associated with electric compressors are considered non-urban emissions.

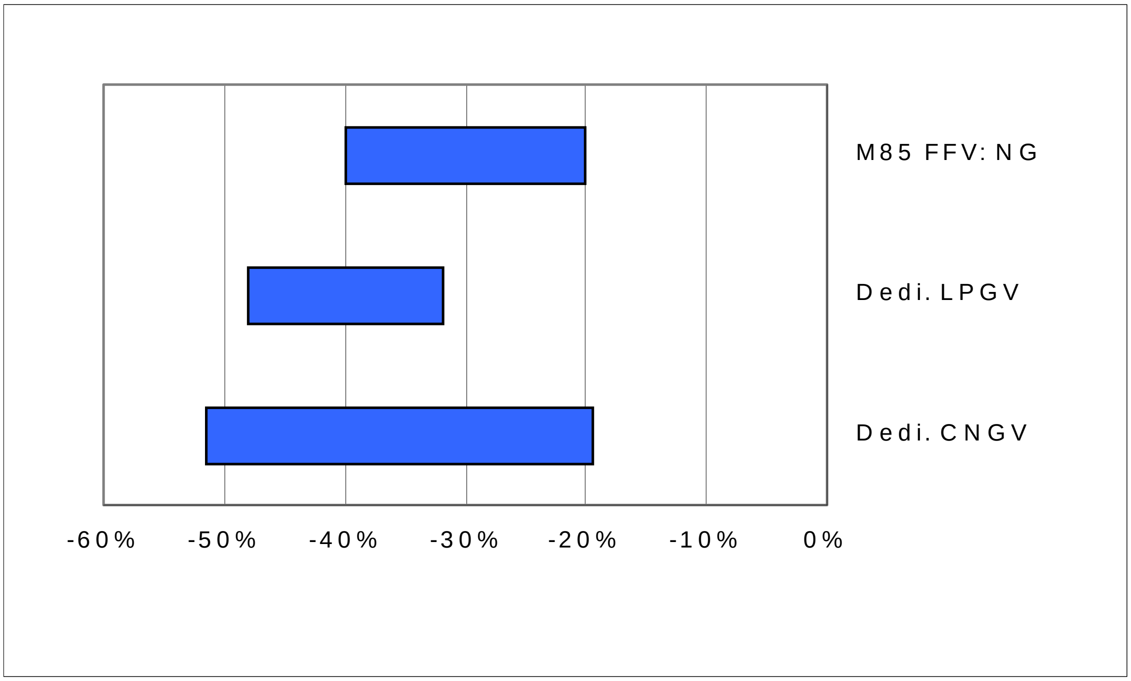

Figure 5.33 Near-Term Technologies: Urban CO Emission Changes (relative to baseline GV fueled with CG)

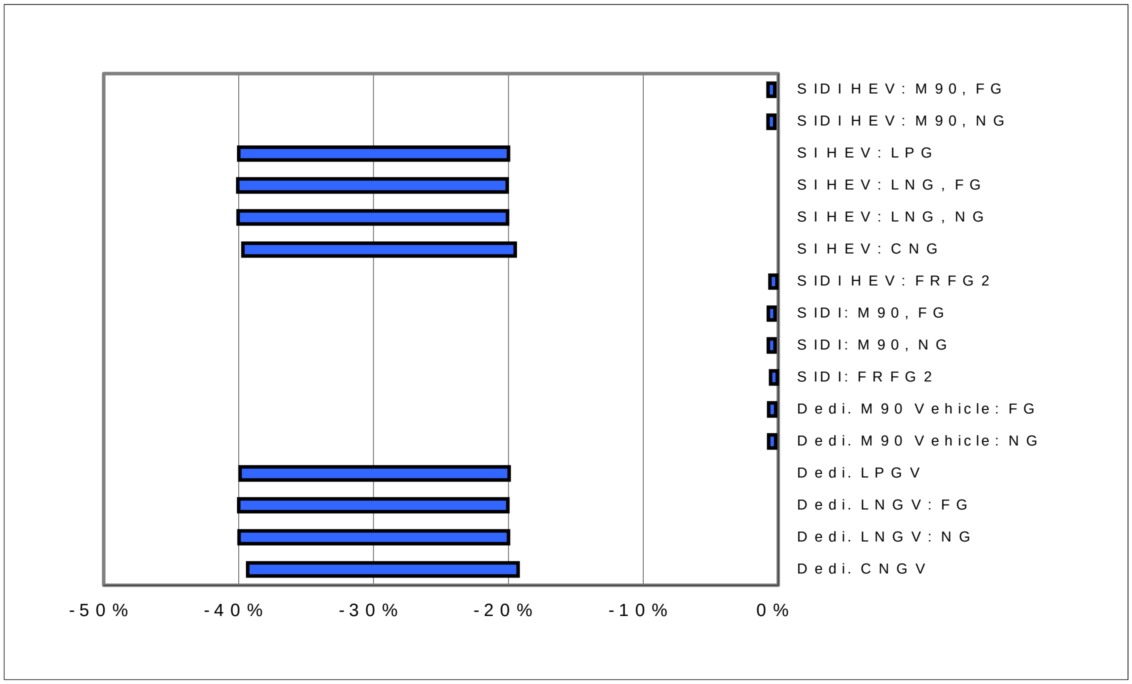

Figure 5.34 Long-Term SI Engine Technologies: Urban CO Emission Changes (relative to baseline GV fueled with RFG)

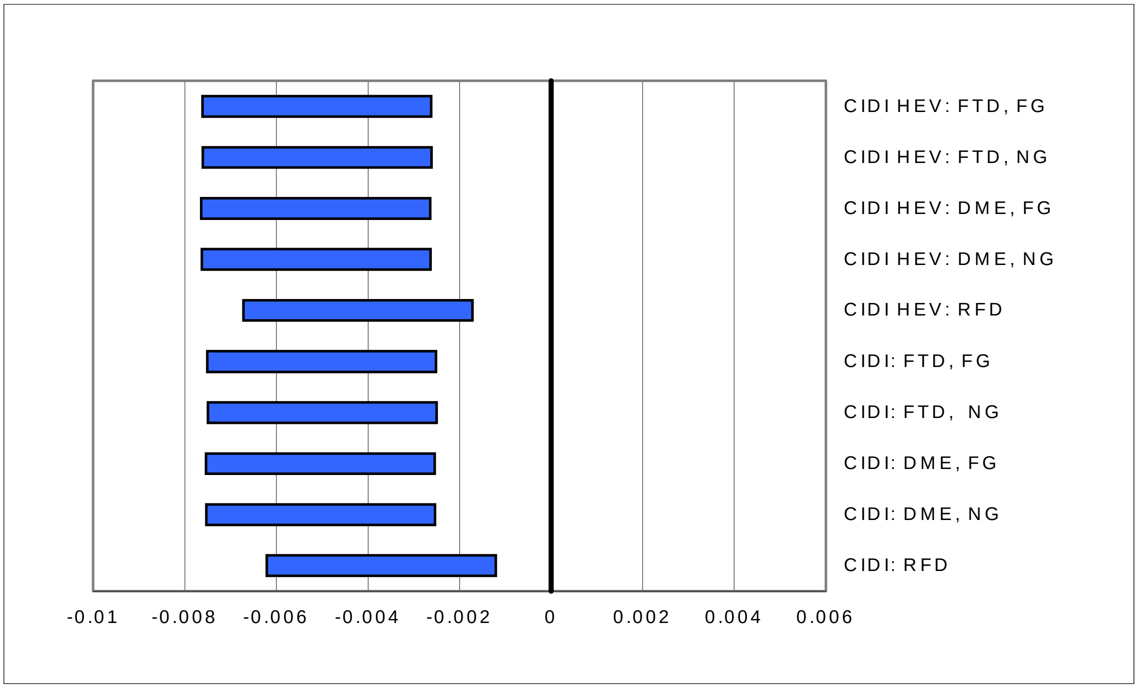

Figure 5.35 Long-Term CI Engine Technologies: Urban CO Emission Changes (relative to baseline GV fueled with RFG)

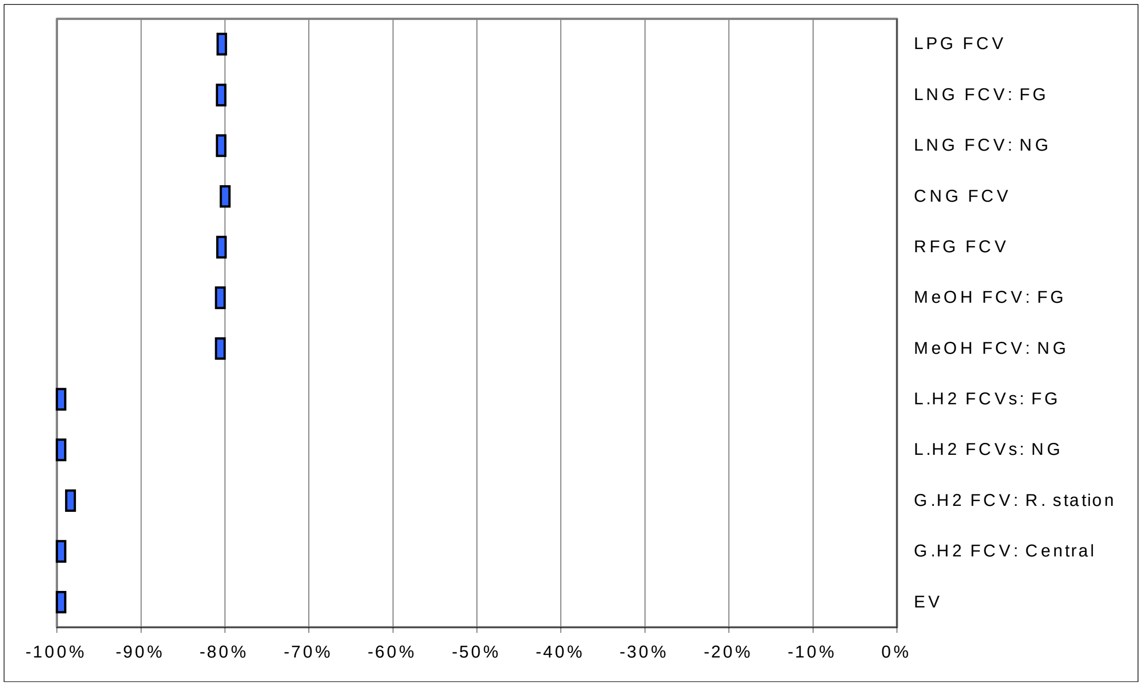

Figure 5.36 Long-Term EV and FCV Technologies: Urban CO Emission Changes (relative to baseline GV fueled with RFG)

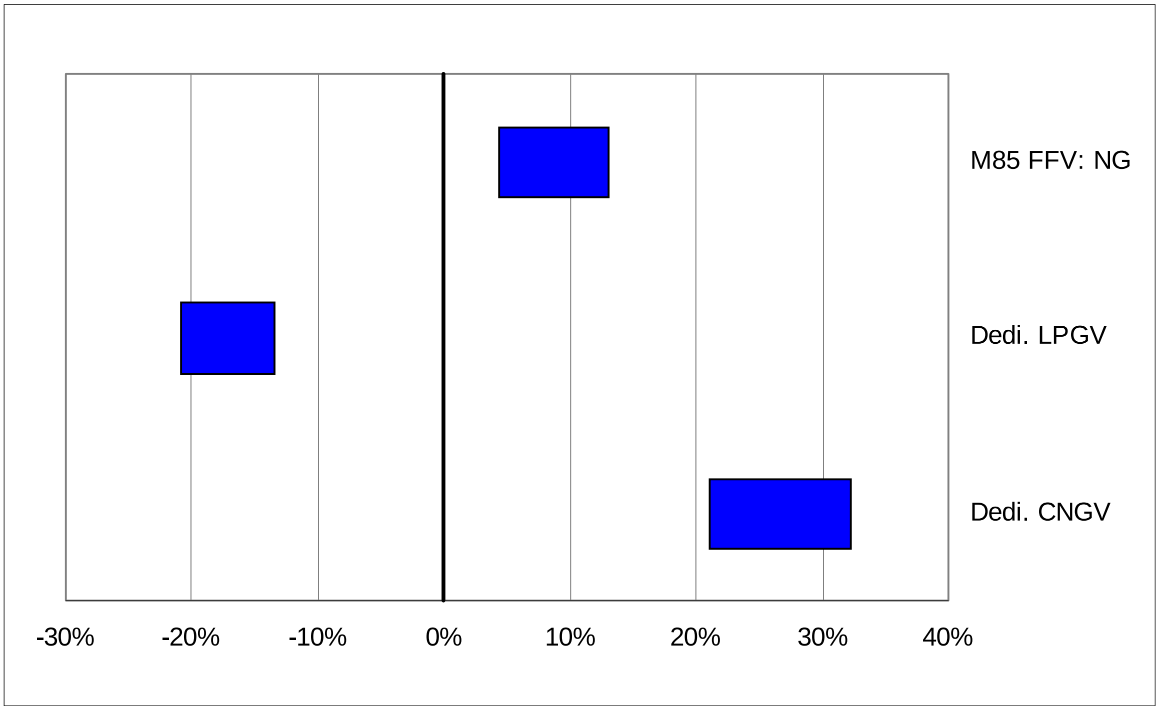

Figure 5.37 Near-Term Technologies: Total NO_x Emission Changes (relative to baseline GV fueled with CG)

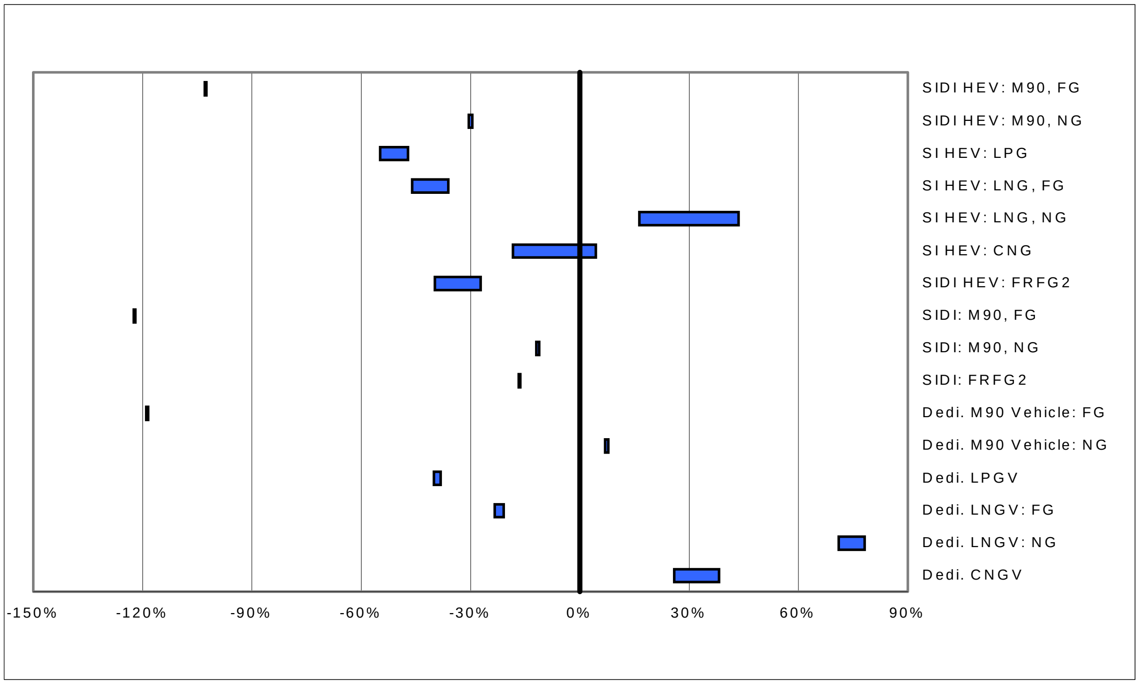

Figure 5.38 Long-Term SI Engine Technologies: Total NO_x Emission Changes (relative to baseline GV fueled with RFG)

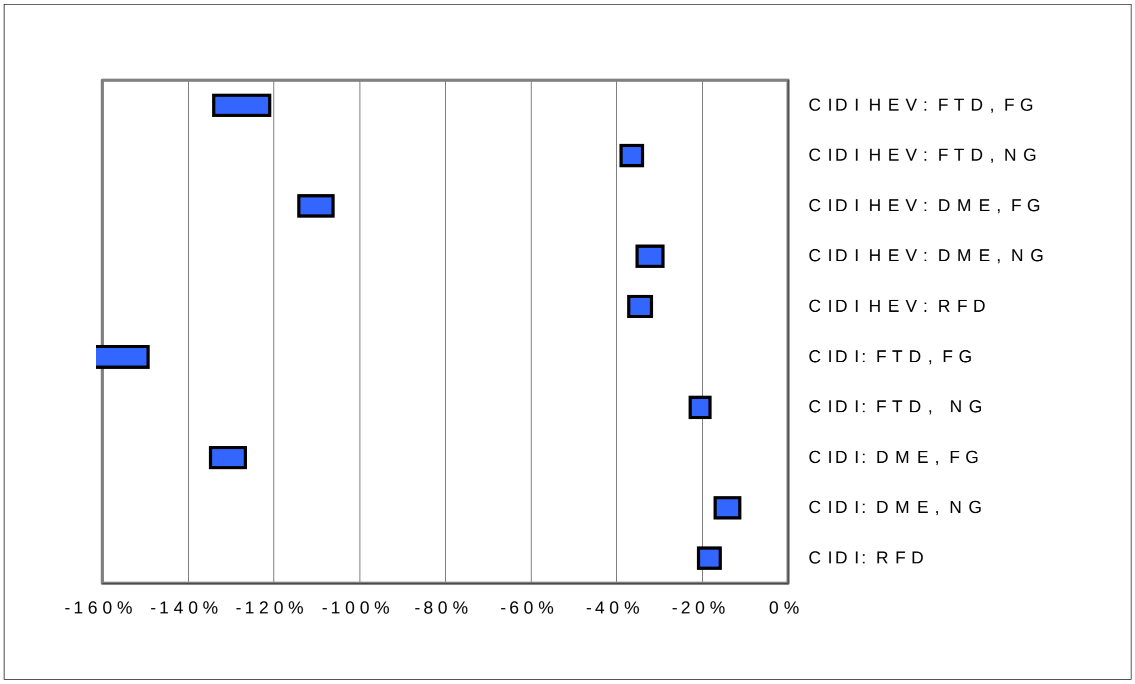

Figure 5.39 Long-Term CI Engine Technologies: Total NO_x Emission Changes (relative to baseline GV fueled with RFG)

