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EMISSIONS OF GREENHOUSE GASES FROM THE USE OF TRANSPORTATION FUELS AND ELECTRICITY

VOLUME 1: SUMMARY

by

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FOREWORD

Argonne National Laboratory report ANL/ESD/TM-22 consists of two volumes. This first volume summarizes the results of the analyses presented in Volume 2. The second volume, a draft, comprises appendixes that provide detailed explanations and tables for their respective subject areas and a complete reference list of all the documents cited as sources in this report. The contents of the appendixes are as follows:

- Appendix A: Review of General Methods
- Appendix B: Emissions from Vehicles; Spills, Leaks, and Other Losses of Fuel; and Heavy-Duty and Light-Duty Emission Factors Combined
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Copies of Volume 1 are available from the National Technical Information Service (NTIS), U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161. Copies of the Volume 2 draft are available from Mark DeLuchi, Institute of Transportation Studies, University of California, Davis, California 95616.

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The estimates made within this report are my own and do not necessarily represent values that are endorsed by any of the reviewers or sponsoring organizations.

NOTATION

ACRONYMS

CNG	compressed natural gas
CSNG	compressed synthetic natural gas
DDGS	distillers' dried grains and solubles
DOE	U.S. Department of Energy
E85	85% ethanol, 15% gasoline
EEC	European Economic Community
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
EV	electric vehicle (battery powered)
FBC	fluidized-bed combustion
FFV	flexible-fuel vehicle
HDV	heavy-duty vehicle
HHV	higher heating value
ICEV	internal-combustion-engine vehicle
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
LDV	light-duty vehicle
LH_2	liquefied hydrogen
LNG	liquefied natural gas
LPG	liquefied petroleum gas
LPM	liquid-phase methanol synthesis
M0	0% methanol, 100% gasoline
M50	50% methanol, 50% gasoline
M85	85% methanol, 15% gasoline
M100	100% methanol
NE	not estimated
NERC	North American Electric Reliability Council
NG	natural gas
NGL	natural gas liquids
NMHC	nonmethane hydrocarbon
NMOC	nonmethane organic compound (used interchangeably with NMHC)
NRC	National Research Council
OECD	Organization for Economic Cooperation and Development
OTM	once-through methanol
RVP	Reid vapor pressure
SNG	synthetic natural gas
SRIC	short-rotation intensive cultivation
VMT	vehicle miles traveled

CHEMICALS

C	carbon

CFC	chlorofluorocarbon
CFC-12	Freon (CF_2Cl_2)
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
Fe	iron
H_2	hydrogen
MeOH	methanol
MTBE	methyl tertiary butyl ether
N_2O	nitrous oxide
NO_x	nitrogen oxides
O_3	ozone
SO_x	sulfur oxides
Ti	titanium

UNITS OF MEASURE

ft^3	cubic foot
g	gram
gal	gallon
kg	kilogram
kWh	kilowatt-hour
L	liter
lb	pound
mi	mile
mpg	miles per gallon
psi	pound per square inch
quad	10^{15} Btu
t	metric ton (2,200 lb)
Tg	teragram (10^{12} grams)
ton	short ton (2,000 lb)

EMISSIONS OF GREENHOUSE GASES FROM THE USE OF TRANSPORTATION FUELS AND ELECTRICITY

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ABSTRACT

This report presents estimates of full fuel-cycle emissions of greenhouse gases from using transportation fuels and electricity. The data cover emissions of carbon dioxide (CO_2), methane, carbon monoxide, nitrous oxide, nitrogen oxides, and nonmethane organic compounds resulting from the end use of fuels, compression or liquefaction of gaseous transportation fuels, fuel distribution, fuel production, feedstock transport, feedstock recovery, manufacture of motor vehicles, maintenance of transportation systems, manufacture of materials used in major energy facilities, and changes in land use that result from using biomass-derived fuels. The results for electricity use are in grams of CO_2-equivalent emissions per kilowatt-hour of electricity delivered to end users and cover generating plants powered by coal, oil, natural gas, methanol, biomass, and nuclear energy. The transportation analysis compares CO_2-equivalent emissions, in grams per mile, from base-case gasoline and diesel fuel cycles with emissions from these alternative-fuel cycles: methanol from coal, natural gas, or wood; compressed or liquefied natural gas; synthetic natural gas from wood; ethanol from corn or wood; liquefied petroleum gas from oil or natural gas; hydrogen from nuclear or solar power; electricity from coal, uranium, oil, natural gas, biomass, or solar energy, used in battery-powered electric vehicles; and hydrogen and methanol used in fuel-cell vehicles.

1 INTRODUCTION

1.1 NEED FOR AND PURPOSE OF REPORT

In recent years, there has been a considerable amount of interdisciplinary research done on the causes and consequences of global climate change (Bolin et al., 1986; Ramanathan, 1988; MacCracken, 1989; Mahlman, 1989; *Climate Change*, 1990). Most scientists now believe that an increase in anthropogenic emissions of greenhouse gases -- primarily carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3) precursors, and chlorofluorocarbons (CFCs) -- will probably change the climate of the earth (*Climate Change*, 1990).

As concern about global climate change has grown, evaluating various energy policies in terms of greenhouse gas emissions has become increasingly important. Energy use accounts for a major fraction of all anthropogenic emissions of greenhouse gases (*Climate Change*, 1990). In particular, the use of transportation fuels and electricity accounts for most energy-use-related CO_2 emissions (Marland and Pippin, 1990). And in the United States and the other developed countries, CO_2 emissions from the use of motor vehicles alone (including emissions from feedstock recovery, processing, and distribution and from vehicle manufacture) have constituted up to 30% of the total CO_2 emissions from the use of all fossil fuels (Table 1).*

In the transportation field, concern about the greenhouse effect is coinciding with a serious interest in developing alternatives to gasoline and diesel fuel (DOE, *Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector*, 1990, and other reports in this series; EPA, August 1990; EPA, September 1989; IEA, *Substitute Fuels for Road Transport*, 1990; U.S. Congress, *Replacing Gasoline*, 1990; EPA, *Clean Air Act Amendments of 1990*, 1990; EPA, *Analysis of the Economics and Environmental Effects of Ethanol as an Automotive Fuel*, 1990; EPA, *Analysis of the Economic and Environmental Effects of Compressed Natural Gas as a Vehicle Fuel*, 1990).† Policymakers and energy analysts want to know if these alternatives -- methanol, ethanol, natural gas (NG), hydrogen, electricity, and liquefied petroleum gas (LPG) -- which can improve urban air quality and reduce the consumption of foreign oil, would also mitigate or exacerbate global warming. Concern about emissions of greenhouse gases is also beginning to figure prominently in the debate over how best to meet the future demand for electricity (DOE Energy
Information Administration [EIA], *Improving Technology, Modeling Energy Futures for the National Energy Strategy,* 1991; IEA, *Energy and the Environment, Policy Overview*, 1989).

This report is designed to help policymakers and analysts understand the effect of energy options on global climate change, through its analysis of greenhouse gas emissions from the production, distribution, and use of transportation fuels and electricity in the year 2000. In particular, it is meant to enable a detailed understanding of how specific technological, economic, and behavioral aspects of the use of energy affect greenhouse gas emissions.

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*In most other countries, the use of motor vehicles contributes less to energy-related CO_2 emissions than it does in the developed countries of the West. In other countries, the extent of automobile ownership and number of vehicle miles traveled (VMT) per capita are several times smaller than they are in the West. Also, the development of the transportation sector usually lags behind the development of other sectors, such as electricity-generating sectors. These facts suggest that as these countries progress, motor transportation will become an increasingly important source of CO_2 emissions in the developing countries of the world.

†References are called out in this volume in the same way that they are called out in Volume 2 of this document. Titles or months are given only when more than one document by a particular author that is published in a particular year is listed in App. S, which is the list of references for the entire document. DOE = U.S. Department of Energy; EPA = U.S. Environmental Protection Agency; and IEA = International Energy Agency.

TABLE 1 Contribution of Highway Fuel Use to Total CO_2 Emissions for Selected Countries

		End-Use Fuel Consumption by Transportation Sector (quads)			Total Fossil Fuel Consumption by All Sectors (quads)[d]			Carbon from Total Fossil Fuel Consumption by All Sectors (Tg)[e]	Carbon from Fuel Consumption by Transportation Sector: Tg		Carbon from Fuel Consumption by Transportation Sector: % of Total Fossil Fuel Carbon Emitted by All Sectors	
Country	Year	Gasoline[a]	Diesel[b]	LPG[c]	Coal	Petroleum	NG		From End Use[f]	From Full Fuel Cycle[g]	From End Use[h]	From Full Fuel Cycle[i]
U.S.	1988	13.68	2.78	0.03	18.87	34.23	18.55	1,455.0	319.8	433.3	22.0	29.8
West Germany	1988	1.18	0.60	0.00	2.47	5.01	2.03	195.2	34.5	45.9	17.7	23.5
Norway	1988	0.08	0.03	0.00	0.03	0.37	0.06	9.0	2.1	2.9	23.6	31.6
Japan	1988	1.30	0.98	0.07	2.98	9.69	1.65	296.4	45.8	60.2	15.4	20.3
U.S.S.R.	1987	3.14	0.13	0.00	13.69	19.07	20.94	1,049.8	63.2	86.8	6.0	8.3
Poland	1988	0.16	0.08	0.00	4.95	0.73	0.47	153.5	4.6	6.1	3.0	4.0
Indonesia	1988	0.17	0.19	0.00	0.13	1.10	0.50	32.6	7.0	9.1	21.3	27.8
India	1987	0.12	0.59	0.00	3.73	2.07	0.23	144.1	13.9	17.5	9.7	12.2
Mexico	1988	0.68	0.07	0.00	0.20	3.27	0.89	83.4	14.5	19.8	17.4	23.8
Argentina	1988	0.19	0.19	0.00	0.28	0.97	0.70	37.0	7.3	9.6	19.8	25.9
Nigeria	1987	0.16	0.05	0.00	0.03	0.44	0.14	11.6	4.1	5.6	35.7	47.9
A	B	C	D	E	F	G	H	I	J	K	L	M

[a]Data on gasoline consumption for the United States, West Germany, Norway, and Japan came from International Energy Agency (IEA) statistics on metric tons of motor gasoline used in road transport (IEA, *Energy Statistics of OECD Countries, 1987-1988*, 1990). I converted metric tons to quads (1 quad = 10^{15} Btu) using the values shown in Table C.1 of this report. For all other countries, gasoline consumption was calculated from U.S. Department of Energy/Energy Information Administration (EIA) statistics on barrels of motor gasoline consumption (EIA, *International Energy Annual 1989*, 1991). I assumed that 97.6% of total motor gasoline consumption occurs during road transport. This is the percentage given for Organization for Economic Cooperation and Development (OECD) countries by IEA (1990) in *Energy Statistics of OECD Countries, 1987-1988*; a small amount of motor gasoline is used by outboard motors and in other applications.

TABLE 1 (Cont'd)

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[b]Data on diesel fuel consumption for the United States, West Germany, Norway, and Japan came from IEA statistics on metric tons of diesel fuel used in road transport (IEA, *Energy Statistics of OECD Countries, 1987-1988,* 1990). I converted metric tons to quads using the values shown in Table C.1 of this report. For all other countries, diesel fuel consumption was calculated as the difference between the total amount of oil energy consumed in road transport, as reported by the IEA (1990) in *World Energy Statistics and Balances, 1985-1988,* and the amount of gasoline energy consumed in road transport (Column C; see footnote a above). This method assumes, quite reasonably in most cases, that all oil used in road transport is either gasoline or diesel fuel. An extremely small amount of kerosene and residual fuel oil are used for road transport. Because the amount is so small (less than 0.05% of total highway fuel energy use), and because kerosene and residual fuel oil are similar to diesel fuel, I counted these fuels as diesel fuel. In addition, a very small amount of natural gas (NG) (0.05% of total highway energy use) is used as a highway fuel, mostly in Italy and New Zealand. I ignored this. The use of natural gas in the U.S.S.R. is not accounted for.

[c]Data on liquefied petroleum gas (LPG) consumption for the United States, West Germany, Norway, and Japan came from IEA statistics on metric tons of motor gasoline used in road transport (IEA, *Energy Statistics of OECD Countries, 1987-1988*, 1990). I assumed that the other countries do not use LPG as a highway fuel.

[d]Data came from EIA world energy consumption statistics (EIA, *International Energy Annual 1989*, 1991).

[e]Teragrams (1 Tg = 10^{12} g) of carbon derived from fossil fuel use are equal to kilograms (1 kg = 10^3 g) of carbon/10^6 Btu of fuel multiplied by quads of fuel consumed (Columns F-H). I assumed worldwide values for carbon emission factors of 14.556 kg of carbon/10^6 Btu of NG, 26.700 kg of carbon/10^6 Btu of coal, and 19.900 kg of carbon/10^6 Btu of petroleum. The carbon emission factor for NG is from Grubb (1989) and is consistent with the U.S. factor calculated in this report (Table C.3). To arrive at the factor for coal, I first calculated the average heating value of coal consumption worldwide, using EIA data. The result, 17.83 10^6 Btu/short ton (higher heating value or HHV), is between the HHV of bituminous coal and lignite; hence, I adopted a carbon emission factor for coal that is between the factors for bituminous and lignite, as given in Grubb (1989) and estimated in this report (App. C). I did a similar calculation for petroleum. According to EIA (*International_Energy Annual 1989*, 1991) data, 5.683 x 10^6 Btu of energy is contained in each barrel of petroleum consumed worldwide; this value is between the value for diesel fuel and gasoline.

[f]This represents the total for all road-transport fuels, which is the sum of the products obtained by multiplying quads of each road fuel consumed (Columns C-E) by kg of carbon/10^6 Btu for each road fuel. For each road fuel, kg of carbon/10^6 Btu factors are from Tables C.1 and C.3.

TABLE 1 (Cont'd)

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[g]The result from Column J, multiplied by the ratio of CO_2 emissions from the whole fuel production and use cycle (including vehicle manufacture) to CO_2 emissions from vehicles only. These ratios are 1.380:1 for gasoline (based on light-duty vehicles), 1.234:1 for diesel fuel (based on heavy-duty vehicles), and 1.272:1 for LPG (based on 94% of vehicle miles being traveled by light-duty vehicles and 6% by heavy-duty vehicles). The ratios were calculated from the greenhouse gas emissions model, with the following key changes: all NO_x and N_2O emissions were set equal to zero; all leaks, venting, and flaring of CH_4 were set equal to zero; nonmethane organic compound (NMOC), CO, and CH_4 combustion emissions were assumed to oxidize to CO_2 (with no other greenhouse effect); the value for miles per gallon (mpg) for gasoline vehicles was set to 20 (the current fleetwide mpg in the United States; pre-reformulation (current) gasoline was specified; and pre-reformulation diesel fuel was specified. These changes ensure that the model counted only the CO_2 emissions that result from the (complete) combustion of fossil fuel.

[h]Column J divided by Column I, multiplied by 100.

[i]Column K divided by Column I, mulitplied by 100.

1.2 ORGANIZATION OF REPORT

Volume 1, the main text of this report, provides an overview of the analysis that was done; it discusses data sources, the methods used, and results. However, only a few details on the methodology are given in the main text; most of that information is provided in the appendixes. The appendix topics are arranged as follows:

- A: Review of General Methods
- B: Emissions from Vehicles; Spills, Leaks, and Other Losses of Fuel; and Heavy-Duty and Light-Duty Emission Factors Combined
- C: Fuel Specifications and the Fate of Fuel Carbon
- D: Electricity Generation and Use
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- F: Coal
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- P: Greenhouse Gas Emissions from Making Material for Vehicles, Power Plants, Pipelines, Ships, Trains, etc., and from Assembling Vehicles
- Q: Chlorofluorocarbons, Ozone, and Water Vapor
- R: Scenarios for Europe and Japan
- S: References for Volumes 1 and 2

1.3 RESULTS OF REPORT

This report provides estimates of (1) the amount of energy used in various fuel cycles, (2) the types and amounts of greenhouse gas emissions related to energy production, (3) the types and amounts of greenhouse gas emissions associated with the use of electricity, and (4) the types and amounts of greenhouse gas emissions related to the use of alternative transportation fuels.

The first set of estimates shows the amount of process energy required at each stage of the fuel production and use cycle, per unit of product energy delivered to consumers or power plants. A fuel production and use cycle, or more simply, a fuel cycle, comprises all activities from resource extraction to fuel use by consumers. An example of one of these estimates would be the amount of energy (in Btu) consumed by a tanker truck per Btu of gasoline delivered to a service station. Results are reported for many fuel cycles: for gasoline, diesel fuel, and residual fuel from crude oil; for methanol from coal, NG, and wood; for NG; for synthetic natural gas (SNG) from wood; for ethanol from corn and wood; for LPG from oil or NG; for hydrogen from nuclear power; and for the coal and uranium fuel cycles.

The second set of estimates covers the total CO_2-equivalent greenhouse gas emissions that result from the recovery, processing, and delivery of energy products and feedstocks. The results are expressed as grams of CO_2-equivalent emissions, at each stage of the fuel cycle (except end-use combustion of the fuel), per million (10^6) Btu of energy delivered to the consumer. (The concept and derivation of "CO_2 equivalency" is explained in App. O.)

The third set of estimates shows the full fuel-cycle CO_2-equivalent emissions that result from the use of coal, oil, NG, uranium, biomass, and methanol to generate electricity. These results are expressed in grams of CO_2-equivalent emissions per kilowatt-hour (kWh) delivered to end users.

The fourth set of estimates gives data on the CO_2-equivalent emissions that result from the production and use of alternative fuels for transportation. Results are given in grams of CO_2-equivalent emissions per mile of travel. Included are the emissions that result from manufacturing the materials to make vehicles and from assembling the vehicles.

2 GREENHOUSE GASES AND GLOBAL CLIMATE CHANGE

2.1 BRIEF EXPLANATION

The earth absorbs short-wave radiation from the sun and radiates long-wave infrared energy back to the atmosphere. Water vapor, CO_2, and other trace gases absorb most of this outgoing energy and reradiate some of it back to the surface of the earth. An increase in the concentration of these infrared-absorbing gases will lead to an increase in the total amount of energy in the atmosphere. This warming of the atmosphere could shift global precipitation and temperature patterns, disrupt established crop-growing regions, raise the global mean sea level, increase incidents of severe weather, change the distribution and abundance of biota and pathogens, and, in the long run, melt portions of the polar ice sheets.*

CO_2 is expected to be responsible for about half of future global warming (*Climate Change*, 1990). The other infrared-absorbing trace gases -- CH_4, N_2O, O_3, and CFCs -- individually will be less important than CO_2, but together will contribute as much to future climate change as will CO_2 (*Climate Change*, 1990). (See Mooney et al., 1987; Bolle et al., 1986; Ramanathan et al., 1985; Wang et al., 1985; Wang and Molnar, 1985 for discussions of these other trace gases.)

The use of energy results in direct emissions of CO_2, CH_4, N_2O, CFCs, and water vapor. Ozone (O_3) as such is not emitted directly but rather is formed as a result of a complex series of chemical reactions involving nonmethane organic compounds (NMOCs), carbon monoxide (CO), nitrogen oxides (NO_x), and other compounds. In this analysis, emissions of CO, NO_x, and NMOCs are used as a proxy for O_3, a procedure that follows the precedent of the Intergovernmental Panel on Climate Change (IPCC) (Shine et al., 1990). These gases, which do not absorb strongly in infrared, affect the concentration of CO_2 and CH_4 as well as O_3.

This report estimates the global-warming potential of emissions of CO_2, CH_4, N_2O, CO, NMOC, and NO_x that result from the use of transportation fuels and electricity. In particular, Apps. M and N discuss CH_4 and N_2O as greenhouse gases and give a detailed review of the current emissions database. Appendix Q discusses how alternative fuels might affect global climate through the changes they could cause in the concentration of tropospheric ozone.

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*This explanation is highly simplified, and one must recognize that many important factors are not fully understood. Some of the more important uncertainties are related to (a) thermal and adsorptive response of the oceans; (b) feedback effect on climate of changes in precipitation, evaporation, and cloud cover that result from a "first-round" warming; (c) exact behavior of clouds; (d) changes in the rate of photosynthesis in the surface mixed layer of the oceans; (e) effect of increased levels of CO_2 on plant growth and thus on CO_2 uptake by plants; (f) sulfur emissions and sulfur chemistry and their effect on cloud albedo (Penner, 1990); (g) rate of release of methane hydrates (solid, ice-like bindings of water and methane) decomposed by a warmer climate; (h) net effect of land-use changes (primarily deforestation); (i) behavior of short-lived, indirect greenhouse gases, such as nitrogen oxides (NO_x) (Penner, 1990); (j) lag between an increase in greenhouse gases and the steady-state climatic response; (k) local changes in weather; and (l) nature of long-term climate change independent of the effects of human activity. Clouds in particular are only crudely modeled (Kerr, 1989), and the oceans are not modeled much better. To complicate the matter further, recent satellite data show no warming trend over the last 10 years (Spencer and Christy, 1990).

This report does not consider emissions of CFCs or water vapor. For one reason, automotive CFCs are already scheduled to be phased out; for another, CFC emissions are independent of the type of fuel used by the vehicle. It is worth noting, however, that current CFC emissions from vehicles are of the same order of magnitude as CO_2 emissions from the tailpipe (see App. Q). Emissions of water vapor from the combustion of fossil fuels worldwide are negligible, accounting for only about 0.05% of the average amount of water in the atmosphere and representing only 0.0013% of current global evaporation (DeLuchi et al., *A Comparative Analysis of Future Transportation Fuels*, 1987). Therefore, these emissions can presumably be ignored.

2.2 PREVIOUS RESEARCH

2.2.1 Emissions from Use of Transportation Fuels

Emissions of greenhouse gases from the use of alternative transportation fuels were first analyzed by White in 1980, when the price of oil had reached an all-time high, and synthetic fuels from coal, oil shale, and other sources were being evaluated as means to reduce U.S. dependence on foreign oil. White calculated CO_2 emissions resulting from the production and use of NG, coal, gasoline from crude oil, gasoline and diesel from shale oil, methanol from coal and wood, and ethanol from corn, and from electric vehicles using oil- and coal-based power (White, 1980). He found that most alternative fuels would emit more CO_2 than would gasoline.

This interest in emissions of greenhouse gases from transportation fuels was short-lived, because the price of oil, and with it, interest in alternative fuels, began to drop in 1981. However, scientists continued to study CO_2 and climate throughout the early and mid-1980s (Marland, 1982; National Research Council [NRC], 1983; Seidel and Keyes, 1983 [an EPA study]; MacCracken and Luther, 1985 [a DOE study]; and Bolin et al., 1986 [the SCOPE study]).

About 1985, interest in alternative transportation fuels resurfaced; however, their use was now considered mainly as a way to improve air quality rather than reduce oil imports. Much of this renewed impetus came from California, where it had already been determined that the use of methanol from coal was a possible way to improve urban air quality (Acurex Corp., 1982). In 1987, the connection between alternative transportation fuels and the greenhouse effect was made again, in reports by DeLuchi et al. (*Transportation Fuels and the Greenhouse Effect*, 1987), MacKenzie (1987), and Gushee (1988). MacKenzie and Gushee estimated emissions of CO_2 from the use of methanol. DeLuchi et al. calculated tons of CO_2-equivalent emissions of CO_2, CH_4, and N_2O generated per year. They found that as an emission source, methanol made from NG ranked about the same as petroleum fuels; compressed natural gas (CNG) and liquefied natural gas (LNG) ranked somewhat better than petroleum fuels; electricity (for electric vehicles) from the current U.S. power mix (mix of electricity-generating sources used nationally by all consumers in 1985) ranked about the same as petroleum fuels; and methanol from coal, electricity from coal-fired power plants, and hydrogen from coal ranked a lot worse than petroleum fuels.

In 1989, the California Energy Commission published an analysis of greenhouse gas emissions from the production and use of gasoline, diesel fuel, methanol from coal and NG, and CNG (Unnasch et al., 1989). The report, which improves on some aspects of the earlier work by

DeLuchi et al. (*Transportation Fuels and the Greenhouse Effect*, 1987), ranks methanol from NG slightly better, and CNG slightly worse, than did DeLuchi and his colleagues.

Recently, Okken (*The Case for Alternative Transportation Fuels*, 1990) published the results of an analysis of emissions of CO_2 from the total fuel cycle for vehicles running on biomass-derived ethanol; biomass-derived, coal-derived, and NG-derived methanol; CNG; gasoline; and hydrogen from nonfossil fuels; and for electric vehicles (EVs) using electricity generated in Europe. Unfortunately, details of his calculation are not yet available in English. Ho and Renner (1990) analyzed emissions of CO_2, CH_4, and N_2O from the production and use of gasoline, diesel fuel, CNG from NG, LPG from NG, methanol from NG and coal, and ethanol from corn. They found that every option except ethanol from corn and methanol from coal could increase or decrease greenhouse gas emissions, depending on the assumptions used. The use of ethanol from corn and methanol from coal causes increases, regardless of the assumptions.

Two reports that analyzed the CO_2 emissions resulting from the use of ethanol from corn came to sharply different conclusions. Marland and Turhollow, as reported by Segal (1989), found a net reduction in emissions from use of ethanol (compared with gasoline). However, Ho (1989), in questioning Marland and Turhollow's assumptions about the productivity of corn acreage, energy use by corn-to-ethanol plants, and by-product credits, found a net increase. Marland and Turhollow responded to Ho's criticisms in an Oak Ridge National Laboratory report (Marland and Turhollow, 1990).

Ford produced its own analyses of emissions (Hammerle et al., 1988; Schwarz, *An Industry Perspective of Transportation and Global Warming*, 1990), as have other auto and oil companies (e.g., Amann, *The Passenger Car and the Greenhouse Effect,* 1990; Amann, *Technical Options for Energy Conservation and Controlling Environmental Impact in Highway Vehicles*, 1990; Amann, Ho, and Renner, 1991). DOE issued a draft analysis (Mueller, 1990) that reviews and compares previous studies and makes its own point estimates of relative emissions. Fisher (1991) also analyzed previous studies and the potential of alternative fuels to reduce emissions of greenhouse gas emissions. I published very preliminary results of the analysis presented here (see DeLuchi, 1990).

2.2.2 Emissions from Use of Fuels to Generate Electricity

Grubb (1989) used very rough estimates of CO_2 emissions from upstream processes (feedstock recovery, transport, and processing) to calculate fuel-cycle emissions of CO_2 from the use of coal, oil, and gas to generate electricity. A year later, Wilson (1990) performed a similar analysis, but he also included CH_4 emissions and used slightly better estimates of emissions from upstream processes. Wilson's main objectives were to evaluate emissions from electricity-generating technologies and demonstrate a method of converting CH_4 and N_2O emissions into CO_2-equivalents rather than to estimate energy use and emissions from upstream fuel production and distribution processes in detail. In *The Case for Alternative Transportation Fuels in the Context of Greenhouse Gas Constraints*, Okken (1990) refers to another report by himself (in Dutch) that calculates emissions of CO_2 from the 1987 European electricity mix, but it is not clear if that report gives full fuel-cycle emissions or results by fuel type.

Three reports estimate, in detail, fuel-cycle emissions of CO_2 for one electricity-generating fuel for one country. Kudama (1990) drafted a detailed analysis of CO_2 emissions from the coal-to-electricity fuel cycle for Japan, which covers emissions from the mining, transport, handling, and combustion of coal and from ash transport. More recently, he analyzed emissions of CO_2 and CH_4 from the LNG-to-power cycle (Kudama, 1991). Mortimer (no date) conducted a detailed analysis of CO_2 emissions from the nuclear-power cycle in Britain.

The reports by Mortimer (no date) and Kudama (1990, 1991) are detailed. However, they cover only one fuel and only one greenhouse gas -- CO_2 (except Kudama's LNG report includes CH_4). To date, there is no single study that evaluates, in detail, emissions of all greenhouse gases, from all stages of the fuel production and use cycle, for all fuels and electricity-generating technologies.

2.3 NEED FOR MORE RESEARCH

Although research on energy use and the greenhouse effect is becoming more sophisticated, important disagreements remain. For example, it is not clear if vehicles powered by methanol, NG, ethanol, or electricity are better or worse than gasoline or diesel vehicles. Neither is it clear under what conditions NG-based electricity generation is worse than coal-based generation. Some of the disagreements result from the different assumptions about key variables, and some result from different methods and different levels of detail used in the analyses. A comprehensive and detailed analysis could resolve many of these disagreements or at least narrow the gaps between them.

The research to date can be built and improved upon in several ways. Some of the important tasks to be conducted are as follows:

- Make original and detailed calculations of the amount and type of energy required at each stage of all the fuel production and use cycles. (The report by Mueller, 1990, goes into some detail, with relatively recent data, for the petroleum cycle.)

- Fully account for "own-use" of energy in each fuel cycle (e.g., the use of coal-derived electricity at coal mines).

- Target the analysis for a future date, when alternative-energy technologies will be more fully developed and more widely used.

- Make complete carbon-balance calculations.

- Analyze precisely the chemical composition of gasoline, NG, and coal.

- Build detailed estimates of emissions from power plants and other combustion sources.

- Estimate the actual mix of fuels used to generate electricity for major electricity-consuming processes used in the transportation fuel cycles (such as petroleum refining).

- Calculate emissions from the nuclear-fuel cycle.

- Calculate emissions from the use of biomass to generate electricity.

- Calculate emissions from the use of advanced electricity-generating technologies, such as fuel cells.

- Perform a comprehensive review of the literature on the energy requirements of petroleum refineries, coal-to-methanol plants, NG-to-methanol plants, and corn-to-ethanol plants.

- Analyze in detail the energy required to make future reformulated gasoline and low-sulfur diesel fuel.

- Estimate in detail the CH_4 emissions that come from coal mines and NG production and delivery systems and the greenhouse gas emissions that come from the venting and flaring of associated gas.

- Estimate the greenhouse gas emissions that come from the manufacture of the materials for vehicles and the assembly of vehicles.

- Estimate the greenhouse gas emissions that come from the manufacture of materials used to make power plants, tankers, and other major energy-processing and transport facilities and equipment.

- Include LPG as a fuel. (The Mueller, 1990, report includes LPG.)

- Include woody biomass as a feedstock for alcohols or SNG. (Okken, *The Case for Alternative Transportation Fuels in the Context of Greenhouse Gas Constraints*, 1990, has reported results for methanol from wood; details are not yet available in English.)

- Consider electric, hydrogen, and fuel-cell vehicles in detail. (DeLuchi et al., *Transportation Fuels and the Greenhouse Effect*, 1987, has some preliminary calculations.)

- Analyze in detail the thermal efficiency and weight of alternative-fuel vehicles relative to petroleum-fuel vehicles.

- Summarize and analyze all the existing data on CH_4 and N_2O emissions from vehicles and power plants. (DeLuchi et al., *Transportation Fuels and the Greenhouse Effect*, 1987, has a partial review.)

- Include emissions of indirect greenhouse gases, CO, NMOC, and NO_x from all combustion sources.

- Correctly convert emissions of non-CO_2 gases to the temperature-equivalent amount of CO_2 (following the precedent set by Shine et al., 1990; Lashof and Ahuja, 1990; and others).

- Model the combined, overall effect of using alternative fuels in both heavy-duty and light-duty applications.

- Account for uncertainty by providing a wide range of scenario analyses (rather than just high and low estimates).

Most of these major tasks could be broken down into many subtasks.

In summary, no study to date analyzes all fuels, all steps of the fuel and vehicle production and use cycle, or all greenhouse gas emissions, for either transportation or electricity-generating fuels. This report is an attempt in this direction.

3 ANALYSIS OF GREENHOUSE GAS EMISSIONS FROM ELECTRICITY AND TRANSPORTATION FUEL CYCLES

3.1 FUEL-CYCLE STAGES AND EMISSIONS STUDIED BY THE MODEL

To obtain the results for the analysis discussed in this report, I used an energy and emissions model. It calculates the emissions of direct (CO_2, CH_4, and N_2O) and indirect (NO_x, CO, and NMOCs) greenhouse gases that result from the electricity and transportation fuel cycles. A particular fuel cycle usually consists of several of the stages that are listed below:

- *End use:* When a finished fuel product, such as gasoline, is used by consumers.
- *Compression or liquefaction:* When gaseous transportation fuels are compressed or liquefied.
- *Fuel distribution:* When a finished fuel product is transported to end users; for example, when gasoline is shipped by truck to a service station.
- *Fuel production:* When a primary resource, such as crude oil or coal, is transformed into a finished fuel product or energy carrier, such as gasoline or electricity.
- *Feedstock transport:* When a primary resource is transported to a fuel production facility; for example, when crude oil is transported from the wellhead to a petroleum refinery.
- *Feedstock recovery:* When a primary resource, such as crude oil or coal, is extracted.
- *Manufacturing for automotive industry:* When the materials used in private motor vehicles are manufactured and the vehicles themselves are assembled.
- *Support for transport:* When building, servicing, and administrative support are provided for transport and distribution modes, such as large, crude-carrying tankers or unit coal trains.
- *Manufacturing for energy utilities:* When materials for major energy facilities, such as petroleum refineries, corn-to-ethanol plants, and coal-burning power plants, are manufactured.
- *Changes in land use:* When changes in land use result from the development of a primary resource; for example, when rangeland is cleared to plant corn to make ethanol.