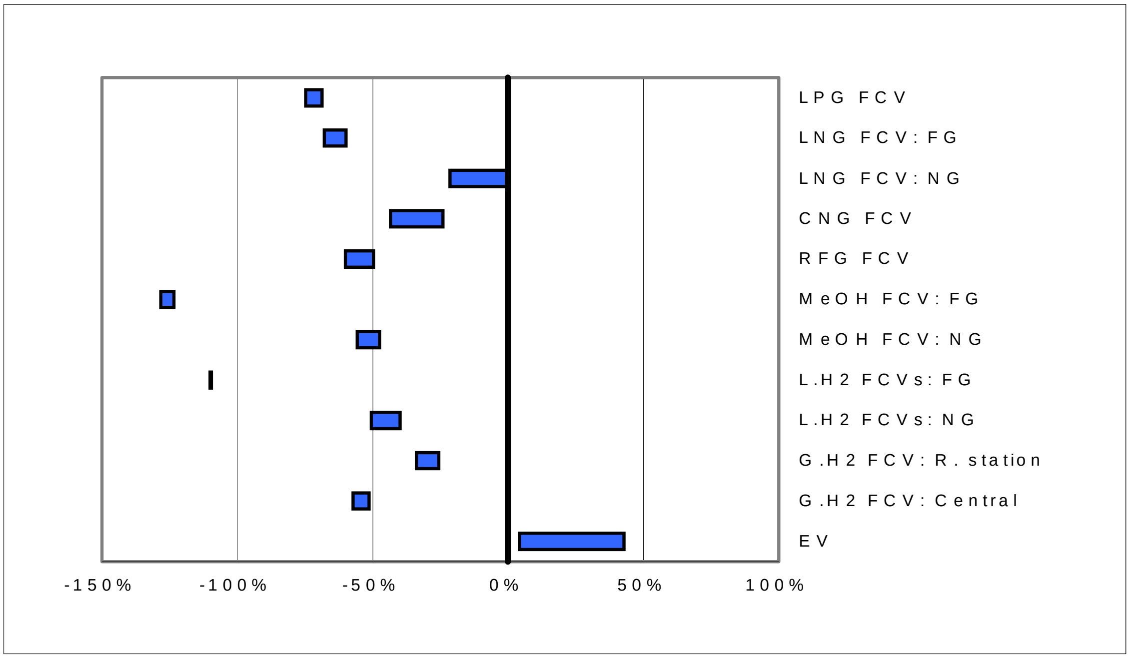

Figure 5.40 Long-Term EV and FCV Technologies: Total NO_x Emission Changes (relative to baseline GV fueled with RFG)

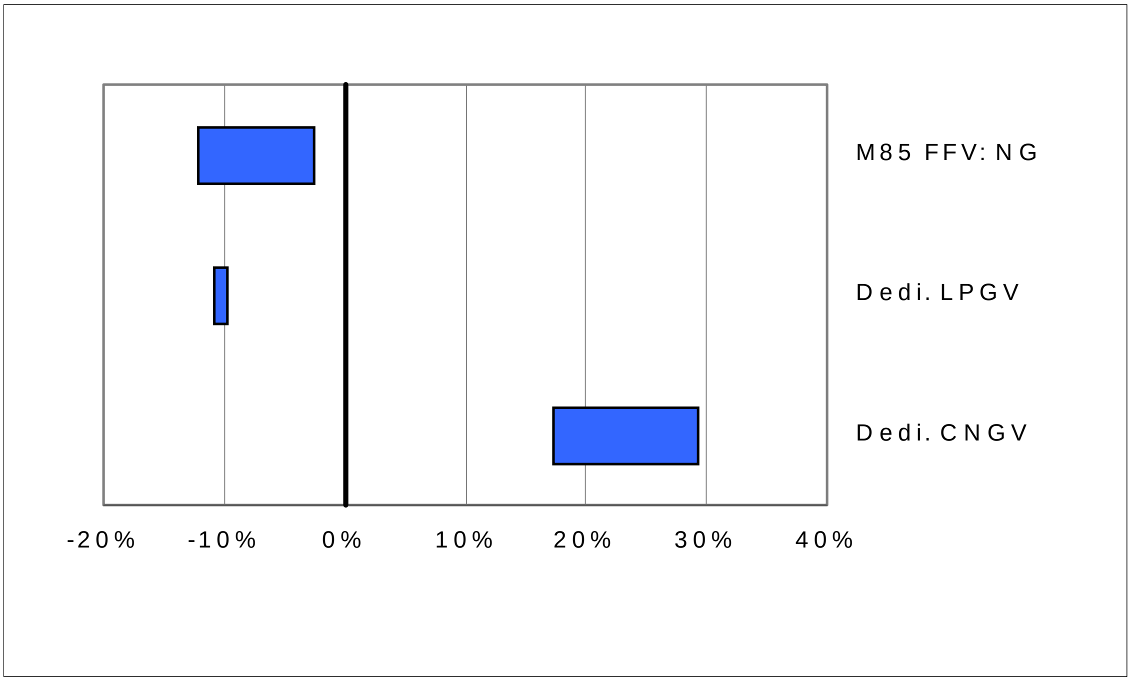

Figure 5.41 Near-Term Technologies: Urban NO_x Emission Changes (relative to baseline GV fueled with CG)

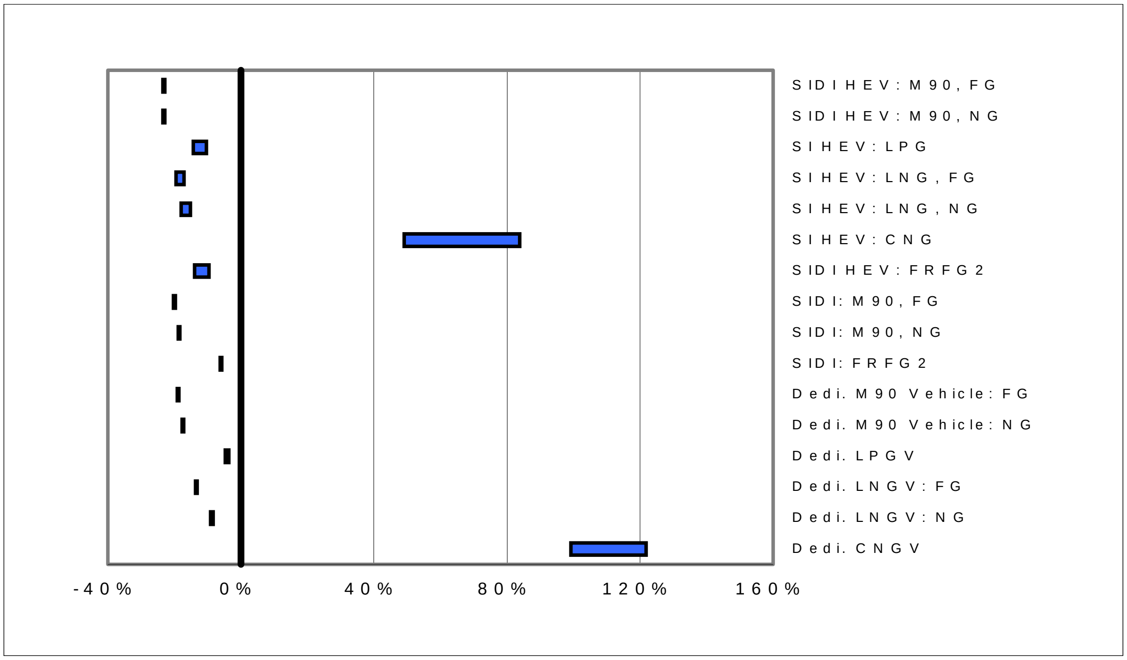

Figure 5.42 Long-Term SI Engine Technologies: Urban NO_x Emission Changes (relative to baseline GV fueled with RFG)

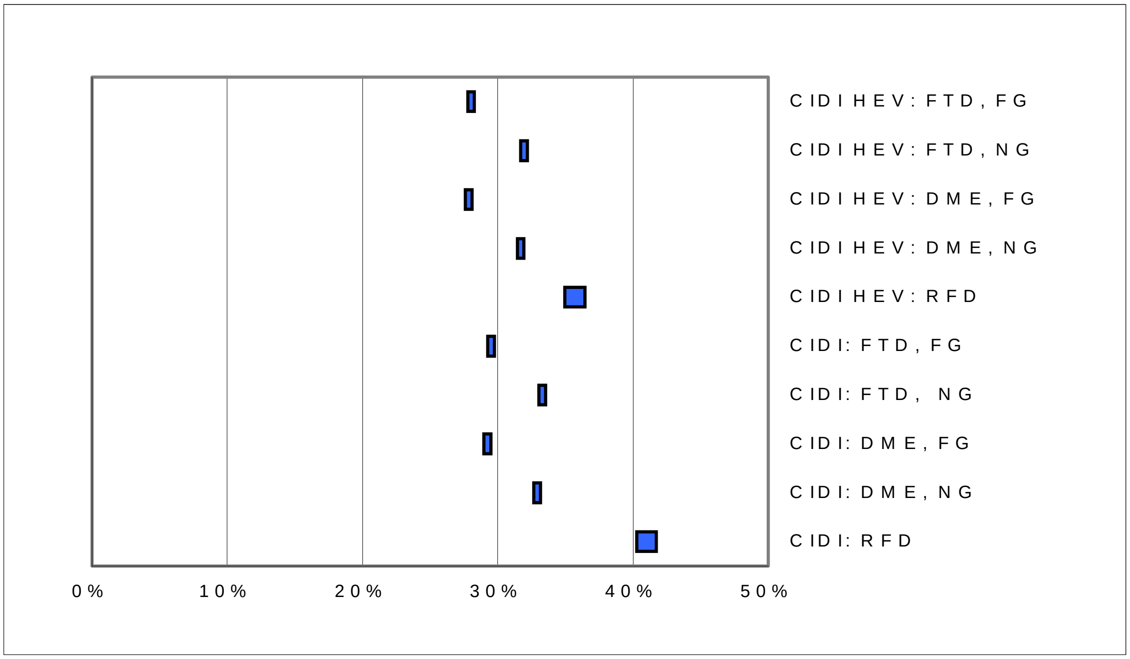

Figure 5.43 Long-Term CI Engine Technologies: Urban NO_x Emission Changes (relative to baseline GV fueled with RFG)

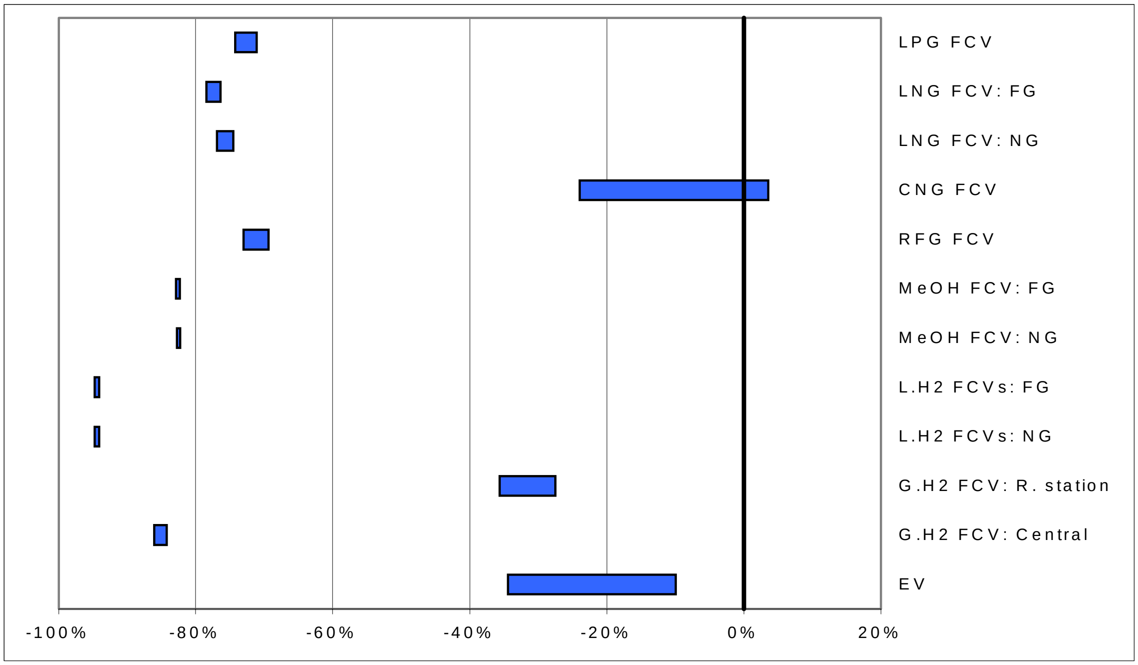

Figure 5.44 Long-Term EV and FCV Technologies: Urban NO_x Emission Changes (relative to baseline GV fueled with RFG)

For the sixteen long-term SI technologies, use of CNG results in increased urban NO_x emissions because of NO_x emissions from NG compressors. Because vehicle tailpipe NO_x emissions from long-term vehicle technology options are so low (see Table 4.3), NG compression results in huge increases in urban NO_x emissions. On the other hand, urban NO_x emission changes by other fuels are relatively small.

CIDI engine technologies generate higher NO_x emissions than baseline GVs because of our assumption that CIDI engines will be certified at a NO_x level higher than the NO_x level for GVs (which will be allowable under the EPA-proposed Tier 2 vehicle emission standards).

The increase in urban NO_x emissions for FCVs fueled with CNG is caused by emissions associated with NG compression at refueling stations. The small reduction in urban NO_x emissions by FCVs fueled with H_2 produced at refueling stations is attributable to NO_x emissions during H_2 production at refueling stations. The small reduction in urban NO_x emissions by EVs is caused by our assumption that some NG combined-cycle power plants will be located within urban areas. Other FCV options offer 60–95% reductions in urban NO_x emissions.

5.12 Total PM_{10} Emissions

Figures 5.45 through 5.48 present changes in total PM_{10} emissions for each technology option. The three near-term technology options result in 20–40% reductions in total PM_{10} emissions, primarily because of reductions in tailpipe emissions.

For the long-term SI technologies, use of RFG in SIDI HEVs and M90 in dedicated and SIDI vehicles offers only small PM_{10} emission reductions. Other fuels offer reductions of 20–40%. Use of RFG in SIDI engines results in a small increase. Use of FG-based LNG and methanol results in larger PM_{10} emission reductions.

Use of CIDI engine technologies results in reductions in total PM_{10} emissions. For NG-based fuels, the reductions are below 40%. If FG-based DME and FTD are used, the reductions increase to above 55%.

Use of EVs and FCVs also reduces total PM_{10} emissions. Reductions range from 30% to 50%. If FG-based LH_2, methanol, and LNG are used in FCVs, reductions increase to above 60%.

5.13 Urban PM_{10} Emissions

Figures 5.49 through 5.52 show urban PM_{10} emission changes. The three near-term options achieve moderate urban PM_{10} emission reductions.

For the sixteen long-term SI technology options, use of SIDI engines fueled by RFG results in small increases. SIDI engines are assumed to generate higher tailpipe PM_{10} emissions than SI engines.

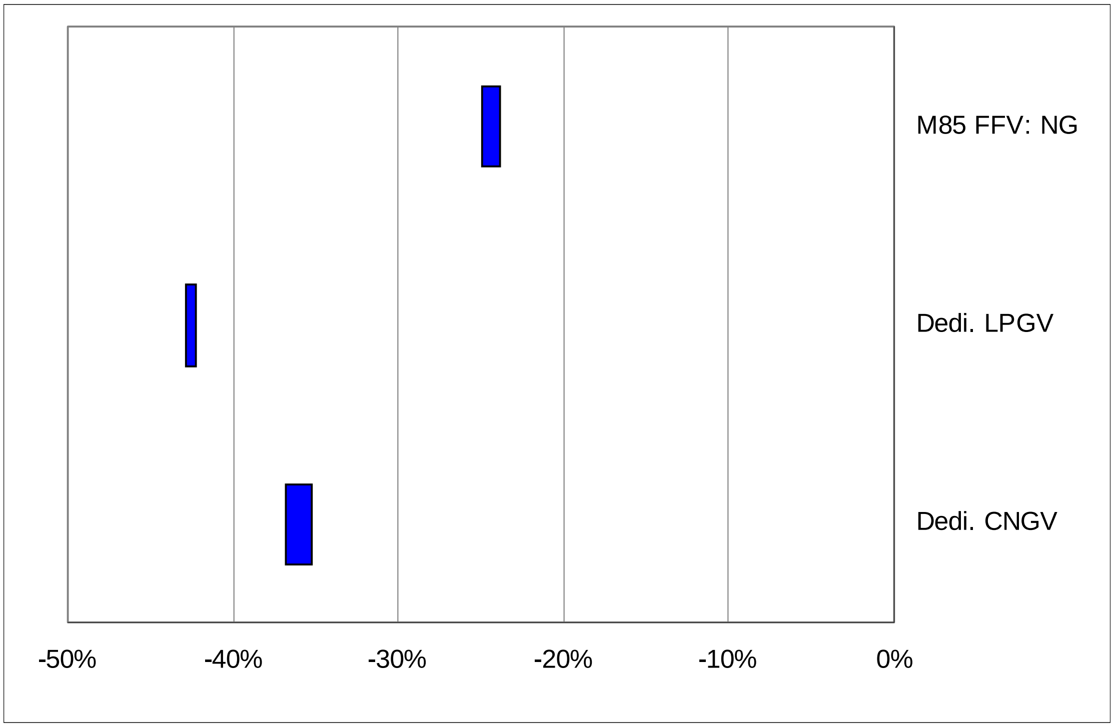

Figure 5.45 Near-Term Technologies: Total PM_{10} Emission Changes (relative to baseline GV fueled with CG)

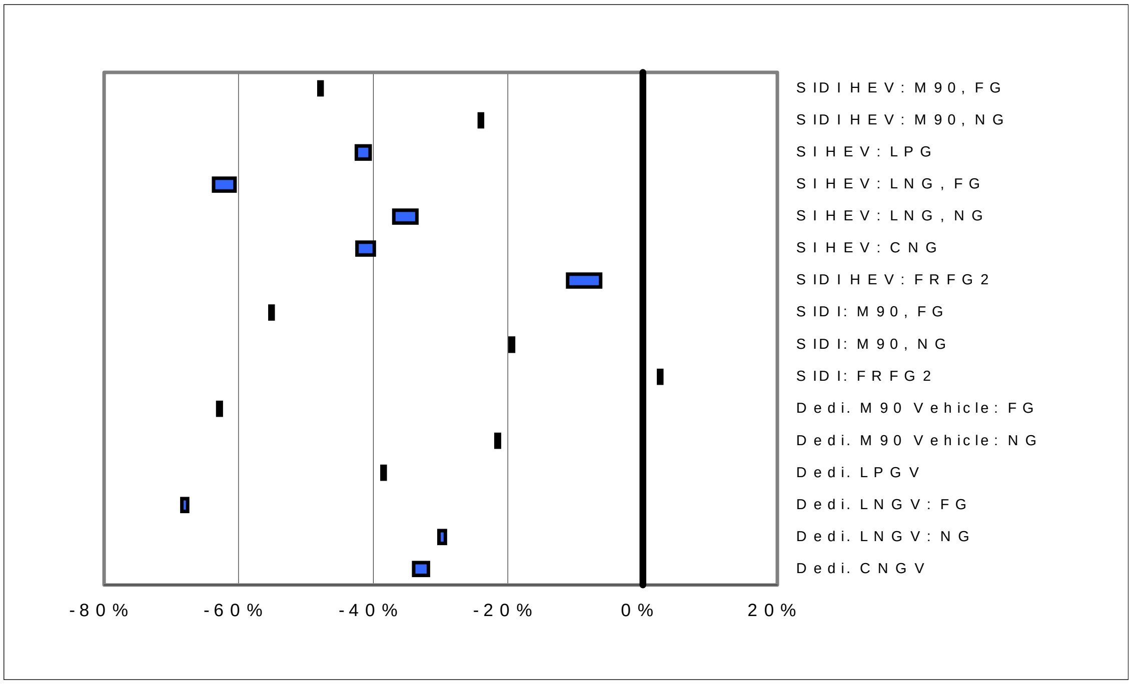

Figure 5.46 Long-Term SI Engine Technologies: Total PM_{10} Emission Changes (relative to baseline GV fueled with RFG)

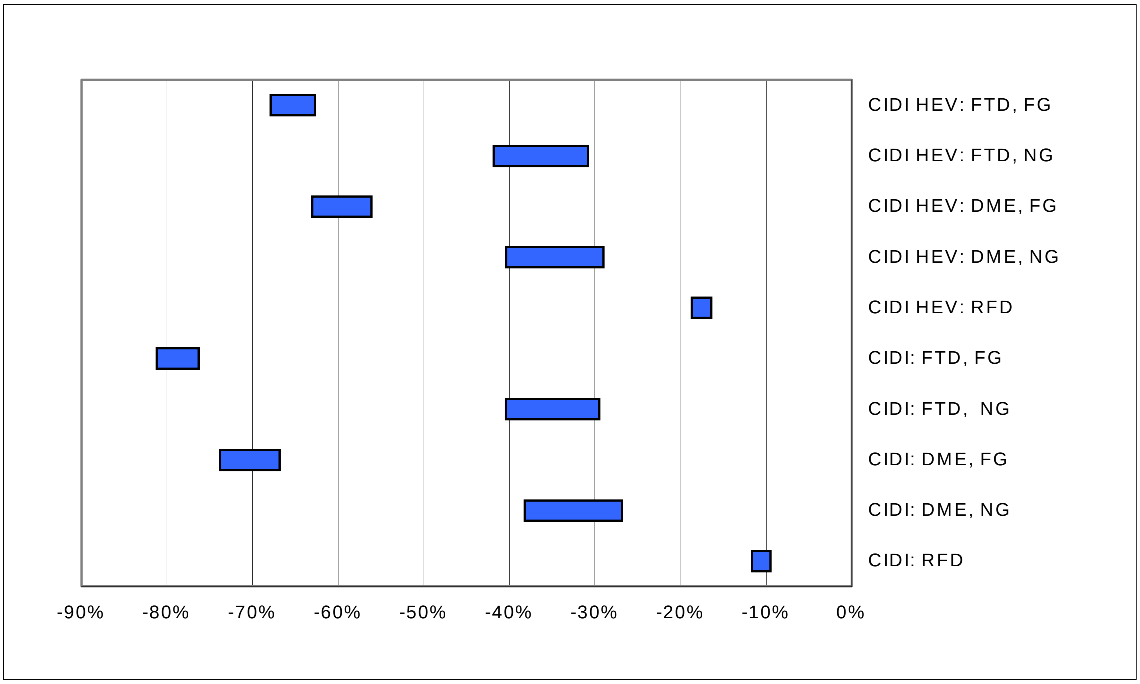

Figure 5.47 Long-Term CI Engine Technologies: Total PM_{10} Emission Changes (relative to baseline GV fueled with RFG)

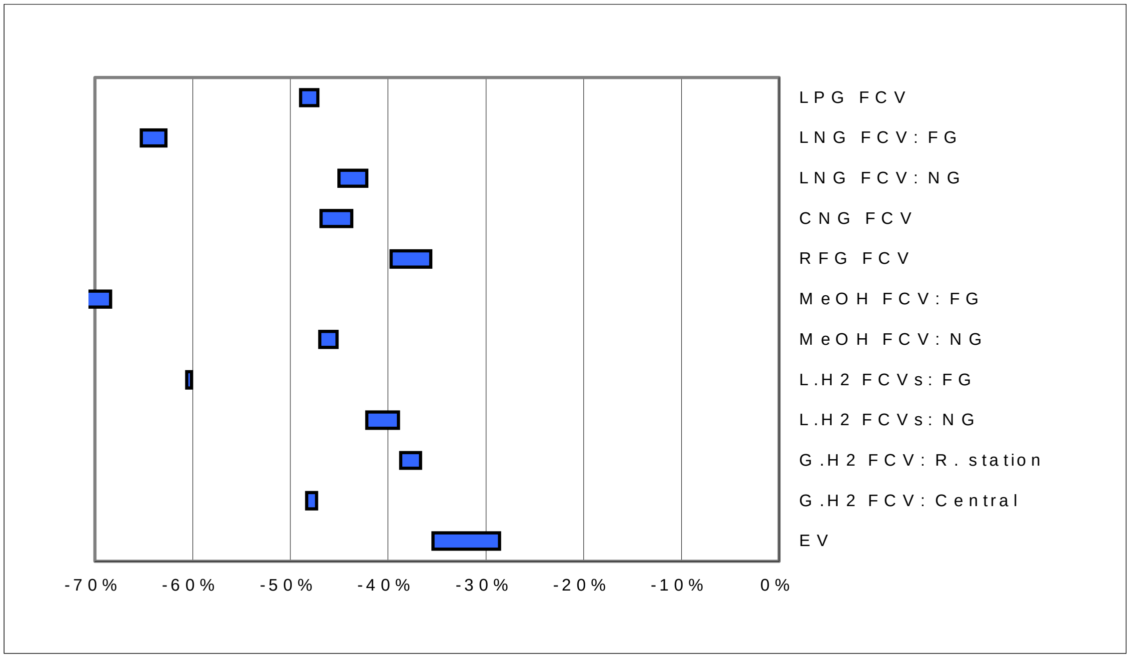

Figure 5.48 Long-Term EV and FCV Technologies: Total PM_{10} Emission Changes (relative to baseline GV fueled with RFG)

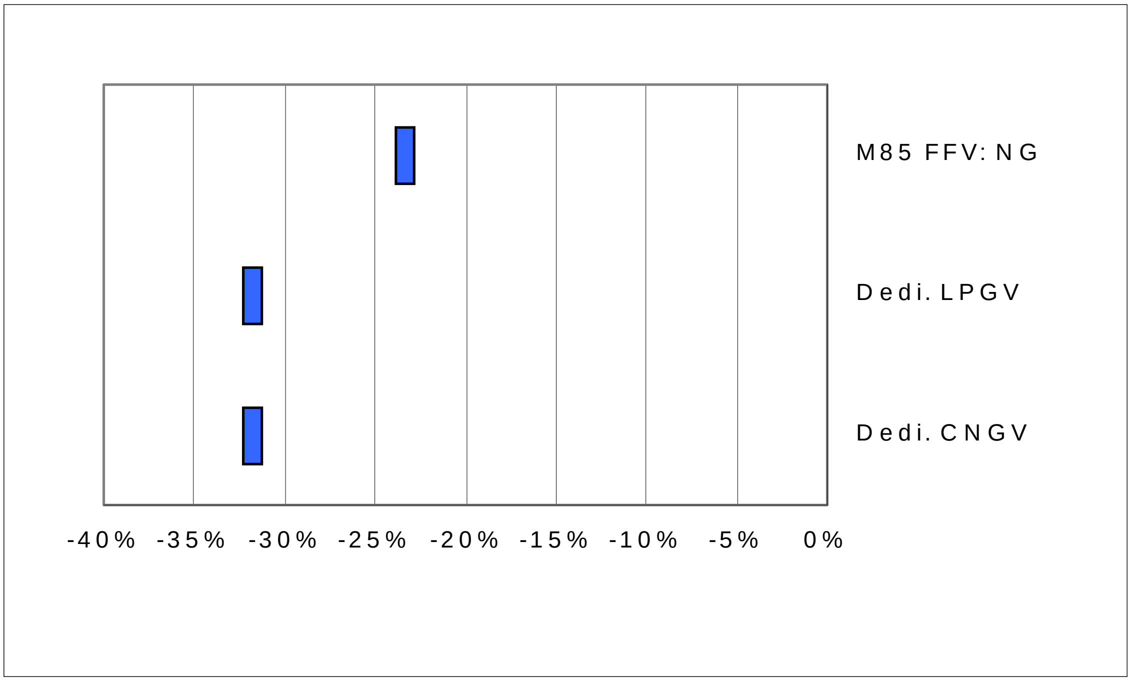

Figure 5.49 Near-Term Technologies: Urban PM_{10} Emission Changes (relative to baseline GV fueled with CG)

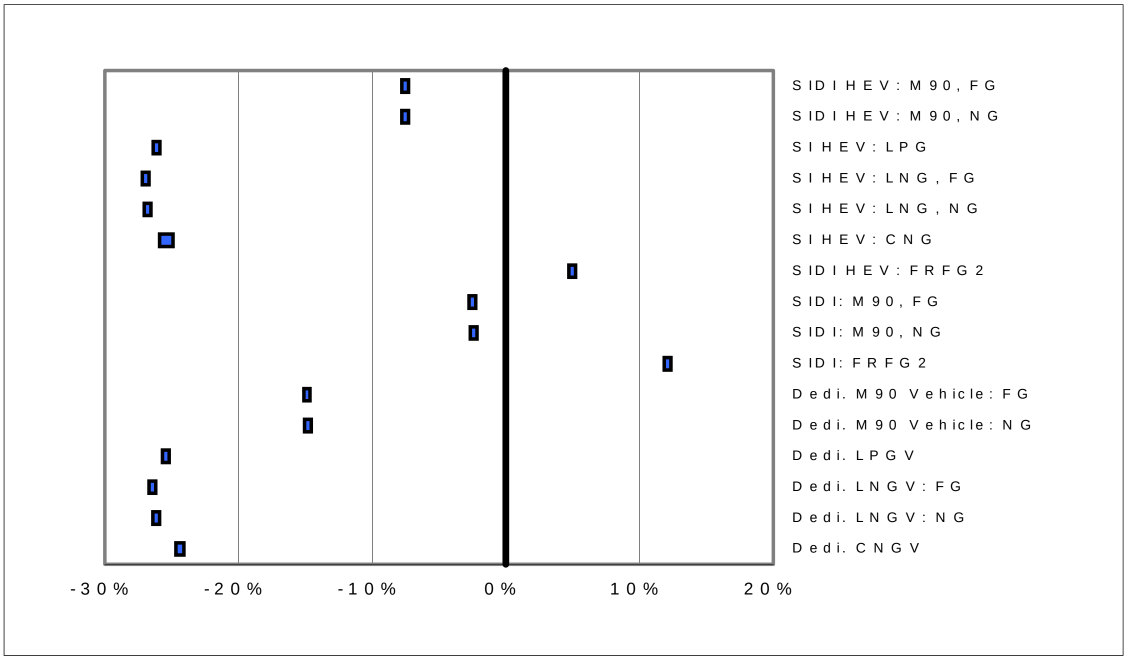

Figure 5.50 Long-Term SI Engine Technologies: Urban PM_{10} Emission Changes (relative to baseline GV fueled with RFG)

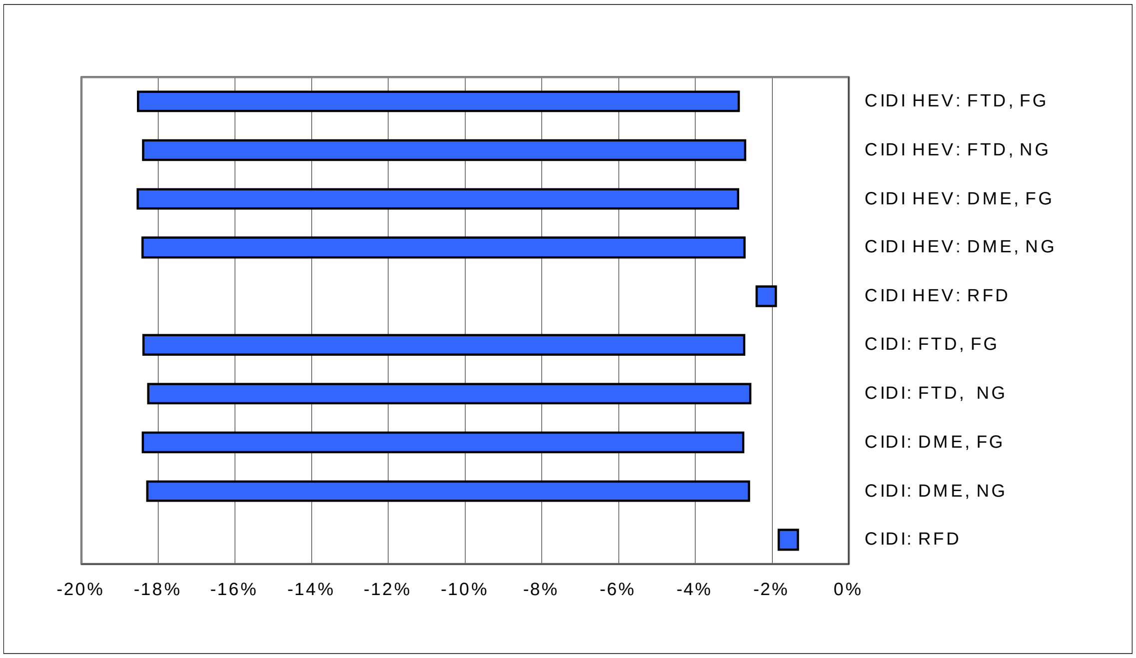

Figure 5.51 Long-Term CI Engine Technologies: Urban PM_{10} Emission Changes (relative to baseline GV fueled with RFG)

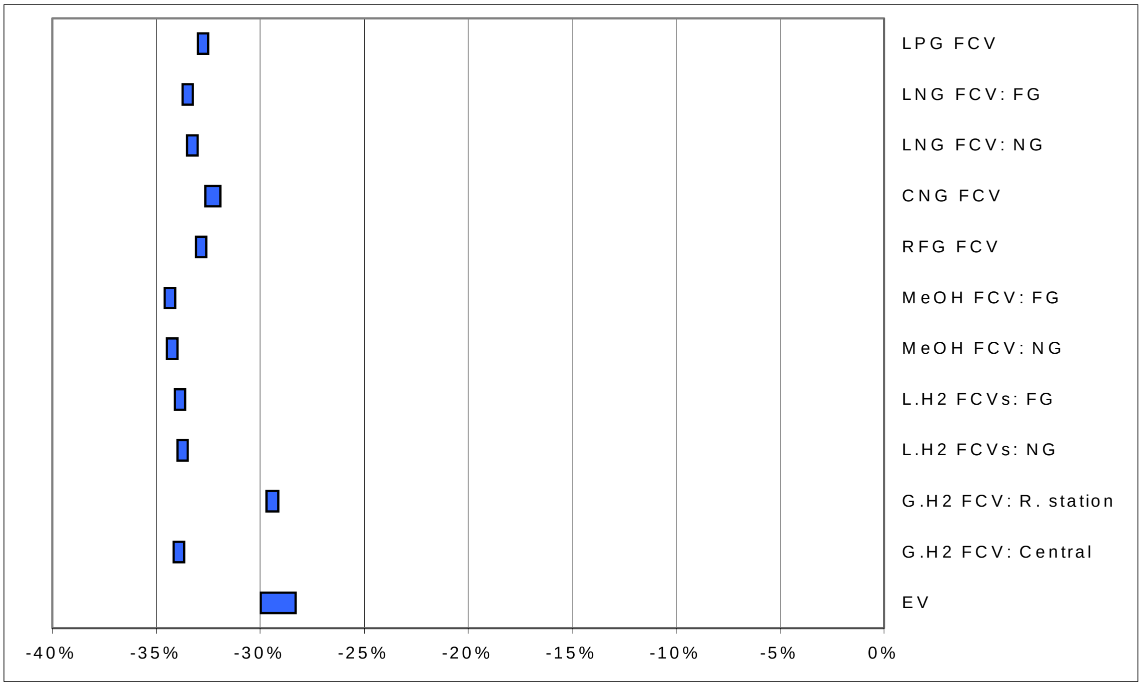

Figure 5.52 Long-Term EV and FCV Technologies: Urban PM_{10} Emission Changes (relative to baseline GV fueled with RFG)

Use of NG-based fuels in CIDI engines achieves only small reductions in urban PM_{10} emissions under the leap-forward scenario. Under the incremental scenario, urban PM_{10} emissions by CIDI engines are virtually unchanged. Use of RFD in CIDI engines does not result in major changes in urban PM_{10} emissions.