At each of these stages of a fuel cycle, greenhouse gases can be produced or emitted in several different ways:

- From the combustion of fuels that provide process energy (for example, the burning of bunker fuel in the boiler of a supertanker or the combustion of refinery gas in a petroleum refinery);

- From the evaporation or leakage of energy feedstocks and finished fuels (for example, the evaporation of NMOCs from gasoline storage terminals); or

- From the venting, leaking, or flaring of gas mixtures that contain greenhouse gases (for example, the venting of coal-bed gas from coal mines); or from chemical transformations not associated with burning process fuels (for example, the curing of cement, which produces CO_2; the denitrification of nitrogenous fertilizers, which produces N_2O; or the scrubbing of sulfur oxides from the flue gas of coal-fired power plants, which can produce CO_2).

The method that is used in this analysis to model emissions from each stage of the fuel cycle is outlined in the following section and described in more detail in App. A. For a recent overview of the fuel-cycle evaluation method, see Ashton et al. (1990).

3.2 SOURCES OF DATA AND METHODS USED BY THE MODEL TO ESTIMATE EMISSIONS, BY FUEL-CYCLE STAGE

3.2.1 End Use by Vehicles

In general usage, end-use emissions refer to emissions of greenhouse gases that result from the combustion and evaporation of fuels at the point of final use by consumers. In this report, however, the term refers specifically to emissions that result from the use of fuels in motor vehicles, since the end use of electricity does not produce greenhouse gases. Motor vehicles emit all the greenhouse gases considered in this analysis: CO_2, CH_4, N_2O, NO_x, CO, and NMOCs.

The amount of CO_2 emitted from a vehicle is a function of the vehicle's energy consumption rate (in 10^6 Btu per mile), the carbon content of its fuel (grams per 10^6 Btu of fuel), and the fate of the carbon in the fuel (e.g., complete oxidation to CO_2 or partial oxidation to CO or emission as NMOC or CH_4; the carbon that ends up as CH_4, CO, and NMOC is counted separately from the carbon that ends up as CO_2). The energy consumption rate of gasoline and diesel vehicles is calculated from the input fuel economy, which is 30 miles per gallon (mpg) for light-duty vehicles (LDVs) on reformulated gasoline in city/highway driving, and 6 mpg for heavy-duty vehicles (HDVs) on diesel fuel in trucking applications. The energy consumption rate for alternative-fuel vehicles is calculated by adjusting the energy consumption rate of baseline petroleum-fuel vehicles for differences between alternative-fuel and baseline petroleum-fuel vehicles in engine thermal efficiency and in vehicle weight. The vehicle's relative weight is determined on the basis of the characteristics of the alternative-energy storage system (e.g., battery or CNG tank) and the vehicle's driving range (number of miles that the vehicle can travel from the time the fuel tank is full until it is empty; see Table 2).

Values for emissions of CH_4, N_2O, NO_x, CO, and NMOCs are input directly into the emissions model. The values for CH_4 and N_2O are based on my analysis of the existing database (documented in Apps. M and N). The NO_x, CO, and NMOC emission values are based on runs of MOBILE4, the EPA's emissions model. I have adjusted input parameters and results of the model to reflect the new Clean Air Act Amendments (see App. B).

3.2.2 Fuel Compression or Liquefaction

Hydrogen and NG must be compressed or liquefied to be stored compactly on board a vehicle. Compression or liquefaction requires energy and produces greenhouse gases. The amounts and types of energy used by compressors and liquefiers are shown in Tables 3 and 4. Emissions of greenhouse gases at this stage are calculated in the same manner as are emissions from fuel production, a procedure discussed in Sec. 3.2.4.

3.2.3 Fuel Distribution

Fuel is distributed from fuel production facilities (such as petroleum refineries) to end users (such as service stations) by train, truck, ship, and/or pipeline. These distribution (or transportation) modes consume energy and emit greenhouse gases. For example, marine tankers use residual fuel #6 (bunker fuel), trains and trucks use diesel fuel, most NG-pipeline compressors burn NG, and oil-pipeline compressors use electricity-driven motors.

The emissions model first calculates the amount and kind of energy used by each distribution mode per unit of product (e.g., gasoline, electricity) made available to end users. In most cases, the amount and type of fuel used by each distribution mode is calculated as the amount of energy required to move one ton of transportation fuel a distance of one mile (i.e., Btu/ton-mi), multiplied by the number of tons of fuel actually moved and the number of miles traveled for an

TABLE 2 Base-Case Input Data Used to Calculate Extra Weight and Overall Relative Efficiency of Alternative-Fuel Vehicles

Efficiency, Range, and Weight	Vehicle Type	Petroleum	Methanol	CNG	LNG	Electric	Hydride[a]	LH_2[a]	Ethanol	LPG
Efficiency (mpg or relative thermal efficiency)[b]	LDV	30	1.15	1.10	1.12	5.70	1.20	1.25	1.14	1.10
	HDV	6	0.97	0.85	0.85	--	1.05	1.07	0.94	0.85
Driving range (mi)	LDV	350	350	250[c]	350	130	150	350	350	350
	HDV	600	400	400[c]	400	--	300	400	400	400
Weight of storage system per lb of fuel (lb)[d]	LDV	0.40[e]	0.31[f]	4.39[g]	1.73[h]	--	66.33[i]	5.76[j]	0.33	1.33[k]
	HDV	0.18[l]	0.14[f]	3.14[m]	1.00[h]	--	65.93[i]	3.61[j]	0.11	0.75[k]
Calculated weight of fuel (lb)[n]	LDV	70.7	126.9	41.2	56.2	815[o]	9.5	18.9	97.4	60.6
	HDV	703.7	976.1	482.4	474.9	--	120.6	141.9	765.9	503.5
Weight or extra weight, full (lb)[p]	LDV	2,487	0	125	54	547[q]	539	29	0	42
	HDV	40,000	0	1,168	119	--	7,240	-175	0	51

[a]Efficiency of water electrolysis for hydrogen production = 83%.

[b]The value for a petroleum-fuel vehicle is input in units of miles per gallon (mpg). The base-case value of 30 mpg for a gasoline vehicle assumes that reformulated gasoline is used for combined city/highway driving. The value for city driving only (used for most comparisons with battery-powered electric vehicles or EVs) is 24.5 mpg. A given vehicle will have a slightly higher mpg when it runs on unreformulated gasoline, because of the greater density of unreformulated gasoline (in 10^6 Btu/gal of gas). However, the efficiency of vehicles on either type of gasoline (in mi/10^6 Btu) will be about the same. The values for alcohol (methanol and ethanol), compressed natural gas (CNG), liquefied natural gas (LNG), liquefied petroleum gas (LPG), and hydrogen (hydride and LH_2) vehicles are input as relative thermal efficiency, which is equal to the thermal efficiency of the alternative-fuel vehicle divided by the thermal efficiency of the comparable gasoline or diesel vehicle used for combined city/highway driving. The value for an EV is calculated as the ratio of the efficiency of the EV powertrain to the efficiency of the internal-combustion-engine vehicle (ICEV) powertrain when used for city driving. Thus, the 5.7 ratio shown here is relative to that of a gasoline vehicle used for city driving at 24.5 mpg, not to one used for combined city/highway driving at 30 mpg. As discussed in App. B, the EV is relatively less efficient for combined city/highway driving; for combined driving, the powertrain efficiency ratio is about 4.7 instead of 5.7. Note that the ratio of city mpg to city/highway mpg for the gasoline vehicle (24.5:30.0) is the same as the ratio of the relative EV powertrain efficiency for combined driving to the relative EV powertrain efficiency for city driving (4.7:5.7). The efficiency ratio does not account for the efficiency of the battery (75%) or the efficiency of battery recharging (92%), which are treated separately. See App. B for sources.

[c]Range for CNG will be about half of this if the vehicle uses medium-Btu synthetic gas (compressed SNG from wood).

[d]This weight includes the weight of any mounting hardware.

[e]A 10-gal tank, holding 61.5 lb of gasoline, weighs about 25 lb.

[f]These values for M100 methanol assume that larger tanks are used in methanol vehicles than in petroleum-fuel vehicles to provide the same range. Larger tanks have a lower surface-to-volume ratio and therefore a lower ratio of weight of tank to weight of fuel (in lb).

[g]Value assumes that fiberglass-wrapped, aluminum-lined, 3000-psi pressure vessels are used. Value was calculated from data in DeLuchi et al. (1988). This weight includes the weight of mounting brackets and 15-20 lb for structural reinforcing to the vehicle.

[h]Using data from Cryogenic Fuels, Inc. (1989 and undated) as a basis, and assuming that LNG is slightly more thermally efficient than gasoline (so that 1.35 gal of LNG provides the same range as 1 gal of gasoline) and that diesel fuel is slightly more thermally efficient than LNG (so that 1.8 gal of LNG provides the same range as 1 gal of diesel fuel), I calculated a ratio of 1.73 for LNG light-duty vehicles (LDVs) and 1.08 for LNG heavy-duty vehicles (HDVs). However, data in the International Energy Agency (IEA) report, *Substitute Fuels for Road Transport* (1990), indicate a value of 0.46 for LNG HDVs. Because the data from Cryogenic appear to be more reliable, I use a value closer to that from the calculation based on Cryogenic's data.

[i]These values for compressed hydrogen (hydrides) are rough estimates for an Fe/Ti hydride, based on data in DeLuchi, *Hydrogen Vehicles: An Evaluation of Fuel Storage, Performance, Safety, and Cost* (1989). The weights include the weight of all auxiliaries, the hydride housing, and structural reinforcing to the vehicle.

[j]These values for liquefied hydrogen (LH_2) were calculated from data in DeLuchi, *Hydrogen Vehicles: An Evaluation of Fuel Storage, Performance, Safety, and Cost* (1989).

[k]LDV values were calculated from data in Webb (1990). The HDV values are my estimate, based on the LDV values.

[l]The IEA report, *Substitute Fuels for Road Transport* (1990), states that a fuel tank containing 250 liters of fuel weighs 250 kg. Given that each liter of diesel fuel weighs 343 g, the tank itself must weigh 39.2 kg. This indicates a ratio of 0.186. For larger tanks, the ratio is probably a bit lower.

[m]This value was calculated from data in Weaver (1989).

[n]For NG and hydrogen vehicles, the fuel weight (in grams) is calculated as (g/10^6 Btu of NG or H_2) x (range) x (10^6 Btu/gal)/(equivalent mpg), on the basis of 0.1387 x 10^6 Btu per gal of diesel fuel, 0.1251 x 10^6 Btu per gal of gasoline, 19,768 g per 10^6 Btu of NG, and 7,470 g per 10^6 Btu of hydrogen. Note that this calculation of fuel weight is explicitly a function of range.

TABLE 2 (Cont'd)

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[o]This value shows the weight of the battery, which is calculated from a separate EV cost and weight model. Some results from this model are reported in DeLuchi et al., *Electric Vehicles: Performance, Life-Cycle Costs, Emissions, and Recharging Requirements* (1989).

[p]For the petroleum-fuel vehicles, the value shown is the total weight of the vehicle, including fuel, tank, and payload. The weight of the gasoline vehicle is calculated from the input fuel economy, using a nonlinear regression equation that relates weight to fuel economy, based on EPA data (see App. B). For the alternative-fuel vehicles (including EVs), the values shown represent the difference between the total weight of the petroleum-fuel vehicle and the total weight of the alternative-fuel vehicle. For all alternative-fuel vehicles except EVs, this difference is assumed to be equal to the difference between the weight of the fuel systems (the fuel system is the fuel plus the fuel tank). The tank plus the fuel weight of the alternative-fuel vehicles is calculated as the fuel weight plus the product of the fuel weight and the tank weight per pound of fuel. For EVs, the extra weight is equal to the weight of the battery plus the weight of extra structural support for he battery minus the weight reduction for the EV powertrain compared with the ICEV powertrain. These EV weight factors are calculated from a separate EV cost and weight model.

[q]Value was from the EV cost and weight model described in DeLuchi et al., *Electric Vehicles: Performance, Life-Cycle Costs, Emissions, and Recharging Requirements* (1989).

TABLE 3 **Base-Case Use of Process Energy at Each Stage of the Fuel Cycles, per Unit of Fuel Energy Made Available to End Users**

Fuel-Cycle Stage	Process Energy Consumed per 10^6 Btu of Net End-Use Energy Available to Consumers, by Fuel Type (10^6 Btu)[a]							
	Reformulated Gasoline from Crude[b]	Standard Gasoline from Crude	Low-Sulfur Diesel from Crude	Fuel Oil from Crude	Coal	NG	Methanol from NG	Methanol from Coal
Compression or liquefaction[c]						0.0500 0.2020		
Fuel distribution	0.0084	0.0083	0.0091	0.0100		0.0360	0.0378	0.0193
Fuel production	0.1847	0.1458	0.0702	0.0519		0.0245	1.5405[d]	1.8006[d]
Feedstock transport	0.0116	0.0122	0.0133	0.0147	0.0075		0.0217	0.0018
Feedstock recovery	0.0254	0.0266	0.0291	0.0320	0.0083	0.0279	0.0788	0.0149
Fertilizer maufacture								

Fuel-Cycle Stage	LPG from NG	LPG from Crude	Methanol from Wood	Ethanol from Corn	Ethanol from Wood	CSNG from Wood	Nuclear	Hydrogen
Compression or liquefaction[c]						0.0500		0.3000 0.3100
Fuel distribution	0.0097	0.0097	0.0239	0.0275	0.0182	0.0452[e]		0.1002
Fuel production	0.0335	0.0550	1.7706[d]	0.5800	2.3501[d]	1.4374[d]	0.0415	
Feedstock transport		0.0122	0.0177	0.0255	0.0235	0.0144	0.00019	
Feedstock recovery	0.0250	0.0265	0.0620	0.1000[f]	0.0823	0.0503	0.0053	
Fertilizer maufacture			0.0689	0.1936[g]	0.0915	0.0557		

See next page for footnotes.

TABLE 3 (Cont'd)

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[a]Data are in 10^6 Btu of process energy consumed per 10^6 Btu of net end-use energy available to consumers (e.g., motorists or power plants), except for data under footnote d, and except for data for natural gas (NG) and compressed synthetic natural gas (CSNG). For NG and CSNG, the values for feedstock recovery, feedstock transport, fuel production, and fuel distribution are in 10^6 Btu of process energy per 10^6 Btu of net energy to the service station, power plant, or methanol plant, not to motorists. The ratios are different because of own-use of NG at the compression or liquefaction stage. The values for NG compression and liquefaction are in Btu of process energy per Btu to motorists, however. For sources and methods, see appendixes on individual fuels. Blank spaces usually mean that there is no such stage in the particular fuel cycle; they can also indicate that the energy use in the stage is counted at another stage.

[b]Values shown are for reformulated gasoline and account for the crude displaced by the methanol component of the 15% (by volume) methyl tertiary butyl ether (MTBE). The energy required to make the alcohol content of the MTBE is not accounted for here. It is accounted for in Table 7.

[c]The compression factor applies to compressed natural gas (CNG) and compressed hydrogen (hydrides); the liquefaction factor applies to liquefied natural gas (LNG) and liquefied hydrogen (LH_2). In calculating total process energy requirements, do not use the compression and liquefaction factors simultaneously. Liquefaction requirements here do not account for boil-off; boil-off is included in the final g/mi results section.

[d]In the cases of methanol (MeOH) from coal, gas, or wood; ethanol from wood; and synthetic natural gas (SNG) from wood, the value shown for fuel production is the total feedstock energy plus the process energy input to the plant, divided by the amount of fuel product available to consumers (that is, the numerator includes not just the process energy used to drive the process but also the feedstock energy that eventually ends up as product energy). The reciprocals of the numbers shown indicate the conversion efficiency of the process (for example, the base-case wood-to-methanol process is 56.5% [1/1.7706] efficient). In all other cases (gasoline, diesel, residual fuel, LPG, NG, ethanol from corn, and uranium), the value shown for fuel production is the energy content of the process fuels (including electricity at 3,412 Btu/kWh) used by the fuel production plant (e.g., a refinery), divided by the amount of product energy (as gasoline, ethanol, NG, etc.) available to consumers.

It is important to note, too, that the greenhouse gas emissions from fuel production are calculated differently for petroleum products than for methanol from coal or NG, and these are calculated differently than for methanol, ethanol, and SNG from biomass. For petroleum products, the bulk of the greenhouse gas emissions are equal to the total amount of process energy, as shown here, multiplied by the factors of Table 4, which allocate the total amount of energy to specific fuels, and then multiplied by the emission factor for each fuel (Table A.1), and summed for all fuels. See Apps. A and H for details. For methanol from coal or NG, CO_2 emissions are calculated from the difference between input carbon in the feedstock and output carbon in the fuels, and non-CO_2 emissions are calculated from emission factors based on total energy input (Table A.1). See Apps. A and J for details. For biofuels, CO_2 emissions from the biomass itself are ignored (they are not net emissions, because CO_2 is simply recycled in a biofuel system). Emissions from electricity use and non-CO_2 emissions, are counted separately (e. g., Table A.1).

The procedure for making a total systems energy calculation (which involves the total process energy -- not feedstock energy -- burned or otherwise lost per unit of fuel energy contained in the final product) for methanol, ethanol from wood, or SNG (for comparison with petroleum, NG, coal, uranium, LPG, or ethanol from corn) follows here. Subtract 1.0 from the figures shown here for "fuel production" for methanol, ethanol from wood, or SNG. The 1.0 represents the energy in the feedstock that ends up as fuel product; thus, subtracting 1.0 leaves the amount of input feedstock energy not converted to fuel product, per unit of fuel product, which is the desired figure.

TABLE 3 (Cont'd)

[e]I assume a slightly higher pipeline distribution factor for NG from biomass than for NG from fossil fuels, because batches and pipelines probably will be smaller.

[f]If corn residue rather than coal were used as a process fuel, the value calculated here would have to account for the extra energy needed to replace the nutrients that are lost as a result of removing the residue from the field (see App. K). However, the value that is shown represents the use of coal as a process fuel (in which case, the corn residue either stays on the field or is burned).

[g]This value represents the total energy embodied in the total fertilizer requirements minus the fertilizer that can be retrieved from the sludge produced by scrubbing SO_x emissions from the coal-fired boiler (see App. K). No other by-product credits are taken here, but all credits are taken in Table 7. This value includes the energy used to make other chemicals (herbicides, insecticides, and seeds). In the case of wood fuels, this other energy is included under feedstock recovery.

TABLE 4 Base-Case Breakdown of Process Energy Used at Each Stage of the Fuel Cycles

Fuel-Cycle Stage and Process Energy	Particular Process Energy Consumed in Stage/Total Process Energy Consumed in That Stage[a]										
	Coal	Oil and Products	CNG or LNG	Methanol from NG	Methanol from Coal	Methanol from Wood	Ethanol from Corn	Ethanol from Wood	CSNG from Wood	Uranium	LPG from NG
Fertilizer use											
NG and LPG						0.866	0.627	0.866	0.866		
Coal						0.000	0.002	0.000	0.000		
Fuel oil						0.004	0.003	0.004	0.004		
Diesel fuel						0.033	0.284	0.033	0.033		
Gasoline						0.000	0.000	0.000	0.000		
Electricity[b]						0.000	0.084	0.000	0.000		
Feedstock recovery											
Crude oil	0.00	0.13	0.01	0.00	0.00					0.00	0.01
Residual fuel	0.05	0.01	0.00	0.00	0.05					0.00	0.00
Diesel and other	0.48	0.14	0.04	0.02	0.48	0.85	0.47	0.85	0.85	0.19	0.04
Natural gas	0.01	0.50	0.92	0.95	0.01	0.05	0.12	0.05	0.05	0.26	0.92
Electricity[b]	0.37	0.17	0.01	0.02	0.37	0.05	0.14	0.05	0.05	0.39	0.01
Gasoline	0.03	0.04	0.01	0.01	0.03	0.05	0.20	0.05	0.05	0.04	0.01
Coal	0.06	0.00	0.00	0.00	0.06		0.07			0.12	0.00
Biofuels[c]						0.00	0.00	0.00	0.00		
Feedstock transport											
Pipe/NG-turbine			0.200	0.200							
Pipe/NG-engine			0.787	0.787							
Pipe/electric	0.000	0.074	0.013	0.013	0.00						
Fuel-oil ship	0.258	0.913	0.000		0.26	0.00	0.00	0.00	0.00		
Diesel train	0.603	0.001			0.60	0.05	0.20	0.05	0.05	0.00	
Diesel truck	0.139	0.012			0.14	0.95	0.80	0.95	0.95	1.00	
Biofuel truck[c]						0.00	0.00	0.00	0.00		
Fuel production											
Electricity[b]		0.05	0.02	0.002	0.00	0.01	0.09	-0.034[d]	0.01	0.98	0.022
Diesel, gasoline		0.00	0.00			0.00	0.00	0.00	0.00		0.002
NG, LPG, steam		0.33	0.98	0.998		0.00	0.00	0.00	0.00	0.02	0.976
Still gas, H_2		0.44									
Coal, coke		0.16	0.00		1.00	0.00	0.91	0.00	0.00		0.000
Residual, oil		0.01	0.00								0.000
Wood/crop residue						0.99	0.00	1.00	0.99		

TABLE 4 (Cont'd)

Fuel-Cycle Stage and Process Energy	Particular Process Energy Consumed in Stage/Total Process Energy Consumed in That Stage									
	Coal	Oil and Products	CNG or LNG	Methanol from NG	Methanol from Coal	Methanol from Wood	Ethanol from Corn	Ethanol from Wood	CSNG from Wood	Uranium	LPG from NG
Fuel distribution											
Pipe/NG-turbine			0.200						0.300		
Pipe/NG-engine			0.787						0.687		
Pipe/electric[b]		0.069	0.013	0.03	0.12	0.01	0.00	0.01	0.013		0.12
Diesel truck		0.674		0.25	0.36	0.39	0.64	0.39		1.00	0.71
Fuel-oil ship		0.226	0.000	0.72	0.19	0.24	0.05	0.24			0.14
Alt-fuel truck[c]				0.00	0.00	0.00	0.00	0.00			0.00
Diesel train		0.031		0.01	0.33	0.37	0.31	0.37		0.00	0.03
Compression											
Electricity[b]			1.000						1.000		
Liquefaction											
Electricity[b]			0.000						NE[e]		
NG			1.000						NE		

[a]The numbers indicate the amount of each type of process energy used at a particular stage of the fuel cycle divided by the total process energy use at that stage. For each fuel cycle, the total use of process energy (in 10^6 Btu) at each stage of the fuel cycle per unit of energy product to consumers is shown in Table 3. See text for data sources. A blank space means that there is no such stage in the particular fuel cycle or that the energy use in that stage is accounted for elsewhere.

[b]The electricity breakdown by generating fuel (the "power mix") is shown in Table 6.

[c]Alternative-fuel trucks and equipment use the fuel they are distributing or making. For example, a biofuel truck used in the methanol-from-wood cycle runs on wood-derived methanol.

[d]The process produces excess power, which can be sold to the local utility.

[e]NE = not estimated. Liquefied SNG is not considered, because medium-Btu syngas must be upgraded to nearly pure methane to be liquefied, and the energy cost of this upgrading has not been estimated here.

average haul. The estimates of the Btu/ton-mi "intensity" of a transportation mode are based on a detailed review of the literature (for example, see Rose, 1979). In the case of oil tankers, their weighted Btu/ton-mi intensity is calculated from data on the number of tankers in each of several tonnage classes and the energy intensity of tankers in each class. Data on tons moved and average haul lengths are analyzed and documented in the appendixes pertaining to individual fuels. Tables 3-5 show the amount of energy and the mode splits used to distribute fuels. See App. E for details.

The model then multiplies the energy-use factors for each mode (in Btu of process fuel per Btu of product made available to end users) by greenhouse-gas emission factors for each mode (in grams of CO_2-equivalent emissions per Btu of process fuel consumed by the distribution mode; see Table A.1), to calculate total CO_2-equivalent greenhouse-gas emissions per unit of product available to end users. The model also includes "second-order" emissions, which are emissions from the production and distribution of the process fuels used by the distribution modes.

The CO_2-equivalent emission factor for each distribution mode is equal to the CO_2 emission factor plus the CO_2-equivalent of the CH_4, N_2O, NO_x, CO, and NMOC emission factors. CO_2 emissions are calculated from the carbon content and energy density of the fuel, with a complete carbon accounting. Emissions of CH_4, N_2O, NO_x, CO, and NMOCs from fuel distribution modes are input to the model directly. Most of the input values for emissions of CH_4, NO_x, CO, and NMOCs were taken from the EPA report, *Compilation of Air Pollutant Emission Factors* (1985, 1988), which is generally referred to as "AP-42" (see Table A.1). I assume that the number of grams of N_2O that are emitted per Btu of fuel "F" used by distribution modes is the same as the number of grams of N_2O that are emitted per Btu of fuel "F" used by power plants. (Appendix A provides a formal expression of these calculations.) Emissions from this stage also include NG from NG transmission and distribution. Data on leaks from NG production were taken from several recent estimates of actual gas leakage (as opposed to estimates of "unaccounted-for gas" in general) (Table 5; App. M).

3.2.4 Fuel Production

In this stage, greenhouse gases are emitted from petroleum refineries, ethanol fermentation facilities, wood gasification and synthesis plants, coal-to-methanol plants, NG-to-methanol plants, NG processing plants, uranium enrichment plants, power plants, and so on. These emissions are a function of the amount and type of process fuel used by the facility. Tables 3 and 4 show the base-case fuel-use data for all facilities except power plants. Table 6a shows the base-case energy efficiency for power plants, by type of fuel. Appendix D provides details on the efficiency and emissions of conventional and advanced electricity-generating technologies.

TABLE 5 Base-Case Gas Leaks, Emissions, and Evaporation from Feedstock Recovery and Transport and Fuel Distribution Stages[a]

	Gas Vented per 10^6 Btu of Net Consumption of Products, by Fuel Type (ft^3)				Gas Emitted from Coal per Ton of Coal Produced (ft^3)	Gas Leaks per Unit of Gas Delivered (ratio)[b]				
Fuel-Cycle Stage	Gasoline	Diesel Fuel	Fuel Oil	LPG		NG[c]	Methanol from NG[c]	LPG	SNG	Hydrogen
Fuel distribution						0.0030	0.0000[d]	0.0000	0.0030	0.0015
Feedstock transport						0.0010	0.0004	0.0000	0.0010	0.0005
Feedstock recovery	16.3	18.7	20.6	17.1	380.0	0.0020	0.0020	0.0020	0.0000[e]	0.0000
CO_2 emitted per 10^3 ft^3 of NG produced (10^3 ft^3)[f]						0.022	0.022	0.022	0.0000	0.0000

[a]Blank spaces indicate that data are not applicable, not estimated, or not known, or that there are no emissions. Liquid evaporation and boil-off losses per gallon of liquid fuel are as follows (see App. B for details):

- Gasoline: 0.145% (4.00 g/gal) is lost from the refinery to the service station. The greenhouse effect of evaporative emissions from refueling and from the vehicle are accounted for separately, in Table B.2.
- Methanol: 0.033% (1.04 g/gal) is lost from the fuel production facility to the service station. Estimate is based on methanol's Reid vapor pressure (RVP) and molecular weight relative to gasoline's. See App. B.
- Ethanol: 0.016% (0.48 g/gal) is lost from fuel production facility to the service station. Estimate is based on ethanol's RVP and molecular weight relative to gasoline's. See App. B.
- Liquefied hydrogen: 1.00% is lost from the vehicle. Boil-off during liquefied hydrogen transfer is accounted for in the liquefaction factor of Table 3.
- LPG: 0.05% is lost.
- LNG: 0.05% is lost.

[b]Delivery refers to delivery to a power plant, methanol plant, or natural gas (NG) station.

TABLE 5 (Cont'd)

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[c]See App. M for documentation of estimates of leaks and emissions of NG and methane. See App. B for a discussion of the liquid loss estimates.

[d]I assume that methanol plants and power plants will not be connected to a low-pressure NG distribution system.

[e]This value refers to leaks from the synthetic natural gas (SNG) production facility. The value is my assumption.

[f]Some gas fields contain large amounts of CO_2, which is vented or reinjected. See App. G.

TABLE 6 Base-Case Breakdown of Electricity ("Mix of Power") Used by Major Processes in the Fuel Cycles

6a Efficiency of Electricity Generation, by Fuel Type

Efficiency	Coal Boiler	Oil Boiler	NG Boiler	NG Turbine	Methanol Boiler	Hydrogen Turbine
Efficiency[a]	0.329	0.318	0.328	0.330[b]	0.330	0.450

[a]Data on the efficiency of coal, oil, and gas plants are from U.S. Department of Energy, Energy Information Administration projections of net efficiency (electricity energy leaving power plant/higher heating value [HHV] of fuel input) for the year 2000 in *Annual Outlook for U.S. Electric Power 1990, Projections through 2010* (EIA, 1990). Estimates for methanol and hydrogen plants are my own.

[b]Assumes that 20% of turbines are combined cycles (45% efficient) and that 80% are simple cycles (30% efficient).

6b Source of Electricity, by Share

Process	Coal Boiler	Oil Boiler	NG Boiler[a]	NG Turbine[a]	Nuclear	Other[b]
Recharging EVs[c]	0.500	0.150	0.225	0.075	0.020	0.030
Petroleum refining/NGLs[d]	0.310	0.050	0.245	0.082	0.227	0.087
Auto manufacture[e]	0.528	0.058	0.049	0.016	0.251	0.097
Uranium enrichment[f]	0.878	0.004	0.001	0.000	0.084	0.033
Converting corn to ethanol[g]	0.719	0.009	0.031	0.010	0.203	0.027
Compressing NG[h]	0.523	0.052	0.131	0.044	0.165	0.086
Compressing or liquefying H_2[h]	0.523	0.052	0.131	0.044	0.165	0.086
Generic power[i]	0.523	0.052	0.131	0.044	0.165	0.086

[a]The breakdown between natural gas (NG) boilers and NG turbines for the year 2000 is based on projections in *Annual Outlook for U.S. Electric Power 1989, Projections through 2010* (EIA, 1989) and the North American Electric Reliability Council report, *1989 Electricity Supply and Demand* (NERC, 1989), which indicate that about 25% of all gas-fired generation will come from combustion turbines or combined-cycle turbines.

[b]Hydro, geothermal, wind, solar, and wood power.

[c]An estimate of the national "marginal" mix of power used specifically to recharge electric vehicles (EVs). See App. D for details.

[d]Mix of power provided to petroleum refineries. See Apps. D and H. I assume that natural gas liquids (NGL) plants are located near petroleum refineries and so use the electricity mix used by refineries.

[e]Mix of power in states with auto-manufacturing facilities; see Apps. D and P.

[f]Mix of power provided by utilities that supply the DOE enrichment facilities; see Apps. D and I.

[g]Mix of power used by power plants in the corn-growing region. See Apps. D and K.

[h]In the base case, I assume that compression and liquefaction facilities use the national average power mix in the year 2000 (see footnote i). In scenario analyses, I consider the effect of different power mixes.

[i]Projected national average electricity mix for the year 2000, taking into account the effect of the new Clean Air Act on fuel choice (EIA, *Improving Technology*, 1991; see App. D). The national average electricity mix is based on total electricity generation in the United States in the year 2000. This average or "generic" mix is used by oil pipelines, petroleum refineries, coal mines, oil wells, NG fields, NG pipelines, and methanol conversion plants, and for materials manufacture.