Use of FCVs and EVs results in moderate PM_{10} emission reductions. The smaller reduction by FCVs fueled with H_2 produced in refueling stations is caused by emissions generated when H_2 is produced at refueling stations. The small reductions by EVs are attributable to the assumption that some of NG combined-cycle electric power plants will be located within urban areas.

Overall, changes in urban PM_{10} emissions by these vehicle technologies are small because our study includes PM_{10} emissions from tire wear and brake wear, which change little across vehicle types.

5.14 Total SO_x Emissions

Figures 5.53 through 5.56 present changes in total SO_x emissions for each vehicle technology. Of the three near-term technologies, CNGVs achieve only 30–35% reductions in total SO_x emissions because of SO_x emissions in electric power plants that provide electricity for NG compression. LPGVs and M85 FFVs achieve 60–80% reductions in SO_x emissions.

For the sixteen long-term SI technology options, SO_x emission reductions are roughly proportional to sulfur contents in the fuels and to fuel economy. Low- or non-sulfur fuels and vehicles with high fuel economy offer large SO_x emission reductions. Small reductions by CNGVs are caused by SO_x emissions associated with electricity generation for NG compression.

For CIDI engines, use of NG-based fuels achieves a greater than 80% reduction in SO_x emissions. Use of RFD in CIDI engines achieves moderate reductions, despite the fact that there is more sulfur in RFD than in RFG. The moderate reductions are caused by the improved fuel economy offered by CIDI engines.

Use of FCVs and EVs achieves greater than 80% reductions in SO_x emissions, except for FCVs fueled with H_2 produced in central plants, with RFG and with CNG. In the first case, production and compression of H_2 in refueling stations consumes electricity, and the production of electricity generates SO_x emissions (under the national electric generation mix).

5.15 Urban SO_x Emissions

Figures 5.57 through 5.60 show urban SO_x emissions changes. For the three near-term options, CNGVs and LPGVs help reduce urban SO_x emissions by more than 95%. M85 FFVs reduce SO_x emissions by more than 70%.

For the long-term SI technologies, use of NG-based fuels reduces SO_x emissions by 80% to almost 100%. Use of RFG in SIDI engines results in 20–50% reductions.

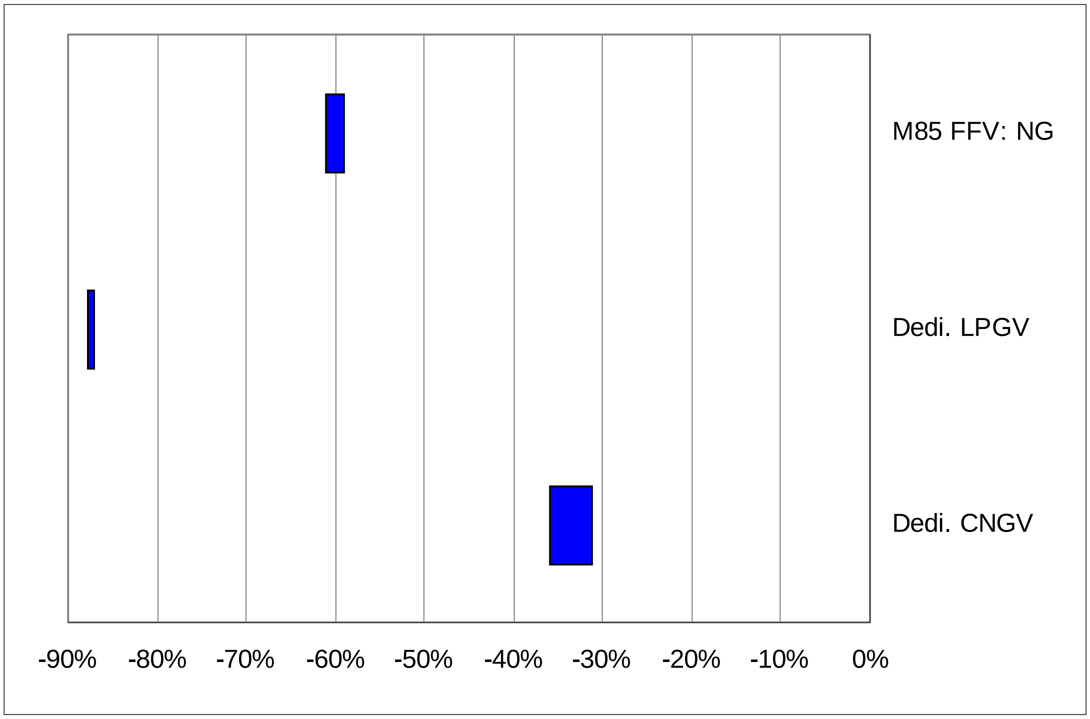

Figure 5.53 Near-Term Technologies: Total SO_x Emission Changes (relative to baseline GV fueled with CG)

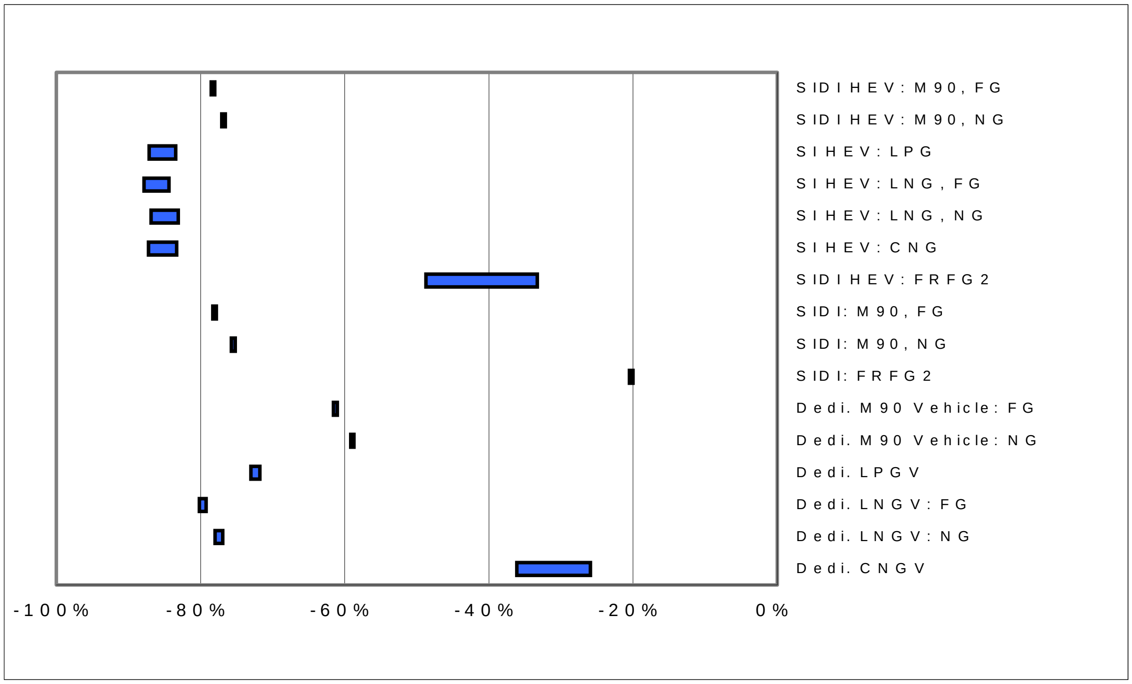

Figure 5.54 Long-Term SI Engine Technologies: Total SO_x Emission Changes (relative to baseline GV fueled with RFG)

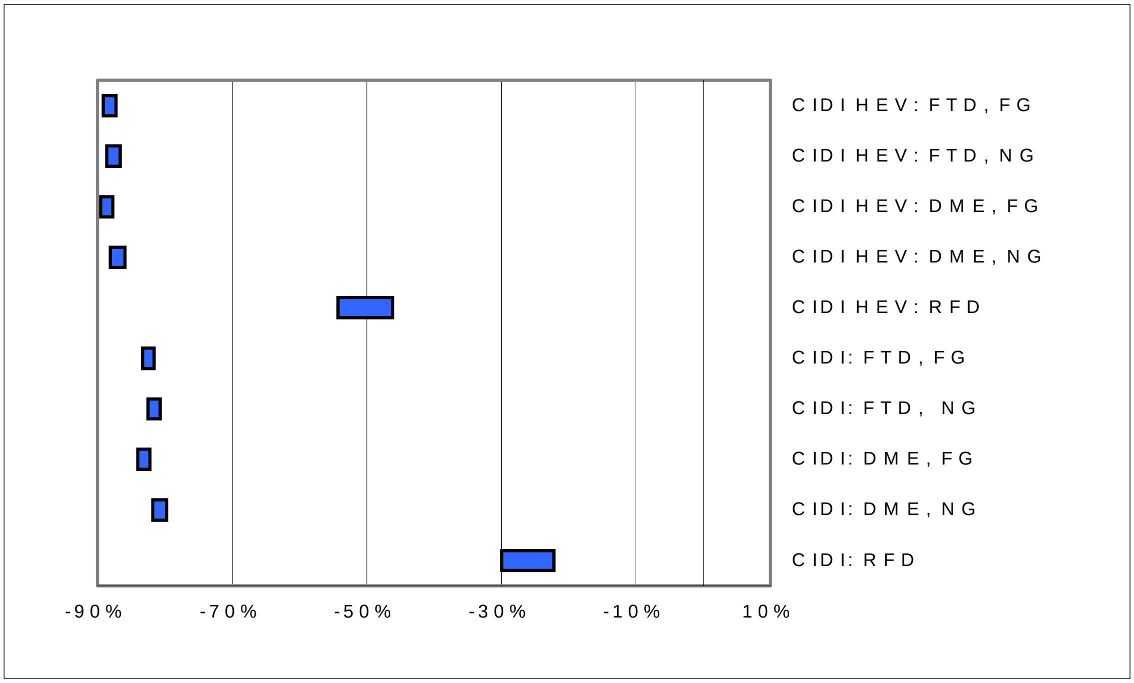

Figure 5.55 Long-Term CI Engine Technologies: Total SO_x Emission Changes (relative to baseline GV fueled with RFG)

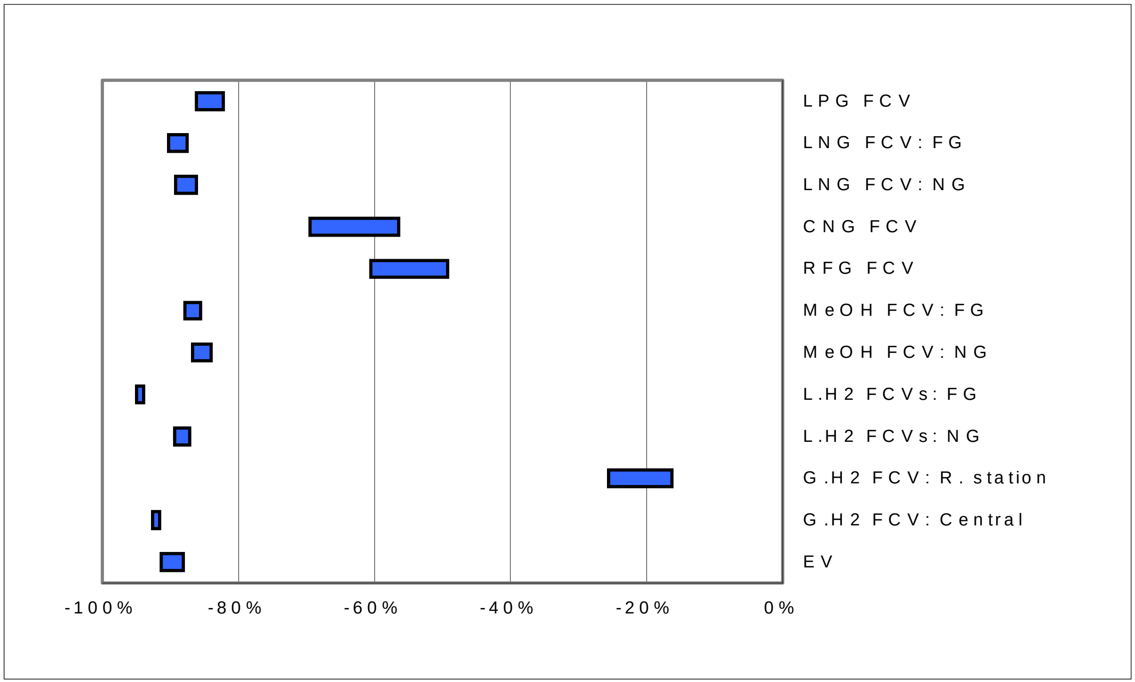

Figure 5.56 Long-Term EV and FCV Technologies: Total SO_x Emission Changes (relative to baseline GV fueled with RFG)

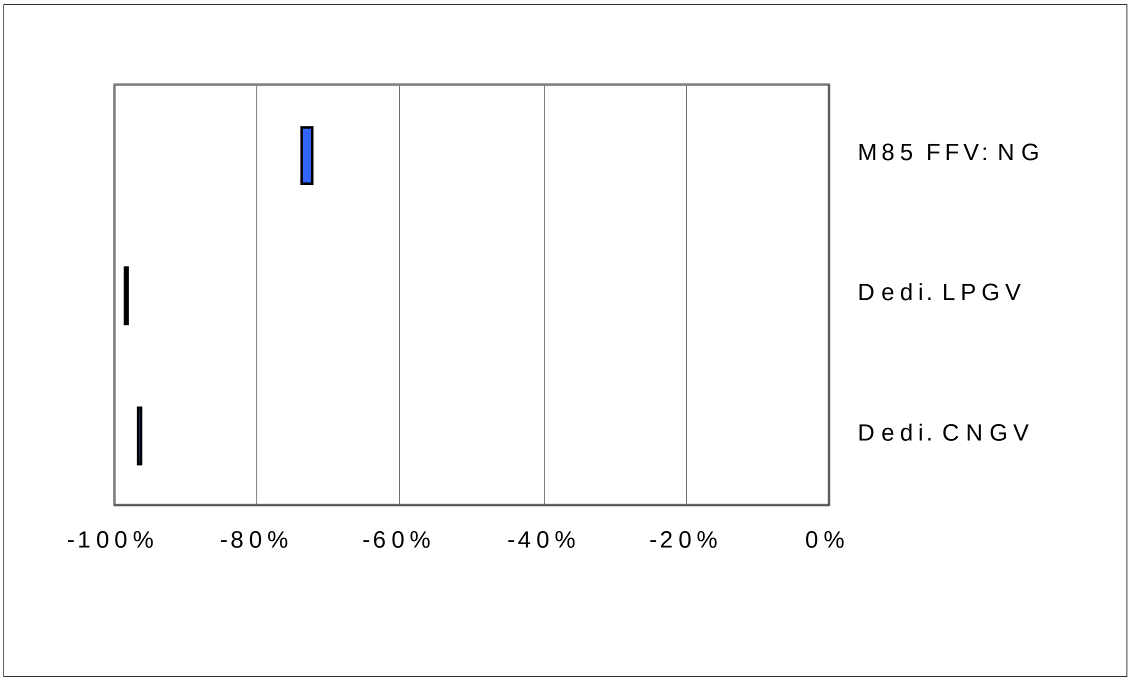

Figure 5.57 Near-Term Technologies: Urban SO_x Emission Changes (relative to baseline GV fueled with CG)

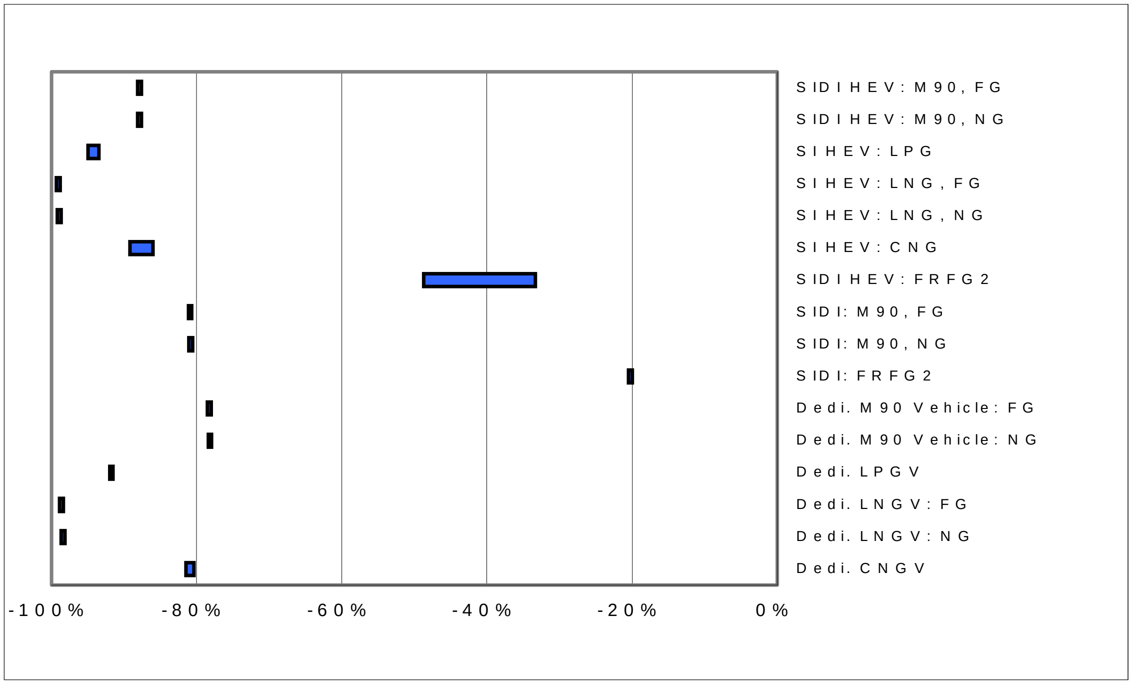

Figure 5.58 Long-Term SI Engine Technologies: Urban SO_x Emission Changes (relative to baseline GV fueled with RFG)

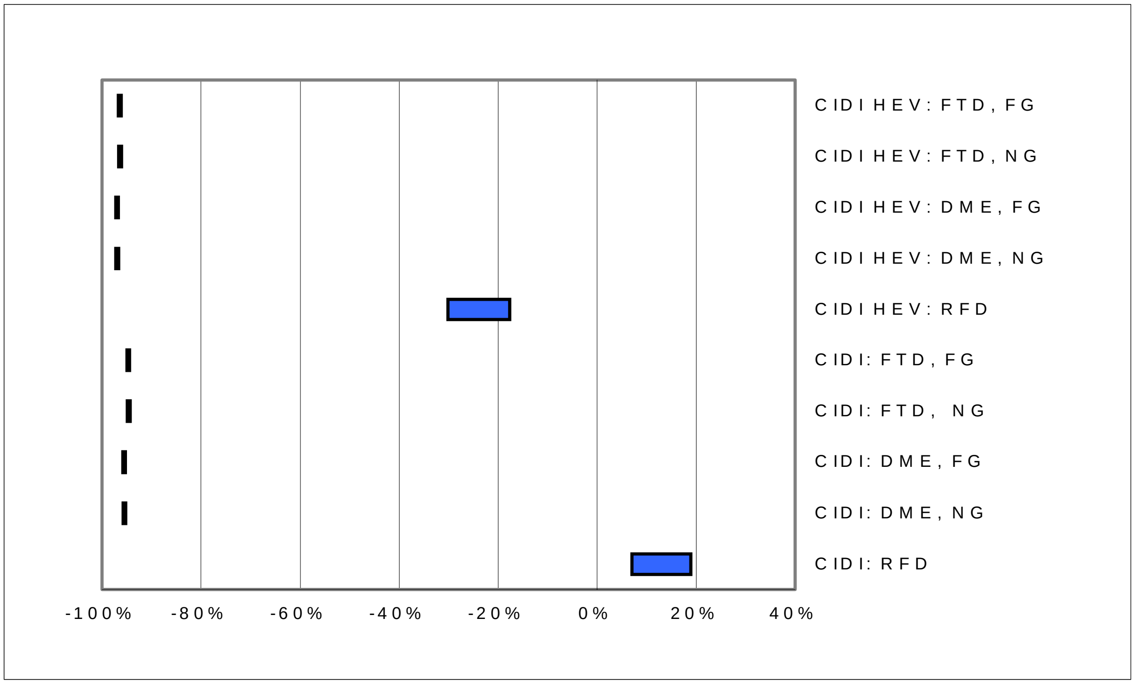

Figure 5.59 Long-Term CI Engine Technologies: Urban SO_x Emission Changes (relative to baseline GV fueled with RFG)

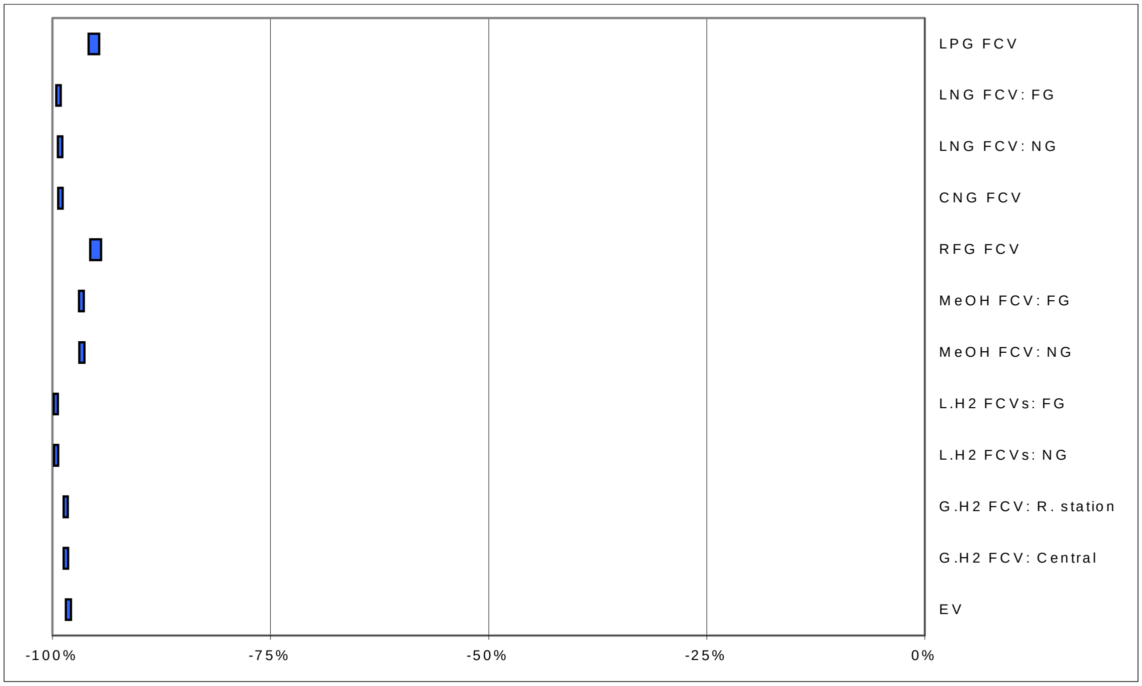

Figure 5.60 Long-Term EV and FCV Technologies: Urban SO_x Emission Changes (relative to baseline GV fueled with RFG)

Use of DME and FTD in CIDI engines results in greater than 90% reductions in urban SO_x emissions because these fuels are virtually sulfur free. Use of RFD in CIDI engines could result in a small increase in urban SO_x emissions because RFD has a higher sulfur content than RFG. However, use of RFD in CIDI HEVs, which have high fuel economy, results in a moderate reduction in SO_x emissions.

Use of FCVs and EVs achieves greater than 90% reductions in urban SO_x emissions.

Section 6
Conclusions

Because of its abundance and because it offers significant energy and environmental advantages, NG has been promoted for use in motor vehicles. Each transportation fuel produced from NG is distinct in terms of upstream production activities and combustion characteristics. As this study shows, use of different NG-based fuels can have significantly different energy and emissions impacts.

Table 6.1 provides a qualitative summary of energy and emission impacts of all the combinations of fuels and vehicle technologies evaluated in our study. Because energy sources, CO_2 emissions, and SO_x emissions are less important than other items, we do not present these three items in the table.

As Table 6.1 shows, use of NG-based fuels can help reduce per-mile fossil energy use considerably and almost eliminate petroleum use in most cases. Except for near-term M85 FFVs, all the technology options included in this study help reduce GHG emissions, although the magnitude of the reductions depends on the conversion efficiencies of upstream fuel production activities and vehicle fuel economies. Use of these technologies results in reductions in both total and urban VOC emissions. Use of gaseous fuels (CNG, LNG, and LPG) and FCV technologies reduces CO emissions significantly. CIDI technology options may result in increased NO_x emissions, especially urban NO_x emissions. Most technologies reduce PM_{10} emissions. If FG, instead of NG, is used to produce liquid fuels, energy and emission benefits generally increase significantly.

Although our study reveals relative energy and emissions benefits for NG-based fuels, selecting one fuel over the others for motor vehicle applications requires that far more factors than just energy and emission impacts be considered. Researchers must also consider the costs of producing and distributing the fuels, the availability of fuel production and distribution infrastructure, and projected advancements in vehicle technologies to best decide which NG-based fuel(s) should be introduced for motor vehicle applications. This study examines only a small piece of the puzzle in selecting the best NG-based transportation fuel.

Our assessment of new vehicle technologies and new transportation fuels is subject to great uncertainties. We developed the incremental and leap-forward scenarios to cover a reasonable range of changes in energy use and emissions. However, our two scenarios by no means cover the whole spectrum of the uncertainties involved in the fuels and vehicle technologies evaluated here.

Table 6.1 Summary of Energy and Emission Impacts of NG-Based Fuels

Technology	Fossil Energy Use	Petroleum Energy Use	GHGs	Total VOC	Urban VOC	Total CO	Urban CO	Total NO_x	Urban NO_x	Total PM_{10}	Urban PM_{10}
Near-Term Technologies											
CNGVs	0	+++++	+	++++	++++	++	++	--	--	++	++
LPGVs	+	+++++	+	++++	+++	++	++	+	0	+++	++
M85 FFVs	-	++++	-	+	+	++	++	-	+	++	++
Long-Term Technologies: NG as Feedstock											
CNGVs	+	+++++	++	++++	+++	++	++	--	-----	++	++
LNGVs	+	+++++	++	+++	+++	++	++	----	+	++	++
LPGVs	+	+++++	++	+++	+++	++	++	++	0	++	++
M90 Vehicles	-	++++	+	+	+	0	0	-	+	++	+
SIDI: RFG	+	++	++	+	+	0	0	+	0	0	0
SIDI: M90	+	+++++	++	++	+	0	0	+	+	+	0
SIDI HEVs: RFG	++	+++	+++	++	++	0	0	++	+	+	0
SIDI HEVs: M90	++	+++++	+++	++	++	0	0	+	+	++	+
SI HEVs: CNG	++	+++++	+++	++++	+++	+++	++	+	----	++	+
SI HEVs: LNG	++	+++++	+++	++++	+++	+++	++	-	+	++	+
SI HEVs: LPG	++	+++++	+++	++++	+++	+++	++	+++	+	++	+
CIDI: RFD	++	++	++	++++	++++	0	0	+	---	+	0
CIDI: DME	+	+++++	++	++++	++++	0	0	+	--	++	+
CIDI: FTD	-	+++++	+	++++	++++	0	0	+	--	++	+
CIDI HEVs: RFD	+++	+++	+++	++++	++++	0	0	++	--	+	0
CIDI HEVs: DME	++	+++++	+++	++++	++++	0	0	++	--	++	+
CIDI HEVs: FTD	++	+++++	+++	++++	++++	0	0	++	--	++	+
Evs	+++	+++++	++++	+++++	+++++	+++++	+++++	--	++	++	++
FCVs: GH_2, Central	+++	+++++	++++	+++++	+++++	+++++	+++++	+++	+++++	+++	++
FCVs: GH_2, Station	+++	+++++	+++	+++++	+++++	+++++	+++++	++	++	++	++
FCVs: LH_2	+++	+++++	+++	+++++	+++++	+++++	+++++	+++	+++++	+++	++
FCVs: MeOH	+++	+++++	+++	++++	++++	++++	+++++	+++	+++++	+++	++

Table 6.1 Summary of Energy and Emission Impacts of NG-Based Fuels (Cont.)

Technology	Fossil Energy Use	Petroleum Energy Use	GHGs	Total VOC	Urban VOC	Total CO	Urban CO	Total NO$_x$	Urban NO$_x$	Total PM$_{10}$	Urban PM$_{10}$
FCVs: RFG	+++	+++	+++	+++++	+++++	++++	+++++	+++	++++	++	++
FCVs: CNG	+++	+++++	+++	+++++	+++++	++++	+++++	++	+	+++	++
FCVs: LNG	+++	+++++	+++	+++++	+++++	++++	+++++	+	++++	+++	++
FCVs: LPG	+++	+++++	++++	+++++	+++++	++++	+++++	++++	++++	+++	++
Long-Term Technologies: FG as Feedstock											
LNGVs	+++++	+++++	+++++	+++	+++	++	++	++	+	++++	++
M90 Vehicles	++++	++++	++++	++	+	0	0	+++++	+	+++	+
SIDI: M90	+++++	+++++	+++++	++	+	0	0	+++++	+	+++	0
SIDI HEVs: M90	+++++	+++++	+++++	++	++	0	0	+++++	+	+++	+
SI HEVs: LNG	+++++	+++++	+++++	++++	+++	+++	++	+++	+	+++	+
CIDI: DME	+++++	+++++	+++++	+++++	++++	0	0	+++++	--	++++	+
CIDI: FTD	+++++	+++++	+++++	++++	++++	0	0	+++++	--	++++	+
CIDI HEVs: DME	+++++	+++++	+++++	+++++	++++	0	0	+++++	--	+++	+
CIDI HEVs: FTD	+++++	+++++	+++++	++++	++++	0	0	+++++	--	++++	+
FCVs: LH$_2$	+++++	+++++	+++++	+++++	+++++	+++++	+++++	+++++	+++++	+++	++
FCVs: MeOH	+++++	+++++	+++++	++++	++++	+++++	+++++	+++++	+++++	++++	++
FCVs: LNG	+++++	+++++	+++++	+++++	+++++	+++++	+++++	++++	++++	++++	++

Notes:

0: no change
+: reductions of 0–20%
++: reductions of 20–40%
+++: reductions of 40–60%
++++: reductions of 60–80%
+++++: reductions of greater than 80%
-: increases of 0–20%
--: increases of 20–40%
---: increases of 40–60%
----: increases of 60–80%
-----: increases of greater than 80%

Section 7
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Appendix A

Per-Mile Fuel-Cycle Energy Use and Emissions

This appendix presents per-mile fuel-cycle energy use (in Btu/mi) and emissions (in g/mi) for all the fuel and vehicle technology options evaluated. The results are presented for vehicle types in the following order: near-term technologies/incremental scenario, near-term technologies/leap-forward scenario, long-term technologies/incremental scenario, and long-term technologies/leap-forward scenario.

Per-mile results for each technology are presented separately for each of the three stages of a fuel cycle: feedstock, fuel, and vehicle operations. The feedstock stage includes activities from feedstock recovery to feedstock delivered at fuel production plants. The fuel stage includes activities from feedstock at fuel production plants to fuel at refueling stations. The vehicle operations stage includes activities from fuel at refueling stations to completion of onboard fuel combustion.

A-I Near-Term Technologies

A-I.1 The Incremental Scenario

	Baseline Conv. GV: CG			Dedicated CNGV			Dedicated LPGV		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	190	1,140	5,156	533	718	5,544	316	354	5,156
Fossil fuels	168	1,093	5,156	524	550	5,544	316	354	5,156
Petroleum	49	543	5,073	26	11	0	23	77	0
VOC: Total	0.018	0.073	0.207	0.027	0.018	0.061	0.008	0.024	0.093
VOC: Urban	0.000	0.025	0.207	0.002	0.014	0.061	0.000	0.015	0.093
CO: Total	0.080	0.049	5.517	0.113	0.042	4.414	0.065	0.033	3.752
CO: Urban	0.000	0.007	5.517	0.004	0.030	4.414	0.000	0.009	3.752
NOx: Total	0.052	0.135	0.275	0.173	0.162	0.275	0.057	0.054	0.275
NOx: Urban	0.000	0.012	0.275	0.011	0.083	0.275	0.000	0.014	0.275
PM10: Total	0.003	0.015	0.033	0.005	0.007	0.022	0.002	0.004	0.022
PM10: Urban	0.000	0.001	0.033	0.000	0.001	0.022	0.000	0.001	0.022
SOx: Total	0.015	0.100	0.050	0.019	0.093	0.002	0.013	0.004	0.000
SOx: Urban	0.000	0.001	0.050	0.000	0.000	0.002	0.000	0.001	0.000
CH4	0.466	0.113	0.084	1.094	0.106	0.840	0.535	0.043	0.134
N2O	0.000	0.001	0.028	0.001	0.001	0.028	0.000	0.000	0.028
CO2	18	66	390	37	45	330	25	23	369
GHGs	28	69	401	61	47	356	36	24	380

	MeOH FFV: M85, NG		
	Feedstock	Fuel	Vehicle Operation
Total energy	277	2,416	5,156
Fossil fuels	277	2,416	5,156
Petroleum	29	260	1,336
VOC: Total	0.011	0.058	0.207
VOC: Urban	0.000	0.010	0.207
CO: Total	0.069	0.170	4.414
CO: Urban	0.000	0.003	4.414
NOx: Total	0.054	0.175	0.275
NOx: Urban	0.000	0.006	0.275
PM10: Total	0.002	0.010	0.026
PM10: Urban	0.000	0.000	0.026
SOx: Total	0.010	0.029	0.013
SOx: Urban	0.000	0.001	0.013
CH4	0.517	0.148	0.042
N2O	0.000	0.001	0.028
CO2	23	92	374
GHGs	34	96	384

A-I Long-Term Technologies

A-I.2 The Leap-Forward Scenario

	Baseline Conv. GV: CG			Dedicated CNGV			Dedicated LPGV		
	Feedstock	**Fuel**	**Vehicle Operation**	**Feedstock**	**Fuel**	**Vehicle Operation**	**Feedstock**	**Fuel**	**Vehicle Operation**
Total energy	190	1,140	5,156	495	668	5,156	301	337	4,911
Fossil fuels	168	1,093	5,156	488	511	5,156	301	337	4,911
Petroleum	49	543	5,073	24	10	0	22	73	0
VOC: Total	0.018	0.073	0.207	0.025	0.017	0.029	0.008	0.023	0.069
VOC: Urban	0.000	0.025	0.207	0.002	0.013	0.029	0.000	0.015	0.069
CO: Total	0.080	0.049	5.517	0.106	0.039	2.648	0.062	0.031	2.869
CO: Urban	0.000	0.007	5.517	0.004	0.028	2.648	0.000	0.009	2.869
NOx: Total	0.052	0.135	0.275	0.161	0.151	0.248	0.054	0.051	0.248
NOx: Urban	0.000	0.012	0.275	0.010	0.078	0.248	0.000	0.014	0.248
PM10: Total	0.003	0.015	0.033	0.004	0.006	0.022	0.002	0.004	0.022
PM10: Urban	0.000	0.001	0.033	0.000	0.001	0.022	0.000	0.001	0.022
SOx: Total	0.015	0.100	0.050	0.017	0.086	0.002	0.012	0.004	0.000
SOx: Urban	0.000	0.001	0.050	0.000	0.000	0.002	0.000	0.001	0.000
CH4	0.466	0.113	0.084	1.018	0.099	0.840	0.509	0.041	0.109
N2O	0.000	0.001	0.028	0.001	0.000	0.014	0.000	0.000	0.028
CO2	18	66	390	35	42	307	24	22	351
GHGs	28	69	401	56	44	329	35	23	362

	MeOH FFV: M85, NG		
	Feedstock	**Fuel**	**Vehicle Operation**
Total energy	264	2,301	4,911
Fossil fuels	264	2,301	4,911
Petroleum	28	248	1,273
VOC: Total	0.010	0.055	0.176
VOC: Urban	0.000	0.009	0.176
CO: Total	0.066	0.162	3.310
CO: Urban	0.000	0.003	3.310
NOx: Total	0.052	0.166	0.248
NOx: Urban	0.000	0.006	0.248
PM10: Total	0.002	0.009	0.026
PM10: Urban	0.000	0.000	0.026
SOx: Total	0.010	0.028	0.013
SOx: Urban	0.000	0.001	0.013
CH4	0.492	0.141	0.042
N2O	0.000	0.001	0.028
CO2	22	88	356
GHGs	32	91	366