Data on fuel use by petroleum refineries were taken from detailed surveys by the EIA's *Petroleum Supply Annual* (various years). I allocate total energy use by refineries to the production of gasoline, diesel fuel, residual fuel, and LPG (App. H). Data on energy use by methanol production facilities are based on a review of many engineering studies (see App. J). Data for the biofuel cycles are based on a review of the literature (App. K). Base-case data on emissions from uranium conversion and enrichment are based on a detailed analysis of the uranium-to-electricity fuel cycle (App. I). For the base case, I assume that uranium is enriched using current U.S. gaseous-diffusion technology. Advanced enrichment technologies are considered in the scenario analyses.

In all cases, CO_2 emission estimates are calculated as they are for distribution modes and vehicles, by using a complete carbon tracking. The CO_2 emissions from the conversion of coal and NG to methanol are calculated by subtracting the carbon in a unit of methanol product from the total carbon in the amount of feedstock gas or coal required to produce the unit of methanol. Estimates of emissions of non-CO_2 greenhouse gases from fuel production facilities were taken from the EPA and other sources (see Table A.1 and pertinent appendixes). For electricity generation, I use the recent revisions of estimates of N_2O emissions (for example, see Ryan and Srivastava, 1989) (Apps. D and N).

3.2.5 Feedstock Transportation

Emissions from this stage include those resulting from the use of fuel by the transport modes that move feedstocks from the site of extraction to fuel production facilities. The modes are the same as those that distribute finished fuels. See Sec. 3.2.3 (Fuel Distribution) for an explanation of the method, Tables 3 and 4 for the base-case energy-use data, and App. A, Table A.1, for emission factors.

3.2.6 Feedstock Recovery

Emissions from this stage include those resulting from the use of process fuel at coal mines, oil- and gas-producing facilities, uranium mines, corn and tree farms, and fertilizer-manufacturing facilities. Data on the amounts and types of energy used by fossil fuel and uranium recovery facilities were taken from surveys administered by the U.S. Bureau of the Census (for example, *1987 Census of Mineral Industries, Subject Series, Fuels and Electric Energy Consumed*, 1990). Data on energy use in wood production were taken from sources in the technical literature (App. K). To obtain data on ethanol from corn, I analyzed in detail the energy required to grow and harvest corn, the amount of energy embodied in fertilizers, and N_2O emissions from denitrification of fertilizer (App. K). Tables 3 and 4 present the base-case energy-use data for all fuels and feedstocks.

CO_2-equivalent emission factors for the equipment used in feedstock recovery (scrapers, well-drilling equipment, trucks, tractors, etc.) are shown in Table A.1. Emissions of CO_2 and CO_2-equivalent emissions of CO, NO_x, CH_4, NMOCs, and N_2O are calculated as they are in the stages described above.

This stage also includes emissions of CH_4 from coal mines, emissions of NG from venting and flaring of associated gas, and emissions of NG from NG recovery operations. Methane emissions from coal mines are calculated from data from the U.S. Bureau of Mines (Deul and Kim, 1988) and other sources. Emissions from flaring of associated NG are calculated country by country from data in the EIA's *International Energy Annual*. Data on leaks from NG production were taken from several recent estimates of actual gas leakage (as opposed to estimates of unaccounted-for gas in general). Table 5 shows the base-case input data. For details, see the pertinent appendixes for data on particular fuels and App. M for data on CH_4.

3.2.7 Manufacture and Assembly

The manufacture and assembly of materials for vehicles, facilities, and equipment -- passenger cars, heavy-duty trucks, power plants, pipelines, tractors, well-drilling equipment, and so on -- are operations that are inherent in every fuel cycle. The use of energy to manufacture and assemble materials produces greenhouse gases. Different fuel cycles involve different amounts and types of materials and thus generate different amounts of greenhouse gases.

The amount of emissions resulting from the manufacture and assembly of materials used in motor vehicles is surprisingly large, on the order of 10-15% of the emissions resulting from the whole gasoline production and use cycle. Even more important are the *differences* in these emissions among the alternative vehicles (for example, the extra emissions that are generated from manufacturing the material used to make CNG tanks); they can amount to more than 2% of the emissions from the fuel production and use cycle. The base-case results of this analysis include estimates of emissions resulting from the manufacture and assembly of materials for motor vehicles. These emissions are calculated from data on the composition of gasoline vehicles, the composition of storage systems for alternative fuels, the amount of energy required to make a pound of each type of material, and the amount of emissions resulting from the use of energy to make the materials (App. P).

The base-case results also include estimates of emissions resulting from the use of energy to build, service, repair, and administer fuel distribution modes: ships, trucks, pipelines, and trains (Rose, 1979). However, the base-case results do *not* include emissions resulting from the use of energy to make the major materials for large facilities (like power plants, petroleum refineries, or coal mines) or feedstock-recovery equipment (tractors, chipper, scrapers, and so on). In App. P, I calculate that the amount of energy embodied in most facilities and equipment is very small when compared with the amount of energy the facilities and equipment actually process, carry, or produce; thus, it can be ignored. However, the biofuel cycles may be an exception (App. P). In some of the scenario analyses for biofuels, I include estimates of emissions from the use of energy to make materials for biomass recovery equipment and fuel production facilities. I ignore any energy embodied in any chemicals used throughout the fuel cycle, because in most cases, this is likely to be quite small.

3.3 PARAMETERS ANALYZED AND ESTIMATED BY THE MODEL

3.3.1 Closed Fuel Cycles

This analysis is "closed." In other words, the fuel cycles modeled in this analysis are, for the most part, complete (i.e., closed). For example, the final estimates include emissions from the use of energy to recover, process, and transport the fuel used to recover and transport the primary feedstock that ultimately ends up as the finished fuel used by consumer.

For each fuel -- coal, oil, NG, uranium -- the model calculates the amount of greenhouse gas emissions that result from making one energy unit of the fuel available to end users (Table 7). First, the model calculates the amount of electricity, coal, etc. that is required to bring an energy unit of fuel (for example, residual fuel oil) to the consumer (Tables 3 and 4). It then multiplies each of these energy-use factors by the appropriate emission factors (for example, grams of CO_2-equivalent emissions per 10^6 Btu of NG used as a process fuel) to arrive at the amount of CO_2-equivalent emissions per energy unit of delivered fuel. The g/10^6 Btu emission factor for NG (used in the calculation of the g/10^6 Btu emission factor for residual fuel oil) is calculated in the same way that the g/10^6 Btu emission factor for residual fuel is calculated. Moreover, the calculation of the g/10^6 Btu factor for NG will at

TABLE 7 Base-Case CO_2-Equivalent Emissions per Unit of Delivered Fuel, by Fuel-Cycle Stage, for 100-Year Time Horizon[a]

Fuel-Cycle Stage	CO_2-Equivalent Emissions per 10^6 Btu of Fuel Available to Consumers, by Fuel Type (g)								
	Reformulated Gasoline from Crude[b]	Standard Gasoline from Crude	Low-Sulfur Diesel from Crude	Fuel Oil from Crude	Coal	NG	Nuclear	Hydrogen from Nuclear Power[c]	LPG from NG and Oil[d]
CO_2 from NG wells	0	0	0	0	0	1,163	0	0	640
Gas leaks/flares[e]	1,255	1,318	1,439	1,583	5,849	2,265	0	0	894
Feedstock recovery	2,904[f]	3,051	3,329[f]	3,662[f]	1,391[g]	1,792	853[g]	1,132	2,159
Feedstock transport	2,593	2,723	2,972	3,270	1,820	0	31[h]	41	1,047
Fuel production	16,751	12,705	6,651	5,227	0	1,468	13,683	18,170	3,313
Fuel distribution	1,453	1,442	1,574	1,731	0	4,427	0	519[i]	1,816
Compression or	0	0	0	0	0	12,667[j]	0	7,777[j]	0
liquefaction	0	0	0	0	0	13,910[j]	0	80,363[j]	0
Total[k]	24,956	21,238	15,964	15,474	9,060	11,115	14,566	19,862	9,869

TABLE 7 (Cont'd)

Fuel-Cycle Stage	Methanol from NG	Methanol from Coal	Methanal from Wood	Ethanol from Corn[l]	Ethanol from Wood	SNG from Wood
	CO-2 Equivalent Emissions 10^6 Btu of Fuel Available to Consumers,					
CO_2 from NG wells	1,792	0	0	0	0	0
Gas leaks/flares[e]	1,395	10,531	0	0	0	537[m]
Fertilizer manufacture	0	0	2,180	20,874[n]	2,926	1,757
N_2O, NO_x from fertilizer	0	0	1,979	28,193	2,657	1,595
Feedstock recovery	4,956	2,592	8,488[o]	2,586	11,395[o]	6,868
Fuel transport	2,672	437[p]	2,892	4,607	3,882	2,340
Fuel production	23,712	113,365	6,777	73,001	-17,662[q]	6,843
Fuel distribution	8,256	4,282	5,195	5,402	3,949	2,444
Compression	0	0	0	0	0	11,099[m]
Total[k]	41,785	131,208	27,510	134,662	7,146	22,382

[a]Table accounts for all activies except end-use combustion. The addition of greenhouse gas emissions from end-use fuel combustion would account for complete fuel-cycle emissions of greenhouse gases. For details, see App. A and pertinent appendixes for particular fuels.

TABLE 7 (Cont'd)

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[b]Values for the reformulated gasoline-from-crude cycle include emissions from the manufacture and use of methyl tertiary butyl ether (MTBE) and account for the displacement of the crude input by MTBE. (The case here assumes that gasoline is 15% MTBE by volume.) In the base case, MTBE is assumed to be made from methanol from natural gas (NG).

[c]If solar power rather than nuclear power were used to make hydrogen, fuel-cycle emissions would be about zero.

[d]In the base case, LPG is 95% propane and 5% butane. Since natural gas liquids (NGL) plants produce about 61% of the total propane produced in the United States and 72% of the total butane produced in the United States (EIA, *Petroleum Supply Annual 1987, Volume 1*, 1988; EIA, *Natural Gas Annual 1987, Volume 1,* 1988), I assume that 61% of the propane and 72% of the butane in LPG comes from NGL plants and the rest comes from petroleum refineries.

[e]Assumes that flared gas is burned completely (no CH_4).

[f]Assumes that diesel fuel used at this stage of this fuel cycle is used by well equipment (see Table A.1).

[g]Assumes that diesel fuel used at this stage of this fuel cycle is used by scrapers and wheeled loaders (see Table A.1).

[h]For uranium, fuel transport includes all truck movements in the fuel production-and-use cycle.

[i]This estimate is based on the assumption that compressors would be located along the hydrogen pipeline, would burn hydrogen, and would emit N_2O and NO_x at the rate assumed for hydrogen power plants (App. D). Alternatively, hydrogen could be compressed by large electric-motor-driven compressors, located at mouth of the pipeline (at the site of hydrogen production) and driven by low-cost nuclear power available at the site (Ogden and Williams, 1989). In this case, minor emissions would result from the generation of the nuclear power.

[j]The process uses either compression or liquefaction but not both.

[k]Excludes emissions associated with compression or liquefaction.

[l]Accounts for individual by-product credits: a fusel-oil energy credit is subtracted from the energy requirements of the fuel production stage; a distillers' dried grains and solubles (DDGS) credit is subtracted from corn production (feed recovery); and an ammonium nitrate fertilizer credit is subtracted from the fertilizer energy requirements. See App. K.

[m]Includes a CO_2-removal credit. Because all the carbon in any leaks of synthetic natural gas (SNG) was orginally removed from the atmosphere as CO_2 by the biomass feedstock, it should not be counted as a net emission.

[n]Includes emissions resulting from the manufacture of other chemicals (herbicides, insecticides, seeds). Also includes emissions resulting from the use of energy to make fertilizer to replace nutrients lost due to the use of crop residue as a fuel. (The value shown assumes no crop residue is used as a process fuel.)

[o]Assumes that diesel fuel used at this stage is used by diesel tractors (see Table A.1).

[p]This is low because I assume that the methanol plant is located at the minemouth. See App. J.

[q]The process produces excess power for sale. Shown here are the emissions from the electricity displaced by the sold electricity.

some point involve the g/10^6 Btu factor for residual fuel oil. Thus, each g/10^6 Btu emission factor relies on every other factor. This circularity, which is handled in the model by iterative calculations, makes the fuel-cycle emission factors complete.

The calculation procedure is delineated formally in App. A. Table 7 shows how many grams of CO_2-equivalent emissions are generated per each 10^6 Btu of fuel that is delivered to end users for every fuel cycle analyzed here. These emission factors are useful in themselves; for example, one can use the g/10^6 Btu emission factor for NG to estimate greenhouse gas emissions from the delivery of NG to residences for heating and cooking.

3.3.2 Net Energy Available to End Users

As noted above, a primary output of this model is an estimate of greenhouse gas emissions from each stage of the fuel cycle per unit of fuel energy made available to end users (Table 7). End users are defined here to be users of energy who are *not* involved in any of the upstream parts of the fuel cycle (fuel distribution, fuel production, feedstock transport, feedstock recovery, and materials manufacture and assembly). The purpose of an energy production and delivery system is to produce *more than enough* energy to keep itself running; if it produced only enough energy to keep itself running, it would be pointless as an energy production and delivery system. This means that "internal" energy use, or "own use" (e.g., the diesel fuel used by trucks that deliver diesel fuel, the petroleum fuels used at petroleum refineries, the nuclear electricity used to enrich the uranium needed for nuclear power plants, the NG used to generate the electricity required to compress NG, or the coal used to provide the power needed to generate the electricity used at coal mining plants), should not be counted as end-use consumption. In this model, therefore, own use is deducted from the total amount of fuel produced to arrive at the net consumption available to end users.

3.3.3 Fate of All Carbon

The model accounts for the fate of all carbon, in detail. First, the carbon contained in CO, CH_4, and NMOC emissions is deducted from all available carbon in the fuel; then remaining carbon is assumed to be oxidized to CO_2. In the case of vehicles, the carbon balance includes CO_2 emissions from the combustion of engine oil.

3.3.4 Gas and Coal Compositions

The compositions of gasoline, gaseous fuels, and coal are analyzed in detail. Emissions of CO_2 resulting from the combustion of a fossil fuel are a function of the carbon content and energy density of the fuel. Because different analysts have assumed different values for carbon content and energy density, estimates of total fuel-cycle emissions have been quite different as well. This study tries to eliminate this uncertainty through a detailed analysis of the compositions and energy contents of petroleum products, gaseous fuels, and coal. Petroleum products are analyzed as a specific mixture of aromatics, paraffins, olefins, and oxygenates. Refinery gas, NG, and LPG are analyzed as a specific mixture of CH_4, ethane, propane, butane, and other compounds. The average composition of coal is derived from several recent coal databases. See App. C for details.

3.3.5 Emissions from Distribution Stage

Emissions from the distribution of fuels and feedstocks are analyzed in detail. At the heart of this calculation are three sets of data: (1) the energy intensity of trains, trucks, pipelines, and tankers, expressed in Btu/ton-mi; (2) the average distance that fuels and feedstocks are shipped by each of these modes; and (3) the amount of fuels or feedstocks shipped. These data are based on a detailed review of the literature. See App. E and the appendix associated with the fuel of interest for details. This report also presents original analyses of the energy intensity of feedstock recovery that are based on survey data of the U.S. Bureau of the Census (for example, *1987 Census of Mineral Industries, Subject Series, Fuels and Electric Energy Consumed*, 1990).

3.3.6 Target Year of 2000

In this analysis, energy use and emissions are projected for the year 2000. The new Clean Air Act Amendments will affect the emission rates of power plants and motor vehicles, the composition of gasoline, and the choice and quality of fuels used by power plants. These effects are taken into account in the projections of emissions. Emissions from motor vehicles are projected by adjusting MOBILE4, the EPA's computer emissions model, to account for the new requirements under the new Clean Air Act Amendments.

Several other important parameters are explicitly projected for the year 2000. The energy intensity of rail and truck transport is projected to improve somewhat by the year 2000 (EIA, *Energy Consumption and Conservation Potential*, 1990). The rate of venting and flaring of associated gas is expected to decline (App. M). The amount of imported oil, and hence the amount of oil moved by ocean-going tankers, is projected to increase by the year 2000 (EIA, *Annual Outlook for Oil and Gas 1990*, 1990). Estimates of the amount of energy embodied in materials are based on year 2000 projections (App. P). Refinery energy use is modeled (qualitatively) for the year 2000 (App. H).

3.3.7 Emissions from Electricity Use

This report includes data on total fuel-cycle, CO_2-equivalent emissions from the use of electricity. These emission factors (in g/kWh) can be used to estimate greenhouse gas emissions from any electricity-consuming process. The total g/kWh emission factors are essentially proportional to the efficiency of generation, which means that emissions from plants operating at efficiencies other than those assumed here can be calculated easily. Complete greenhouse-gas emission factors for electricity generation and use are shown in Tables D.4, D.6, and D.7. Emissions are estimated for several advanced electricity-generating technologies, including fuel cells, and for biomass fuel cycles as well as for conventional fuels and technologies. Production of N_2O from the corona discharge from high-voltage transmission lines is included (see App. N).

3.3.8 Actual Fuel Mixes Used to Generate Electricity

In several cases discussed in this report, I estimate the actual mix of fuels used to generate the electricity used by major electricity-consuming processes rather than simply assume a nationwide average (or "generic") power mix. For example, because petroleum refineries use a fair amount of electricity, the emissions of greenhouse gases from the petroleum fuel cycle depend in part on the characterization of the fuels used to generate that electricity. I estimate this mix of fuels (for U.S. consumption of petroleum fuels) by matching every major U.S. refining center with an electric utility, then obtaining data on the actual mix of fuels used by these utilities in 1988 (using various EIA publications, unpublished EIA data, and the *Electrical World Directory of Electric Utilities*, 1988). I also match the contribution (to U.S. consumption) of overseas refining with country-specific data on fuel inputs to electricity generation.

In addition, I estimate the actual input electricity mixes for U.S. uranium-enrichment plants, auto-manufacturing facilities, and corn-to-ethanol plants by using the same method as that used for petroleum refineries. In most cases, the calculated mix is quite different from the national average electricity mix (Table 6). For electric vehicles, I adapt the EPA's detailed calculation of the actual mix of power (sometimes called the "marginal" power mix) used to recharge batteries (EPA, *Analysis of the Economic and Environmental Effects of Electricity as an Automotive Fuel*, 1990). When information on the actual mix is not available, I use the U.S. national average power mix projected for the year 2000. The results are shown in Table 6. Details are given in App. D and in the appendix associated with the fuel of interest.

3.3.9 Emissions from Nuclear Fuel Cycle

This report includes an estimate of emissions from the nuclear fuel cycle. Most previous analyses assume zero emissions from the nuclear fuel production and use cycle, despite the fact that uranium enrichment requires a substantial amount of electricity -- electricity that at present is produced almost entirely by coal-fired plants. Other stages of the uranium-to-power cycle also produce greenhouse gases. This analysis estimates greenhouse gas emissions from the mining, milling, conversion, enrichment, and transport of uranium and from the fabrication and disposal of fuel (App. I). Mortimer's (no date) recent analysis produces very similar results.

3.3.10 Natural Gas Production and Transmission

The production and transmission of NG is analyzed in detail. This fuel is an important and difficult-to-analyze transportation feedstock. It is important because it can be made into methanol, CNG, or LNG (or even gasoline) and used to generate electricity; it is difficult to analyze because it is coproduced with oil and because natural gas liquids (NGL) plants produce both dry gas and NGL.

This model first separates the values for energy used for NG production from those for energy used for oil production, then allocates energy used at NGL plants to both NGLs and dry gas (EIA, *Natural Gas Annual* and other publications, see App. G; U.S. Bureau of the Census, *1987 Census of Mineral Industries, Subject Series, Fuels and Electric Energy Consumed*, 1990). Leaks and venting of CH_4 and CO_2 are quantified.

Information from a small phone survey of major gas transmission companies was used to break down the energy used to transmit NG into electricity for electric-motor-driven compressors, NG for gas-turbine-driven compressors, and NG for reciprocating-engine-driven compressors. This breakdown is important because different types of compressors emit different amounts of non-CO_2 greenhouse gases (Table A.1).

Finally, the model accounts for the fact that the NG used to make methanol probably will not be transported as far as the NG used to make CNG or LNG, and it will probably not go through a low-pressure gas-distribution system.

3.3.11 Energy Used to Refine Crude Oil

The energy used to refine crude oil is allocated to individual products. The model starts with detailed input data on the amounts and types of energy required to refine crude oil based on data in EIA's *Petroleum Supply Annual* and other sources (see App H). It then allocates total refinery fuel use to gasoline, diesel fuel, and residual fuel specifically, on the basis of data in several papers and reports that show refinery energy use by process area. Next, these results are updated to account for the reformulation of gasoline and the reduction in the sulfur content of diesel fuel required under the new Clean Air Act Amendments. The final process-fuel requirements for gasoline, diesel fuel, residual oil, and LPG are multiplied by emission factors for each of the process fuels. As a result of this apportioning of emissions from refineries, gasoline is assigned a much larger share of refinery energy use, and diesel fuel a much smaller share, than in most previous analyses. Details are given in App. H.

Although the model does estimate refining energy intensity separately for gasoline, diesel fuel, and residual fuel, it does not calculate this intensity as a function of the mix of products demanded. Neither does it consider how changes in the product mix might affect demand for (and recovery energy associated with) different kinds of crude oil. In general, the method assumes that the net effect of using a mile's worth of an alternative fuel is elimination of a mile's worth of gasoline or diesel fuel, with concomitant eliminations in the crude oil use and processing stages. The method ignores how the use of an alternative (substitute) fuel might change the price of petroleum fuels and thereby affect demand for (and emissions from) petroleum products, or how a change in the product slate might affect prices, demand, and emissions. These areas may be appropriate for future research.

3.3.12 Emissions from Wood-Derived Fuels

This model estimates emissions of greenhouse gases that result from the production and use of woody biofuels: ethanol, methanol, and SNG from wood. The calculation is made on the basis of a detailed review of the energy requirements for short-rotation, intensive cultivation and for the conversion of wood to transportation fuels (App. K).

3.3.13 Corn-to-Ethanol Process

This report attempts to settle some of the points of contention in estimates of greenhouse gas emissions from processes that convert corn to ethanol. It does so by analyzing in detail the amount of fertilizer used to grow corn, the amount of energy used by corn farmers, and the amount of emissions that should be assigned to by-products of the corn-to-ethanol process. Previous analyses that estimate energy and fertilizer inputs to corn farming on the basis of separate data sets on corn yield per acre, fertilizer use per acre, and energy use have not agreed on appropriate values (Segal, 1989; Ho, 1989). As discussed in App. K, because corn yield is related to the amount of energy and fertilizer used, one should estimate corn yield as a function of fertilizer and energy input. This procedure is done here on the basis of several data series from the U.S. Department of Agriculture (App. K).

In the base-case analysis, I assume that coal is used to provide the process energy for a corn-to-ethanol plant, but in the scenario analyses, I consider the effect of using NG or corn-crop residue as process fuels. I estimate the by-product credit in two ways: first, by calculating the amount of energy saved in specific products displaced by the by-products, and second, by considering the total energy content of the by-products.

Finally, this analysis covers both emissions of N_2O from the denitrification of fertilizer (which were first calculated by Stefan Unnasch of Acurex Corporation, in Mountain View, California) and emissions of NO_x from the nitrification of fertilizer. Details are given in App. K.

3.3.14 Liquefied Petroleum Gas

Most previous analyses do not include LPG. (The Mueller, 1990, report is an exception.) Yet the LPG fuel cycle produces the smallest amount of greenhouse gas emissions of all the fossil fuel options for internal-combustion-engine vehicles (ICEVs), so LPG should not be ignored as a potential fuel source. Greenhouse gas emissions from the use of LPG as a fuel depend on how much of the LPG comes from refineries and how much comes from NGL plants, because refineries use more energy to produce LPG than do NGL plants. The source of the LPG, in turn, perhaps can be inferred from the composition of the LPG (its percentage of propane and butane), because NGL plants produce a greater share of total (NGL plus refinery) butanes than they do of total propane. This model calculates greenhouse gas emissions from both refineries and NGL plants, then weighs the final result according to the amount of propane and butane in the LPG and the amount of propane and butane produced from refineries and NGL plants.

3.3.15 Reformulated Gasoline and Diesel Fuels

Reformulated gasoline and diesel fuels are used for the base-case analysis, for comparison with alternative fuels in the year 2000. Reformulating gasoline to be less volatile and to produce less NMOCs and toxic compounds will have several partially counterbalancing effects. It will take more energy to make reformulated gasoline (including the extra energy to make the oxygenates), and reformulated gasoline will have a lower energy density than regular gasoline (primarily because of the oxygenates). These factors will increase per-mile greenhouse gas emissions from reformulated gasoline when compared with nonreformulated gasoline. However, reformulated gasoline will have a lower carbon content than nonreformulated gasoline, because of its lower aromatics and higher oxygen content, and this will reduce per-mile CO_2 emissions. The reduction of the sulfur content of diesel fuel will increase refinery energy requirements and hence increase emissions of greenhouse gases. Appendixes C and H discuss these effects.

3.3.16 Advanced Battery-Powered and Fuel-Cell-Powered Electric-Motor-Driven Vehicles

Most previous analyses have not included battery-powered and fuel-cell-powered vehicles, even through it has long been known that they have great potential to reduce emissions of greenhouse gases. This analysis considers a wide range of fuels and feedstocks for both battery-powered and fuel-cell-powered electric vehicles.

3.3.17 Alternative-Fuel Vehicle Efficiency

The mi/10^6 Btu efficiency of alternative-fuel vehicles relative to the mi/10^6 Btu efficiency of gasoline and diesel vehicles is analyzed in detail. Greenhouse gas emissions from alternative-fuel ICEVs are directly related to the thermal efficiency of the engines. Many factors affect the thermal efficiency of alternative-fuel vehicles relative to gasoline vehicles. In the future, emission standards will probably be the most important of these. The potential gain in thermal efficiency to be achieved with alternative fuels will probably be constrained by the 0.40 g/mi NO_x standard required under the new Clean Air Act Amendments. Appendix B analyzes the effect of the 0.40 g/mi NO_x standard on the possibility of using lean-burn technology to improve the relative thermal efficiency of alternative-fuel vehicles.

Greenhouse gas emissions from battery-powered electric vehicles (EVs) are especially sensitive to the energy consumption rate (mi/10^6 Btu) relative to that of gasoline ICEVs. I compare the measured values for city-cycle energy consumption (from the battery terminals) of 10 EVs with the measured city-cycle mpg of the internal-combustion-engine version of the same vehicles, holding vehicle weight constant. I then factor in the efficiency effect of vehicle weight, the efficiency of battery recharging, and the efficiency of the battery itself to arrive at a relative fuel consumption rate for EVs in mi/10^6 Btu. See App. B, especially Table B.1, for details.

3.3.18 Unusual Sources of Emissions

This report covers several sources typically not included in greenhouse gas analyses. They include CO_2 emissions from the use of calcium carbonate ($CaCO_3$) to scrub SO_2 from the flue gas of power plants; N_2O and NO emissions from the denitrification and nitrification of fertilizer; CO_2 emissions from NG fields; N_2O emissions formed by the corona discharge from power lines; and emissions from the use of energy to build, maintain, and administer trains, trucks, ships, and pipelines.

3.3.19 Methane and Nitrous Oxide

Estimates of N_2O and CH_4 emissions from fuel combustion are derived from a comprehensive database. Data on the CH_4 and N_2O emissions from vehicles powered by gasoline, diesel fuel, methanol, and NG are compiled in Tables M.1 and N.1 and analyzed in Apps. M and N. The analysis produces some interesting results. For example, it shows that the CH_4 emissions from "flexible-fuel" methanol/gasoline vehicles are proportional to the gasoline content of the fuel.

All available EPA AP-42 data on CH_4 emissions (from power plants, trains, ships, engines, etc.) are used in the analysis. For refineries, I use data on CH_4 emissions reported by refineries to air quality control boards in Texas and California (App. M).

Early estimates of N_2O emissions appear to be in error because of a "sampling artifact." This analysis uses recent analyses of N_2O emissions as a function of fuel type and combustion conditions (Table N.2). Details are given in App. N.

3.3.20 Venting and Flaring

Venting and flaring from coal mines, NG operations, and oil wells are analyzed in detail. Emissions of CH_4 from coal mining are calculated as a function of the CH_4 content of various ranks of coal and the rate of production for the various ranks; CH_4 leakage from sidewalls and pillars is accounted for.

Leaks from NG operations are categorized as coming from three sources: production fields, transmission lines, and distribution lines. Recent estimates of actual leak rates (as opposed to estimates of unaccounted-for gas) are used. Gas that is used by very-high-volume consumers, such as methanol plants and electricity plants, is assumed to *not* go through a low-pressure distribution system. This point is important, because the bulk of total leakage from an NG system occurs in the distribution lines.

Venting and flaring of associated gas are analyzed in detail, with consideration given to such issues as the breakdown between venting and flaring, the correct assignment of venting and flaring to oil and gas, and the completeness of the available data. A weighted-average venting and flaring rate is calculated, based on the rates projected for eight regions in the year 2000 and the amount of of oil that the United States will import from each of those regions.

3.3.21 Nitrogen Oxide, Carbon Monoxide, and Nonmethane Organic Compounds

The base-case analysis considers emissions of NO_x, CO, and NMOCs in all fuel cycles. Emissions from the base-line petroleum-fuel vehicles are estimated by adjusting MOBILE4 results to account for changes required under the new Clean Air Act Amendments. Emissions from alternative-fuel vehicles are estimated relative to the gasoline case, on the basis of a detailed analysis of the expected difference in emissions between alternative-fuel vehicles and petroleum-fuel vehicles (Sperling and DeLuchi, 1991; see App. B). The base-case analysis also considers emissions of CO, NO_x, and NMOC from petroleum refineries, power plants, methanol plants, trains, ships, and other sources (Table A.1).

3.3.22 CO_2-Equivalent Emissions

To compare the aggregate greenhouse effect of all emissions from all fuel cycles, the global warming potential of all greenhouse gases must be expressed by a single unit or measure. This model uses a detailed and conceptually correct procedure to convert CH_4, N_2O, CO, NMOC, and NO_x emissions to CO_2 emissions with the same temperature effect. This analysis examines recent work by Shine et al. (1990), Rodhe (1990), Lashof and Ahuja (1990), and Wilson (1990), who provide good analyses of how to convert non-CO_2 greenhouse gas emissions into "equivalent" CO_2 emissions. It studies the data and formulas used in these analyses and presents further calculations that clarify the use of these conversion factors. Table 8 shows the conversion factor used in this analysis. Because conversion factors are a function of how far one looks into the future, and because it is not possible to specify the exact appropriate time horizon, I present results for short-, medium-, and long-term horizons. However, as I argue in App. O, global warming is a long-term problem, and it is difficult to justify using a time horizon as short as 20 years.

3.3.23 Light-Duty and Heavy-Duty Vehicles

This report examines the combined effect of greenhouse gas emissions from both light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs). Most previous analyses compare alternative fuels with gasoline for light-duty applications. The few that do compare alternative fuels with diesel fuel for heavy-duty applications conclude that most alternative fuels fare worse than diesel fuel, and this finding is confirmed here. However, so far, no one has pursued the implication of this finding; namely, that since an alternative-fuels program is likely to include heavy-duty as well as light-duty applications (consider the new emission standards for heavy-duty trucks and buses, which are likely to force the use of alternative fuels), the overall effect of an alternative-fuels policy (the topic of interest) will be less favorable than will its effect in the LDV sector only.

TABLE 8 Factors for Converting Greenhouse Gas Emissions to CO_2-Equivalent Emissions, Mass Basis[a]

Time (yr)	CH_4[b]	N_2O	CO	NMOC-C[c]	NO_x[d]	CFC-12[e]
20	60	270	7	36	150	7,100
100	20	290	3	13	40	7,300
500	9	190	2	7	14	4,500

[a]Factors are taken from the Intergovernmental Panel on Climate Change (IPCC) document (Shine et al., 1990), with some modifications. They account for indirect effects, such as the effect of CO, NMOC, and CH_4 on the concentration of O_3. See App. O for details.

[b]I reduced the IPCC's values by a token amount to account for recent evidence that the radiative adsorption strength of CH_4 may be less than previously believed (Gamache and Golomb, 1990).

[c]This expresses the warming effect per unit of carbon (C) weight. It is equal to the IPCC factors divided by 0.85. (I estimate that the generic nonmethane organic compound [NMOC] content in the IPCC analysis is 85% carbon). See App. O.

[d]The U.S. Environmental Protection Agency (EPA), in its AP-42 report, expresses NO_x emissions from power plants and vehicles as NO_2 emissions, even though most of the NO_x in the exhaust gas is actually NO. It does so because the measuring process converts NO to NO_2. The IPCC's NO_x conversion factor is also based on NO_2 (Shine et al., 1990), so the conversion factor and the emission data have the same basis.