A-II Long-Term Technologies

A-II.1 The Incremental Scenario

	Baseline Conv. GV: FRFG2			Dedicated CNGV			Dedicated LNGV, NG			Dedicated LNGV, FG		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	169	1,028	4,678	428	570	4,455	282	806	4,455	277	-4,151	4,455
Fossil fuels	153	995	4,678	422	463	4,455	278	797	4,455	277	-4,151	4,455
Petroleum	44	424	4,105	20	8	0	20	79	0	20	165	0
VOC: Total	0.015	0.064	0.125	0.010	0.007	0.062	0.004	0.031	0.062	0.004	0.019	0.062
VOC: Urban	0.000	0.023	0.125	0.001	0.004	0.062	0.000	0.003	0.062	0.000	0.002	0.062
CO: Total	0.073	0.068	2.759	0.090	0.034	2.207	0.057	0.124	2.207	0.057	0.005	2.207
CO: Urban	0.000	0.008	2.759	0.003	0.023	2.207	0.000	0.006	2.207	0.000	0.005	2.207
NOx: Total	0.044	0.127	0.036	0.132	0.117	0.036	0.048	0.284	0.036	0.047	0.073	0.036
NOx: Urban	0.000	0.013	0.036	0.008	0.064	0.036	0.000	0.009	0.036	0.000	0.008	0.036
PM10: Total	0.002	0.014	0.031	0.004	0.005	0.023	0.002	0.008	0.023	0.002	-0.011	0.023
PM10: Urban	0.000	0.001	0.031	0.000	0.001	0.023	0.000	0.001	0.023	0.000	0.001	0.023
SOx: Total	0.009	0.069	0.007	0.014	0.048	0.001	0.013	0.007	0.000	0.011	0.002	0.000
SOx: Urban	0.000	0.001	0.007	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
CH4	0.423	0.219	0.065	0.879	0.090	0.325	0.468	0.493	0.325	0.468	-0.134	0.325
N2O	0.000	0.001	0.028	0.001	0.001	0.014	0.000	0.001	0.014	0.000	-0.004	0.014
CO2	16	68	354	30	37	266	22	46	263	22	-257	263
GHGs	25	73	364	49	39	277	32	57	274	32	-261	274

	Dedicated LPGV			Dedicated MeOH Vehicle: M90, NG			Dedicated MeOH Vehicle: M90, FG		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	265	318	4,252	246	2,137	4,252	239	-3,193	4,252
Fossil fuels	262	297	4,252	240	2,121	4,252	239	-3,193	4,252
Petroleum	19	64	0	23	178	800	22	177	800
VOC: Total	0.004	0.019	0.068	0.006	0.046	0.125	0.006	0.032	0.125
VOC: Urban	0.000	0.013	0.068	0.000	0.006	0.125	0.000	0.006	0.125
CO: Total	0.054	0.027	2.207	0.056	0.156	2.759	0.056	0.020	2.759
CO: Urban	0.000	0.008	2.207	0.000	0.002	2.759	0.000	0.002	2.759
NOx: Total	0.045	0.047	0.036	0.044	0.142	0.036	0.043	-0.115	0.036
NOx: Urban	0.000	0.011	0.036	0.000	0.004	0.036	0.000	0.005	0.036
PM10: Total	0.002	0.004	0.023	0.002	0.008	0.027	0.002	-0.012	0.027
PM10: Urban	0.000	0.001	0.023	0.000	0.000	0.027	0.000	0.000	0.027
SOx: Total	0.012	0.012	0.000	0.011	0.023	0.001	0.009	0.014	0.001
SOx: Urban	0.000	0.001	0.000	0.000	0.001	0.001	0.000	0.001	0.001
CH4	0.441	0.033	0.072	0.431	0.143	0.033	0.431	-0.200	0.033
N2O	0.000	0.000	0.028	0.000	0.001	0.028	0.000	-0.004	0.028
CO2	21	21	304	20	81	310	19	-231	310
GHGs	30	22	314	29	85	319	29	-236	319

A-II Long-Term Technologies

A-II.1 The Incremental Scenario (Cont.)

	SIDI Vehicle: FRFG2			SIDI Dedicated MeOH Vehicle: M90, NG			SIDI Dedicated MeOH Vehicle: M90, FG		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	122	793	3,742	216	1,732	3,742	210	-2,952	3,742
Fossil fuels	122	793	3,742	211	1,723	3,742	210	-2,952	672
Petroleum	35	338	3,284	20	96	704	20	95	704
VOC: Total	0.012	0.051	0.119	0.006	0.034	0.119	0.005	0.023	0.119
VOC: Urban	0.000	0.018	0.119	0.000	0.006	0.119	0.000	0.006	0.119
CO: Total	0.058	0.054	2.759	0.049	0.128	2.759	0.049	0.009	2.759
CO: Urban	0.000	0.006	2.759	0.000	0.002	2.759	0.000	0.002	2.759
NOx: Total	0.033	0.096	0.036	0.039	0.109	0.036	0.038	-0.117	0.036
NOx: Urban	0.001	0.011	0.036	0.000	0.004	0.036	0.000	0.004	0.036
PM10: Total	0.002	0.010	0.035	0.002	0.005	0.031	0.002	-0.012	0.031
PM10: Urban	0.000	0.001	0.035	0.000	0.000	0.031	0.000	0.000	0.031
SOx: Total	0.002	0.042	0.006	0.010	0.010	0.001	0.008	0.005	0.001
SOx: Urban	0.000	0.001	0.006	0.000	0.001	0.001	0.000	0.000	0.001
CH4	0.339	0.179	0.065	0.379	0.094	0.033	0.379	-0.208	0.033
N2O	0.000	0.001	0.028	0.000	0.001	0.028	0.000	-0.004	0.028
CO2	12	52	283	18	62	273	17	-212	273
GHGs	19	56	293	26	64	282	25	-218	282

	CIDI Vehicle: RFD			CIDI Vehicle: DME, NG			CIDI Vehicle: DME, FG		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	113	619	3,465	216	1,773	3,465	213	-3,352	3,465
Fossil fuels	113	619	3,465	213	1,764	3,465	213	-3,352	0
Petroleum	32	314	3,465	15	91	0	15	91	0
VOC: Total	0.011	0.020	0.049	0.003	0.019	0.034	0.003	-0.005	0.034
VOC: Urban	0.000	0.006	0.049	0.000	0.001	0.034	0.000	0.001	0.034
CO: Total	0.054	0.032	2.759	0.044	0.112	2.759	0.044	-0.021	2.759
CO: Urban	0.000	0.004	2.759	0.000	0.001	2.759	0.000	0.001	2.759
NOx: Total	0.030	0.072	0.063	0.037	0.083	0.063	0.036	-0.167	0.063
NOx: Urban	0.001	0.008	0.063	0.000	0.002	0.063	0.000	0.002	0.063
PM10: Total	0.001	0.009	0.031	0.002	0.002	0.031	0.002	-0.017	0.031
PM10: Urban	0.000	0.001	0.031	0.000	0.000	0.031	0.000	0.000	0.031
SOx: Total	0.002	0.038	0.009	0.010	0.008	0.000	0.009	0.003	0.000
SOx: Urban	0.000	0.000	0.009	0.000	0.000	0.000	0.000	0.000	0.000
CH4	0.313	0.056	0.011	0.359	0.012	0.022	0.359	-0.237	0.022
N2O	0.000	0.001	0.016	0.000	0.000	0.016	0.000	-0.006	0.016
CO2	11	44	280	17	66	243	17	-234	243
GHGs	18	45	285	25	66	249	24	-241	249

A-II Long-Term Technologies

A-II.1 The Incremental Scenario (Cont.)

	CIDI Vehicle: FTD, NG			CIDI Vehicle: FTD, FG			SIDI HEV: FRFG2		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	216	3,096	3,465	212	-3,156	3,465	101	661	3,118
Fossil fuels	213	3,087	3,465	212	-3,157	0	101	661	3,118
Petroleum	15	113	0	15	113	0	29	282	2,737
VOC: Total	0.003	0.007	0.049	0.003	-0.008	0.049	0.010	0.042	0.106
VOC: Urban	0.000	0.000	0.049	0.000	0.000	0.049	0.000	0.015	0.088
CO: Total	0.044	0.108	2.759	0.044	-0.051	2.759	0.048	0.045	2.759
CO: Urban	0.000	0.001	2.759	0.000	0.001	2.759	0.000	0.005	2.759
NOx: Total	0.037	0.069	0.063	0.036	-0.224	0.063	0.027	0.080	0.036
NOx: Urban	0.000	0.002	0.063	0.000	0.002	0.063	0.001	0.009	0.036
PM10: Total	0.002	0.000	0.031	0.002	-0.022	0.031	0.001	0.008	0.033
PM10: Urban	0.000	0.000	0.031	0.000	0.000	0.031	0.000	0.001	0.033
SOx: Total	0.010	0.007	0.000	0.009	0.003	0.000	0.002	0.035	0.005
SOx: Urban	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.005
CH4	0.359	0.011	0.011	0.359	-0.295	0.011	0.282	0.149	0.065
N2O	0.000	0.000	0.016	0.000	-0.007	0.016	0.000	0.001	0.028
CO2	17	100	268	17	-234	268	10	43	236
GHGs	25	100	273	24	-243	273	16	47	246

	SI HEV: CNG			SI HEV: LNG, NG			SI HEV: LNG, FG		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	316	328	3,341	208	596	3,341	208	-3,113	3,341
Fossil fuels	316	328	3,341	208	596	3,341	208	-3,113	3,341
Petroleum	15	1	0	15	59	0	15	123	0
VOC: Total	0.007	0.004	0.062	0.003	0.023	0.062	0.003	0.014	0.062
VOC: Urban	0.000	0.003	0.062	0.000	0.002	0.062	0.000	0.002	0.062
CO: Total	0.067	0.024	2.207	0.043	0.093	2.207	0.043	0.004	2.207
CO: Urban	0.002	0.018	2.207	0.000	0.005	2.207	0.000	0.004	2.207
NOx: Total	0.098	0.071	0.036	0.035	0.211	0.036	0.035	0.055	0.036
NOx: Urban	0.006	0.051	0.036	0.000	0.007	0.036	0.000	0.006	0.036
PM10: Total	0.003	0.002	0.023	0.002	0.006	0.023	0.002	-0.008	0.023
PM10: Urban	0.000	0.001	0.023	0.000	0.001	0.023	0.000	0.000	0.023
SOx: Total	0.009	0.001	0.001	0.008	0.002	0.000	0.008	0.001	0.000
SOx: Urban	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
CH4	0.659	0.075	0.325	0.351	0.371	0.325	0.351	-0.100	0.325
N2O	0.000	0.000	0.014	0.000	0.001	0.014	0.000	-0.003	0.014
CO2	22	20	199	16	34	197	16	-193	197
GHGs	36	22	211	24	42	208	24	-196	208

A-II Long-Term Technologies

A-II.1 The Incremental Scenario (Cont.)

	SI HEV: LPG			SIDI HEV: M90, NG			SIDI HEV: M90, FG		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	205	229	3,341	135	1,194	2,399	135	-1,801	2,399
Fossil fuels	205	229	3,341	135	1,194	2,399	135	-1,801	431
Petroleum	15	50	0	13	100	451	13	100	451
VOC: Total	0.003	0.015	0.068	0.003	0.026	0.106	0.003	0.018	0.106
VOC: Urban	0.000	0.010	0.068	0.000	0.004	0.106	0.000	0.004	0.106
CO: Total	0.042	0.021	2.207	0.031	0.088	2.759	0.031	0.011	2.759
CO: Urban	0.000	0.006	2.207	0.000	0.001	2.759	0.000	0.001	2.759
NOx: Total	0.035	0.033	0.036	0.024	0.079	0.036	0.024	-0.065	0.036
NOx: Urban	0.000	0.009	0.036	0.000	0.003	0.036	0.000	0.003	0.036
PM10: Total	0.002	0.003	0.023	0.001	0.004	0.030	0.001	-0.007	0.030
PM10: Urban	0.000	0.001	0.023	0.000	0.000	0.030	0.000	0.000	0.030
SOx: Total	0.008	0.002	0.000	0.005	0.009	0.001	0.005	0.008	0.001
SOx: Urban	0.000	0.001	0.000	0.000	0.000	0.001	0.000	0.000	0.001
CH4	0.347	0.028	0.072	0.243	0.081	0.033	0.243	-0.113	0.033
N2O	0.000	0.000	0.028	0.000	0.001	0.028	0.000	-0.002	0.028
CO2	16	15	239	11	45	175	11	-130	175
GHGs	24	16	249	16	47	184	16	-133	184

	CIDI HEV: RFD			CIDI HEV: DME, NG			CIDI HEV: DME, FG		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	78	429	2,399	150	1,228	2,399	147	-2,321	2,399
Fossil fuels	78	429	2,399	148	1,221	2,399	147	-2,321	0
Petroleum	22	217	2,399	11	63	0	11	63	0
VOC: Total	0.008	0.014	0.049	0.002	0.013	0.034	0.002	-0.004	0.034
VOC: Urban	0.000	0.004	0.049	0.000	0.001	0.034	0.000	0.001	0.034
CO: Total	0.037	0.022	2.759	0.030	0.077	2.759	0.030	-0.014	2.759
CO: Urban	0.000	0.003	2.759	0.000	0.001	2.759	0.000	0.001	2.759
NOx: Total	0.021	0.050	0.063	0.025	0.058	0.063	0.025	-0.116	0.063
NOx: Urban	0.000	0.006	0.063	0.000	0.001	0.063	0.000	0.001	0.063
PM10: Total	0.001	0.006	0.031	0.001	0.001	0.031	0.001	-0.012	0.031
PM10: Urban	0.000	0.000	0.031	0.000	0.000	0.031	0.000	0.000	0.031
SOx: Total	0.001	0.026	0.006	0.007	0.005	0.000	0.006	0.002	0.000
SOx: Urban	0.000	0.000	0.006	0.000	0.000	0.000	0.000	0.000	0.000
CH4	0.217	0.039	0.011	0.249	0.008	0.022	0.249	-0.164	0.022
N2O	0.000	0.000	0.016	0.000	0.000	0.016	0.000	-0.004	0.016
CO2	8	31	194	12	46	168	12	-162	168
GHGs	12	31	199	17	46	174	17	-167	174

A-II Long-Term Technologies

A-II.1 The Incremental Scenario (Cont.)

	CIDI HEV: FTD			CIDI HEV: FTD, FG			EV		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	150	2,143	2,399	147	-2,185	2,399	245	2,594	0
Fossil fuels	148	2,137	2,399	147	-2,185	0	245	2,594	0
Petroleum	11	78	0	11	78	0	12	0	0
VOC: Total	0.002	0.005	0.049	0.002	-0.006	0.049	0.006	0.004	0.000
VOC: Urban	0.000	0.000	0.049	0.000	0.000	0.049	0.000	0.001	0.000
CO: Total	0.030	0.075	2.759	0.030	-0.035	2.759	0.052	0.010	0.000
CO: Urban	0.000	0.001	2.759	0.000	0.001	2.759	0.002	0.002	0.000
NOx: Total	0.025	0.048	0.063	0.025	-0.155	0.063	0.076	0.203	0.000
NOx: Urban	0.000	0.001	0.063	0.000	0.002	0.063	0.005	0.041	0.000
PM10: Total	0.001	0.000	0.031	0.001	-0.015	0.031	0.002	0.009	0.021
PM10: Urban	0.000	0.000	0.031	0.000	0.000	0.031	0.000	0.002	0.021
SOx: Total	0.007	0.005	0.000	0.006	0.002	0.000	0.007	0.001	0.000
SOx: Urban	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CH4	0.249	0.008	0.011	0.249	-0.204	0.011	0.512	0.006	0.000
N2O	0.000	0.000	0.016	0.000	-0.005	0.016	0.000	0.003	0.000
CO2	12	69	186	12	-162	186	17	155	0
GHGs	17	69	191	17	-168	191	28	156	0

	GH2 FCV: Central			GH2 FCV: Refueling Stations			LH2 FCV: NG		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	105	917	1,671	160	1,337	1,671	106	1,726	1,671
Fossil fuels	103	915	1,671	158	1,191	1,671	105	1,667	1,671
Petroleum	7	4	0	8	13	0	8	35	0
VOC: Total	0.002	0.006	0.000	0.004	0.007	0.000	0.002	0.010	0.000
VOC: Urban	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.001	0.000
CO: Total	0.021	0.070	0.000	0.034	0.074	0.000	0.022	0.084	0.000
CO: Urban	0.000	0.003	0.000	0.001	0.058	0.000	0.000	0.001	0.000
NOx: Total	0.018	0.083	0.000	0.049	0.104	0.000	0.018	0.106	0.000
NOx: Urban	0.000	0.008	0.000	0.003	0.032	0.000	0.000	0.003	0.000
PM10: Total	0.001	0.003	0.021	0.001	0.007	0.021	0.001	0.007	0.021
PM10: Urban	0.000	0.000	0.021	0.000	0.002	0.021	0.000	0.000	0.021
SOx: Total	0.005	0.002	0.000	0.005	0.066	0.000	0.005	0.006	0.000
SOx: Urban	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CH4	0.174	0.040	0.000	0.330	0.100	0.000	0.177	0.146	0.000
N2O	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.002	0.000
CO2	8	152	0	11	181	0	8	199	0
GHGs	12	153	0	18	184	0	12	203	0

A-II Long-Term Technologies

A-II.1 The Incremental Scenario (Cont.)