[e]Used to calculate CO_2-equivalent of CFC emissions from vehicle air-conditioning systems (in App. Q).

In this report, I estimate the aggregate effect of alternative-fuels programs that will probably include both LDVs and HDVs by weighting light-duty and heavy-duty emission factors (in g/mi) by the proportion of vehicle miles traveled (VMT) by LDVs and HDVs. Even though the number of VMT by HDVs is small, most alternative fuels fare so much worse in heavy-duty applications that inclusion of even the small amount of HDV VMT significantly changes the result. In some cases, this change alters the nature of the overall conclusions qualitatively. See App. B for more details.

3.3.24 Scenario Analyses

Scenario analyses are used to test the effect of varying important and uncertain variables. Economic, technical, and political uncertainties make it impossible to use point estimates of many of the major variables, including the efficiency of alternative-fuel vehicles relative to gasoline vehicles, the mix of fuels used to generate electricity for electric vehicles, the efficiency of fuel conversion processes, and tailpipe emissions of non-CO_2 greenhouse gases. I use many scenario analyses to examine the effect of uncertainty with respect to these and many other variables.

4 BASE-CASE ANALYSIS

4.1 GENERAL DESCRIPTION OF RESULTS

Tables 3 through 7 show the base-case assumptions and calculated results for the following parameters:

- Overall energy intensity of each stage of the various fuel cycles (in Btu of process fuel per Btu of net product output),
- Type of energy used at each stage of the fuel cycle,
- Venting and flaring of CH_4,
- Electricity mixes for several processes such as recharging EVs or compressing NG,
- Efficiency of electricity generation, and
- Amount of greenhouse gases emitted (in grams per 10^6 Btu of delivered fuel).

The base case for vehicles compares projected fuel-cycle emissions from alternative-fuel vehicles with those from gasoline LDVs and diesel HDVs in the year 2000. The base-case vehicle parameters, including the relative thermal efficiency of alternative-fuel ICEVs, the relative power-train efficiency of battery-powered EVs, the efficiency of batteries and battery recharging, the characteristics of fuel storage systems, and the desired driving range, are shown in Table 2 and documented in Apps. B, M, and N. All the alternatives except the EV are compared with the gasoline vehicle under a condition that represents combined city/highway driving (30 mpg). The comparison of the EV with the gasoline vehicle assumes city driving only (24.5 mpg), because EVs will usually not be used for long highway trips. The base-case diesel HDV gets 6 mpg. In general, I assume that alternative-fuel LDVs are more efficient than gasoline LDVs and that alternative-fuel HDVs are less efficient than diesel HDVs.

The base case for methanol LDVs and HDVs assumes that methanol is made primarily from remote NG through the use of state-of-the-art conversion technology. The mix of power plants dispatched to meet the incremental electricity demand arising from EV recharging patterns is shown in Table 6 and discussed in App. D. I assume that hydro, geothermal, biomass, solar, and wind plants do not emit greenhouse gases (see App. D for justification). The base case for hydrogen ICEVs and fuel-cell vehicles assumes that either solar or nuclear power is used to make hydrogen from water, then the hydrogen is compressed or liquefied on the basis of the projected U.S. average power mix in the year 2000. The base case for ethanol from corn assumes that coal is used as a process fuel. The base case for bio-methanol and bio-SNG assumes gasification of wood. The base case assumptions about the efficiency that is achieved in converting NG to methanol, coal to methanol, and corn to ethanol are shown in Table 3. The base-case assumptions with respect to electricity generation are discussed in App. D.

Given the input data and assumptions discussed above and a lot of other input data not discussed in this section, the emissions model calculates the number of grams of CO_2-equivalent greenhouse gases (actual CO_2 emissions plus the CO_2-equivalent of CH_4, CO, NMOCs, NO_x, and N_2O) that are emitted per mile of travel by a vehicle or per kilowatt-hour of electricity delivered to end users. For vehicles, the g/mi results are broken down by stage of the fuel production and use cycle in Table 9, by CO_2-equivalent emissions of individual greenhouse gases in Table 10, and as a function of the fuel efficiency of motor vehicles in Table 11. Finally, Table 12 shows the results of comparing the alternative-fuel vehicles to the petroleum-fuel vehicles, expressed as a percentage change, for many scenario analyses. The percentage changes given in Table 12 account for emissions from the manufacture and assembly of materials for vehicles. (As discussed in App. P, emissions from the manufacture of materials for major facilities, such as power plants, appear to be quite minor.) It is relatively easy to calculate the percentage changes without accounting for materials by using the data from Tables 9 and 12. (Tables 9 through 12 appear later in this document, closer to the pages that discuss them in detail.)

4.2 RESULTS FOR ELECTRICITY USE (Fig. 1 and Tables 13, D.4, D.7, and D.8)

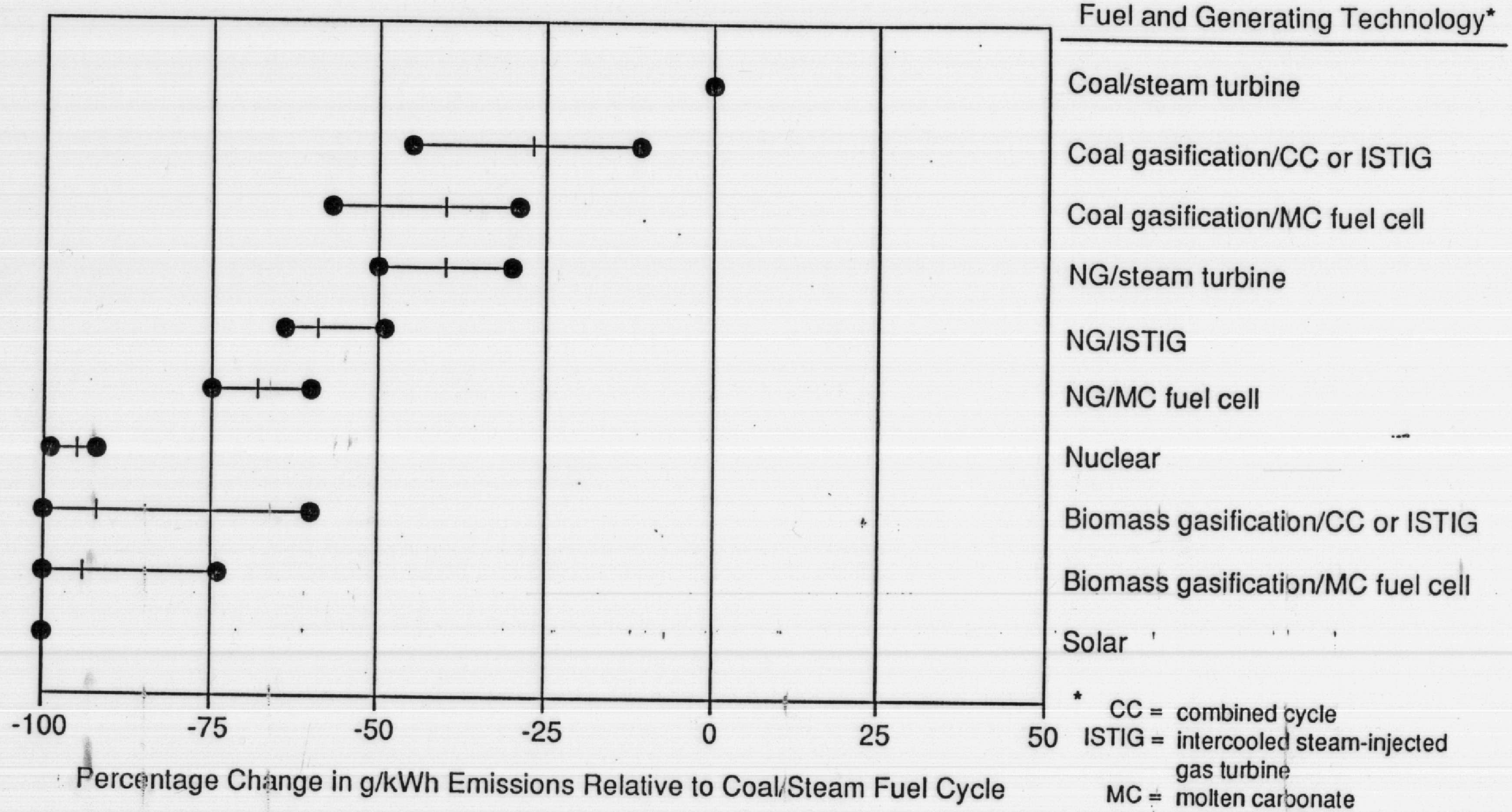
4.2.1 Different Fuels Result in Different Emissions

Over all the scenarios and time horizons considered here, the NG-to-power fuel cycle produces about 50-60% of the CO_2-equivalent emissions of the coal-to-power fuel cycle (Fig. 1, Table 13, and Tables D.4 and D.7 in App. D). This result occurs when future advanced NG turbines are compared with future integrated coal gasification/advanced gas-turbine plants, when fuel-cell technologies are compared, and when current boiler technologies are compared. There do not appear to be any conditions in the United States under which the use of NG to generate electricity would contribute anywhere near as much to global warming as would the use of coal.

The current nuclear fuel cycle, which uses gaseous-diffusion enrichment technology, produces about 6% of the CO_2-equivalent emissions of the current coal-to-power fuel cycle. Most of these emissions come from the coal-fired power plants that supply electricity to the two operating DOE gaseous-diffusion uranium-enrichment facilities. If, in the future, uranium is enriched not by gaseous diffusion

FIGURE 1

(landscape)



Notes: Each line shows the range of results, from the most favorable to the least favorable, for the fuel cycle listed to its right. The results are expressed as a percentage change in CO_2-equivalent emissions relative to the baseline coal/steam fuel cycle of Table D.7. Emissions from the manufacture and assembly of facilities are not included. The solid circle at the left end of the range marks the most favorable case, which is the greatest percentage reduction or least percentage increase. The solid circle at the right end of the range marks the least favorable case, which is the least percentage reduction or greatest percentage increase. The solid tick between the circles represents the base-case value, which is my best estimate. The ranges shown include comparisons under all three time horizons (20 years, 100 years, and 500 years). Sources: Tables D.4 and D.7 and Figure D.1.

FIGURE 1 Spans between the Most and Least Favorable Emission Results for Various Electricity-Use Fuel Cycles

TABLE 13 Total Fuel-Cycle CO_2-Emissions of Greenhouse Gases from Electricity Generation, as a Function of Net Generation Efficiency for 20-Year, 100-Year, and 500-Year Time Horizons[a]

	CO_2-Equivalent Emissions per Kilowatt-Hour of Energy Delivered to End Users, by Source (g)						
Generation Scenario[b]	Coal	Oil	NG Boiler	NG Turbine/ Other	Nuclear	Methanol from NG	Biomass
100-year time horizon[c]							
1. 32% efficiency	1,335	1,132	803	793	69	1,278	d
2. 35% efficiency	1,220	1,032	734	725	83	1,162	
3. 38% efficiency	1,123	949	676	668	22	1,073	
4. 38% efficiency, low emissions	1,079	917	653	650		1,049	
5. 40% efficiency	1,067	900	643	634		1,018	
6. 40% efficiency, low emissions	1,025	871	620	617		1,000	
7. NG combined cycle				565			
8. Fluidized-bed combustion	1,768						
9. Gasification/gas turbine	949						107
10. ISTIG				526			
11. CRISTIG				466			
12. Molten-carbonate fuel cell	781		419				74
500-year time horizon[c]							
1. 32% efficiency	1,219	1,061	738	735	60	1,174	
2. 35% efficiency	1,114	968	675	672	72	1,072	
3. 38% efficiency	1,025	890	621	618	17	986	
4. 38% efficiency, low emissions	1,010	879	612	612		991	
8. Fluidized-bed combustion	1,470						
9. Gasification/gas turbine	904						76
10. ISTIG				495			
12. Molten-carbonate fuel cell	751			403			57
20-year time horizon[c]							
1. 32% efficiency	1,779	1,407	1,055	1,016	100	1,689	
2. 35% efficiency	1,625	1,283	964	929	118	1,541	
3. 38% efficiency	1,496	1,175	888	855	38	1,399	
4. 38% efficiency, low emissions	1,328	1,059	799	788		1,323	
8. Fluidized-bed combustion	2,098						
9. Gasification/gas turbine	1,400						205
10. ISTIG				639			
12. Molten-carbonate fuel cell	890			476			130

[a]All values include 3 g/kWh CO_2-equivalent of N_2O from corona discharge. This figure could be as high as 61 g/kWh, however (App. N). Emissions from the construction of power plants are not included; these probably would amount to 2-5 g/kWh. All efficiencies are net generation efficiencies based on higher heating values. ISTIG = intercooled steam-injected gas turbine. CRISTIG = chemically recuperated intercooled steam-injected gas turbine.

[b]See full Table D.7 in App. D for details.

[c]Using the CO_2-equivalent factors of Table 8 for the time horizon indicated.

[d]A blank space means that the data either were not estimated or would not be applicable.

but by the considerably more efficient laser-isotope-separation technique or by gas centrifuge, the nuclear fuel cycle will produce only 2% of the emissions of coal fuel cycle.

Solar power will do even better, however. It will eliminate all emissions of greenhouse gases, except N_2O emissions from high-voltage transmission lines and emissions from the use of energy to build power plants, and both these sources are quite small. The solar power cycle produces less greenhouse gases than does any electricity-generating fuel cycle.

Under the 100- and 500-year time horizons (corresponding to the conversion factors of Table 8), oil-fired plants produce 85-87% the total fuel-cycle, CO_2-equivalent emissions of coal-fired plants. Under the 20-year time horizon, oil-fired plants produce about 80% of the emissions of coal-fired plants. Oil improves its standing relative to coal in the 20-year case because the coal cycle produces more non-CO_2 greenhouse gas emissions than does the oil cycle (the coal cycle produces a large amount of CH_4 emissions from coal mining and a large amount of NO_x emissions from power generation) and because non-CO_2 greenhouse gases are weighted much more heavily in the short-term case. However, as argued in App. O, there is little justification for choosing a period of less than 100 years.

4.2.2 Electricity-Generating Efficiency Correlates with Emissions

Complete fuel-cycle, CO_2-equivalent emissions from electricity generation are, as expected, almost directly proportional to the efficiency with which that electricity is generated (Table D.5). This situation occurs because both fuel use (and hence CO_2 emissions) and emissions of non-CO_2 gases are proportional to the efficiency of the power plant. Emissions of non-CO_2 gases are proportional to efficiency because power plant emissions are regulated per unit of fuel input, not per unit of electricity output. N_2O emissions from transmission lines are not related to the efficiency of generation, but are too small to upset the general relationship between efficiency and emissions.

4.2.3 There Are Several Significant Emission Sources

There are several significant sources of non-CO_2 greenhouse gases within the electricity fuel cycles (Table D.8): NO_x emissions from power plants, CH_4 emissions from coal mines and NG production and transmission operations, N_2O emissions from power plants and high-voltage transmission lines, and NO_x emissions from upstream processes for NG and oil production. Together, non-CO_2 greenhouse gases account for 10-15% of total fuel-cycle, CO_2-equivalent, g/kWh emissions of greenhouse gases from fossil fuel plants and for 24% of fuel-cycle emissions from nuclear power plants. Non-CO_2 greenhouse gases are more important in the nuclear fuel cycle because standby diesel generators emit a large amount of non-CO_2 greenhouse gases (see the diesel-engine emission factors of Table A.1). However, the emissions from these generators need to be better characterized.

In the base case for coal, the CO_2-equivalent emissions of CH_4, NMOC, CO, N_2O, and NO_x that come from fuel combustion at the generating facility constitute 9% of total fuel-cycle, CO_2-equivalent emissions (Tables D.4 and D.8). CO_2-equivalent emissions of these gases from an oil-fired boiler and a gas-fired turbine constitute 7% of their respective total fuel-cycle emissions. The corresponding figure for gas-fired boilers is 8%. The higher percentage for coal is primarily a result of the higher NO_x emission rate associated with coal combustion.

4.2.4 Coal Fuel Cycle Generates More Methane Emissions than Does Gas Fuel Cycle

The global warming potential (in grams of CO_2-equivalent emissions per kilowatt-hour of generation) of CH_4 emissions from coal mines in the coal-to-power fuel cycle exceeds that of CH_4 leaks from NG production and transmission in the NG-to-power cycle by a factor of four (Table D.8). Only if the gas lines serving power plants were to lose as much NG as the low-pressure distribution systems were previously thought to (around 3% of throughput) would the CH_4 emissions from the NG-to-power cycle become more important than those from the coal-to-power cycle. However, this situation seems extremely unlikely. First, as discussed in App. M, all recent estimates of gas leaks per se (as opposed to estimates of generally unaccounted-for gas) suggest that much less than 1% of throughput is lost from modern low-pressure distribution systems. Second, the systems serving power plants are not likely to be as leaky as low-pressure gas-distribution systems, because gas pressure and throughput at power plants are much higher, and because it is easier and more important to monitor leaks in high-pressure, high-volume systems.

This analysis also indicates that NO_x emissions from power plants contribute substantially more to global warming than do CH_4 emissions and leaks (Table D.8), although it must be remembered that the NO_x equivalency factor of Table 8 is both relatively high and very uncertain. It therefore follows that concerns about CH_4 emissions from the NG-to-power fuel cycle may be misplaced, both because CH_4 emissions themselves are likely to be small and because other non-CO_2 greenhouse gases, such as NO_x, may be more important with respect to global warming.

4.2.5 Production and Transport Stages Generate a Lower Percentage of Emissions in Coal Fuel Cycle than in Oil or Gas Fuel Cycles

In the base case for coal (Table D.4), CO_2-equivalent emissions from feedstock mining, preparation, and transport are 8% of total fuel-cycle, CO_2-equivalent emissions. The corresponding figures for oil and gas are 16% and 14%. This result occurs because it takes more energy to transport oil and gas than coal, and because coal-fired power plants themselves produce more greenhouse gases than do oil- or gas-fired power plants.

4.2.6 Emission Results Vary with the Time Frame

For all fossil fuels, total fuel-cycle, CO_2-equivalent emissions are only 5-10% higher in the 100-year case than in the 500-year case, but are 15-33% higher in the 20-year case than in the 100-year case. This result illustrates the combined importance of the magnitude of emissions of non-CO_2 greenhouse gases and the time horizon of the analysis. There can be a considerable difference in the absolute emissions levels calculated for a short-term versus a medium-term analysis. However, it is difficult to justify using a 20-year time horizon (see App. O).

4.2.7 Cutting NO_x and SO_x Emissions Has Less Effect in the Long Term

The low-emissions scenario, in which NO_x and SO_x emissions from all power plants are cut by 50% from the base-case level, results in 1-4% lower total fuel-cycle greenhouse gas emissions in the 100- and 500-year cases. In the 20-year case, the low-emissions scenario results in about 10% lower total emissions. This result occurs because in the 20-year case, the non-CO_2 gases -- and hence the cuts in emissions of these gases -- are weighted more heavily.

4.2.8 High-Efficiency, Low-NO_x, Gasification and Advanced Gas-Turbine Technologies and Fuel Cells Could Greatly Reduce Emissions from Electricity Use

High-efficiency, low-NO_x, gasification and advanced gas-turbine technologies or, better still, fuel cells, are among the most promising means of reducing emissions of greenhouse gases from the use of electricity.

4.2.8.1 Natural Gas

A fuel cycle using a high-efficiency, low-NO_x, intercooled steam-injected gas turbine (see App. D) would produce nearly two-thirds less fuel-cycle greenhouse gases than does the current U.S. coal-to-power cycle. However, the use of high-temperature fuel cells would provide even higher efficiency and lower emissions of criteria pollutants, and hence even lower fuel-cycle CO_2-equivalent emissions.

4.2.8.2 Coal

The integrated coal gasification/advanced gas-turbine technologies, using either combined-cycle turbines or intercooled steam-injected gas turbines, are the most promising means of reducing greenhouse gas emissions from coal-based *combustion* plants. The combination of (1) high efficiency, (2) a small amount of NO_x emissions, and (3) a method of removing sulfur that does not produce CO_2 results in lower total fuel-cycle greenhouse gas emissions than does the current petroleum-to-electricity fuel cycle. Fuel cells, however, would allow for an even higher efficiency and result in an even smaller amount of NO_x emissions, hence leading to even fewer greenhouse gas emissions. In fact, fuel cells are the most efficient and least polluting coal conversion technology known (Rastler, 1990). An integrated gasification/molten-carbonate fuel-cell cycle, using internal reforming (see App. D), would produce about 40% less fuel-cycle CO_2-equivalent emissions than does a conventional coal-to-steam-power fuel cycle.

On the other hand, the possibility of the extremely high N_2O emissions that could result from low-temperature combustion and from the use of limestone injection to remove SO_x tends to undermine the moderately high efficiency of fluidized-bed combustion (FBC), making this advanced technology much less attractive than gasification/gas-turbine generation from a greenhouse standpoint. Emissions of N_2O from FBC need to be verified, however.

4.2.8.3 Biomass

The efficient use of biomass in gasification/advanced gas-turbine power plants would produce relatively few greenhouse gas emissions, because any CO_2 emissions per se would not count as a net emission to the atmosphere. In fact, the greenhouse gas emission rate from the biomass gasification/gas-turbine fuel cycle would be as low as that from the current nuclear fuel cycle, except under the 20-year horizon. (The biomass fuel cycle would fare less well under the 20-year horizon, because a large fraction of its fuel-cycle emissions would be non-CO_2 greenhouse gases from biomass production and combustion, whereas in the nuclear fuel cycle, most of the greenhouse gas emissions are CO_2.) The use of gasified biomass with fuel cells instead of turbines would result in even fewer emissions. Furthermore, if a biofuel development effort permanently increased the standing stock of carbon in biomass, it would receive a one-time CO_2 "sequestering" credit that could cancel decades of fuel-cycle greenhouse gas emissions, including emissions from the use of energy embodied in equipment and facilities.

4.3 RESULTS FOR VEHICULAR FUELS

4.3.1 Comparison of Emissions from Various Fuel and Vehicle-Type Combinations with Those from Base-Case Petroleum-Fuel Vehicles

Table 9 shows the base-case results for all the vehicle and fuel combinations considered here. Figure 2 shows the base-case results graphically for the full fuel cycle for LDVs; Fig. 3 shows them for HDVs. Figure 4 shows the base-case results for a fleet of HDVs and LDVs combined, using the VMT weighting factors of Table B.4. Figure 5 shows the base-case emissions from vehicle end use only (i.e., all upstream emissions are excluded).

4.3.1.1 Standard Gasoline

This analysis indicates that the use of reformulated gasoline would result in essentially the same fuel-cycle CO_2-equivalent emissions as the use of standard, nonreformulated gasoline. As shown in Table 9, reformulated gasoline would produce only 1% more total fuel-cycle, CO_2-equivalent emissions than would standard gasoline, a difference that is less than the uncertainty in the calculation. Consequently, the results throughout this report can be viewed as applying to any kind of gasoline, although I use reformulated gasoline for the reference case.

The reason reformulated gasoline and standard gasoline give essentially the same result is because of counterbalancing factors. Reformulated gasoline takes considerably more energy to make than does standard gasoline, a factor that, by itself, would increase fuel-cycle greenhouse gas emissions by 3%. However, reformulated gasoline contains less carbon per Btu than does standard gasoline, a factor that would result in 1.5% lower total fuel-cycle, CO_2-equivalent g/mi emissions. Reformulated gasoline also produces less NMOC and CO from the tailpipe, and this would reduce fuel-cycle greenhouse gas emissions by 0.5%. Thus, the increase in emissions due to extra refining energy (3%) would be slightly greater than the decrease due to the lower carbon content and tailpipe emissions (1.5% + 0.5% = 2.0%).

Table 9 shows that the recovery and transport of crude oil would result in a slightly greater amount of emissions when standard gasoline is used than when reformulated gasoline is used. This result occurs because reformulated gasoline requires less crude oil than does standard gasoline, since methyl tertiary butyl ether (MTBE) has displaced some of the crude. Here, all emissions from MTBE manufacture are included under "fuel production."

TABLE 9 Base-Case, Total Fuel-Cycle, CO_2-Equivalent Emissions from the Use of Transportation Fuels, by Fuel-Cycle Stage, for 100-Year Time Horizon

9a Fossil Fuels Used in Internal-Combustion-Engine Vehicles (ICEVs)[a]

	CO_2-Equivalent Emissions, by Fuel and Vehicle Type (g/mi)													
	Reform. Gas	Std. Gas	Diesel	Methanol from NG[b]		CNG		LNG		LPG from NG and Oil[c]		Methanol from Coal[d]		Diesel
Source or Fuel-Cycle Stage	LDV	LDV	HDV	LDV	HDV	LDV	HDV	LDV	HDV	LDV	HDV	LDV	HDV	LDV[e]
Vehicle end use	333.7	344.5	2,052.1	277.4	1,906.1	269.0	1,892.6	262.0	1,869.6	283.6	2,086.7	277.4	1,906.1	325.0
Compression or liquefaction	0.0	0.0	0.0	0.0	0.0	48.3	350.5	51.3[f]	379.1[f]	0.0	0.0	0.0	0.0	0.0
Fuel distribution	5.9	5.9	36.4	29.2	196.7	17.4	126.0	19.6	145.1	6.8	49.4	15.2	102.0	5.6
Fuel production	68.2[g]	51.2	153.7	84.0	565.1	5.8	41.8	6.5	48.1	12.4	90.2	401.5	2,701.5	23.7
Feedstock transport	10.6	11.1	68.7	9.5	63.7	0.0	0.0	0.0	0.0	3.9	28.5	1.5	10.4	10.6
Feedstock recovery	11.8	12.4	76.9	17.6	118.1	7.0	51.0	7.9	58.7	8.1	58.8	9.2	61.8	11.8
CH_4 leaks/flares	5.1	5.4	33.3	11.3	76.0	13.5	97.6	15.9	117.2	5.7	41.8	37.3	251.0	5.1
First total	435.3	430.4	2,421.1	428.9	2,925.7	360.9	2,559.5	363.2	2,617.9	320.5	2,355.3	742.1	5,032.8	381.8
Change (%)[h]	--	-1.1	--	-1.5	20.8	-17.1	5.7	-16.6	8.1	-26.4	-2.7	66.8	107.9	-12.4
Car assembly	14.0	14.0	51.5	14.0	51.5	14.6	54.4	14.4	52.2	14.3	52.0	14.0	51.5	10.5[i]
Materials in cars	41.9	41.9	154.5	41.9	154.5	47.6	177.0	43.6	157.2	42.8	155.8	41.9	154.5	31.6[i]
Second total	491.2	486.3	2,627.1	484.8	3,131.7	423.2	2,791.0	421.2	2,827.3	377.6	2,563.1	798.0	5,238.8	423.9
Change (%)[h]	--	-1.0	--	-1.3	19.2	-13.9	6.2	-14.3	7.6	-23.1	-2.4	59.3	99.4	-13.7
LDV + HDV[j]	619.4	614.8		643.6		565.2		565.6		508.7		1,064.5		
Change (%)[h]	--	--		3.9		-8.7		-8.7		-17.9		69.4		

See next page for footnotes.

TABLE 9 (Cont'd)

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[a]Percentage changes for light-duty vehicles (LDVs) are relative to base-case reformulated-gasoline LDVs, and percentage changes for heavy-duty vehicles (HDVs) are relative to base-case diesel HDVs. The base-case LDV in combined city/highway driving gets 30 miles per gallon (mpg) on reformulated gasoline and 30.7 mpg on standard gasoline, because of the higher density (in Btu/gal) of standard gasoline. The base-case g/mi results for gasoline and diesel fuel for all the time horizons (the 20-, 100-, and 500-year equivalency factors of Table 8) are:

Fuel	20-year	100-year (this table)	500-year
Reformulated gasoline (30 mpg, city/highway)	636.6	491.2	449.2
Diesel (6 mpg)	3,819.3	2,627.1	2,331.4

[b]100% methanol, all from remote natural gas (NG) in this base case.

[c]61.4% of the liquefied petroleum gas (LPG) comes from natural gas liquids (NGL) plants and 38.6% comes from petroleum refineries (see App. G).

[d]100% methanol, all from coal.

[e]Assumes that a diesel LDV gets 39 mpg (27% better than a comparable vehicle on standard gasoline and 30% better than a comparable vehicle on reformulated gasoline), weighs 100 lb more than a comparable gasoline vehicle, lasts 150,000 miles (as opposed to 108,000 miles for the gasoline vehicle), and emits non-CO_2 greenhouse gases at the rate shown in Table B.3. See App. B.

[f]Assumes liquefaction occurs at the service station, from the use of NG-powered liquefiers

[g]Includes emissions from the production and delivery of methanol and ethanol used to make MTBE.

[h]To make an internally consistent scenario, methanol from coal is compared with reformulated gasoline that contains methyl tertiary butyl ether (MTBE) made from coal-derived methanol. The first total for this reformulated gasoline is 445.0 g/mi; the second total is 500.9 g/mi, and the LDV + HDV total is 628.4 g/mi. These totals are higher than the totals (shown above) for reformulated gasoline that contains NG-derived MTBE. The liquefied natural gas (LNG) vehicle and the diesel LDV are compared with the baseline gasoline vehicle using NG-derived MTBE.

[i]Low values are due to the long life of the diesel vehicle.

[j] Emissions from LDVs (in g/mi), weighted by the LDV share of total vehicle miles traveled (VMT), plus emissions from HDVs (in g/mi), weighted by HDV VMT share (see Table B.4 and Table 2).

TABLE 9 (Cont'd)

9b Biomass-Derived Fuels Used in ICEVs[a]

Source or Fuel-Cycle Stage	CO_2-Equivalent Emissions, by Fuel and Vehicle Type (g/mi)							
	Methanol from Wood[b]		CSNG from Wood[c]		Ethanol from Corn		Ethanol from Wood	
	LDV	HDV	LDV	HDV	LDV	HDV	LDV	HDV
Vehicle end use	51.4	386.0	64.4	408.9	51.0	389.4	51.0	389.4
Compression or liquefaction	0.0	0.0	42.3[d]	307.1[d]	0.0	0.0	0.0	0.0
Fuel distribution	18.4	123.8	9.6	69.6	19.3	132.8	14.1	97.1
Fuel production	24.0	161.5	26.9	194.8	260.8	1,795.1	-63.1	-434.3
Feedstock transport	10.2	68.9	9.2	66.6	16.5	113.3	13.9	95.5
Feedstock recovery and fertilizer manufacture[e]	44.8	301.4	40.1	290.9	184.6[f]	1,270.2[f]	60.7	417.5
CH_4 leaks/flares	0.0	0.0	2.1	15.3	0.0	0.0	0.0	0.0
First total	148.8	1,041.6	194.6	1,353.3	532.2	3,700.8	76.6	565.1
Change (%)	-65.8	-57.0	-55.3	-44.1	22.2	52.9	-82.4	-76.7
Car assembly	14.0	51.5	14.6	54.4	14.0	51.5	14.0	51.5
Materials in cars	41.9	154.5	47.6	177.0	41.9	154.5	41.9	154.5
Second total	204.7	1,247.6	256.9	1,584.7	588.1	3,906.8	132.5	771.1
Change (%)	-58.3	-52.5	-47.7	-39.7	19.7	48.7	-73.0	-70.6
LDV + HDV[g]	267.3[h]		336.6[h]		787.2[h]		170.8[h]	
Change (%)	-56.8		-45.7		27.1		-72.4	

See next page for footnotes.

TABLE 9 (Cont'd)

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[a]Percentage changes for LDVs are relative to base-case reformulated-gasoline LDVs, and percentage changes for HDVs are relative to base-case diesel HDVs.

[b]Assumes 100% methanol and that methanol is not used as a process fuel at any point in the fuel cycle.

[c]Compressed synthetic natural gas (CSNG) from wood. In these cases, I assume that all SNG, including any used at power plants and by pipeline compressors, is made from biomass. The SNG produced here is a medium-Btu gas, which means that in the case of a LDV, the CSNG vehicle has a range (about 125 miles) that is about half the range of a regular CNG vehicle (250 miles).

[d]Compressors use electricity generated from the same mix of fuels as that found in the fossil-fuel CNG case; however, in this case, NG used by NG-fired power plants is assumed to be made from wood (CO_2 emissions are not counted).

[e]Emissions from feedstock recovery and fertilizer manufacture are added together. They include N_2O and NO_x emissions from the denitrification and nitrification of nitrogenous fertilizers.

[f]Accounts for by-product credits. See App. K.

[g]Emissions from LDVs (in g/mi), weighted by the LDV VMT share, plus emissions from HDVs (in g/mi), weighted by the HDV VMT share (Table B.4).

[h]These totals do not account for emissions of greenhouse gases resulting from changes in land use. For example, if a short-rotation intensive clultivation (SRIC) plantation replaces marginal cropland, the increase in carbon in the biomass and soil will offset decades of fuel-cycle CO_2-equivalent emissions (see App. K).

TABLE 9 (Cont'd)

9c Solar- and Nuclear-Derived Fuels Used in Hydrogen ICEVs[a]

Source or Fuel-Cycle Stage	CO_2-Equivalent Emissions, by Fuel and Vehicle Type (g/mi)					
	H_2 from Solar[b]		Hydrides from Nuclear		LH_2 from Nuclear	
	LDV	HDV	LDV	HDV	LDV	HDV
Vehicle end use	22.6	344.2	22.6	344.2	22.6	344.2
Compression or liquefaction	0.0	0.0	29.8	189.8	266.3	1,748.8
Fuel distribution[c]	1.7	11.3	2.0	12.7	1.7	11.3
Fuel production	0.0	0.0	69.7d[d]	443.4[d]	60.2[d]	395.4[d]
Feedstock transport	0.0	0.0	0.16[e]	0.99[e]	0.13[e]	0.89[e]
Feedstock recovery	0.0	0.0	4.3[f]	27.6[f]	3.8[f]	24.6[f]
CH_4 leaks/flares	0.0	0.0	0.0	0.0	0.0	0.0
First total	24.4	355.5	128.7	1,018.8	354.8	2,525.3
Change (%)	-94.4	-85.3	-70.4	-57.9	-18.5	4.3
Car assembly	14.5	51.8	15.2	60.4	14.5	51.8
Materials in cars	45.2	157.0	54.4	236.3	45.2	157.0
Second total	84.1	564.4	198.3	1,315.5	414.5	2,734.1
Change (%)	-82.9	-78.5	-59.6	-49.9	-15.6	4.1
LDV + HDV[g]	112.9		265.4		553.6	
Change (%)	-81.8		-57.2		-10.6	

See next page for footnotes.

TABLE 9 (Cont'd)

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[a]Percentage changes for LDVs are relative to base-case reformulated-gasoline LDVs, and percentage changes for HDVs are relative to base-case diesel HDVs.

[b]Assumes that solar power is used to electrolyze water and to compress or liquefy hydrogen.

[c]There are emissions of N_2O and NO_x from pipelines burning hydrogen as a compressor fuel. If the hydrogen were compressed by large electric-motor-driven compressors that used solar power generated at the hydrogen-production site, there would be no emissions from hydrogen transmission and distribution.

[d]Emissions from uranium conversion, enrichment, and fabrication.

[e]Emissions from uranium transport.

[f]Emissions from uranium mining and milling.

[g]Emissions from LDVs (in g/mi), weighted by the LDV VMT share, plus emissions from HDVs (in g/mi), weighted by the HDV VMT share (see Table B.4).

TABLE 9 (Cont'd)

9d Battery-Powered Light-Duty Electric Vehicles[a]

Source or Fuel-Cycle Stage	CO_2-Equivalent Emissions, by Source of Electricity (g/mi)				
	U.S. National ("Marginal") Power Mix[b]	Coal-Fired Plants Only	NG-Fired Plants Only	Nuclear Power Plants Only	Solar Power Plants Only
Vehicle end use	0.0	0.0	0.0	0.0	0.0
Fuel distribution	7.6[c]	0.0	21.1[d]	0.0	0.0
Fuel production[e]	402.8	502.7	288.5	27.6	1.3[f]
Feedstock transport	6.7	8.6	0.0	0.0	0.0
Feedstock recovery	8.6	6.6	8.5	1.3	0.0
CH_4 leaks/flares	19.9	27.7	16.3	0.0	0.0
First total	445.6	545.6	334.4	29.0	1.3
Change (%)	-14.5	4.7	-35.8	-94.4	-99.7
Car assembly	14.4	14.4	14.4	14.4	14.4
Materials in cars[g]	46.6	46.6	46.6	46.6	46.6
Second total	506.6	606.6	395.4	90.0	67.3
Change (%)	-12.2	5.1	-31.5	-84.4	-89.2

See next page for footnotes.

TABLE 9 (Cont'd)

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[a]Because in the base case, battery-powered electric vehicles (EVs) are assumed to be used in city driving only, they are compared with reformulated-gasoline LDVs in the city driving cycle. The reformulated-gasoline LDV that gets 30 mpg in combined city/highway driving gets 24.5 mpg in city driving only. The base-case g/mi results (second total in the table) for the gasoline LDV in city driving, for all time horizons, are as follows:

Fuel	20-year	100-year	500-year
Reformulated gasoline (24.5 mpg, city driving)	727.7	577.1	533.1

The percentage changes in this table are given with respect to the value of 577.1 g/mi found in the reformulated gasoline LDV fuel cycle. In a few scenarios in Table 12, EVs are compared with ICEVs in city/highway driving, where the ICEVs get 30 mpg.

[b]The mix of power used nationally specifically to recharge EVs. See Table 6 and App. D.

[c]Emissions from the distribution of fuel oil to power plants.

[d]Emissions from the transmission and distribution of NG by pipeline to power plants.

[e]Emissions from power plants plus emissions from the facilities that make the fuel used at power plants plus N_2O emissions from high-voltage power lines.

[f]Emissions of N_2O formed by the corona discharge from high-voltage transmission lines.

[g]This estimate of emissions from the manufacture of materials for an EV is only approximate. I assume that the breakdown of the materials in an EV, excluding the battery, is the same as the breakdown for an ICEV. However, this assumption is obviously not correct, since the powertrain in an EV is very different from that in an ICEV.

TABLE 9 (Cont'd)

9e Methanol and Hydrogen Fuel-Cell Vehicles[a]

Source or Fuel-Cycle Stage	CO_2-Equivalent Emissions, by Fuel and Vehicle Type (g/mi)									
	Methanol from Coal[b]		Methanol from NG[b]		Methanol from Wood[b]		Hydrides from Nuclear[c]		H_2 from Solar[c]	
	LDV	HDV	LDV	HDV	LDV	HDV	LDV	HDV	LDV	HDV
Vehicle end use	145.4	962.5	145.4	962.5	0.9[d]	4.1[d]	0.0	0.0	0.0	0.0
Compression or liquefaction	0.0	0.0	0.0	0.0	0.0	0.0	15.6	100.6	0.0	0.0
Fuel distribution	9.7	64.3	18.7	123.9	11.8	78.0	1.0	6.7	1.0	6.7
Fuel production	256.5	1,701.6	53.7	355.9	15.3	101.7	36.4	235.0	0.0	0.0
Feedstock transport	1.0	6.6	6.0	40.1	6.5	43.4	0.08	0.53	0.00	0.00
Feedstock recovery and fert. mfg.[e]	5.9	38.9	11.2	74.4	28.6	189.9	2.3	14.6	0.0	0.0
CH_4 leaks/flares	23.8	158.1	7.2	47.8	0.0	0.0	0.0	0.0	0.0	0.0
First total	442.3	2,931.8	242.2	1,604.6	63.1	417.0	55.4	357.4	1.0	6.7
Change (%)	-0.6	21.1	-44.4	-33.7	-85.5	-82.8	-87.3	-85.2	-99.8	-99.7
Car assembly	14.6	52.1	14.6	52.1	14.6	52.1	14.8	56.1	14.8	56.1
Materials in cars[f]	43.8	156.3	43.8	156.3	43.8	156.3	50.5	197.5	50.5	197.5
Second total	500.7	3,140.3	300.6	1,813.1	121.6	625.5	120.7	611.0	66.3	260.3
Change (%)	0.0	19.5	-38.8	-31.0	-75.3	-76.2	-75.4	-76.7	-86.5	-90.1
LDV + HDV[g]	659.1		391.4		151.8		150.1		78.0	
Change (%)			-36.8		-75.5		-75.8		-87.4	

See next page for footnotes.

TABLE 9 (Cont'd)

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[a]Percentage changes for LDVs are relative to base-case reformulated-gasoline LDVs, and percentage changes for HDVs are relative to base-case diesel HDVs.

[b]These are reformed-methanol fuel-cell vehicles; the methanol is made from the feedstock shown. See App. B for an explanation of how methanol fuel-cell vehicles were modeled.

[c]These are hydrogen fuel-cell vehicles; the hydrogen is made from the feedstock shown. See App. B for an explanation of how hydrogen fuel-cell vehicles were modeled.

[d]Mostly due to evaporative NMOC emissions.

[e]Emissions from feedstock recovery and fertilizer manufacture are added together. They include N_2O and NO_x emissions from the denitrification and nitrification of nitrogenous fertilizers.

[f] These estimates of emissions from the manufacture of materials for a fuel-cell vehicle are only approximate. I assume that the breakdown of the materials in a fuel-cell vehicle, excluding the fuel storage system, is the same as the breakdown for an ICEV. However, this assumption is obviously not correct, since the powertrain in a fuel-cell vehicle is very different from that in an ICEV.

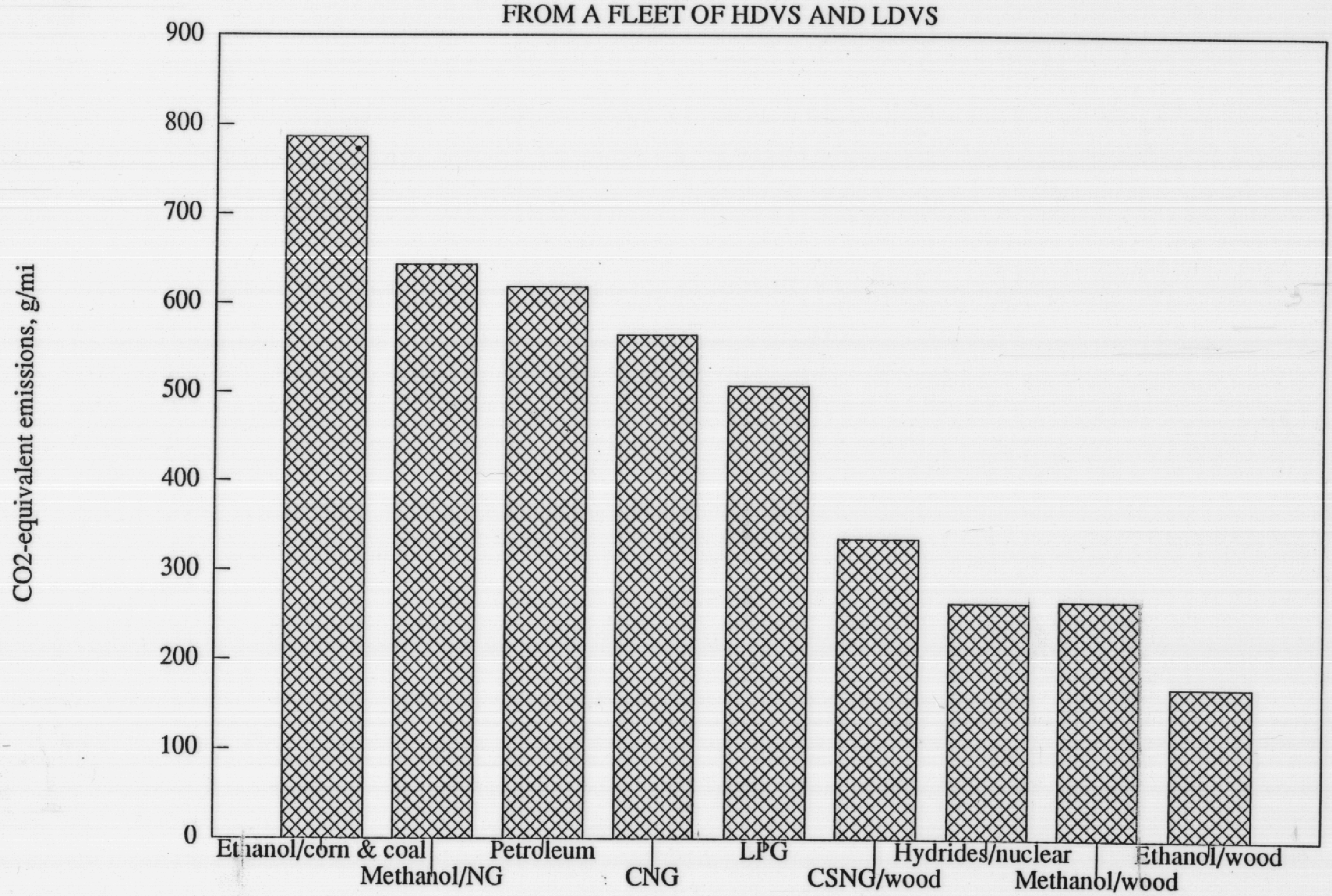
[g]Emissions from LDVs (in g/mi), weighted by the LDV VMT share, plus emissions from HDVs (in g/mi), weighted by the HDV VMT share (see Table B.4).

FIGURE 2 Total Fuel-Cycle, CO_2-Equivalent Emissions for Light-Duty Vehicles

FIGURE 3 Total Fuel-Cycle, CO_2-Equivalent Emissions for Heavy-Duty Vehicles

FIGURE 4 Total Fuel-Cycle, CO_2-Equivalent Emissions for a Fleet of Light-Duty and Heavy-Duty Vehicles Combined

GREENHOUSE GAS EMISSIONS



4.3.1.2 Diesel Light-Duty Vehicles

Diesel-powered LDVs, using low-sulfur diesel fuel, would produce 10-15% less total fuel-cycle, greenhouse gas emissions than comparable spark-ignition vehicles using reformulated gasoline. Of interest is the fact that the bulk of this reduction would not be a result of the greater fuel economy of the diesel vehicle (39 mpg versus 30 mpg on reformulated gasoline and 30.7 mpg on standard gasoline) but rather of the lower energy requirement for diesel manufacture and the longer life of diesel vehicles. The lower refinery energy requirement would substantially reduce emissions from diesel refining (compared with gasoline refining), and the longer life of the diesel vehicle would reduce emissions resulting from the manufacture of materials and vehicles (compared with making gasoline LDVs). The greater fuel economy of diesel vehicles tends to reduce tailpipe CO_2 emissions, but this benefit would be somewhat offset by their higher tailpipe NO_x emissions and the higher carbon content of diesel fuel.

When compared with the standard gasoline fuel LDV cycle, the greater fuel economy of diesel LDVs would also reduce upstream emissions from crude oil recovery and transport, because less crude would have to be recovered and moved to provide a mile's worth of fuel. However, the diesel fuel cycle does not enjoy this advantage over the reformulated gasoline LDV fuel cycle, because the upstream emissions reduction that would result from the greater fuel economy of diesel LDVs would be about the same as the reduction that would result from replacing some crude oil with MTBE. A comparison of upstream crude recovery and transport emissions from reformulated gasoline with upstream emissions from low-sulfur diesel fuel will confirm this conclusion.

In the United States today, few LDVs use diesel fuel. In 1988, U.S. households bought only 1.1 billion gallons of diesel fuel, scarcely more than 1% of the amount of gasoline bought (EIA, *Household Vehicles Energy Consumption 1988*, 1990). However, diesel's share of the LDV market is much higher in Europe and may grow in the United States.

4.3.1.3 Natural-Gas-Derived-Methanol Vehicles

Methanol LDVs, using 100% methanol (M100) derived mainly from remote NG, would emit roughly the same amount of greenhouse gases over the whole fuel cycle as would year-2000 gasoline vehicles. Methanol vehicles emit substantially less greenhouse gases from the tailpipe than do gasoline vehicles because of their greater thermal efficiency and the lower carbon content of methanol. However, the production of methanol is less energy efficient than the production of gasoline and produces more greenhouse gas emissions. Moreover, the greater feedstock requirements of methanol production mean that more feedstock must be recovered and transported per unit of fuel ultimately provided, which causes emissions from recovery and transport to be higher. Also, the CO_2-equivalent emissions from gas leaks associated with the production and transmission of the NG used to make methanol exceed the CO_2-equivalent emissions from the venting and flaring of gas associated with oil production.

Methanol HDVs would emit about 20% more greenhouse gases per mile than diesel LDVs. Methanol fares worse when it is compared with diesel fuel than when it is compared with gasoline because methanol does not have a thermal efficiency advantage over diesel fuel, and because diesel fuel takes much less energy to produce and has a lower carbon/Btu content than does gasoline.

FIGURE 5 CO_2-Equivalent Emissions from Vehicle End Use Only

If methanol were to be used in both HDVs and LDVs, the combined greenhouse gas emissions from the methanol fleet would be slightly greater than those from the replaced petroleum fleet (under the base-case assumptions used here). This result would occur because methanol HDVs emit a much greater amount of greenhouse gases than do diesel HDVs. Even though HDVs account for less than 10% of total highway vehicle miles traveled (VMT), they emit several times more greenhouse gases per mile and hence contribute significantly to total fleet emissions of greenhouse gases.

4.3.1.4 CNG and LNG Vehicles

The use of CNG and LNG in LDVs would decrease emissions of greenhouse gases by 10-15%. LNG would actually be very slightly better than CNG, because LNG vehicles weigh less than CNG vehicles (LNG tanks are lighter than CNG tanks), LNG is slightly more thermally efficient than CNG, LNG tanks require less energy to make than do CNG tanks, and liquefaction produces only slightly more CO_2-equivalent emissions than does compression. (Liquefaction requires more total energy but uses NG as a fuel.) Emissions from gas production and transport would be higher in the LNG case, because LNG uses more of its "own" fuel -- NG -- for process energy, but this increase would be relatively minor.

In heavy-duty applications, CNG and LNG would cause a 5-10% increase in emissions of greenhouse gases (compared with diesel fuel). This increase would result from the much lower thermal efficiency of NG HDVs (compared with diesel HDVs) and the lower energy requirements of diesel production (compared with gasoline production). Consequently, a policy promoting NG use in both heavy-duty and light-duty applications would be less beneficial than a policy promoting NG use in light-duty applications only -- if used in both applications, NG would result in only a 5-10% reduction in fuel-cycle greenhouse gas emissions, whereas a 10-15% reduction would be achieved if it were used in light-duty applications alone.

4.3.1.5 LPG Vehicles

Liquefied petroleum gas, consisting of 95% propane and 5% butane, offers a 20-25% reduction in emissions of greenhouse gas from LDVs (compared with gasoline). Moreover, the use of LPG in HDVs would actually decrease greenhouse gas emissions (compared with diesel fuel). The combined HDV-plus-LDV effect of an LPG policy would be a better-than-15% reduction in fuel cycle emissions of greenhouse gases. The LPG fuel cycle would thus produce the least amount of greenhouse gases of all the fossil fuel cycles, including that of diesel fuel.

There are several reasons why LPG would result in such relatively large reductions in emissions of greenhouse gases. LPG has a lower carbon content than does gasoline, and LPG vehicles are more efficient than gasoline vehicles. LPG vehicles also emit less CO, which is an indirect greenhouse gas. Although methanol, CNG, and LNG vehicles would offer similar benefits, their lower emissions would be largely offset by higher upstream emissions (compared with gasoline). By contrast, upstream emissions from the LPG fuel cycle are relatively low: it takes much less energy to liquefy propane than to compress or liquefy CH_4, convert NG to methanol, or refine crude oil to gasoline, and there are no CH_4 leaks from the distribution of LPG. Also, LPG tanks are lighter than CNG tanks and hence take less energy to make and are less of a drag on fuel economy.

Emissions from the use of LPG depend on the source of the LPG (refineries emit more greenhouse gases than do NGL plants), the efficiency of the LPG vehicle, and other factors. Variations in these factors are examined in Table 12 (which appears later).

Note that the range of results presented here is based on the assumption that the LPG is made of NGL extracted from wet NG or of propane and butane produced from refinery streams. The results do not apply to LPG made of propane produced by reforming NG, because the energy requirements of producing large amounts of propane from NG are not considered here.

4.3.1.6 Coal-Derived-Methanol Vehicles

The use of methanol from coal would cause a very large increase in per-mile emissions of greenhouse gases: about 70% for LDVs and 100% for HDVs. The increase would primarily result from the very large amount of emissions generated by the coal-to-methanol facility itself, although the amount of emissions from coal-bed CH_4 is also large. (Emissions from feedstock transport and fuel distribution actually would be lower in the methanol-from-coal case than the methanol-from-NG case, because it takes less energy to transport coal than NG, and because it would take less energy to distribute methanol from domestic coal plants to domestic end users than from foreign gas plants to domestic end users.) There is no combination of assumptions about vehicle technology, conversion technology (including advanced technologies that coproduce methanol and electricity), or CH_4 emissions that would alter this basic conclusion. Inevitably, the use of coal to make methanol would cause a substantial increase in per-mile emissions of greenhouse gases.

4.3.1.7 Corn-Derived-Ethanol Vehicles

The use of ethanol made from corn (by using coal as the process fuel) would cause an increase in greenhouse gas emissions of about 29%, given the base-case assumptions used here. (However, there are many other reasonable sets of assumptions; some of these are examined in the scenario analyses of Table 12.) There are two sources in the corn-to-ethanol cycle that result in a large amount of emissions: the combustion of coal at the ethanol production facility and the use of fertilizers in corn farming. A coal-fired ethanol production facility emits large amounts of greenhouse gases because it consumes relatively large amounts of coal and electricity (in the Midwest, where ethanol is and would be made, most electricity is generated from coal). However, the use of more efficient conversion technologies or low-CO_2-producing process fuels (such as residues from corn farming) could greatly reduce emissions from a corn-to-ethanol plant.

The corn field itself appears to be the source of a large amount of greenhouse gases -- not so much because of direct or indirect energy use, but because nitrogen-containing fertilizers can denitrify to produce N_2O or nitrify to produce NO_x. In fact, these emissions by themselves swing the final result on the use of ethanol from slightly favorable to unfavorable (compared with the gasoline base case). However, N_2O and NO_x emissions from the use of fertilizer have not been well characterized. The possibility that these emissions might be much less than assumed here is examined in Table 12 (which appears later).

4.3.1.8 Wood-Derived-Biofuel Vehicles

The use of wood-based biofuels -- methanol, ethanol, and SNG -- would offer large reductions in per-mile emissions of greenhouse gases when compared with petroleum-based (gasoline and diesel) fuels: approximately 45% for SNG, 55% for methanol, and 70% for ethanol. The reductions would ultimately result from the fact that CO_2 emissions from the combustion of a biofuel are not a net emission to the atmosphere, because the carbon in the emitted CO_2 originally came from the atmosphere, as CO_2, via photosynthesis. This reduction would be found in two places: as greatly reduced CO_2-equivalent emissions from vehicle tailpipes and somewhat reduced emissions from fuel production facilities that use a part of the wood as a process fuel.

The use of biofuels would not entirely eliminate CO_2-equivalent emissions (Table 9). There are several reasons for this. First, emissions of non-CO_2 gases, primarily from the vehicles themselves, would be substantial even after the CO, NMOC, and CH_4 emissions would be given a credit because they contain carbon that originally came from CO_2 in the atmosphere. Second, fossil fuels would be used at several points of the wood-to-fuel cycle: to transport wood and wood-fuel products, generate electricity, make fertilizer, and so on. The use of fossil fuels always results in CO_2 emissions. Third, N_2O emissions from denitrification and NO_x emissions from nitrification of the fertilizers used on wood plantations could be substantial. (However, the data on these emissions are quite poor, and the assumptions embodied in the results of Table 9 are very uncertain.) In the scenario analyses of Table 12 (which appears later), I examine the effects of varying assumptions about fossil fuel and fertilizer use in wood-to-fuel cycles.

The importance of non-CO_2 greenhouse-gas emissions in the biofuel cycle is demonstrated well in the 20-year case, which weights non-CO_2 gases heavily. Biofuels offer much less of a reduction in the 20-year case than in the 100-year and 500-year cases and, in fact, are relatively unimpressive.

The relatively small reduction in emissions that would result from using compressed synthetic natural gas (CSNG) from wood and the relatively large reduction that would result from using ethanol from wood are related to electricity generation and use. The compression of wood-derived SNG would require a fair amount of electricity, which would probably be generated, at least in part, from fossil fuels. This generation would produce greenhouse gases. On the other hand, ethanol-from-wood plants would probably produce more electricity than they would need, and they would sell the excess. This situation would result in an electricity-generating credit for ethanol.

4.3.1.9 Electric Vehicles

Emissions attributable to battery-powered electric-motor-driven vehicles, called electric vehicles or EVs, are a function of two key variables: the mix of fuels used to generate electricity and the efficiency (in mi/10^6 Btu) of the EV relative to the base-case gasoline ICEV. If the EVs were to use the estimated marginal power mix for recharging (see Table 6 and App. D), EVs would reduce total fuel-cycle, CO_2-equivalent emissions by more than 10%. For the base-case EV fuel cycle, the vast majority of greenhouse gas emissions come from power plants, primarily coal-fired plants. There is also a surprisingly large emission of CH_4 from coal mines. If EVs were recharged solely by electricity generated by coal-fired power plants, there would be a slight increase in total fuel-cycle, CO_2-equivalent emissions (compared with a reformulated gasoline fuel cycle). The use of electricity generated by NG-fired plants would result in a 30% reduction in emissions (compared with gasoline). The largest reductions would be obtained by using nuclear- or solar-generated electricity to recharge EVs; in fact, the use of solar power would eliminate all emissions except those arising from materials manufacture and vehicle assembly.

The efficiency of the EV is a function of the powertrain technology and of how the vehicle is driven. Thus, emissions from the use of EVs depend on where, when, and how the vehicle is used. Table 12, which appears later in the document, shows the results for combinations of different values of these variables.

4.3.1.10 Internal-Combustion-Engine Vehicles Powered by Nuclear-Made Hydrogen

The use of nuclear power to electrolyze water to make hydrogen is an interesting case. If fossil-based electricity were used to liquefy hydrogen to obtain liquefied H_2 (LH_2) or compress the hydrogen to make hydrides, and if the hydrogen were used in an ICEV, there would be four sources of greenhouse gases, one of them emitting quite a large amount. First, hydrogen-powered ICEVs would emit NO_x and trace amounts of HC, CO, and CO_2, which together would have a global warming potential equal to 5% of the CO_2-equivalent emissions from the petroleum-vehicle fuel cycle. Second, the production of nuclear electricity would produce greenhouse gases, mainly at the uranium-enrichment stage, which consumes a large amount of coal-derived electricity. These emissions would equal roughly 15% of emissions from the petroleum-vehicle fuel cycle (hydrogen LDVs compared with gasoline LDVs, or hydrogen HDVs compared with diesel HDVs). Third, emissions from the manufacture of materials and the assembly of vehicles would amount to about 15% of CO_2-equivalent emissions from the petroleum-vehicle fuel cycle. The final source of greenhouse gas emissions would be the electricity generation used to supply power to the hydrogen compressors or liquefiers. Compression of hydrogen to 500-750 psi (to make a hydride) does not require much power; hence, emissions resulting from compressing hydrogen would be less than 10% of petroleum fuel-cycle emissions. However, it takes a large amount of electricity to liquefy hydrogen, and the generation of this electricity can produce a huge amount of greenhouse gases. In fact, hydrogen liquefaction is so energy intensive that the use of hydrogen liquefied by power from fossil fuel power plants would cause only a modest decrease in emissions of greenhouse gases (compared with the base-case petroleum vehicle). This case demonstrates the importance of considering emissions from all processes related to the provision of a transportation fuel.

4.3.1.11 Fuel-Cell and Internal-Combustion-Engine Vehicles Using Solar-Made Hydrogen

The use of fuel-cell vehicles could greatly reduce emissions of greenhouse gases. Fuel cells, which convert the chemical energy in fuels to electricity, are roughly twice as efficient as internal combustion engines and produce virtually no non-CO_2 greenhouse gases. The use of solar power to make and compress or liquefy hydrogen for electric-motor-driven fuel-cell vehicles would eliminate all greenhouse gas emissions except those associated with making vehicles, equipment, and the materials for energy facilities. This result would be achieved because solar power plants and electric motors (using either a battery or a fuel cell) produce no greenhouse gases. If emissions from materials manufacture and vehicle assembly were included, the reduction in CO_2-equivalent emissions (compared with petroleum-based vehicles) would be 85-90%. If the solar-made hydrogen were used in an ICEV instead of a fuel-cell vehicle, the NO_x and trace organic emissions from the engine would be about 5% of the fuel-cycle emissions from a gasoline ICEV and would slightly reduce the benefit of using hydrogen. These cases assume that solar power is used to compress or liquefy hydrogen. The use of fossil electricity for this purpose would produce moderate (in the case of compression) to substantial (in the case of liquefaction) greenhouse gas emissions (see Table 12, which appears later).

4.3.1.12 Fuel-Cell Vehicles Using Methanol

A fuel-cell vehicle using reformed methanol made from NG would have about 40% lower total fuel-cycle, CO_2-equivalent emissions than the comparable gasoline ICEV. A fuel cell could bring the level of greenhouse gas emissions from the use of coal-derived methanol down to the level of emissions from a gasoline ICEV. And a fuel-cell vehicle using biomass-derived methanol would have 75% lower emissions than a comparable gasoline ICEV. In fact, the biomethanol fuel-cell vehicle is the lowest-emitting *liquid-fuel* option available.

However, the lowest emitters of all the options are electric-motor-driven vehicles that use solar or nuclear energy, either as electricity or as hydrogen. The use of hydrogen-powered fuel-cell vehicles, like the use of solar-powered battery-operated EVs, would eliminate all emissions of greenhouse gases other than those associated with materials manufacture and vehicle assembly.

Note that if they were to run on methanol from NG, fuel-cell LDVs would reduce greenhouse gas emissions more than would fuel-cell HDVs (compared with gasoline and diesel vehicles, respectively). However, if they were to run on biomass-derived methanol or solar hydrogen, fuel-cell HDVs would provide the greater reduction. This result would occur because relative CO_2 emissions from the methanol fuel-cell vehicle are proportional to the relative efficiency of the fuel cell, and a fuel cell has a greater efficiency advantage over a light-duty spark-ignition engine than it has over a heavy-duty compression-ignition engine. This relative efficiency advantage is also true for hydrogen fuel-cell vehicles and biomethanol fuel-cell vehicles, but it is largely irrelevant, because greenhouse gas emissions from these fuel cycles are only weakly related to efficiency: the vehicles themselves emit no greenhouse gases (hydrogen combustion produces no CO_2, and biomass combustion does not produce net CO_2), and the upstream fuel processes emit very little. For the case of hydrogen and biomass fuel-cell vehicles, the bulk of the emissions would come from materials manufacture and vehicle assembly, and emissions from the manufacturing stage of LDVs are a greater percentage of total emissions from the whole fuel cycle for LDVs than for HDVs.

4.3.2 Contribution of Individual Greenhouse Gas Emissions to Total Fuel-Cycle Emissions

Table 10 shows the g/mi CO_2-equivalent emissions of individual greenhouse gases that come from the vehicles themselves (tailpipe plus evaporative emissions) and from all upstream (nonvehicular) processes. (Figure 4 showed CO_2-equivalent emissions from vehicle end use only.) Non-CO_2 greenhouse gases account for 20-25% of the total CO_2-equivalent emissions from vehicles using fossil fuels (considering just the vehicles themselves) and nearly 100% of total greenhouse gas emissions from vehicles using biofuels. Emissions of CO, NO_x, and N_2O from vehicles are relatively important contributors to total emissions, and emissions of CH_4 are not, except in the case of NG vehicles. This situation occurs because emissions of CH_4 (in g/mi) are less than those of NMOCs, CO, and NO_x (Table B.2) and because the CH_4-to-CO_2 conversion factor is less than the N_2O-to-CO_2 and NO_x-to-CO_2 conversion factors (Table 8). This large contribution of non-CO_2 greenhouse gases to total emissions underscores the importance of accurately estimating emissions of all direct and indirect greenhouse gases and using appropriate CO_2-equivalency factors.

Non-CO_2 greenhouse gases account for 15-20% of total CO_2-equivalent emissions from upstream fossil-fuel-based processes (Table 10). These gases constitute a much larger percentage of total emissions from biomass-based processes, because N_2O and NO_x are emitted from the fertilizer used to grow the biomass. However, these fertilizer emissions need to be better documented.