	LH2 FCV: FG			FCV: MeOH, NG			FCV: MeOH, FG		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	0	-509	1,671	139	1,257	2,227	137	-2,142	2,227
Fossil fuels	0	-527	1,671	137	1,250	2,227	137	-2,142	0
Petroleum	0	36	0	10	70	0	10	69	0
VOC: Total	0.000	0.000	0.000	0.002	0.023	0.038	0.002	0.014	0.038
VOC: Urban	0.000	0.001	0.000	0.000	0.002	0.038	0.000	0.002	0.038
CO: Total	0.000	0.016	0.000	0.028	0.092	0.552	0.028	0.006	0.552
CO: Urban	0.000	0.001	0.000	0.000	0.001	0.552	0.000	0.001	0.552
NOx: Total	0.000	-0.020	0.000	0.023	0.078	0.007	0.023	-0.086	0.007
NOx: Urban	0.000	0.003	0.000	0.000	0.001	0.007	0.000	0.002	0.007
PM10: Total	0.000	-0.003	0.021	0.001	0.004	0.021	0.001	-0.009	0.021
PM10: Urban	0.000	0.000	0.021	0.000	0.000	0.021	0.000	0.000	0.021
SOx: Total	0.000	0.004	0.000	0.006	0.007	0.000	0.005	0.004	0.000
SOx: Urban	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CH4	0.000	-0.067	0.000	0.231	0.068	0.013	0.231	-0.151	0.013
N2O	0.000	-0.001	0.000	0.000	0.001	0.006	0.000	-0.003	0.006
CO2	0	67	0	11	45	161	11	-154	161
GHGs	0	65	0	16	46	163	16	-158	163

	FCV: RFG			FCV: CNG		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	85	559	2,673	257	342	2,673
Fossil fuels	85	559	2,673	253	278	2,673
Petroleum	25	241	2,346	12	5	0
VOC: Total	0.008	0.036	0.057	0.006	0.004	0.016
VOC: Urban	0.000	0.013	0.057	0.000	0.003	0.016
CO: Total	0.041	0.039	0.552	0.054	0.020	0.552
CO: Urban	0.000	0.004	0.552	0.002	0.014	0.552
NOx: Total	0.023	0.068	0.007	0.079	0.070	0.007
NOx: Urban	0.000	0.008	0.007	0.005	0.038	0.007
PM10: Total	0.001	0.007	0.021	0.002	0.003	0.021
PM10: Urban	0.000	0.001	0.021	0.000	0.001	0.021
SOx: Total	0.001	0.030	0.000	0.008	0.029	0.000
SOx: Urban	0.000	0.000	0.000	0.000	0.000	0.000
CH4	0.242	0.127	0.013	0.528	0.054	0.065
N2O	0.000	0.001	0.006	0.000	0.000	0.006
CO2	8	36	202	18	22	160
GHGs	14	39	204	29	24	163

A-II Long-Term Technologies

A-II.1 The Incremental Scenario (Cont.)

	FCV: LNG, NG			FCV: LNG, FG			FCV: LPG		
	Feedstock	**Fuel**	**Vehicle Operation**	**Feedstock**	**Fuel**	**Vehicle Operation**	**Feedstock**	**Fuel**	**Vehicle Operation**
Total energy	169	484	2,673	166	-2,491	2,673	167	200	2,673
Fossil fuels	167	478	2,673	166	-2,491	2,673	164	187	2,673
Petroleum	12	47	0	12	99	0	12	40	0
VOC: Total	0.002	0.018	0.016	0.002	0.011	0.016	0.002	0.012	0.016
VOC: Urban	0.000	0.002	0.016	0.000	0.001	0.016	0.000	0.008	0.016
CO: Total	0.034	0.075	0.552	0.034	0.003	0.552	0.034	0.017	0.552
CO: Urban	0.000	0.004	0.552	0.000	0.003	0.552	0.000	0.005	0.552
NOx: Total	0.029	0.170	0.007	0.028	0.044	0.007	0.028	0.029	0.007
NOx: Urban	0.000	0.005	0.007	0.000	0.005	0.007	0.000	0.007	0.007
PM10: Total	0.001	0.005	0.021	0.001	-0.006	0.021	0.001	0.002	0.021
PM10: Urban	0.000	0.000	0.021	0.000	0.000	0.021	0.000	0.001	0.021
SOx: Total	0.008	0.004	0.000	0.007	0.001	0.000	0.008	0.008	0.000
SOx: Urban	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CH4	0.281	0.296	0.065	0.281	-0.080	0.065	0.277	0.021	0.013
N2O	0.000	0.001	0.006	0.000	-0.003	0.006	0.000	0.000	0.006
CO2	13	28	160	13	-154	160	13	13	160
GHGs	19	34	163	19	-157	163	19	14	162

A-II Long-Term Technologies

A-II.2 The Leap-Forward Scenario

	Baseline Conv. GV: FRFG2			Dedicated CNGV			Dedicated LNGV, NG			Dedicated LNGV, FG		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	168	1,019	4,678	408	472	4,252	269	769	4,252	264	-3,964	4,252
Fossil fuels	153	986	4,678	403	383	4,252	265	761	4,252	264	-3,964	4,252
Petroleum	44	424	4,105	20	6	0	19	75	0	19	157	0
VOC: Total	0.015	0.064	0.125	0.009	0.006	0.059	0.004	0.029	0.059	0.004	0.018	0.059
VOC: Urban	0.000	0.023	0.125	0.001	0.004	0.059	0.000	0.003	0.059	0.000	0.002	0.059
CO: Total	0.073	0.068	2.759	0.086	0.028	1.655	0.054	0.119	1.655	0.054	0.005	1.655
CO: Urban	0.000	0.008	2.759	0.003	0.019	1.655	0.000	0.006	1.655	0.000	0.005	1.655
NOx: Total	0.044	0.127	0.036	0.126	0.097	0.036	0.045	0.271	0.036	0.045	0.069	0.036
NOx: Urban	0.000	0.012	0.036	0.008	0.053	0.036	0.000	0.008	0.036	0.000	0.007	0.036
PM10: Total	0.002	0.014	0.031	0.004	0.004	0.023	0.002	0.008	0.023	0.002	-0.010	0.023
PM10: Urban	0.000	0.001	0.031	0.000	0.001	0.023	0.000	0.001	0.023	0.000	0.001	0.023
SOx: Total	0.009	0.069	0.007	0.013	0.040	0.001	0.012	0.007	0.000	0.011	0.002	0.000
SOx: Urban	0.000	0.001	0.007	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
CH4	0.423	0.219	0.065	0.839	0.074	0.325	0.447	0.471	0.325	0.447	-0.128	0.325
N2O	0.000	0.001	0.028	0.001	0.000	0.014	0.000	0.001	0.014	0.000	-0.004	0.014
CO2	16	67	354	29	31	254	21	44	251	21	-245	251
GHGs	25	72	364	47	33	265	31	54	262	30	-249	262

	Dedicated LPGV			Dedicated MeOH Vehicle: M90, NG			Dedicated MeOH Vehicle: M90, FG		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	254	304	4,068	245	1,897	4,252	238	-3,196	4,252
Fossil fuels	250	284	4,068	240	1,882	4,252	238	-3,196	4,252
Petroleum	18	62	0	23	177	800	22	177	800
VOC: Total	0.004	0.018	0.065	0.006	0.046	0.125	0.006	0.032	0.125
VOC: Urban	0.000	0.012	0.065	0.000	0.006	0.125	0.000	0.006	0.125
CO: Total	0.051	0.026	1.655	0.056	0.154	2.759	0.056	0.020	2.759
CO: Urban	0.000	0.007	1.655	0.000	0.002	2.759	0.000	0.002	2.759
NOx: Total	0.043	0.045	0.036	0.044	0.140	0.036	0.043	-0.116	0.036
NOx: Urban	0.000	0.010	0.036	0.000	0.004	0.036	0.000	0.005	0.036
PM10: Total	0.002	0.004	0.023	0.002	0.008	0.027	0.002	-0.012	0.027
PM10: Urban	0.000	0.001	0.023	0.000	0.000	0.027	0.000	0.000	0.027
SOx: Total	0.012	0.012	0.000	0.011	0.023	0.001	0.009	0.014	0.001
SOx: Urban	0.000	0.001	0.000	0.000	0.001	0.001	0.000	0.001	0.001
CH4	0.422	0.032	0.072	0.431	0.139	0.033	0.431	-0.201	0.033
N2O	0.000	0.000	0.028	0.000	0.001	0.028	0.000	-0.004	0.028
CO2	20	20	291	20	68	310	19	-231	310
GHGs	29	21	301	29	71	319	28	-237	319

A-II Long-Term Technologies

A-II.2 The Leap-Forward Scenario (Cont.)

	SIDI Vehicle: FRFG2			SIDI Dedicated MeOH Vehicle: M90, NG			SIDI Dedicated MeOH Vehicle: M90, FG		
	Feedstock	**Fuel**	**Vehicle Operation**	**Feedstock**	**Fuel**	**Vehicle Operation**	**Feedstock**	**Fuel**	**Vehicle Operation**
Total energy	119	783	3,742	216	1,522	3,742	209	-2,953	3,742
Fossil fuels	119	783	3,742	211	1,514	3,742	209	-2,953	672
Petroleum	35	338	3,284	20	95	704	20	95	704
VOC: Total	0.012	0.051	0.119	0.006	0.034	0.119	0.005	0.023	0.119
VOC: Urban	0.000	0.018	0.119	0.000	0.006	0.119	0.000	0.006	0.119
CO: Total	0.058	0.054	2.759	0.049	0.127	2.759	0.049	0.009	2.759
CO: Urban	0.000	0.006	2.759	0.000	0.002	2.759	0.000	0.002	2.759
NOx: Total	0.033	0.095	0.036	0.039	0.107	0.036	0.038	-0.117	0.036
NOx: Urban	0.001	0.011	0.036	0.000	0.004	0.036	0.000	0.004	0.036
PM10: Total	0.002	0.010	0.035	0.002	0.005	0.031	0.002	-0.012	0.031
PM10: Urban	0.000	0.001	0.035	0.000	0.000	0.031	0.000	0.000	0.031
SOx: Total	0.002	0.042	0.006	0.010	0.010	0.001	0.008	0.005	0.001
SOx: Urban	0.000	0.001	0.006	0.000	0.001	0.001	0.000	0.000	0.001
CH4	0.339	0.178	0.065	0.379	0.090	0.033	0.379	-0.208	0.033
N2O	0.000	0.001	0.028	0.000	0.001	0.028	0.000	-0.004	0.028
CO2	12	51	283	18	50	273	17	-212	273
GHGs	19	55	293	26	52	282	25	-218	282

	CIDI Vehicle: RFD			CIDI Vehicle: DME, NG			CIDI Vehicle: DME, FG		
	Feedstock	**Fuel**	**Vehicle Operation**	**Feedstock**	**Fuel**	**Vehicle Operation**	**Feedstock**	**Fuel**	**Vehicle Operation**
Total energy	99	554	3,118	194	1,527	3,118	191	-3,019	3,118
Fossil fuels	99	554	3,118	192	1,519	3,118	191	-3,019	0
Petroleum	29	282	3,118	14	82	0	14	81	0
VOC: Total	0.010	0.018	0.049	0.003	0.017	0.034	0.003	-0.004	0.034
VOC: Urban	0.000	0.005	0.049	0.000	0.001	0.034	0.000	0.001	0.034
CO: Total	0.048	0.029	2.759	0.039	0.101	2.759	0.039	-0.017	2.759
CO: Urban	0.000	0.004	2.759	0.000	0.001	2.759	0.000	0.001	2.759
NOx: Total	0.027	0.065	0.063	0.033	0.075	0.063	0.032	-0.147	0.063
NOx: Urban	0.001	0.007	0.063	0.000	0.002	0.063	0.000	0.002	0.063
PM10: Total	0.001	0.008	0.031	0.002	0.001	0.026	0.001	-0.016	0.026
PM10: Urban	0.000	0.001	0.031	0.000	0.000	0.026	0.000	0.000	0.026
SOx: Total	0.002	0.034	0.008	0.009	0.007	0.000	0.008	0.002	0.000
SOx: Urban	0.000	0.000	0.008	0.000	0.000	0.000	0.000	0.000	0.000
CH4	0.282	0.050	0.011	0.323	0.011	0.022	0.323	-0.210	0.022
N2O	0.000	0.001	0.016	0.000	0.000	0.016	0.000	-0.005	0.016
CO2	10	39	252	15	56	219	15	-211	219
GHGs	16	41	257	22	56	224	22	-217	224

A-II Long-Term Technologies

A-II.2 The Leap-Forward Scenario (Cont.)

	CIDI Vehicle: FTD, NG			CIDI Vehicle: FTD, FG			SIDI HEV: FRFG2		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	194	2,807	3,118	191	-2,855	3,118	76	502	2,399
Fossil fuels	192	2,799	3,118	191	-2,855	0	76	502	2,399
Petroleum	14	102	0	14	100	0	22	217	2,105
VOC: Total	0.003	0.007	0.049	0.003	-0.007	0.049	0.008	0.033	0.106
VOC: Urban	0.000	0.000	0.049	0.000	0.000	0.049	0.000	0.012	0.088
CO: Total	0.039	0.098	2.759	0.039	-0.040	2.759	0.037	0.035	2.759
CO: Urban	0.000	0.001	2.759	0.000	0.001	2.759	0.000	0.004	2.759
NOx: Total	0.033	0.063	0.063	0.032	-0.192	0.063	0.021	0.061	0.036
NOx: Urban	0.000	0.002	0.063	0.000	0.002	0.063	0.000	0.007	0.036
PM10: Total	0.002	0.000	0.026	0.001	-0.019	0.026	0.001	0.006	0.033
PM10: Urban	0.000	0.000	0.026	0.000	0.000	0.026	0.000	0.001	0.033
SOx: Total	0.009	0.006	0.000	0.008	0.003	0.000	0.001	0.027	0.004
SOx: Urban	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004
CH4	0.323	0.010	0.011	0.323	-0.256	0.011	0.217	0.114	0.065
N2O	0.000	0.000	0.016	0.000	-0.006	0.016	0.000	0.000	0.028
CO2	15	91	241	15	-203	241	8	33	181
GHGs	22	91	246	22	-211	246	12	35	192

	SI HEV: CNG			SI HEV: LNG, NG			SI HEV: LNG, FG		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	245	213	2,599	161	463	2,599	161	-2,423	2,599
Fossil fuels	245	213	2,599	161	463	2,599	161	-2,423	2,599
Petroleum	12	1	0	12	46	0	12	96	0
VOC: Total	0.006	0.003	0.059	0.002	0.018	0.059	0.002	0.011	0.059
VOC: Urban	0.000	0.002	0.059	0.000	0.002	0.059	0.000	0.001	0.059
CO: Total	0.052	0.016	1.655	0.033	0.072	1.655	0.033	0.003	1.655
CO: Urban	0.002	0.012	1.655	0.000	0.004	1.655	0.000	0.003	1.655
NOx: Total	0.076	0.047	0.036	0.027	0.164	0.036	0.027	0.042	0.036
NOx: Urban	0.005	0.034	0.036	0.000	0.005	0.036	0.000	0.004	0.036
PM10: Total	0.002	0.001	0.023	0.001	0.004	0.023	0.001	-0.006	0.023
PM10: Urban	0.000	0.001	0.023	0.000	0.000	0.023	0.000	0.000	0.023
SOx: Total	0.007	0.001	0.001	0.006	0.002	0.000	0.006	0.001	0.000
SOx: Urban	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
CH4	0.513	0.049	0.325	0.273	0.288	0.325	0.273	-0.078	0.325
N2O	0.000	0.000	0.014	0.000	0.001	0.014	0.000	-0.003	0.014
CO2	17	13	155	13	26	153	13	-150	153
GHGs	28	14	166	19	33	164	19	-152	164

A-II Long-Term Technologies

A-II.2 The Leap-Forward Scenario (Cont.)

SI HEV: LPG

	Feedstock	Fuel	Vehicle Operation
Total energy	159	176	2,599
Fossil fuels	159	176	2,599
Petroleum	11	39	0
VOC: Total	0.002	0.011	0.065
VOC: Urban	0.000	0.008	0.065
CO: Total	0.033	0.016	1.655
CO: Urban	0.000	0.005	1.655
NOx: Total	0.027	0.026	0.036
NOx: Urban	0.000	0.007	0.036
PM10: Total	0.001	0.002	0.023
PM10: Urban	0.000	0.001	0.023
SOx: Total	0.006	0.002	0.000
SOx: Urban	0.000	0.000	0.000
CH4	0.270	0.021	0.072
N2O	0.000	0.000	0.028
CO2	13	12	186
GHGs	18	12	196

SIDI HEV: M90, NG

	Feedstock	Fuel	Vehicle Operation
Total energy	134	1,058	2,399
Fossil fuels	134	1,058	2,399
Petroleum	13	99	451
VOC: Total	0.003	0.026	0.106
VOC: Urban	0.000	0.004	0.106
CO: Total	0.031	0.087	2.759
CO: Urban	0.000	0.001	2.759
NOx: Total	0.024	0.077	0.036
NOx: Urban	0.000	0.003	0.036
PM10: Total	0.001	0.004	0.030
PM10: Urban	0.000	0.000	0.030
SOx: Total	0.005	0.009	0.001
SOx: Urban	0.000	0.000	0.001
CH4	0.243	0.079	0.033
N2O	0.000	0.001	0.028
CO2	11	38	175
GHGs	16	39	184

SIDI HEV: M90, FG

	Feedstock	Fuel	Vehicle Operation
Total energy	134	-1,803	2,399
Fossil fuels	134	-1,803	431
Petroleum	13	100	451
VOC: Total	0.003	0.018	0.106
VOC: Urban	0.000	0.004	0.106
CO: Total	0.031	0.011	2.759
CO: Urban	0.000	0.001	2.759
NOx: Total	0.024	-0.065	0.036
NOx: Urban	0.000	0.003	0.036
PM10: Total	0.001	-0.007	0.030
PM10: Urban	0.000	0.000	0.030
SOx: Total	0.005	0.008	0.001
SOx: Urban	0.000	0.000	0.001
CH4	0.243	-0.113	0.033
N2O	0.000	-0.003	0.028
CO2	11	-130	175
GHGs	16	-133	184

CIDI HEV: RFD

	Feedstock	Fuel	Vehicle Operation
Total energy	65	361	2,034
Fossil fuels	65	361	2,034
Petroleum	19	184	2,034
VOC: Total	0.006	0.011	0.049
VOC: Urban	0.000	0.003	0.049
CO: Total	0.032	0.019	2.759
CO: Urban	0.000	0.003	2.759
NOx: Total	0.018	0.042	0.063
NOx: Urban	0.000	0.005	0.063
PM10: Total	0.001	0.005	0.031
PM10: Urban	0.000	0.000	0.031
SOx: Total	0.001	0.022	0.005
SOx: Urban	0.000	0.000	0.005
CH4	0.184	0.033	0.011
N2O	0.000	0.000	0.016
CO2	6	26	164
GHGs	10	27	169

CIDI HEV: DME, NG

	Feedstock	Fuel	Vehicle Operation
Total energy	127	996	2,034
Fossil fuels	125	990	2,034
Petroleum	9	53	0
VOC: Total	0.002	0.011	0.034
VOC: Urban	0.000	0.001	0.034
CO: Total	0.026	0.066	2.759
CO: Urban	0.000	0.000	2.759
NOx: Total	0.021	0.049	0.063
NOx: Urban	0.000	0.001	0.063
PM10: Total	0.001	0.001	0.026
PM10: Urban	0.000	0.000	0.026
SOx: Total	0.006	0.004	0.000
SOx: Urban	0.000	0.000	0.000
CH4	0.211	0.007	0.022
N2O	0.000	0.000	0.016
CO2	10	36	143
GHGs	15	36	148

CIDI HEV: DME, FG

	Feedstock	Fuel	Vehicle Operation
Total energy	124	-1,969	2,034
Fossil fuels	124	-1,969	0
Petroleum	9	53	0
VOC: Total	0.002	-0.003	0.034
VOC: Urban	0.000	0.001	0.034
CO: Total	0.026	-0.011	2.759
CO: Urban	0.000	0.001	2.759
NOx: Total	0.021	-0.096	0.063
NOx: Urban	0.000	0.001	0.063
PM10: Total	0.001	-0.010	0.026
PM10: Urban	0.000	0.000	0.026
SOx: Total	0.005	0.001	0.000
SOx: Urban	0.000	0.000	0.000
CH4	0.211	-0.137	0.022
N2O	0.000	-0.003	0.016
CO2	10	-138	143
GHGs	14	-141	148

A-II Long-Term Technologies

A-II.2 The Leap-Forward Scenario (Cont.)