Table 10 reveals some interesting results. The first is that giving the production of ethanol from corn a "by-product credit" results in negative CO emissions from the production stage, because large amounts of CO are produced by the gasoline engines (used in the soybean farming) that are displaced by the by-product. (See the notes to Table 10 for additional explanation.) The second is that emissions of NO_x are surprisingly large in several upstream processes: the production of methanol, the generation of electricity for EVs, and the nitrification of fertilizer applied to corn and trees. However, there is a lot of uncertainty associated with the NO_x emission factors for methanol production and fertilizer nitrification. A final point is that CH_4 emissions from the generation of electricity for EVs, arising primarily from the venting of coal mines, exceed CH_4 emissions from the NG system used to supply NG vehicles.

Overall, non-CO_2 gases are least important (as a percentage of total fuel-cycle emissions) in the EV fuel cycle, because in this cycle, there are only two significant sources: coal-fired plants that emit NO_x and coal mines that emit CH_4. Among fossil-based processes, the non-CO_2 gases are most important in the NG vehicle's fuel cycle (because it emits a relatively large amount of CH_4 and small amount of CO_2). Among all fuel cycles, non-CO_2 gases are most important in the biofuel cycles -- the wood-to-ethanol cycle in particular -- because these cycles produce very little CO_2 per se.

TABLE 10 Base-Case, Total Fuel-Cycle, CO_2-Equivalent Emissions from the Use of Transportation Fuels, by Individual Greenhouse Gas, for 100-Year Time Horizon

Fuel-Cycle Stage and Emissions[a]	Total Fuel-Cycle CO_2-Equivalent Emissions, by Fuel Type (g/mi)								
	Reform. Gasoline	Methanol from NG	CNG	EV[b]	LPG from NG and Oil[c]	Hydrides from Nuclear	Ethanol from Corn	Methanol from Wood	Ethanol from Wood
Vehicular									
CH_4	1.0	0.5	24.0	0.0	1.0	0.1	0.5[d]	0.5[d]	0.5[d]
N_2O	17.4	17.4	17.4	0.0	17.4	0.0	17.4	17.4	17.4
NMOC	8.4	3.2	2.2	0.0	2.5	0.4	3.0[d]	3.4[d]	3.0[d]
CO	18.4	21.6	10.8	0.0	16.5	2.1	21.6[d]	21.6[d]	21.6[d]
NO_x	18.0	18.0	18.0	0.0	18.0	18.0	18.0	18.0	18.0
Total non-CO_2[e]	63.2	60.7	72.4	0.0	55.4	20.6	60.5	61.0	60.5
CO_2	270.5	216.6	196.5	0.0	228.2	2.0[f]	-9.5[g]	-9.5[g]	-9.5[g]
Total vehicular[e]	333.7	277.4	269.0	0.0	283.6	22.6	51.0	51.4	51.0
Upstream[h]									
CH_4	5.3	8.7	14.5	20.7	4.7	7.8	18.3	4.6	1.0
N_2O	3.0	2.0	1.6	6.6	1.4	2.4	97.2[i]	7.1[i]	8.3[i]
NMOC	1.2	0.8	0.8	0.7	0.6	0.2	2.0	1.3	1.7
CO	0.6	0.4	0.2	0.5	0.3	0.2	-0.8[j]	2.1	3.2
NO_x	13.8	29.2	16.5	42.7	7.8	16.2	58.4[k]	26.3[k]	25.8[k]
Total non-CO_2	23.8	41.1	33.6	71.2	14.8	26.8	175.0	41.3	39.9
CO_2	133.6	166.4	120.6	435.7	79.2	148.8	362.0	112.0	41.5
Total upstream	157.5	207.4	154.2	506.6	94.0	175.7	537.0	153.3	81.4
Total non-CO_2	87.0	101.8	106.0	71.2	70.1	47.5	235.5	102.3	100.4
Total CO_2	404.1	383.0	317.1	435.4	307.4	150.8	352.5	102.4	32.0
Total[l]	491.2	484.8	423.2	506.6	377.6	198.3	588.1	204.7	132.5

See next page for footnotes.

TABLE 10 (Cont'd)

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[a]Totals may not equal sum of components shown because of independent rounding. CO_2-equivalence is calculated using the 100-year conversion factors of Table 8.

[b]Battery-powered electric vehicles (EVs) draw power from the base-case marginal power mix for EVs (Table 6).

[c]Liquefied petroleum gas (LPG) includes propane and butane from natural gas liquids (NGL) plants and petroleum refineries in the base-case proportions.

[d]These are "gross" CO_2-equivalent emissions; they do not include a credit for the carbon originally removed from the atmosphere as CO_2. That credit is taken below, under "CO_2."

[e]Vehicular emissions consist of tailpipe plus evaporative emissions, including those from refueling. These totals are the same as the totals from Table B.2.

[f] Emissions from the combustion of engine oil.

[g]This is the CO_2 credit for carbon emitted as CH_4, CO, or nonmethane organic compounds (NMOCs) from biofuel vehicles. Recall that the net warming effect of organic emissions from a biofuel vehicle is equal to the total effect of emissions from the tailpipe (e.g., total CH_4 emissions per mile multiplied by the CH_4-to-CO_2 equivalency factor), minus the amount of carbon, expressed as CO_2, contained in the emissions. This deduction accounts for the fact that all carbon in emissions from a biofuel is removed originally from the atmosphere as CO_2. The carbon-removal credit shows up here as a negative CO_2 emission.

[h]Emissions from all sources except vehicles. Includes emissions from materials manufacture and vehicle assembly.

[i] Emissions are primarily from the denitrification of nitrogenous fertilizers.

[j] This is negative because ethanol from corn is given a credit for distillers' dried grains and solubles (DDGS) by-product (see App. K). This credit is taken by subtracting from corn-farming energy the energy required to farm the soybeans displaced by the DDGS. A large part of this subtracted soybean-farming energy is gasoline used by gasoline tractors and engines, which produce very large amounts of CO (see Table A.1). Hence, the effect of the credit is to eliminate a large amount of CO-based greenhouse gas emissions. If the by-product credit were eliminated, the CO value here would become slightly positive. Overall, after the credit is given, corn farming is a net emitter of total greenhouse gases, even though it is a net displacer of CO emissions in particular. The CO credit is so large that it exceeds all CO emissions from the upstream part of the corn-to-ethanol process and produces the negative value of the table. This is an interesting and subtle consequence that results from making particular assumptions about by-product credit, fuel use, and CO emissions.

[k]Includes minor emissions from the nitrification of fertilizer to NO_x. These estimates are very uncertain.

[l]These values are the same as the values of Table 9.

4.3.3 Emissions as a Function of Fuel Economy

Table 11 shows total fuel-cycle, CO_2-equivalent emissions as a function of the fuel economy (mpg) of the base-case gasoline vehicle. Total fuel-cycle emissions of CO_2 only (i.e., not NO_x, CH_4, NMOCs, CO, and N_2O) are directly proportional to mpg. Total fuel-cycle, CO_2-equivalent emissions of all gases, however, are not linearly proportional to mpg (except in the case of EVs), because g/mi tailpipe emissions of non-CO_2 greenhouse gases are fairly independent of mpg. (Upstream evaporative emissions of NMOC are not independent of the mpg of the vehicle.) Thus, as shown in Table 11, increasing the fuel economy of ICEVs by a factor of two (from 20 to 40 mpg, for example) does not reduce total fuel-cycle, CO_2-equivalent emissions by a factor of two. This nonproportionality is more pronounced if emissions from vehicle manufacture and assembly are included, because these emissions, although not fixed, are not directly proportional to fuel economy. (They are assumed here to be proportional to vehicle weight, but vehicle weight is not linearly related to fuel economy.)

In the case of EVs, however, the change in total fuel-cycle, CO_2-equivalent emissions is directly proportional to the change in the efficiency ($mi/10^6$ Btu) of the EV itself and "more than proportional" to the change in fuel economy of the base-case gasoline vehicle (in the sense, explained below, that increasing the mpg of the baseline ICEV by a factor of two reduces EV-cycle emissions by more than a factor of two). Emissions are proportional to the efficiency of the EV because power plant emissions are regulated per unit of fuel consumed. They are not proportional in the case of the gasoline vehicle, because ICEV emissions are regulated per mile of travel and hence independent of the rate of fuel consumption. The EV-cycle emissions are more than proportional to the fuel economy of the baseline ICEV because a 10% improvement in the mpg (or $mi/10^6$ Btu efficiency) of the ICEV translates into a greater than 10% improvement in the $mi/10^6$ Btu efficiency of the EV, which in turn results in an emissions reduction that is greater than 10%. This situation occurs because of the interactive effect between the efficiency of the baseline ICEV and the weight of the EV battery: the increased baseline ICEV efficiency reduces the size of the battery needed to provide a given driving range, which leads to a reduction in the weight of the EV, which increases the EV's efficiency, which reduces the size of battery needed, and so on. (Of course, the opposite occurs if the baseline ICEV becomes less efficient.) See App. B for a formal explanation of the calculation of EV energy use.

TABLE 11 Base-Case, Total Fuel-Cycle, CO_2-Equivalent Emissions from the Use of Transportation Fuels as a Function of Baseline Vehicular Fuel Economy, for 100-Year Time Horizon

	Total Fuel-Cycle CO_2-Equivalent Emissions, by Fuel Type (g/mi)								
Baseline Fuel Economy (mpg)[a]	Reform. Gasoline	Methanol from NG	CNG	EV Using U.S. Power Mix[b]	LPG from NG and Oil	Hydrides from Nuclear	Ethanol from Corn	Methanol from Wood	Ethanol from Wood
Excluding emissions from materials manufacture and vehicle assembly									
20	627	618	510	684	457	184	773	198	89
25	512	505	421	539	375	150	628	168	82
30	435	429	361	446	320	129	532	149	77
35	381	375	318	379	281	113	463	135	73
40	340	334	286	328	252	101	412	124	70
45	308	303	261	287	229	92	372	116	68
50	282	278	241	253	211	84	340	110	66
Including emissions from materials manufacture and vehicle assembly[c]									
20	706	698	600	773	539	284	852	277	169
25	578	571	494	613	443	233	695	235	148
30	491	485	423	507	378	198	588	205	132
35	429	423	372	432	331	173	512	183	121
40	384	378	335	375	297	156	456	168	114
45	350	345	308	330	273	143	414	159	111
50	326	322	289	295	256	136	384	154	110

[a]Fuel economy shown in miles per gallon (mpg) is that achieved in combined/city highway driving, which is the baseline for all vehicles shown except the battery-powered electric vehicle (EV). EV emissions are compared with the base-case gasoline vehicle being driven in the city only. Corresponding city-only fuel economies are shown in footnote b. The efficiencies of the alternative-fuel vehicles relative to that of the baseline reformulated-gasoline vehicle are as assumed in the base case (Table 2).

TABLE 11 (Cont'd)

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[b]Emissions from the EV are calculated on the basis of the assumption that the EV would replace the baseline internal-combustion-engine vehicle (ICEV) for city driving only. For each city/highway mpg shown in the far left column of the table below in this footnote, the corresponding city-only mpg for the baseline ICEV, shown in the next column, is lower. Emissions from EVs are calculated on the basis of the assumption that city-only driving takes place. The driving range of the EV is held constant at 130 miles for all baseline city-only fuel economcy levels (in mpg). Thus the weight of the battery and the vehicle decline as the baseline fuel economy (mpg) improves. The data on weight calculated for each mpg level are shown below.

Gasoline ICEV Fuel Economy (mpg)		EV Weight (lb)	
City/ Highway	City Only	Battery	Extra Vehicle Wt.
20	16.3	1,248	888
25	20.4	985	678
30	24.5	815	547
35	28.6	694	456
40	32.7	601	379
45	36.8	525	306
50	40.8	462	232

As the fuel economy of the baseline ICEV increases, the battery and EV weight more than proportionately decrease. This situation occurs because of the interactive effect described in the text.

[c]As the weight of the vehicle decreases, fuel economy (mpg) increases; hence, emissions from making materials and assembling the vehicle decrease with increasing mpg. However, the relationship is not 1:1, and emissions from material manufacture and assembly constitute an increasingly greater percentage of total fuel-cycle emissions as fuel economy improves.

5 SCENARIO ANALYSES

The scenarios show how the assumptions about important input variables, if changed from their base-case values, could affect total fuel-cycle emissions under 20-year, 100-year, and 500-year time horizons. The scenario description column of Table 12 identifies all the variables that change for each scenario. All other variables (that is, all those not specifically mentioned in the scenario) retain their base-case values. The table shows how much the total fuel-cycle, CO_2-equivalent emissions in each scenario differ -- in percentage terms -- from those in the petroleum-fuel (gasoline or diesel fuel) baseline. A change of X% means that, for the scenario described, total fuel-cycle emissions (in grams per mile) are equal to total fuel-cycle emissions from the petroleum-fuel baseline multiplied by 1 + (X/100). The gasoline or diesel-fuel baseline is different for different scenarios, depending on whether the changes described in the scenario affect the original petroleum-fuel base-case values (e.g., Tables 2-7). The petroleum-fuel baseline values are listed in the footnotes to Table 12. The results of the scenario analyses are summarized graphically in Figs. 6 and 7.

5.1 SCENARIOS 1, 2, AND 3

These scenarios recapitulate the results of Table 9 but also show results for the 20-year and 500-year time horizons. There are several noteworthy results. First, in most cases, the alternative fuels fare better than the petroleum fuels over longer time horizons; that is, they offer a bigger percentage reduction in total fuel-cycle, CO_2-equivalent greenhouse gas emissions over 500 years than over 20 years. This result occurs because actual per-mile emissions of CO_2 and differences among the alternatives in emissions of CO_2 are constant regardless of the time horizon, whereas the CO_2-equivalent of non-CO_2 greenhouse gas emissions decreases as the time horizon lengthens. In other words, the difference (usually a reduction) in total emissions among the alternatives that is due to CO_2 emissions alone "stands out" more (i.e., contributes to a larger percentage reduction) in long-term projections because it is seen against a smaller CO_2 plus non-CO_2 emissions total in the longer run. The differences among the alternatives in emissions of non-CO_2 gases could change in such a way as to counter this result, but this happens in only a few cases.

Second, for almost all fuels, the difference between the 20-year and 100-year cases is greater than the difference between the 100-year and the 500-year cases, because the ratio of the 20-year to the 100-year conversion factors for emissions is greater than the ratio of the 100-year to the 500-year conversion factors, with the exception of the conversion factor for N_2O (Table 8; CFCs excluded). The N_2O conversion factor has an interesting effect in the corn-to-ethanol case. Corn farming appears to produce large amounts of N_2O and NO_x as a result of the denitrification and nitrification of fertilizer, respectively (App. N). These emissions account for a large portion of the total CO_2-equivalent emissions from the corn-to-ethanol fuel

TABLE 12 Comparison of Total Fuel-Cycle, CO_2-Equivalent Emissions (measured in grams per mile) from the Use of Alternative Transportation Fuels with Emissions from the Use of Baseline Petroleum Fuels under Different Scenarios

Scenario Number and Description[a]	Percentage Change in Emissions from Baseline Value, by Time Horizon[b] 20 yr	100 yr	500 yr
1. Base-case alternative-fuel LD ICEVs, EVs, and fuel-cell vehicles[c]			
Standard gasoline		-1.0	
Methanol/NG	5.8	-1.3	-3.6
Methanol/coal		59.3	
CNG	-2.1	-13.8	-18.1
LNG		-14.3	
Marginal U.S. mix/EV	-7.9	-12.6	-12.8
Ethanol/corn+coal	37.0	19.7	6.7
Hydride/nuclear electrolysis	-50.5	-59.6	-62.2
LH_2/nuclear electrolysis		-15.6	
LPG/oil and NG	-23.0	-23.1	-23.4
Methanol/wood	-40.7	-58.3	-65.6
CSNG/wood	-21.8	-47.7	-57.7
Ethanol/wood	-53.4	-73.0	-81.3
Hydrogen/all-solar		-82.9	
All-solar/EV		-89.2	
Methanol/NG/fuel cell	-40.9	-38.8	-37.2
Methanol/coal/fuel cell		- 0.0	
Methanol/wood/fuel cell	-70.6	-75.3	-76.8
Hydride/nuclear electrolysis/fuel cell	-74.4	-75.4	-75.5
Hydrogen/all-solar/fuel cell		-86.5	
2. Base-case alternative-fuel HD ICEVs and fuel-cell vehicles[c]			
Methanol/NG	24.2	19.2	17.3
Methanol/coal		99.4	
CNG	13.7	6.2	3.2
LNG		7.6	
Ethanol/corn+coal	62.3	48.7	33.4
Hydride/nuclear electrolysis	-33.2	-49.9	-56.7
LH_2/nuclear electrolysis		4.1	
LPG/oil and NG	-3.2	-2.4	-2.1
Methanol/wood	-27.5	-52.5	-63.0
CSNG/wood	-9.9	-39.7	-52.2
Ethanol/wood	-40.8	-70.6	-83.3
Hydrogen/all-solar		-78.5	
Methanol/NG/fuel cell	-41.3	-31.0	-26.8
Methanol/coal/fuel cell		19.5	
Methanol/wood/fuel cell	-74.0	-76.2	-77.4
Hydride/nuclear electrolysis/fuel cell	-78.4	-76.7	-76.1
Hydrogen/all-solar/fuel cell		-90.1	

TABLE 12 (Cont'd)

Scenario Number and Description[a]	Percentage Change in Emissions from Baseline Value, by Time Horizon[b] 20 yr	100 yr	500 yr
3. Base-case alternative-fuel LD + HD ICEVs and fuel-cell vehicles[c]			
Methanol/NG	10.9	3.9	1.6
Methanol/coal		69.4	
CNG	2.3	-8.7	-12.8
LNG		-8.7	
Ethanol/corn+coal	44.0	27.1	13.4
Hydride/nuclear electrolysis	-45.7	-57.2	-60.8
LH_2/nuclear electrolysis		-10.6	
LPG/oil and NG	-17.5	-17.9	-18.1
Methanol/wood	-37.0	-56.8	-64.9
CSNG/wood	-18.5	-45.7	-56.3
Ethanol/wood	-49.9	-72.4	-81.8
Hydrogen/all-solar		-81.8	
Methanol/NG/fuel cell	-41.0	-36.8	-34.6
Methanol/coal/fuel cell		4.9	
Methanol/wood/fuel cell	-71.6	-75.5	-76.9
Hydride/nuclear electrolysis/fuel cell	-75.5	-75.8	-75.6
Hydrogen/all-solar/fuel cell		-87.4	
4. Base-case alternative-fuel LD ICEVs and EVs, NO_x excluded, NMOCs oxidize only (3.66 CO_2-equivalency factor)			
Methanol/NG	-1.5	-3.9	-4.6
CNG	-1.5	-14.6	-18.5
Marginal U.S. mix/EV	-11.7	-13.5	-13.3
Ethanol/corn+coal	16.1	12.3	3.6
Hydride/nuclear electrolysis	-62.5	-63.8	-63.8
LPG/oil and NG	-21.8	-22.7	-23.3
Methanol/wood	-59.7	-65.3	-68.3
CSNG/wood	-40.3	-55.2	-60.8
Ethanol/wood	-75.6	-81.1	-84.5
5. Base-case alternative-fuel HD ICEVs, NO_x excluded, NMOCs oxidize only (3.66 CO_2-equivalency factor)			
Methanol/NG	19.0	16.9	16.4
CNG	17.0	5.8	2.9
Ethanol/corn+coal	46.9	42.0	30.0
Hydride/nuclear electrolysis	-57.2	-59.6	-60.5
LPG/oil and NG	-2.0	-2.0	-1.9
Methanol/wood	-63.3	-67.0	-68.8
CSNG/wood	-42.4	-54.0	-58.1
Ethanol/wood	-85.8	-88.6	-90.5

TABLE 12 (Cont'd)

Scenario Number and Description[a]	Percentage Change in Emissions from Baseline Value, by Time Horizon[b]		
	20 yr	100 yr	500 yr
6. Base-case alternative-fuel HD + LD ICEVs, NO_x excluded, NMOCs oxidize only (3.66 CO_2-equivalency factor)			
Methanol/NG	3.3	1.1	0.5
CNG	2.8	-9.7	-13.3
Ethanol/corn+coal	23.2	19.4	10.0
Hydride/nuclear electrolysis	-61.3	-62.8	-63.0
LPG/oil and NG	-17.2	-17.8	-18.1
Methanol/wood	-60.5	-65.7	-68.5
CSNG/wood	-40.8	-54.9	-60.1
Ethanol/wood	-78.0	-82.9	-86.0
7. Base-case alternative-fuel LD ICEVs and EVs, actual CO_2 emissions only			
Methanol/NG		-5.2	
CNG		-21.5	
Marginal U.S. mix/EV		-10.4	
Ethanol/corn+coal		-12.7	
Hydride/nuclear electrolysis		-62.7	
LPG/oil and NG		-23.9	
Methanol/wood		-74.7	
CSNG/wood		-68.0	
Ethanol/wood		-92.1	
8. Base-case alternative-fuel HD ICEVs, actual CO_2 emissions only			
Methanol/NG		16.1	
CNG		1.0	
Ethanol/corn+coal		8.7	
Hydride/nuclear electrolysis		-61.3	
LPG/oil and NG		-1.5	
Methanol/wood		-72.6	
CSNG/wood		-63.1	
Ethanol/wood		-95.0	

TABLE 12 Cont'd)

Scenario Number and Description[a]	Percentage Change in Emissions from Baseline Value, by Time Horizon[b]		
	20 yr	100 yr	500 yr
9. Lean-burn, low-emission, high-efficiency alternative-fuel LD ICEVs and EVs			
a. Methanol/NG: 30% efficiency advantage, CO reduced by 50% from methanol base case; NMOCs and CH_4 reduced by 25% from methanol base case.	-6.2	-11.4	-13.2
b. CNG: 20% thermal efficiency advantage; CO reduced 75% from CNG base case; NMOCs reduced 25% from CNG base case; CH_4 reduced 33% from CNG base case.	-13.6	-21.6	-24.6
c. Marginal U.S. mix/EV: Powertrain 6.1 times more efficient than ICEV powertrain.	-13.3	-17.3	-17.9
d. Ethanol/corn+coal: 28% vehicle efficiency advantage over standard gasoline; CO reduced 50% from ethanol base case; NMOCs and CH_4 reduced 25% from ethanol base case.	22.0	7.8	-3.6
e. Hydride/nuclear electrolysis: 35% efficiency advantage over gasoline.	-53.8	-62.7	-65.3
f. LPG/oil and NG: 20% thermal efficiency advantage over gasoline; CO reduced 75% from LPG base case; NMOCs and CH_4 reduced 25% from LPG base case.	-31.0	-29.4	-29.1
g. Methanol/wood: Vehicles same as in Scenario 9-a.	-47.2	-61.9	-68.1
h. CSNG/wood: Vehicles same as in Scenario 9-b.	-31.5	-52.5	-60.8
i. Ethanol/wood: Vehicles same as in Scenario 9-d.	-58.3	-74.8	-82.0
10. High-efficiency alternative-fuel HD ICEVs			
a. Methanol/NG: 5% efficiency advantage over diesel HD ICEVs.	18.0	11.8	9.5
b. CNG: 10% efficiency loss compared with diesel HD ICEVs.	9.8	1.5	-1.8
c. Ethanol/corn+coal: No efficiency loss compared with diesel HD ICEVs.	55.1	41.1	26.3
d. Hydride/nuclear electrolysis: 10% efficiency advantage over diesel HD ICEVs.	-34.6	-51.4	-58.2
e. LPG/oil and NG: 10% efficiency loss compared with diesel HD ICEVs.	-6.3	-6.7	-6.8
f. Methanol/wood: 5% efficiency advantage over diesel HD ICEVs.	-29.8	-54.4	-64.7
g. CSNG/wood: 10% efficiency loss compared with diesel HD ICEVs.	-12.5	-41.8	-54.1
h. Ethanol/wood: No efficiency loss compared with diesel HD ICEVs.	-41.7	-71.1	-83.5

TABLE 12 (Cont'd)

Scenario Number and Description[a]	Percentage Change in Emissions from Baseline Value, by Time Horizon[b] 20 yr	100 yr	500 yr
11. Dual-fuel alternative-fuel LD ICEVs			
a. Methanol/NG: Operation on M85; 5% efficiency advantage on methanol over dedicated gasoline vehicles (Sperling and DeLuchi, 1991; Sapre, 1988); 15% lower NO_x emissions than dedicated gasoline or methanol vehicle (Sperling and DeLuchi, 1991; Sapre, 1988); 0.029 g/mi CH_4 (App. M); evaporative emissions (in g/gal) 50% of those from gasoline (assuming that the Reid vapor pressure [RVP] of M85 is 70% that of gasoline [Sapre, 1988], that the vapors have 70% of the weight of gasoline vapors, and that the evaporative emission control system is the same as for gasoline); tailpipe NMOC emissions 21% higher than from dedicated M100 vehicles (EPA, *Analysis of the Economic and Environmental Effects of Methanol as an Automotive Fuel*, 1989); NMOC emissions contain 55% carbon.	8.0	3.4	2.0
b. Methanol/NG: Same as Scenario 11-a, except 50% of vehicle miles traveled (VMT) on M85, 50% on gasoline; 3.5% thermal efficiency advantage over dedicated gasoline vehicle; 9% reduction in NO_x emissions compared with dedicated gasoline or methanol vehicle; tailpipe NMOC emissions 10% higher than those from dedicated M100 vehicle (emissions assumptions [based on data in Sapre, 1988] indicate that an increase in efficiency, a decrease in NO_x, and an increase in NMOCs are proportional to methanol content); same g/gal evaporative emissions as gasoline (the RVP of M50 is 12% higher than the RVP of M0 according to Sapre, 1988; I assume that the molecular weight of M50 evaporative emissions is slightly less than that of gasoline evaporative emissions); 65% carbon in NMOC.	4.0	1.7	1.0
d. CNG: Operation on CNG; no thermal efficiency advantage over dedicated gasoline vehicle; 150-mi range on CNG (smaller tank than in dedicated vehicle) but retains the gasoline tank; CH_4 and NMOC emissions 10% higher than from dedicated CNG vehicle.	3.6	-8.5	-12.8
e. Ethanol/corn+coal: E85; 4% efficiency advantage over dedicated gasoline vehicle; NO_x and CH_4 emissions same as from methanol flexible-fuel vehicle (FFV) (EPA, *Analysis of the Economic and Environmental Effects of Ethanol as an Automotive Fuel*, 1990); NMOC tailpipe emissions 21% higher than from dedicated E100 vehicle; g/gal evaporative emissions 30% of those from gasoline; NMOC emissions contain 66% carbon.	36.3	22.8	12.0
f. LPG/oil and NG: No thermal efficiency advantage over dedicated gasoline; operation on LPG 100% of the time; 250-mi driving range on LPG; retain gasoline tank; CH_4 and NMOC emissions 10% higher than from dedicated LPG vehicle.	-18.4	-17.5	-17.3
g. Ethanol/wood: Same changes in assumptions about vehicles as in Scenario 11-e.	-42.6	-58.3	-65.0

TABLE 12 (Cont'd)

Scenario Number and Description[a]	Percentage Change in Emissions from Baseline Value, by Time Horizon[b] 20 yr	100 yr	500 yr
12. Gasoline LD ICEVs			
a. Refinery energy requirement higher than in base case (0.20 Btu/Btu of gasoline).	1.1	1.2	1.2
b. Crude recovery energy 25% higher (due to low-quality crude).	0.7	0.6	0.6
c. Venting and flaring emissions 25% higher; 10% vented (versus 6% in base case).	0.9	0.5	0.3
d. Tailpipe emissions same as for standard gasoline (0.40 g/mi for NMOCs, 7.21 g/mi for CO).	1.2	0.4	0.2
e. Methyl tertiary butyl ether (MTBE) does not displace crude; extra crude is input as refinery fuel.	0.2	0.2	0.2
f. Scenarios 12-a through 12-e combined.	4.1	2.9	2.5
g. 1987 level of crude imports (less international crude movement than there is in year-2000 scenario).		-0.5	
13. Diesel LD ICEVs (versus base-case gasoline LD ICEVs)			
a. 39 mpg (indirect-injection diesel engine; 27% efficiency advantage over standard gasoline); low-sulfur diesel; 400-mi range; 1.10 g/mi for NO_x, 1.45 g/mi for CO, 0.40 g/mi for NMOCs, 0.02 g/mi for CH_4, 0.054 g/mi for N_2O (see App. B); 150,000-mi life; 100 lb more weight than gasoline LDV.	-6.0	-13.7	-16.2
b. 36 mpg; all else same as in Scenario 12-a.	-1.5	-8.4	-10.5
c. 42 mpg (45% efficiency advantage; direct-injection engine).	- 9.8	-18.3	-21.1
d. 45 mpg.	-13.1	-22.2	-25.3
e. Regular diesel (not low-sulfur diesel); all else same as in Scenario 12-a.	-6.5	-14.2	-16.8
14. Gasoline HD ICEVs (versus base-case diesel HD ICEVs)			
a. 4.8 mpg on reformulated gasoline (versus 6.0 on diesel; 25% advantage for diesel); 1.13 g/mi for exhaust NMOCs (15% reduction from MOBILE4 value of Table B.3 to account for effect of unreformulated gasoline); 1.27 g/mi evaporative and refueling losses; 0.18 g/mi for CH_4; 14.05 g/mi for CO (15% reduction from MOBILE4 value of Table B.3 to account for effect of reformulated gasoline); 4.26 g/mi for NO_x (emission factors from Table B.3); 0.06 g/mi for N_2O (Table N.1); 500 lb less weight (versus diesel HDV); lifetime 33% that of diesel HD ICEV (based on data in California Air Resources Board, November 1986).	10.8	23.0	27.7
b. Same as in Scenario 14-a, but 4.5 mpg (33% advantage for diesel).	15.0	29.1	34.2
c. Same as in Scenario 14-a, but NO_x emissions excluded.	32.8	31.4	30.8

TABLE 12 (Cont'd)

Scenario Number and Description[a]	Percentage Change in Emissions from Baseline Value, by Time Horizon[b]		
	20 yr	100 yr	500 yr
15. Alternative-fuel LD ICEVs in European Economic Community (EEC) (versus gasoline LD ICEVs in EEC)[d]			
a. Methanol/NG: Stoichiometric operation.	1.1	-1.1	-1.9
b. Methanol/NG: Lean burn (25% efficiency advantage; lower CO, NMOC, and CH_4 emissions).	-8.8	-9.2	-9.1
c. CNG: Stoichiometric operation.	-7.0	-14.8	-18.5
d. CNG: Lean burn (20% efficiency advantage; lower CO, NMOC, and CH_4 emissions).	-17.8	-22.8	-25.3
e. Ethanol/corn+coal: Stoichiometric operation.	23.6	16.8	6.7
f. Ethanol/corn+coal: Lean burn (24% efficiency advantage; lower CO, NMOC, and CH_4 emissions).	11.8	7.3	-1.3
g. Hydride/nuclear electrolysis: Stoichiometric operation.	-58.8	-69.3	-73.5
h. Hydride/nuclear electrolysis: Lean burn (30% efficiency advantage).	-59.6	-70.3	-74.5
i. LPG/oil and NG: Stoichiometric operation.	-22.6	-21.9	-21.7
j. LPG/oil and NG: Lean burn (20% efficiency advantage; lower CO, NMOC, and CH_4 emissions).	-31.0	-28.7	-27.8
k. Methanol/wood: Stoichiometric operation.	-33.5	-53.7	-63.9
l. Methanol/wood: Lean burn (25% efficiency advantage; lower CO, NMOC, and CH_4 emissions).	-40.7	-57.7	-66.2
m. CSNG/wood: Stoichiometric operation.	-21.8	-46.4	-58.6
n. CSNG/wood: Lean burn (20% efficiency advantage; lower CO, NMOC, and CH_4 emissions).	-41.4	-51.7	-61.7
o. Ethanol/wood: Stoichiometric operation.	-39.4	-63.1	-75.0
p. Ethanol/wood: Lean burn (24% efficiency advantage; lower CO, NMOC, and CH_4 emissions).	-46.2	-66.3	-76.5
16. Alternative-fuel HD ICEVs in EEC (versus diesel HD ICEVs in EEC)[d]			
Methanol/NG	-18.6	-2.1	7.8
CNG	-8.8	-5.4	-3.6
Ethanol/corn+coal	4.6	20.6	21.1
Hydride/nuclear electrolysis	-66.0	-71.1	-74.4
LPG	-16.5	-9.5	-5.2
Methanol/wood	-47.8	-58.3	-65.6
CSNG/wood	-22.3	-41.8	-54.7
Ethanol/wood	-49.8	-66.6	-78.0

TABLE 12 Cont'd)

Scenario Number and Description[a]	Percentage Change in Emissions from Baseline Value, by Time Horizon[b] 20 yr	100 yr	500 yr
17. EVs versus gasoline LD ICEVs used for city only driving in EEC, Japan, or Canada[d]			
a. Canada	-66.7	-68.4	-68.7
b. France	-83.8	-81.5	-80.4
c. Germany	-51.9	-44.9	-41.3
d. Japan	-54.5	-56.0	-55.7
e. Sweden	-84.0	-81.6	-80.5
f. United Kingdom	-35.2	-25.4	-20.4
g. European Community	-53.4	-46.3	-42.7
18. Methanol/NG LD ICEVs			
a. Methanol from advanced conversion plants (71% efficient).		- 6.9	
b. All methanol from remote NG (versus 75% in base case).		- 0.0	
c. All methanol from domestic gas (no international transport); advanced conversion plants (71% efficient).		-10.4	
d. NO_x emissions from methanol-from-NG plants 75% lower than in base case of Table A.1.		- 3.5	
e. Methanol made from flared gas (CO_2 from methanol plant set equal to zero; CH_4 leaks given a CO_2 credit; biomethanol vehicle emission factors used; compared with original base-case gasoline emission factor, 491.2 g/mi).		-62.1	
f. Same g/gal evaporative emissions as from gasoline vehicle (control system is reduced to save cost).		- 0.8	
g. Natural gas liquids (NGL) not removed from NG (zero energy requirements at NGL plant; 2% boost in methanol production; gas has less CH_4, C_2, and higher hydrocarbon emissions.		- 1.6	
h. 10% thermal efficiency advantage over gasoline.		2.2	
i. Best for methanol/NG: Scenarios 18-c, d, and g combined with 9-a.	-20.4	-21.8	-22.4
j. Worst for methanol/NG: Scenarios 18-b and h, plus 25% higher tailpipe NMOC emissions than in methanol base case.	10.9	3.7	1.4
k. 75% of methanol from base-case NG; 25% from base-case coal.		14.1	
19. Methanol/NG HD ICEVs			
a. Same as Scenario 18-c only for HD ICEVs.		12.0	
b. Low-NO_x conversion plants (75% lower emissions than in base case of Table A.1).		16.4	
c. Methanol/NG 5% more thermally efficient than diesel HD ICEVs.		11.8	
d. Methanol/NG 10% less thermally efficient than diesel HD ICEVs.		26.8	
e. Best for methanol/NG: Scenarios 19-a, b, and c combined with 18-g; CO, CH_4, and NMOCs 25% lower than in methanol/NG HD ICEV base case.	0.1	- 2.5	- 3.5
f. Worst for methanol/NG: Scenarios 18-b and 19-d; CO, CH_4, and NMOCs 25% higher than in methanol/NG HD ICEV base case.	33.4	28.9	27.3
g. 75% of methanol from base-case NG; 25% from base-case coal.		39.3	

TABLE 12 (Cont'd)

Scenario Number and Description[a]	Percentage Change in Emissions from Baseline Value, by Time Horizon[b] 20 yr	100 yr	500 yr
20. Methanol/coal LD ICEVs (base case is second-generation coal conversion, 56% efficient)			
a. OTM/LPM/IGCC (once-through methanol/liquid-phase methanol synthesis/integrated gasification combined-cycle) technology coal conversion; 70% efficient; very low NO_x emissions.		30.6	
b. CH_4 emissions from coal mining reduced to 250 ft^3/ton (versus 380 in the base case).		57.0	
c. Lean-burn methanol vehicles (Scenario 9-a); base-case coal conversion.		42.2	
d. Best for methanol/coal: Scenarios 20-a, b, and c.	11.8	15.1	16.4
e. CO_2 removed from coal-to-methanol plants.		-14.4	
f. Scenarios 20-a and e.		-19.5	
21. Methanol/coal HD ICEVs			
a. OTM/LPM/IGCC.		61.1	
b. Best for methanol/coal: Scenarios 21-a, 20-b, and 19-c, plus 25% lower CO, NMOCs, and CH_4 than in methanol/coal HD ICEV base case.	39.0	47.8	51.2
c. CO_2 removed from coal-to-methanol plants.		2.3	
d. Scenarios 21-a and c.		- 4.3	
22. Methanol/wood LD ICEVs			
a. Non-CO_2 emissions from wood-to-methanol plants reduced by 75% from base case (Table A.1).		-59.2	
b. Methanol/wood used by all trucks and tractors involved in the fuel cycle.		-63.9	
c. No SRIC (short-rotation intensive-cultivation) acreage fertilized (carbon factor of 50% in base case).		-61.2	
d. 9 tons/acre yield (versus 6 in base case).		-59.2	
e. Takes into account sequestering of CO_2 resulting from converting grassland to forest.	Cancels about 30 years of fuel-cycle emissions		
f. Add 0.10 Btu of energy embodied in materials (in the conversion plant and in field eqiupment) per Btu of ethanol; assume all material energy from oil.		-48.3	
g. All acreage fertilized; lime added on all acres (2000 lb/acre)		-46.3	
h. N_2O emissions per lb of fertilizer tripled over base case.		-56.2	
i. Best for methanol/wood: Scenarios 9-a and 22-a, b, c, and d.	-58.2	-70.7	-75.9
j. Worst for methanol/wood: Scenarios 18-h and 22-f, g, and h.	- 5.5	-30.6	-41.8

TABLE 12 (Cont'd)

Scenario Number and Description[a]	Percentage Change in Emissions from Baseline Value, by Time Horizon[b] 20 yr	100 yr	500 yr
23. NG LD ICEVs			
a. CH_4 tailpipe emissions of 0.8 g/mi (versus 1.2 in base case).		-15.3	
b. Gas turbine instead of electricity used to compress gas (assume 25% efficient turbine).		-12.8	
c. CNG tanks last for 300,000 mi in LD ICEVs; vehicles themselves last 130,000 mi.		-16.5	
d. CNG compressor located on high-pressure pipeline; energy requirement reduced to 0.02 Btu of electricity/Btu of CNG.		-19.9	
e. All gas-fired power used to drive compressor.		-14.9	
g. 150-mi range (versus 250 in base case).		-15.1	
h. All NG from dry gas (no NGL plant needed).		-15.0	
i. Dedicated CNG vehicles only 5% more thermally efficient than gasoline vehicles.		-10.7	
j. CNG from foreign LNG from flared gas (CO_2 emissions from gas not counted as a net emission; see description in Scenario 23-r; result is compared with gasoline at 491.2 g/mi).		-53.2	
k. LNG from foreign LNG from flared gas (CO_2 emissions from gas not counted as a net emission; see Scenario 23-r; result is compared with gasoline at at 491.2 g/mi).		-65.3	
l. CH_4 tailpipe emissions of 2.1 g/mi.		-10.7	
m. Same CO emissions as gasoline vehicle on standard gasoline (versus 50% reduction in base case).		-12.7	
n. Hard to meet the NO_x standard: Cannot increase compression ratio (no thermal efficiency advantage over gasoline); larger tanks to compensate for lower fuel efficiency; no CO reduction (same CO emissions as gasoline vehicle on standard gasoline); 25% higher NMOCs and CH_4 than in CNG base case because of need to operate slightly rich to meet NO_x standard.		- 5.0	
o. All coal-fired power used to drive compressor.		- 9.2	
p. CNG from unconventional sources of NG (25% extra recovery energy).		-13.5	
q. 350-mi range (larger, heavier tanks reduce fuel economy).		-11.9	
r. CNG from remote LNG (0.10 Btu of NG for liquefaction/Btu of LNG; 0.059 Btu for transport/Btu of LNG delivered [64% NG, 36% fuel oil]); 0.025 Btu for regasification/Btu of CNG; extra pipeline transport; result is compared with gasoline at 491.2 g/mi.		2.9	
s. All NG from wet gas (must go through NGL plant).		-13.2	
t. LNG from remote LNG (no regasification; LNG used around port city; shorter pipeline transport than in NG vehicle base case; see Scenario 23-r; result is compared with gasoline at 491.2 g/mi).		-13.5	

TABLE 12 (Cont'd)

Scenario Number and Description[a]	Percentage Change in Emissions from Baseline Value, by Time Horizon[b] 20 yr	100 yr	500 yr
23. NG LD ICEVs (Cont'd)			
u. 2% leakage from NG distribution system (versus 0.3% in the base case).		- 8.8	
v. Best for CNG: Scenarios 9-b and 23-c, d, e, h, and z.	-23.0	-31.4	-34.4
w. Worst for CNG #1: Scenarios 23-l, n, o, q, and u.	36.5	10.3	1.0
x. Worst for CNG #2: Scenarios 23-w, p, and s.	37.5	11.3	2.0
y. Lower-quality NG (86% CH_4).		-12.7	
z. CH_4 from pipeline engines 80% lower than in base case of Table A.1.		-14.1	
24. CNG HD ICEVs			
a. 10% thermal efficiency loss compared with diesel HDVs.		1.5	
b. 20% thermal efficiency loss compared with diesel HDVs.		11.6	
c. 2% distribution system leaks.		13.2	
d. CH_4 tailpipe emissions of 1 g/mi.		4.9	
e. CH_4 tailpipe emissions of 5 g/mi.		7.6	
f. 25% lower CO and NMOC emissions than in CNG base case.		6.1	
g. 50% higher CO and NMOC emissions than in CNG base case.		6.5	
h. Best for CNG: Scenarios 23-d, e, and z combined with 24-a, d, and f.	- 2.0	- 8.6	-11.1
i. Worst for CNG: Scenarios 23-o and p and 24-b, c, e, and g.	44.0	27.6	20.7
25. LPG LD ICEVs			
a. All LPG from petroleum refineries (versus 39% in base case).		-19.8	
b. All LPG from NGL plants (versus 61% in base case).		-25.2	
c. LPG is 100% propane (versus 95% propane/5% butane in base case).		-23.2	
d. LPG is 50% propane, 50% butane.		-22.7	
e. Same CO emissions as gasoline vehicle on standard gasoline.		-22.6	
f. LPG only 5% more thermally efficient than gasoline.		-20.4	
g. Best for LPG: Scenarios 25-b and c and 9-f.	-33.2	-31.4	-34.0
h. Worst for LPG #1: Scenarios 25-a, e, and f.	-15.3	-16.3	-16.9
i. Worst for LPG #2: Scenario 25-h, plus 0.18 Btu of refinery energy/Btu of LPG (see App. H).		-8.4	

TABLE 12 Cont'd)

Scenario Number and Description[a]	Percentage Change in Emissions from Baseline Value, by Time Horizon[b] 20 yr	100 yr	500 yr
26. LPG HD ICEVs			
a. All LPG from refineries.		2.1	
b. All LPG from NGL plants.		- 5.3	
c. LPG is 100% propane.		- 2.5	
d. LPG is 50% propane, 50% butane.		- 1.9	
e. LPG has 10% lower thermal efficiency than diesel HDVs.		- 6.7	
f. LPG has 20% lower thermal efficiency than diesel HDVs.		2.4	
g. CO, CH_4, and NMOCs are 25% lower than in LPG base case.		- 2.7	
h. CO, CH_4, and NMOCs are 50% higher than in LPG base case.		- 1.9	
i. Best for LPG: Scenarios 26-b, c, e, and g.	- 9.7	- 9.8	- 9.7
j. Worst for LPG #1: Scenarios 26-a, f, and h.	6.6	7.8	8.2
k. Worst for LPG #2: Scenario 26-j, plus 0.18 Btu of refinery energy/Btu of LPG (see App. H).		18.7	
27. Ethanol/corn LD ICEVs			
a. Lower N_2O emissions: 0.8% N evolved as N_2O on site instead of 1.3%; 25% additional N_2O off site instead of 100%; corn is assigned 50% of the emissions instead of 80%.		4.8	
b. Low-input agriculture: Reduce fertilizer inputs by 70%.		- 8.0	
c. Fertilizer manufacture 30% more efficient than in ethanol base case.		15.2	
d. Ethanol made from corn diverted from feed; diverted corn feed made up of grass, not crops (no emissions from fertilized agriculture assignable to ethanol).		16.2	
e. Ethanol vehicles only 9% more efficient than gasoline vehicles.		24.2	
f. By-product credits estimated as a function of value or energy content; 45% of emissions assigned to by-products.		-13.3	
g. Advanced coal-to-ethanol conversion technology; 0.45 Btu of heat/Btu of ethanol; 0.05 Btu of electricity/Btu of ethanol.		8.9	
h. Corn-to-ethanol plants use U.S. average power mix.		18.6	
i. NG instead of coal used as process fuel; no sulfur-to-fertilizer credit.		3.6	
j. Corn stover instead of coal used as process fuel (no sulfur-to-fertilizer credit; need extra fertilizer to make up for nutrients lost due to removing residue).		-17.3	
k. Do not dry distillers' dried grains and solubles (DDGS); subtract 0.30 Btu of heat/Btu of ethanol.		- 5.1	
l. Reduce by-product credits by 15%.		21.5	
m. Add amortized emissions from building conversion plant (0.05 Btu of embodied energy in physical plant/Btu of ethanol) and from building farm equipment (0.10 Btu of embodied energy in equipment/Btu of ethanol); assume all this Btu energy is from oil.		33.3	

TABLE 12 Cont'd)

Scenario Number and Description[a]	Percentage Change in Emissions from Baseline Value, by Time Horizon[b] 20 yr	100 yr	500 yr
27. Ethanol/corn LD ICEVs (Cont'd)			
n. Land use effects: One-time emissions from clearing a forest to plant corn (see App. K).	Equivalent to an additional 50-60 yr of fuel-cycle emissions		
o. Land use effects: Grassland cleared to plant crops (one-time release of 20 metric tons of CO_2/acre, mainly from soil; see Table K.12).	Equivalent to an additional 5-6 yr of fuel-cycle emissions		
p. Marginal farm land used: Farming energy (but not fertilizer) requirements increased by 50%.		25.0	
q. Corn-to-ethanol plant uses all coal-fired electricity.		23.0	
r. Bioethanol used by all trucks and tractors involved in the fuel cycle (this scenario actually is favorable, if ethanol is better than diesel fuel).		24.2	
s. Best for ethanol/corn+coal: Scenarios 27-a, b, c, f, g, h, and r, and 9-d.	-31.8	-44.5	-50.0
t. Best for ethanol/corn+corn stover: Scenarios 27-a, b, c, f, h, j, and r, and 9-d.	-47.8	-61.1	-67.1
u. Maximum best for ethanol/corn+coal: Scenarios 27-s and k.	-45.9	-58.0	-63.6
v. Maximum best for ethanol/corn+corn stover: Scenarios 27-t and k.	-49.9	-62.2	-67.8
w. Worst for ethanol/corn+coal: Scenarios 27-e, l, m, o, p, and q.	78.4	50.3	33.8
28. Ethanol/wood LD ICEVs			
a. Non-CO_2 emissions from wood-to-ethanol plants 75% less than in base case of Table A.1.		-74.7	
b. Bioethanol used by all trucks and tractors involved in the fuel cycle.		-78.4	
c. No short-rotation intensive cultivation (SRIC) acreage fertilized (versus 50% in base case).		-77.1	
d. 9 short tons/acre yield (versus 6 in base case).		-74.4	
e. Land-use effects: One-time sequestering of CO_2 resulting from converting grassland to forest (see App. K).	Cancels about 40 yr of fuel-cycle emissions		
f. 0.10 Btu of energy embodied in materials (in the physical plant and in field equipment) added per Btu of ethanol; assume that all this energy is oil.		-63.2	
g. All acreage fertilized.		-69.0	
h. Lime added on all fertilized acres (2000 lb/acre).		-67.1	
i. N_2O emissions per lb of fertilizer tripled over those in base case.		-70.4	
j. No electricity generation credit.		-58.0	
k. Ethanol vehicles only 9% more efficient than gasoline vehicles.		-72.8	
l. Best for ethanol/wood: Scenarios 9-d and 28-a, b, c, and d.	-73.4	-85.3	-90.5
m. Worst for ethanol/wood: Scenarios 28-f, g, h, i, j, and k.	3.5	-24.6	-33.7

TABLE 12 (Cont'd)

Scenario Number and Description[a]	Percentage Change in Emissions from Baseline Value, by Time Horizon[b] 20 yr	100 yr	500 yr
29. EVs (versus gasoline LD ICEVs)			
a. Very advanced EVs: 6.5 times more efficient than ICEVs (this factor accounts for the use of drag-reducing techniques); ultra-lightweight materials; 95% battery-recharging efficiency; 140 Watt-hour/kg, 80%-efficient battery (battery weighs 496 lb; whole vehicle, including the battery, weighs same as comparable ICEV).		-37.5	
b. EVs have a 200,000-mi life.		-13.7	
c. EVs in mixed city/highway driving: Same EV and ICEV as in the city-driving-only base case, but the ICEV gets 30 mpg in city/highway driving, and the EV powertrain is only 4.7 times more efficient than ICEV powertrain (versus 5.7 times more efficient in the city-driving-only case).		2.3	
d. EVs with lead/acid battery: 40 Watt-hour/kg; 65-mi range; 75% recharging efficiency (battery weighs 1,224 lb; whole vehicle weighs 981 lb more than comparable gasoline vehicle).		16.3	
e. Battery only 60% efficient due to repeated shallow discharging (versus 75% in base case).		7.1	
f. Best for EVs using marginal U.S. power mix: Scenarios 29-a and b.	-35.8	-38.8	-39.2
g. Worst for EVs using marginal U.S. power mix: Scenarios 29-c, d, and e; 1,470-lb Pb/acid battery; 1,242 lb extra vehicle weight; more weight than in Scenario 29-d because the vehicle is less efficient and the range is the same.	79.4	74.8	75.3
h. EVs using New York average power mix (16.9% coal, 39.3% nuclear, 14.5% NG, 26% oil).		-41.5	
i. EVs using Chicago average power mix (21.3% coal, 77.7% nuclear, 0.4% NG, 0.6% oil).		-64.7	
j. EVs using Houston average power mix (31.4% coal, 11.7% nuclear, 56.4% NG, 0.5% oil).		-26.1	
k. EVs using Los Angeles average power mix (31.2% coal, 24.5% nuclear, 33.1% gas, 5.3% oil).		-35.1	
l. EVs using Atlanta average power mix (79.3% coal, 19.2% nuclear, 0% NG, 0.3% oil).		-13.2	
m. EVs recharged by base-case nuclear power only.		-84.4	
n. EVs recharged by nuclear power characterized by 1982 mining energy intensity; 1977-2010 energy intensity for uranium enrichment and burn-up rate ("new-plants" scenario; see App. I).		-82.0	
o. EVs recharged by nuclear power only; advanced uranium-enrichment technologies: U-AVLIS and/or gas centrifuge (both are 20 times more efficient than gaseous diffusion).		-85.1	
p. EVs recharged by conventional coal-fired plants only.		5.1	

TABLE 12 (Cont'd)

Scenario Number and Description[a]	Percentage Change in Emissions from Baseline Value, by Time Horizon[b] 20 yr	100 yr	500 yr
29. EVs (versus gasoline LD ICEVs) (Cont'd)			
q. EVs recharged by coal-gasification/fuel-cell power plants (see Table D.6 for power-plant efficiency and emissions).		-32.5	
r. Best for EVs recharged by coal-fired plants only: Scenarios 29-a, b, and q, plus 250 ft^3 CH_4/ton of coal from coal mining.		-53.8	
s. Worst for EVs recharged by coal-fired plants only: Scenarios 29-c, d, e, and p.		97.2	
t. EVs recharged by conventional oil-fired plants only.		-6.5	
u. EVs recharged by conventional gas-fired plants only (75% boilers; 25% turbines).		-31.5	
v. EVs recharged by natural-gas/fuel-cell power plants (see Table D.6 for power-plant efficiency and emissions).		-58.3	
w. Best for EVs recharged by gas-fired plants only: Scenarios 29-a, b, and v.		-71.2	
x. Scenario 29-r, plus CO_2 removed from coal-fired plants.		-92.1	
y. EVs have an 80-mi range (versus 130 in base case); 398-lb battery; 106-lb total extra vehicle weight.		-21.8	
z. EVs have a 180-mi range; 1171-lb battery; 925 lb extra vehicle weight.		-4.0	
aa. High-end estimate of N_2O from corona discharge from power lines (0.21 g/kWh).		-8.1	
ab. EVs recharged by biomass-gasification/fuel-cell power plants (see Table D.6 for power-plant efficiency and emissions).		-84.0	
30. Hydrogen LD ICEVs			
a. Hydride ICEVs: Hydride lasts for 600,000 mi.		-61.1	
b. Hydride ICEVs: 300-mi driving range (versus 150-mi range in base case).		-51.5	
c. Hydride ICEVs: U-AVLIS or gaseous-centrifuge uranium enrichment (20 times more efficient than gaseous diffusion).		-72.8	
d. Hydride ICEVs: Solar electrolysis, U.S. average power mix for compression.		-74.7	
e. LH_2 ICEVs: All liquefaction power comes from coal-fired plants (at service station).		9.6	
f. LH_2 ICEVs: All liquefaction power comes from nuclear plants.		-65.6	
g. LH_2 ICEVs: Gas centrifuge or U-AVLIS enrichment.		-27.5	
h. LH_2 ICEVs: Scenarios 30-f and g combined.		-79.9	
i. LH_2 ICEVs: Solar electrolytic hydrogen; liquefiers use solar power.		-82.9	
j. LH_2 ICEVs: Solar electrolytic hydrogen; U.S. average power mix for liquefaction.		-28.7	

TABLE 12 (Cont'd)

Scenario Number and Description[a]	Percentage Change in Emissions from Baseline Value, by Time Horizon[b] 20 yr	100 yr	500 yr
31. LD fuel-cell vehicles[e]			
a. Best for methanol/NG/fuel cell: Same as Scenarios 18-c and d.		-46.0	
b. Best for methanol/coal/fuel cell: Same as Scenarios 20-a and b.		-19.7	
c. Best for methanol/wood/fuel cell: Same as Scenarios 22-a, b, c, and d.		-81.6	
d. Scenario 31-b plus CO_2 disposal.		-51.8	

[a]The original petroleum-fuel base case makes estimates of total fuel-cycle, CO_2-equivalent emissions in the United States in the year 2000. It assumes that light-duty vehicles (LDVs) run on reformulated gasoline and that heavy-duty vehicles (HDVs) run on reformulated diesel fuel. The assumed vehicle efficiencies or fuel economy, in miles per gallon (mpg), are as shown below in this footnote. The original input values for the different variables associated with the base case are specified in Tables 2 through 7, A.1, and B.2 (for emissions from vehicles), C.1 and C.3 (for fuel specifications), D.4 (for emissions from power plants), E.1 (for feedstock and fuel transport), and so on. For the alternative-fuel scenarios considered here, the description lists all the base-case variables whose values have changed to make the scenario. All variables not specifically mentioned retain their base-case values.

The original base-case emissions from vehicles running on reformulated gasoline and low-sulfur diesel fuel are as follows:

Fuel	Vehicle Type	Efficiency or Fuel Economy (mpg)	Driving Conditions	Base-Case CO_2-Equivalent Emissions, by Time Horizon (g/mi) 20 yr	100 yr	500 yr
Gasoline	LDV	30	City/highway	633.6	491.2	449.2
Diesel	HDV	6	Truck test cycle	3,819.3	2,627.1	2,331.4
Gasoline	LDV	24.5	City only	727.7	577.1	533.1

Battery-powered electric vehicles (EVs) are compared with 24.5-mpg gasoline vehicles; all other alternatives are compared with 30-mpg gasoline vehicles. Note that the 100-year values are the same as those from Table 9. In all scenarios in which the variables being tested do not significantly affect the petroleum fuel cycle, these "original" base-case values become the baseline values against which the alternatives are compared.

However, in several scenarios, the variables being tested also significantly affect the petroleum-fuel base case. These variables include (a) the rate of venting of CH_4 from coal mines, (b) the efficiency of coal-fired and gas-fired power plants, (c) the amount of non-CO_2 greenhouse gas emissions from coal- and gas-fired power plants, (d) the extent of NG leaks from gas distribution systems, (e) the energy intensity of mining and enriching uranium, and (f) the energy intensity of NG recovery and processing. When I changed the values for these variables for a scenario analysis, I also changed the values in the gasoline or diesel-fuel baselines, against which the alternatives were compared, unless I intentionally "froze" the baselines at their original base-case values. I generally allowed the petroleum-fuel baseline to change in response to changes in input variables because it allows for an internally consistent comparison and makes the analysis easier to do.

The scenarios in which the petroleum-fuel baseline is affected, and the corresponding changed g/mi results for the petroleum baseline (against which the alternatives are then compared), are as follows:

Revised Baseline Values
for CO_2-Equivalent Emissions,
by Time Horizon (g/mi)

Scenario	20 yr	100 yr	500 yr
4 (except EVs)	490.0	452.5	435.6
4 (EVs)	575.1	535.8	518.4
5	2,326.8	2,227.8	2,191.5
6	600.2	559.1	541.2
7		404.0	
8		2,128.2	
15	841.6	535.8	453.8
16	6,697.6	3,376.0	2,577.3
17 (except Japan)	932.4	618.5	534.4
18-c		489.8	
18-i	630.4	490.1	448.9
18-j	633.8	491.4	449.6
19-a		2,627.0	
19-e	3,823.4	2,632.8	2,338.7
19-f	3,818.5	2,627.1	2,332.4
20-a		496.3	
20-c		489.2	
20-d	635.0	495.1	453.8
20-f		488.9	
21-a		2,627.1	
21-b	3,807.9	2,623.7	2,330.7
23-u		494.6	
24-c		2,638.3	
29-o		576.7	
29-q		563.5	
29-r		562.8	
29-v, w		576.3	
29-x		546.3	
29-aa		580.0	
30-c, g, and h		490.8	

In most other scenarios, the petroleum baseline either is not affected significantly or is intentionally frozen at its "original" base case value. The baseline values in some of the methanol scenarios (18-c, i, j) change because I assume that the methanol in the MTBE in gasoline is made from the same feedstock, and by the same process, as is the methanol used as a fuel. The baseline values in the EV scenarios change because the power plants that supply EV batteries also supply the petroleum-fuel cycle.

NOTES TO TABLE 12

These are full descriptions of the abbreviated forms used in the Description column of the table to describe the alternative vehicle types and fuels considered in the analysis. LD = light-duty; HD = heavy duty; ICEV = internal-combustion-engine vehicle; EV = electric-motor-driven vehicle powered by a battery; and fuel cell = electric-motor-driven vehicle running on a fuel cell. If EV or fuel cell is not specified, the vehicle is assumed to be an ICEV. LDVs or HDVs refer to all light-duty vehicles or heavy-duty vehicles, respectively, whether they are ICEVs, EVs, or fuel-cell vehicles.

Abbreviated Form	Full Description
Standard gasoline	ICEV running on gasoline that is not reformulated
Methanol/NG	ICEV running on methanol derived from natural gas
Methanol/coal	ICEV running on methanol derived from coal
CNG	ICEV running on compressed natural gas
LNG	ICEV running on liquefied natural gas
Marginal U.S. mix/EV	Battery-powered electric vehicle recharged with the "marginal" U.S. power mix; i.e., the mix used by EVs specifically
Ethanol/corn+coal	ICEV running on ethanol derived from corn by using coal as process fuel
Hydride/nuclear electrolysis	ICEV running on compressed hydrogen that was electrolyzed from water with nuclear power and compressed with year-2000 power mix
LH_2/nuclear electrolysis	ICEV running on liquefied hydrogen that was electrolyzed from water with nuclear power and liquefied with year-2000 power mix
LPG/oil and NG	ICEV running on liquefied petroleum gas derived from oil and natural gas
Methanol/wood	ICEV running on methanol derived from wood
CSNG/wood	ICEV running on compressed synthetic natural gas derived from wood
Ethanol/wood	ICEV running on ethanol derived from wood
Hydrogen/all-solar	ICEV running on hydrogen electrolyzed from water with solar power and compressed or liquefied with solar power
All-solar/EV	EV recharged with solar power
Methanol/NG/fuel cell	Fuel cell vehicle powered by methanol derived from natural gas
Methanol/coal/fuel cell	Fuel cell vehicle powered by methanol derived from coal
Methanol/wood/fuel cell	Fuel cell vehicle powered by methanol derived from wood
Hydride/nuclear electrolysis/ fuel cell	Fuel cell vehicle powered by compressed hydrogen that was electrolyzed from water with nuclear power and compressed with year-2000 power mix
Hydrogen/all-solar/fuel cell	Fuel cell vehicle powered by hydrogen electrolyzed from water with solar power and compressed or liquefied with solar power

[b]A change of X% means that total fuel-cycle emissions (in grams per mile) from the alternative-fuel vehicle are equal to those from the baseline petroleum-fuel vehicle multiplied by 1 + (X/100). The baseline g/mi values for the petroleum-fuel cycles were shown in footnote a. To calculate the percentage change relative to any other baseline (such as standard gasoline, fuel-cycle emissions excluding emissions from vehicle and materials manufacture and assembly, or the "high" case for reformulated gasoline [Scenario 12-f]), use the following formula:

$$Pn = -100 \times \{1 - [Bo/Bn \times (1 + Po/100)]\}$$

where:

Pn = change for the alternative-fuel vehicle scenario of interest relative to the new baseline Bn (expressed as a percentage),

Bo = old baseline (reformulated gasoline or low-sulfur diesel fuel) emission rate (g/mi),

Bn = new baseline (such as standard gasoline) emission rate (g/mi), and

Po = change for the alternative-fuel vehicle scenario of interest relative to the original baseline (expressed as a percentage).

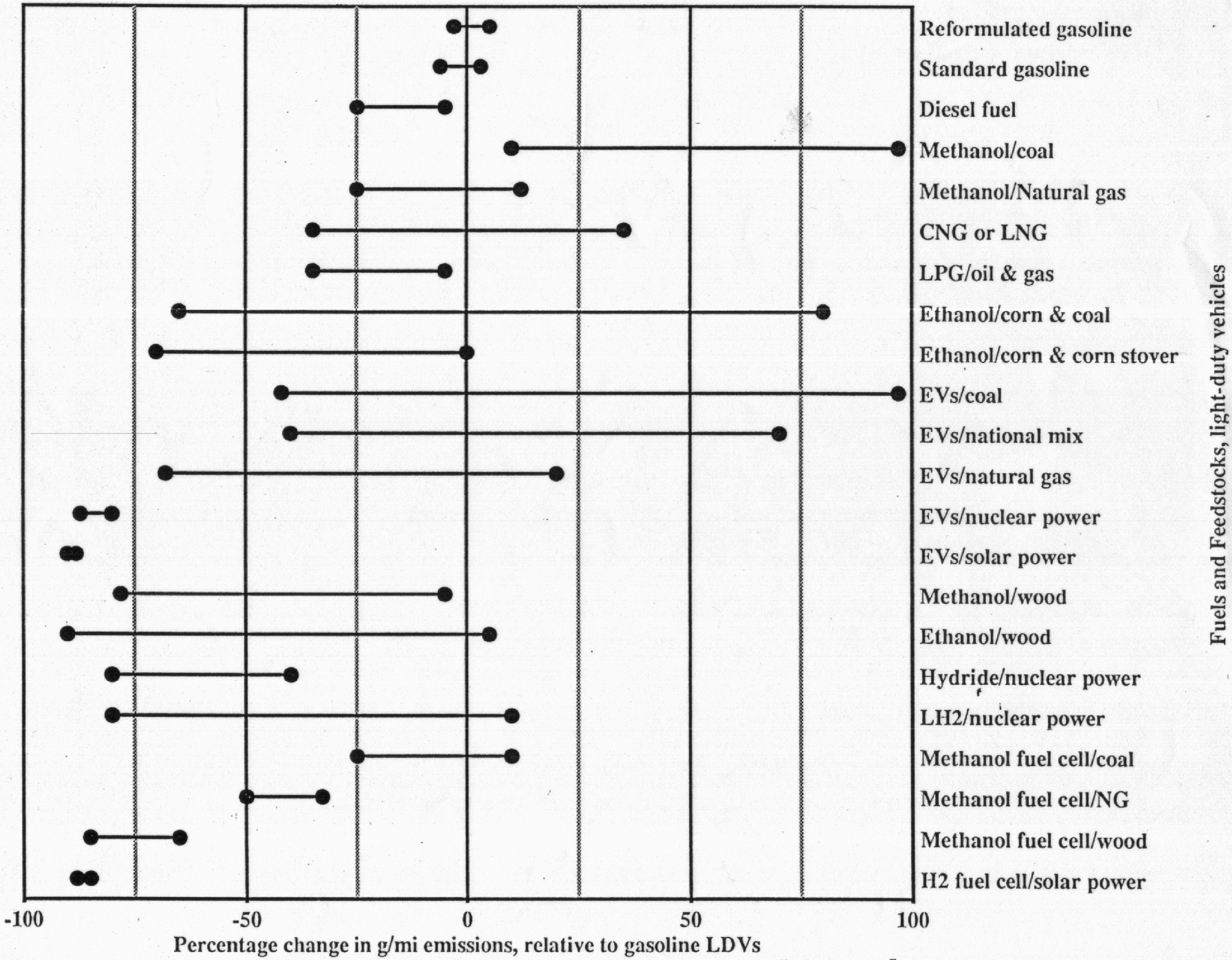
[c]Base-case alternative-fuel LDV and HDV scenarios show the results of running the model with all the base-case assumptions, under the three different time horizons. The results shown under the "100-year" column are the same as those shown in Table 9.