	CIDI HEV: FTD, NG			CIDI HEV: FTD, FG			EV		
	Feedstock	**Fuel**	**Vehicle Operation**	**Feedstock**	**Fuel**	**Vehicle Operation**	**Feedstock**	**Fuel**	**Vehicle Operation**
Total energy	127	1,831	2,034	124	-1,862	2,034	178	1,883	0
Fossil fuels	125	1,825	2,034	124	-1,862	0	178	1,883	0
Petroleum	9	66	0	9	65	0	9	0	0
VOC: Total	0.002	0.004	0.049	0.002	-0.004	0.049	0.004	0.003	0.000
VOC: Urban	0.000	0.000	0.049	0.000	0.000	0.049	0.000	0.001	0.000
CO: Total	0.026	0.064	2.759	0.026	-0.026	2.759	0.038	0.007	0.000
CO: Urban	0.000	0.001	2.759	0.000	0.001	2.759	0.001	0.001	0.000
NOx: Total	0.021	0.041	0.063	0.021	-0.125	0.063	0.055	0.147	0.000
NOx: Urban	0.000	0.001	0.063	0.000	0.001	0.063	0.004	0.029	0.000
PM10: Total	0.001	0.000	0.026	0.001	-0.012	0.026	0.001	0.007	0.021
PM10: Urban	0.000	0.000	0.026	0.000	0.000	0.026	0.000	0.001	0.021
SOx: Total	0.006	0.004	0.000	0.005	0.002	0.000	0.005	0.001	0.000
SOx: Urban	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CH4	0.211	0.007	0.011	0.211	-0.167	0.011	0.372	0.005	0.000
N2O	0.000	0.000	0.016	0.000	-0.004	0.016	0.000	0.002	0.000
CO2	10	59	157	10	-133	157	13	113	0
GHGs	15	59	163	14	-137	163	20	114	0

	GH2 FCV: Central			GH2 FCV: Refueling Stations			LH2 FCV: NG		
	Feedstock	**Fuel**	**Vehicle Operation**	**Feedstock**	**Fuel**	**Vehicle Operation**	**Feedstock**	**Fuel**	**Vehicle Operation**
Total energy	93	794	1,485	143	1,185	1,485	95	1,359	1,485
Fossil fuels	92	792	1,485	141	1,055	1,485	93	1,309	1,485
Petroleum	7	3	0	7	11	0	7	30	0
VOC: Total	0.001	0.005	0.000	0.003	0.006	0.000	0.001	0.008	0.000
VOC: Urban	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.001	0.000
CO: Total	0.019	0.062	0.000	0.030	0.066	0.000	0.019	0.072	0.000
CO: Urban	0.000	0.003	0.000	0.001	0.051	0.000	0.000	0.001	0.000
NOx: Total	0.016	0.072	0.000	0.044	0.092	0.000	0.016	0.086	0.000
NOx: Urban	0.000	0.007	0.000	0.003	0.029	0.000	0.000	0.003	0.000
PM10: Total	0.001	0.002	0.021	0.001	0.006	0.021	0.001	0.005	0.021
PM10: Urban	0.000	0.000	0.021	0.000	0.001	0.021	0.000	0.000	0.021
SOx: Total	0.004	0.002	0.000	0.005	0.059	0.000	0.004	0.005	0.000
SOx: Urban	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CH4	0.155	0.035	0.000	0.293	0.089	0.000	0.157	0.112	0.000
N2O	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.001	0.000
CO2	7	134	0	10	161	0	7	167	0
GHGs	11	135	0	16	163	0	11	169	0

A-II Long-Term Technologies

A-II.2 The Leap-Forward Scenario (Cont.)

	LH2 FCV: FG			FCV: MeOH, NG			FCV: MeOH, FG		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	0	-537	1,485	117	928	1,871	114	-1,800	1,871
Fossil fuels	0	-552	1,485	115	922	1,871	114	-1,800	0
Petroleum	0	31	0	8	58	0	8	58	0
VOC: Total	0.000	0.000	0.000	0.002	0.019	0.038	0.002	0.012	0.038
VOC: Urban	0.000	0.001	0.000	0.000	0.001	0.038	0.000	0.001	0.038
CO: Total	0.000	0.014	0.000	0.024	0.077	0.552	0.024	0.005	0.552
CO: Urban	0.000	0.001	0.000	0.000	0.001	0.552	0.000	0.001	0.552
NOx: Total	0.000	-0.019	0.000	0.020	0.064	0.007	0.019	-0.072	0.007
NOx: Urban	0.000	0.003	0.000	0.000	0.001	0.007	0.000	0.001	0.007
PM10: Total	0.000	-0.003	0.021	0.001	0.003	0.021	0.001	-0.007	0.021
PM10: Urban	0.000	0.000	0.021	0.000	0.000	0.021	0.000	0.000	0.021
SOx: Total	0.000	0.003	0.000	0.005	0.006	0.000	0.005	0.003	0.000
SOx: Urban	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CH4	0.000	-0.058	0.000	0.194	0.055	0.013	0.194	-0.127	0.013
N2O	0.000	-0.001	0.000	0.000	0.001	0.006	0.000	-0.002	0.006
CO2	0	54	0	9	30	135	9	-129	135
GHGs	0	52	0	13	32	137	13	-133	137

	FCV: RFG			FCV: CNG		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	66	435	2,079	200	231	2,079
Fossil fuels	66	435	2,079	197	187	2,079
Petroleum	19	188	1,824	10	3	0
VOC: Total	0.007	0.028	0.057	0.005	0.003	0.016
VOC: Urban	0.000	0.010	0.057	0.000	0.002	0.016
CO: Total	0.032	0.030	0.552	0.042	0.014	0.552
CO: Urban	0.000	0.003	0.552	0.002	0.009	0.552
NOx: Total	0.018	0.053	0.007	0.061	0.048	0.007
NOx: Urban	0.000	0.006	0.007	0.004	0.026	0.007
PM10: Total	0.001	0.006	0.021	0.002	0.002	0.021
PM10: Urban	0.000	0.000	0.021	0.000	0.000	0.021
SOx: Total	0.001	0.024	0.000	0.006	0.020	0.000
SOx: Urban	0.000	0.000	0.000	0.000	0.000	0.000
CH4	0.188	0.099	0.013	0.410	0.036	0.065
N2O	0.000	0.000	0.006	0.000	0.000	0.006
CO2	7	28	157	14	15	124
GHGs	11	30	159	23	16	128

A-II Long-Term Technologies

A-II.2 The Leap-Forward Scenario (Cont.)

	FCV: LNG, NG			FCV: LNG, FG			FCV: LPG		
	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation	Feedstock	Fuel	Vehicle Operation
Total energy	131	376	2,079	129	-1,938	2,079	130	155	2,079
Fossil fuels	130	372	2,079	129	-1,938	2,079	128	145	2,079
Petroleum	9	37	0	9	77	0	9	31	0
VOC: Total	0.002	0.014	0.016	0.002	0.009	0.016	0.002	0.009	0.016
VOC: Urban	0.000	0.001	0.016	0.000	0.001	0.016	0.000	0.006	0.016
CO: Total	0.027	0.058	0.552	0.027	0.002	0.552	0.026	0.013	0.552
CO: Urban	0.000	0.003	0.552	0.000	0.002	0.552	0.000	0.004	0.552
NOx: Total	0.022	0.132	0.007	0.022	0.034	0.007	0.022	0.023	0.007
NOx: Urban	0.000	0.004	0.007	0.000	0.004	0.007	0.000	0.005	0.007
PM10: Total	0.001	0.004	0.021	0.001	-0.005	0.021	0.001	0.002	0.021
PM10: Urban	0.000	0.000	0.021	0.000	0.000	0.021	0.000	0.000	0.021
SOx: Total	0.006	0.003	0.000	0.005	0.001	0.000	0.006	0.006	0.000
SOx: Urban	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CH4	0.218	0.230	0.065	0.218	-0.063	0.065	0.216	0.016	0.013
N2O	0.000	0.001	0.006	0.000	-0.002	0.006	0.000	0.000	0.006
CO2	10	22	124	10	-120	124	10	10	125
GHGs	15	27	128	15	-122	128	15	11	127

Appendix B

Change in Per-Mile Fuel-Cycle Energy Use and Emissions

This appendix presents numerical changes in fuel-cycle energy use and emissions by technology options relative to baseline gasoline vehicles. The values presented in this appendix were used to generate the charts presented in Section 5 of this report. Numerical changes are presented in the following order: near-term technologies/incremental scenario, near-term technologies/leap-forward scenario, long-term technologies/incremental scenario, and long-term technologies/leap-forward scenario.

B-I Near-Term Technologies

	The Incremental Scenario				The Leap-Forward Scenario		
	Dedicated CNGV	Dedicated LPGV	MeOH FFV: M85, NG		Dedicated CNGV	Dedicated LPGV	MeOH FFV: M85, NG
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%

B-II Long-Term Technologies

B-II.1 The Incremental Scenario

	Dedi. CNGV	Dedi. LNGV: NG	Dedi. LNGV: FG	Dedi. LPGV	Dedi. M90 Vehicle: NG	Dedi. M90 Vehicle: 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	GH2 FCV: Central	GH2 FCV: R. station	LH2 FCV: NG	LH2 FCV: 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%	-54.2%	-46.1%	-40.4%	-80.0%	-38.4%	-96.2%	-42.9%	-44.4%	-43.5%	-94.0%	-48.3%
Fossil fuels	-135.0%	-51.2%	-53.9%	-48.2%	-41.0%	-80.4%	-38.0%	-134.4%	-42.9%	-45.1%	-43.1%	-94.0%	-48.2%
Petroleum	-98.1%	-99.7%	-99.8%	-99.6%	-99.1%	-99.2%	-98.3%	-98.3%	-42.9%	-99.6%	-98.7%	-97.6%	-98.9%
VOC: Total	-77.5%	-95.5%	-96.5%	-94.9%	-94.7%	-100.0%	-70.1%	-73.6%	-50.2%	-87.6%	-82.5%	-85.6%	-85.6%
VOC: Urban	-66.7%	-99.3%	-99.7%	-97.7%	-99.5%	-99.5%	-73.4%	-73.4%	-53.0%	-87.5%	-88.3%	-88.6%	-84.1%
CO: Total	-5.0%	-97.9%	-96.9%	-96.3%	-96.4%	-99.4%	-76.8%	-79.8%	-78.2%	-78.4%	-77.2%	-79.7%	-79.2%
CO: Urban	-0.3%	-99.9%	-99.9%	-97.9%	-99.9%	-99.9%	-80.0%	-80.0%	-79.9%	-79.5%	-79.9%	-79.9%	-79.9%
NOx: Total	-134.1%	42.8%	-51.4%	-25.6%	-39.9%	-109.9%	-47.4%	-128.4%	-49.7%	-24.1%	-0.1%	-59.9%	-68.6%
NOx: Urban	27.9%	-9.9%	-84.2%	-27.5%	-94.1%	-94.1%	-82.2%	-82.3%	-69.4%	3.6%	-74.5%	-76.4%	-71.1%
PM10: Total	-62.7%	-28.6%	-47.3%	-36.7%	-39.0%	-60.6%	-45.2%	-71.2%	-35.6%	-43.7%	-42.2%	-65.3%	-47.2%
PM10: Urban	-2.9%	-28.3%	-33.7%	-29.1%	-33.5%	-33.6%	-34.0%	-34.1%	-32.6%	-31.9%	-33.0%	-33.2%	-32.5%
SOx: Total	-87.3%	-88.1%	-91.6%	-16.3%	-87.2%	-94.0%	-84.1%	-85.6%	-49.3%	-56.5%	-86.2%	-87.5%	-82.3%
SOx: Urban	-96.1%	-97.9%	-98.2%	-98.2%	-99.3%	-99.4%	-96.3%	-96.4%	-94.4%	-98.8%	-98.9%	-99.0%	-94.6%
CH4	-92.2%	-27.2%	-69.8%	-39.3%	-54.5%	-109.4%	-55.9%	-86.9%	-46.3%	-8.7%	-9.4%	-62.7%	-56.0%
N2O	-60.8%	-89.1%	-97.1%	-95.9%	-93.9%	-103.4%	-77.7%	-90.3%	-78.5%	-78.4%	-77.8%	-89.2%	-79.4%
CO2	-91.9%	-60.2%	-63.4%	-56.2%	-52.7%	-84.6%	-50.6%	-95.9%	-42.9%	-54.3%	-54.2%	-95.6%	-57.5%
GHGs	-91.3%	-59.7%	-64.3%	-56.4%	-53.6%	-85.8%	-51.3%	-95.5%	-43.7%	-53.3%	-53.2%	-94.4%	-57.9%

B-II Long-Term Technologies

B-II.2 The Leap-Forward Scenario

	Dedi. CNGV	Dedi. LNGV: NG	Dedi. LNGV: FG	Dedi. LPGV	Dedi. M90 Vehicle: NG	Dedi. M90 Vehicle: 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	GH2 FCV: Central	GH2 FCV: R. station	LH2 FCV: NG	LH2 FCV: FG	MeOH FCV: NG	MeOH FCV: FG	RFG FCV	CNG FCV	LNG FCV: NG	LNG FCV: FG	LPG FCV
Total energy	-64.5%	-59.6%	-52.1%	-50.0%	-83.7%	-50.4%	-96.8%	-55.6%	-57.3%	-56.0%	-95.4%	-59.7%
Fossil fuels	-64.5%	-59.3%	-54.0%	-50.4%	-83.9%	-50.1%	-129.0%	-55.6%	-57.7%	-55.7%	-95.4%	-59.6%
Petroleum	-99.8%	-99.8%	-99.6%	-99.2%	-99.3%	-98.6%	-98.5%	-55.6%	-99.7%	-99.0%	-98.1%	-99.1%
VOC: Total	-96.8%	-96.9%	-95.4%	-95.4%	-100.0%	-72.0%	-74.9%	-55.1%	-88.9%	-84.7%	-87.1%	-87.1%
VOC: Urban	-99.5%	-99.7%	-97.9%	-99.5%	-99.5%	-73.6%	-73.6%	-54.9%	-88.1%	-88.6%	-88.8%	-85.3%
CO: Total	-98.4%	-97.2%	-96.7%	-96.8%	-99.5%	-77.5%	-80.0%	-78.8%	-79.0%	-78.1%	-80.0%	-79.6%
CO: Urban	-99.9%	-99.9%	-98.1%	-100.0%	-100.0%	-80.0%	-80.0%	-79.9%	-79.7%	-80.0%	-80.0%	-79.9%
NOx: Total	4.2%	-57.2%	-33.9%	-50.5%	-109.6%	-55.8%	-123.4%	-60.1%	-43.5%	-21.4%	-67.9%	-74.8%
NOx: Urban	-34.4%	-86.1%	-35.6%	-94.7%	-94.7%	-82.7%	-82.9%	-73.0%	-23.9%	-76.9%	-78.4%	-74.2%
PM10: Total	-35.4%	-48.3%	-38.7%	-42.2%	-60.1%	-47.0%	-68.4%	-39.7%	-46.9%	-45.1%	-62.7%	-48.9%
PM10: Urban	-30.0%	-33.7%	-29.7%	-33.6%	-33.7%	-34.0%	-34.1%	-33.0%	-32.6%	-33.3%	-33.5%	-32.9%
SOx: Total	-91.4%	-92.6%	-25.6%	-89.4%	-95.0%	-86.8%	-87.9%	-60.5%	-69.5%	-89.2%	-90.3%	-86.2%
SOx: Urban	-98.5%	-98.4%	-98.4%	-99.4%	-99.5%	-96.9%	-97.0%	-95.7%	-99.2%	-99.1%	-99.3%	-95.8%
CH4	-47.0%	-73.2%	-46.1%	-62.0%	-108.2%	-63.0%	-88.7%	-57.8%	-27.7%	-27.4%	-68.9%	-65.4%
N2O	-92.1%	-97.5%	-96.4%	-95.2%	-103.1%	-78.3%	-88.8%	-79.0%	-79.0%	-78.5%	-87.4%	-79.7%
CO2	-71.0%	-67.7%	-61.0%	-60.3%	-87.6%	-60.1%	-96.6%	-55.6%	-64.9%	-64.3%	-96.6%	-66.9%
GHGs	-70.6%	-68.5%	-61.2%	-61.0%	-88.5%	-60.5%	-96.2%	-56.1%	-64.0%	-63.4%	-95.5%	-67.1%