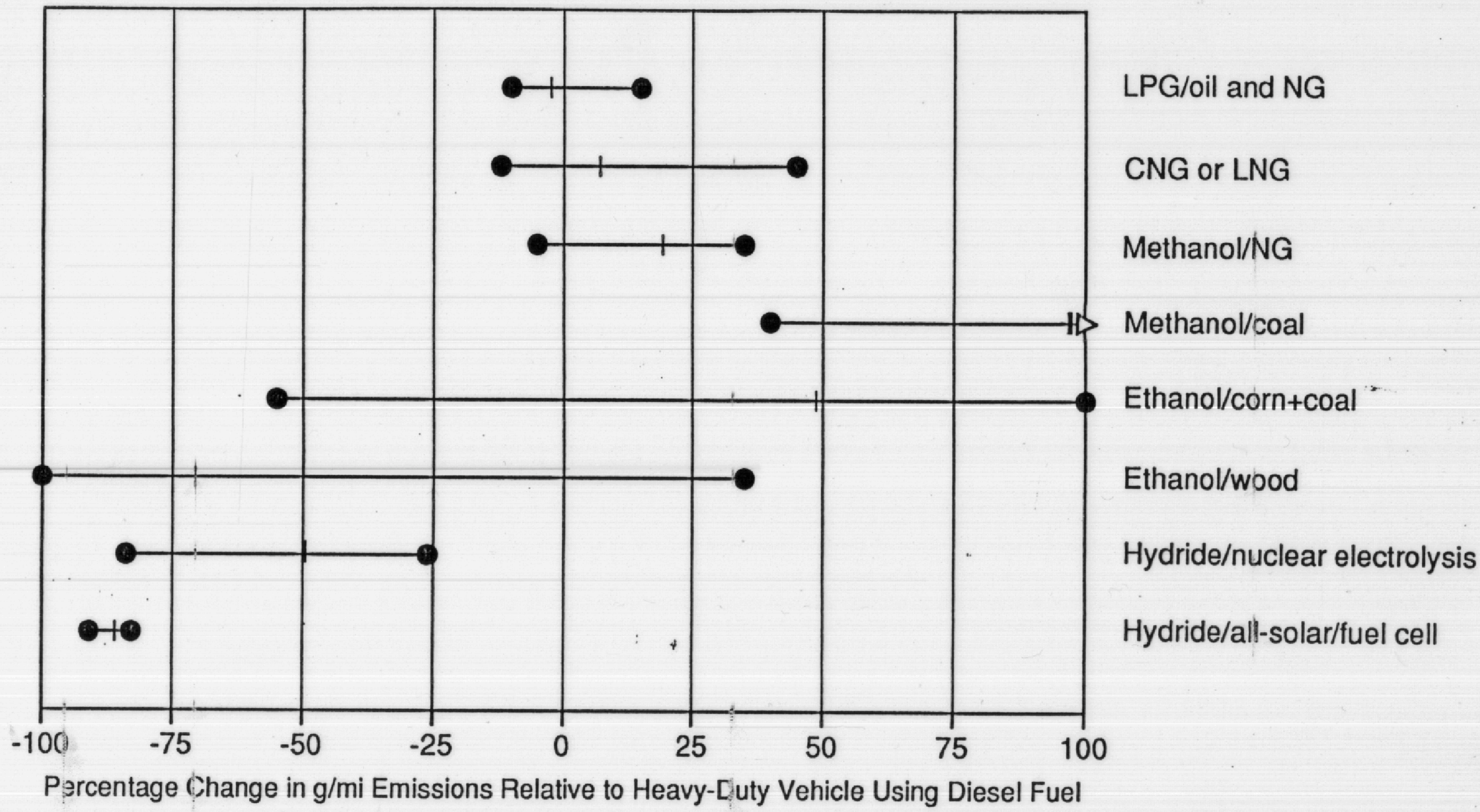
[d]See App. R for a discussion of the changes made to model Europe and Japan.

[e]See App. B for explanation of method used to estimate emissions from fuel-cell vehicles.

FIGURE 6
(landscape)

FIGURE 7
(landscape)


Reformulated gasoline
Standard gasoline
Diesel fuel
Methanol/coal
Methanol/Natural gas
CNG or LNG
LPG/oil & gas
Ethanol/corn & coal
Ethanol/corn & corn stover
EVs/coal
EVs/national mix
EVs/natural gas
EVs/nuclear power
EVs/solar power
Methanol/wood
Ethanol/wood
Hydride/nuclear power
LH2/nuclear power
Methanol fuel cell/coal
Methanol fuel cell/NG
Methanol fuel cell/wood
H2 fuel cell/solar power
-100
-50
0
50
100
Percentage change in g/mi emissions, relative to gasoline LDVs
Fuels and Feedstocks, light-duty vehicles



Notes: Each line shows the range of results, from the most favorable to the least favorable, for the fuel cycle listed to its right. The results are expressed as a percentage change in CO_2-equivalent emissions relative to a baseline heavy-duty vehicle fuel cycle using low-sulfur diesel fuel. Emissions from vehicle manufacture and assembly are included. The solid circle at the left end of the range marks the most favorable case, which is the greatest percentage reduction or least percentage increase. The solid circle at the right end of the range marks the least favorable case, which is the least percentage reduction or greatest percentage increase. The solid tick between the circles represents the base-case value, which is my best estimate. The ranges shown include comparisons under all three time horizons (20 years, 100 years, and 500 years). Sources: Tables 9 and 12 and unpublished runs of the greenhouse gas emissions model.

FIGURE 7 Spans between the Most and Least Favorable Emission Results for Various Heavy-Duty-Vehicle Fuel Cycles

cycle. The 20-year and 100-year N_2O-to-CO_2 conversion factors are nearly equal, but the 500-year factor is much lower; hence, for ethanol from corn, there is a large difference between the 500-year result and the 100-year and the 20-year results.

Third, the more that non-CO_2 greenhouse gases contribute to total fuel-cycle emissions, the more important the time horizon is in determining the final g/mi emission total. This situation occurs because the time horizon determines the relative importance of the non-CO_2 greenhouse gases. Thus, total fuel-cycle g/mi emissions from CNG vehicles depend, for example, on how heavily the relatively large amount of CH_4 emitted from the tailpipe is weighted. Total fuel-cycle emissions from vehicles running on corn-derived ethanol depend on how heavily the N_2O emissions from fertilizer are weighted.

In a similar fashion, a substantial difference in the relative importance of non-CO_2 greenhouse gases to total emissions between an alternative-fuel cycle and the petroleum-fuel cycle can affect how the alternative fuel compares with the petroleum fuel at different time horizons. For example, the percentage reduction in emissions provided by methanol-based fuel-cell vehicles (when the methanol is derived from coal or NG) decreases over longer time horizons, because the fuel cycle of a fuel-cell vehicle emits a moderate amount of CO_2 but very little non-CO_2 greenhouse gases, while the fuel cycle of a gasoline vehicle emits a substantial amount of both CO_2 and non-CO_2 gases. Since non-CO_2 emissions are responsible for a larger share of total gasoline-fuel-cycle emissions than of total fuel-cell-cycle emissions, the down-weighting of the non-CO_2 emissions in the longer time horizon confers more of an advantage on gasoline. On the other hand, the percentage reduction provided by methanol-based fuel-cell vehicles in cases where the methanol is derived from biomass rather than from coal or NG increases with longer time horizons. This result occurs because the biofuel cycle produces very little CO_2 as well as very little non-CO_2 gases. In fact, the biofuel cycle produces so little CO_2 that non-CO_2 gases, even though minor, are slightly more important in the biofuel cycle than in the gasoline cycle.

The fourth result is represented by the 20-year case for SNG from wood, which offers only a modest reduction in emissions of greenhouse gases. This result indicates that the use of wood as a feedstock does not automatically greatly reduce fuel-cycle emissions of greenhouse gases. In this case, the benefit of using wood has been greatly eroded by the use of fossil-fuel-based electricity to compress CNG, by the heavy weighting of emissions of non-CO_2 greenhouse gases that occurs over the short-term horizon, and by leaks of SNG from pipelines. Moreover, compressed SNG vehicles in this analysis have about half the driving range of regular CNG vehicles, because SNG is a medium-Btu gas.

5.2 SCENARIOS 4, 5, AND 6

In these scenarios, NO_x emissions are excluded, and NMOC emissions are considered only with respect to their oxidation to CO_2. As shown in Table 8, the IPCC (Shine et al., 1990) has estimated that a gram of NO_x has 14-150 times the warming potential of a gram of CO_2, and a gram of carbon in an NMOC has 7 to 36 times the warming potential of CO_2. Therefore, together, NO_x and NMOC emissions could account for a large fraction of total fuel-cycle, CO_2-equivalent emissions. Nevertheless, NO_x and NMOC emissions contribute to global warming only indirectly, through a series of chemical reactions that can lead to an increase in the concentration of tropospheric ozone. The atmospheric chemistry of ozone formation and the greenhouse behavior of tropospheric ozone are quite complex, making it difficult to estimate CO_2-equivalency factors for NO_x and NMOCs. Therefore, because NO_x and NMOC equivalency factors are both important and uncertain, and because different fuel cycles emit different amounts of NO_x and NMOCs, the emissions model excludes the ozone-forming effect of NO_x and NMOCs under Scenarios 4-6. It does so by assuming that the equivalency factor for NO_x is zero (i.e., NO_x is "zeroed out"), and by treating NMOCs as having no warming effect other than oxidizing to CO_2.

Scenarios 4-6 of Table 12 show the results of rerunning the base case with the changes described above. The alternative-fuel cycles in which NO_x emissions are relatively important benefit the most (compare Scenarios 4-6 with 1-3). This benefit is most pronounced over the 20-year time horizon, because the NO_x has a huge warming effect in the 20-year case because of its very high equivalency factor (150; see Table 8). This benefit is strikingly illustrated in the 20-year case for biofuel HDV fuel cycles (compare Scenario 5 with 2). The percentage reduction provided by biofuel HDVs increases by about 40% in absolute percentage points in the 20-year case, when NO_x emissions are excluded. This extraordinary improvement occurs because in the 20-year base case, NO_x emissions from the tailpipes of biofuel HDVs actually account for the bulk of total fuel-cycle, CO_2-equivalent emissions. (Given 8.05 g/mi NO_x [Table B.2] and an equivalency factor of 150 [Table 8], NO_x emissions amount to 1,208 g/mi, which is about 50% of total CO_2-equivalent emissions in the 20-year case.) Eliminating NO_x emissions thus reduces CO_2-equivalent emissions from the biofuel cycle to nearly zero and greatly improves its relative standing. The effect is not as pronounced in the 100-year case but is still large.

In general, all fuel cycles that have very small amounts of CO_2 emissions per se (e.g., biofuel cycles and hydrogen cycles) look better when NO_x and NMOCs are excluded, and, given this exclusion, look better the longer the horizon is. This result occurs because non-CO_2 greenhouse gases are more important in these fuel cycles than in fuel cycles that produce a lot of CO_2.

The ethanol-from-corn cycle also looks much better when NO_x and NMOCs are excluded. In fact, in the 500-year case, the ethanol-from-corn fuel cycle results in only a slight increase in CO_2-equivalent emissions (compared with gasoline). The ethanol-from-corn fuel cycle has several sources that contribute a large amount of NO_x emissions: vehicles, ethanol-making facilities (which burn coal), and fertilizer nitrification. When these NO_x emissions are excluded, ethanol's standing improves.

The LPG, CNG, and EV fuel cycles are relatively unaffected by the exclusion of NO_x and NMOCs. The methanol fuel cycle improves slightly, in part because of the exclusion of the relatively large NO_x emissions from methanol facilities (see Table A.1; this estimate needs to be corroborated, however).

The general conclusion of these scenarios is that, to the extent that the NO_x equivalency factor is too high, emissions from biofuel and hydrogen fuel cycles look worse than they should.

5.3 SCENARIOS 7 AND 8

These scenarios compare total fuel-cycle emissions of CO_2 only; NMOCs, CH_4, CO, NO_x, and N_2O have been "zeroed out." Virtually all the alternatives look much better when non-CO_2 greenhouse gases are excluded. Some alternatives benefit dramatically. Ethanol from corn is one that does, because much of the greenhouse impact of ethanol from corn is from N_2O and NO_x. All the wood fuels benefit as well, because they have very low CO_2 emissions, especially when they are given a CO_2 credit for emissions of non-CO_2 organic species. (The results shown give a CO_2-removal credit for the carbon in all CO, CH_4, and NMOC emissions from the wood fuel cycles, but give zero weight to the CO, CH_4, and NMOC emissions themselves.) NG vehicles look modestly better in the CO_2-only scenario, because of the low carbon/Btu content of NG. LPG rates the same in the CO_2-only scenario as in the all-gases scenario, because the emissions-reduction benefit of LPG is distributed fairly evenly over CO_2 and non-CO_2 gases.

5.4 SCENARIOS 9 AND 10

These high-efficiency scenarios examine how greatly increasing the relative efficiency of alternative-fuel vehicles affects greenhouse gas emissions. I assume that alternative-fuel LDVs have a 20-30% thermal efficiency advantage over gasoline LDVs and that alternative-fuel HDVs suffer little or no efficiency loss relative to diesel HDVs. I group all the ICEVs into one scenario because some of the most effective efficiency-improving technologies apply to most or all of the vehicles, and because all LDVs face the same constraint on efficiency improvements: the tight NO_x standard, which may foreclose the use of lean-burn technology.

As expected, the higher efficiency and lower emissions of CO, NMOCs, and CH_4 that result from the use of lean-burn technology markedly reduce total greenhouse gas emissions in almost every case. Most of the alternative-fuel cases improve by approximately 10 percentage points relative to the petroleum-fuel baseline. The emission reductions are largest for methanol from NG and ethanol from corn, because the assumed efficiency gains are largest. The ethanol-from-wood case shows only a small reduction in total fuel-cycle, CO_2-equivalent greenhouse gas emissions because the vast portion of total emissions in this case consists of emissions from vehicle manufacture and non-CO_2 emissions from the tailpipe of the vehicle, both of which are independent of fuel economy. Consequently, there is little opportunity for efficiency improvement (the major benefit of lean-burn technology) to have an effect.

5.5 SCENARIO 11

This scenario compares the emissions from dual-fuel or flexible-fuel LDVs operating on the alternative fuels M85, M50, CNG, LPG, or E85 with the emissions from comparable single-fuel (dedicated) vehicles operating on only reformulated gasoline. A dual-fuel vehicle has two separate fuel storage and delivery systems; it can operate on either gasoline or the alternative fuel but not on a mixture of them. CNG/gasoline and LPG/gasoline vehicles are dual-fuel vehicles. A flexible-fuel vehicle (FFV) has one fuel storage and delivery system; it can operate on either gasoline or the alternative fuel or on any mixture of gasoline and the alternative fuel. Alcohol/gasoline vehicles are flexible-fuel vehicles. Alcohol FFVs are assumed to use 85% alcohol and 15% reformulated gasoline.

Alcohol FFVs are slightly more efficient than comparable dedicated gasoline vehicles. They generate a somewhat greater amount of tailpipe NMOC emissions than do dedicated methanol vehicles because of the gasoline that is added to the fuel (Sperling and DeLuchi, 1991; EPA, *Analysis of the Economic and Environmental Effects of Ethanol as an Automotive Fuel*, 1990; EPA, *Analysis of the Economic and Environmental Effects of Methanol as an Automotive Fuel*, 1989). FFV evaporative emissions are also greater, because the addition of gasoline increases the vapor pressure over that of a pure alcohol. However, future FFVs operating on alcohol (M85 or M100) will emit *less* NO_x than will dedicated gasoline or methanol vehicles. This result will occur because these FFVs, when running on gasoline, will be designed to emit the same level of NO_x as dedicated alcohol or gasoline vehicles because they will all have to meet the same NO_x standards under the Clean Air Act Amendments. Given a particular pollution control system and engine design, an FFV operating on alcohol will have a smaller amount of NO_x emissions than an FFV operating on gasoline (and hence a smaller amount of NO_x emissions than a dedicated methanol or gasoline vehicle) because of the lower flame temperature, faster speed, and higher latent heat of vaporization of alcohol (Sperling and DeLuchi, 1991).

In the case of the alcohols, emissions from the upstream gasoline production-and-transport processes are weighted by the contribution of gasoline to the total energy of the fuel mixture. Emissions from the upstream alcohol production-and-transport processes are weighted by the contribution of alcohol to the total energy of the fuel mixture.

In the case of E85, tailpipe emissions of CO_2 from the combustion of the ethanol are ignored (because the ethanol is derived from biomass), and tailpipe emissions of non-CO_2 organic gases from the combustion of the ethanol portion of the mixture are given a CO_2 removal credit. All emissions (CO_2 and non-CO_2) from the combustion of the gasoline portion of the mixture are counted at their full global warming potential. Total tailpipe emissions of CO, CH_4, and NMOCs are assigned to gasoline or ethanol on the basis of the contribution of each fuel to the total carbon content of the mixture.

I assume that dual-fuel NG or LPG vehicles, when operated on LPG or NG, have the same thermal efficiency as comparable dedicated gasoline vehicles. I assume they have the same NO_x and CO emissions but slightly higher CH_4 and NMOC emissions than dedicated NG and LPG vehicles. I also assume that the dual-fuel gaseous-fuel vehicles have a shorter range when they run on CNG or LPG than do dedicated CNG or LPG vehicles, an assumption that is consistent with actual practice. However, I assume that both the dual-fuel LPG and the dual-fuel NG vehicles have a gasoline tank, which adds to the total weight of the vehicles and reduces efficiency.

The results show that dual-fuel vehicles fare worse than dedicated vehicles, primarily because of their lower thermal efficiency. FFVs using 85% ethanol from wood fare considerably worse than dedicated ethanol vehicles, not only because of their lower efficiency but because of the CO_2 emissions from the 15% gasoline portion of the mixture (Scenario 11-g), which are not canceled by CO_2 uptake in the way that CO_2 emissions from biofuels are. Ethanol from corn does not do as poorly under this scenario as does ethanol from wood, because the emissions from the combustion of gasoline in the vehicle are balanced somewhat by the fact that the production and transport of the gasoline produces a much smaller amount of greenhouse gases than does the production and transport of the ethanol replaced by the gasoline (Scenario 11-e).

Greenhouse gas emissions from an FFV decline very slightly as the methanol content of the mixture declines (Scenario 11-a versus 11-c). This situation occurs because the small improvement in efficiency and the reduction in NO_x emissions (relative to gasoline operation) gained by adding methanol is slightly more than offset by the greater upstream emissions from methanol manufacture than from gasoline manufacture. If the FFV could take full advantage of the efficiency-improving potential of methanol, this would not be the case.

5.6 SCENARIO 12

This scenario examines the effect of varying the values of some of the more uncertain input variables from those assumed in the gasoline base case. Results somewhat surprisingly reveal that the uncertainty in the variables examined is relatively unimportant, at least over the ranges considered. For example, even if refinery energy requirements were 0.20 instead of 0.182 Btu of process energy per Btu of gasoline, total fuel-cycle, CO_2-equivalent emissions would increase by only 1.2% in the 100-year scenario (Scenario 12-a). In another example, if, because of the extensive use of low-quality crude and enhanced oil recovery, it would take 25% more energy than estimated in the base case to recover crude oil, total fuel-cycle, CO_2-equivalent emissions would increase by only 0.6% over the base case (Scenario 12-b). Increasing per-barrel emissions from venting and flaring by 25% and assuming that 10% rather than 6% of the gas is vented rather than flared would increase total emissions by only 0.5% (Scenario 12-c). Assuming that reformulated gasoline would provide no reduction in tailpipe emissions of CO and NMOCs would increase total greenhouse gas emissions by 0.4% (Scenario 12-d). Finally, if crude input were not reduced as a result of using MTBE, and if part of the extra crude available were used as refinery fuel, emissions would be only 0.2% higher than they are in the base case, because the increase resulting from not displacing the crude would be nearly canceled by the decrease resulting from using refinery gas instead of purchased NG (Scenario 12-e).

Even if all the uncertain variables examined here were simultaneously higher than in the base case, the result would still only be a 2.9% increase in total fuel-cycle, greenhouse gas emissions in the 100-year case (Scenario 12-f). The increase would be larger in the 20-year case because of the heavier weight given to the extra vented gas and the extra tailpipe emissions. This uncertainty analysis leads one to the tentative conclusion that the estimates here are accurate to within 5%.

5.7 SCENARIO 13

The reduction in greenhouse gas emissions provided by diesel vehicles depends somewhat on the relative fuel economy of the vehicle. If diesel LDVs were to have only 20% better fuel economy than gasoline LDVs (36 mpg versus 30 mpg on reformulated gasoline and 30.7 mpg on standard gasoline), which is at the low end of the range reported for current diesel vehicles, their operation would result in a 10% reduction in total fuel-cycle, CO_2-equivalent emissions (Scenario 13-b). On the other hand, ultra-efficient technologies, like direct injection coupled with turbocharging, could allow for an improvement of more than 40% in fuel economy and would result in a reduction of nearly 20% in total fuel-cycle, CO_2 equivalent emissions (Scenario 13c). In the best case, diesel LDVs could rival LPG vehicles as having the lowest-greenhouse-gas-emitting fuel cycles of all ICEVs (Scenario 13-d). Battery-powered EVs that run on electricity supplied by advanced NG-fired turbines or by NG fuel cells would have lower emissions.

Allowing the sulfur content of diesel fuel to remain at current levels would provide only a minor greenhouse gas benefit (compare Scenario 13-e with 13-a). This situation would occur because, in any case, emissions from the refinery are only a small portion of the total emissions in a diesel fuel cycle, and low-sulfur diesel fuel would require only a small increase in energy to manufacture over current diesel fuel.

5.8 SCENARIO 14

Although most heavy-duty trucks use diesel fuel, some do use gasoline, and alternative fuels may replace gasoline in heavy-duty applications. This scenario allows for an indirect comparison between alternative-fuel HDVs and gasoline HDVs, by directly comparing diesel HDVs and gasoline HDVs.

Gasoline HDVs emit much greater amounts of greenhouse gases per mile than do diesel HDVs, because of the much lower thermal efficiency of the spark-ignition engine. Depending on the efficiency loss and the time horizon, gasoline LDVs can have 10-35% higher total fuel-cycle, CO_2-equivalent emissions per mile than do diesel HDVs. In Scenarios 14-a and b, the relative standing of gasoline HDVs is very sensitive to the time horizon, because of the considerable amount of NO_x emitted from HDVs. If these NO_x emissions were not counted (Scenario 14-c), two interesting results would occur. First, the gasoline HDV would fare even worse, because its one main advantage over the diesel HDV -- lower NO_x emissions -- would no longer be effective. In fact, not counting NO_x emissions is worse for the gasoline HDV than is reducing its fuel economy from 4.8 to 4.5 mpg. Second, the influence of the time horizon would be reversed: with NO_x, the gasoline vehicle would fare better the shorter the time horizon; without NO_x, the reverse would be true. Thus, these results show, once again, the potentially great importance of non-CO_2 greenhouse gases in total emission results.

This analysis reveals one more noteworthy result. Changing from gasoline to diesel fuel causes more of a percentage reduction in emissions for HDVs than LDVs at any given percentage of fuel economy improvement. (Convert the results here to a gasoline-to-diesel basis, by taking the reciprocal; then compare these results with the gasoline-to-diesel results of Scenario 13.) This situation occurs because fuel economy improvements affect CO_2 emissions, and CO_2 emissions constitute a larger percentage of total greenhouse gas emissions from low-mpg vehicles than from high-mpg vehicles.

5.9 SCENARIOS 15 AND 16

These scenarios compare emissions from alternative-fuel vehicles with emissions from future gasoline vehicles in Europe. In these scenarios, I respecify (1) emission factors for gasoline and diesel vehicles and for power plants and petroleum refineries, (2) the mix of fuels used by petroleum refineries, (3) emissions from coal mining, (4) the efficiency of power plants, (5) the mix of fuels used by power plants, (6) the geographic distribution of major electricity-consuming activities, and (7) transportation patterns for oil and coal, to represent Europe in the year 2000. These changes are detailed in App. R.

I establish two scenarios for the alternative-fuel vehicles: (1) they operate at stoichiometry, use a three-way catalyst, and are moderately more thermally efficient than comparable gasoline vehicles; and (2) they use lean-burn technology, are much more thermally efficient than the comparable gasoline vehicle, and have lower CO and NMOC emissions than in the stoichiometry scenario. Since the new European NO_x standard is not as stringent as the new U.S. Clean Air Act NO_x standard, it is more likely that alternative-fuel vehicles will be able to use lean-burn technology in Europe than in the United States.

The European stoichiometric case is not dramatically different from the U.S. base case. This result occurs because the higher tailpipe emissions in Europe, which tend to make the alternative-fuel vehicles look somewhat better, are partly offset by lower emissions from the refining stage for gasoline (that result primarily from lower refinery energy requirements), which tends to make gasoline vehicles look better.

The lean-burn case noticeably improves the emissions standing of the alternative-fuel vehicles relative to gasoline vehicles. In most cases, the alternative-fuel vehicles show an improvement of 5 to 10 absolute percentage points. Thus, the relatively lax NO_x standard in Europe may make alternative-fuel vehicles more attractive, from a greenhouse standpoint, than they would be in the United States, because of the possibility of using lean-burn technology.

The HDV analysis for Europe differs sharply from the HDV analysis for the United States: alternative-fuel HDVs fare much better than diesel HDVs in Europe than in the United States (compare Scenario 16 with 2). For example, in Europe, methanol and CNG HDVs are projected to have lower greenhouse gas emissions than diesel HDVs, whereas in the United States, they are projected to have higher emissions. Similarly, ethanol HDVs cause less of an increase in greenhouse gas emissions in the European case than in the U.S. case.

However, this HDV analysis for Europe should be viewed with caution, and even skepticism, because it is driven almost entirely by the IEA's (1991) projection of very high NO_x emissions -- 27.40 g/mi -- from future diesel HDVs in the European Economic Community (EEC). With emissions of 27 g/mi and a CO_2-emission equivalency factor of 40 (for the 100-year time horizon), NO_x from the tailpipe would account for about one-third of total fuel-cycle, CO_2-equivalent emissions. For the 20-year time horizon, NO_x from the tailpipe of diesel HDVs would account for nearly two-thirds of total emissions! Since I have assumed that alternative-fuel HDVs will have significantly less NO_x emissions than diesel HDVs, it follows that the assumptions about NO_x emissions are extremely important in the final results. Unfortunately, the calculation of the impact of NO_x is as uncertain as it is important. As discussed in App. O, the equivalency factor for NO_x is only preliminary. Moreover, the estimation of NO_x emissions from future diesel and alternative-fuel HDVs is virtually impossible. The IEA (1991) projection of NO_x emissions from diesel HDVs is itself questionable; however, even if it were totally accepted, it would still be very difficult to project relative NO_x emissions from alternative-fuel HDVs. Although they certainly have the potential to emit less NO_x than do diesel HDVs, the extent to which this potential will be realized will depend on regulations, technology development, and tradeoffs between performance, emissions, and cost. Assumptions quite different from mine could be made.

The perhaps implausibly great importance of NO_x emissions in the EEC scenario produces some interesting results. For example, in the U.S. base case, all the alternative-fuel HDV cases improve their standing relative to diesel HDV cases as the time horizon gets longer. In the U.S. base case, non-CO_2 gases are relatively more important in the alternative-fuel cycles than in the diesel HDV cycle, and the longer time horizon "down-weights" non-CO_2 gases. In the European case, however, NO_x emissions from diesel HDVs dominate so much that non-CO_2 gases are more important in the diesel HDV cycle than in some of the alternative-fuel HDV cycles; hence, some alternative-fuel vehicles fare better the shorter the time horizon. However, in Europe, alternative-fuel HDVs using wood fuels still fare better the longer the time horizon, because in the case of wood fuels, most of the emissions are non-CO_2 gases. Nevertheless, the differences that occur (with wood-based fuels) over different time horizons are much less pronounced in Europe than the United States, because of the increased NO_x emissions from the diesel HDVs in the European case.

Although the results shown here for diesel HDVs in Europe may not be meaningful, because of the dubiously large impact of NO_x and the difficulty of projecting NO_x emissions, they are nevertheless quite instructive: they show that assumptions about the magnitude and effectiveness of non-CO_2 gases can drive the total emissions results.

5.10 SCENARIO 17

This scenario analyzes the use of EVs in Europe and Japan (see App. R for details). The use of EVs in Europe and Japan would substantially reduce CO_2-equivalent emissions of greenhouse gases, although the greenhouse impact of EVs would vary considerably from country to country. The countries that rely the least on coal and other fossil fuels and use them most efficiently would show the greatest benefits. For example, in Sweden, Canada, and France, which would continue to rely heavily on nuclear or hydro power and not much on coal, the use of EVs would greatly reduce total g/mi greenhouse gas emissions. In Germany and Great Britain, which would rely much more heavily on coal, the use of EVs would provide a smaller (but still large) reduction in emissions of greenhouse gases.

In fact, the reductions in g/mi emissions achieved through the use of EVs are strikingly large. Even in countries that use a lot of coal-based power, the reductions are much larger than they are in the United States. There are two main reasons for this. First, the IEA (1991) projections of emissions from gasoline LDVs in Europe are much higher than my comparable projections for the United States, primarily because the new U.S. emission standards for vehicles are much tighter than the new EEC emission standards (see App. R). These much higher tailpipe emissions of CO, NMOC, NO_x, and CH_4, combined with higher evaporative emissions, greatly increase greenhouse gas emissions from the baseline gasoline vehicle and make the EV look better. Conversely, the IEA (1991) projections of emissions from power plants in Europe are lower than my comparable projections of emissions for U.S. power plants, probably because in most European countries, NO_x emission limits are somewhat tighter than they are in this country (IEA, *Emission Controls in Electricity Generation and Industry*, 1988). Thus, the relatively lax tailpipe standards and relatively stringent power-plant standards make EVs more attractive in Europe.

5.11 SCENARIOS 18 AND 19

Total fuel-cycle, CO_2-equivalent emissions from LDVs using NG-derived methanol can range from 11% higher to 22% lower than emissions from gasoline vehicles (Scenarios 18-i and j). The key factors are the time horizon, efficiency of the methanol engines (Scenarios 9-a and 18-h), efficiency of the NG-to-methanol plant (Scenario 18-a), amount of non-CO_2 emissions from methanol vehicles and conversion plants (Scenarios 9-a and 18-d), and location of the gas feedstock (Scenarios 18-b and c). The efficiency and emissions variables are the most important; other variables, such as the rate of evaporative emissions (Scenario 18-f), and whether or not NGL is removed (Scenario 18-g), are less important. The location of the feedstock is important, because methanol made from remote gas would have to be transported thousands of miles by tanker to the United States, and this journey would produce a considerable amount of greenhouse gas emissions. Also, foreign plants would be less efficient than domestic plants because the feedstock gas would be cheaper.

If methanol vehicles could be operated lean and still meet the new NO_x standards (this is an important uncertainty), and if methanol could be made from relatively efficient domestic conversion plants, the emission reduction (compared with the gasoline baseline) would be in the range of 20%. This scenario, then, can be viewed as representing the longer-term potential for methanol, relative to gasoline. However, in the short run, if methanol is made entirely from foreign NG and used in vehicles with an efficiency advantage of only 10%, the use of NG-based methanol vehicle will cause a slight increase in greenhouse gas emissions.

If methanol were made from gas that would otherwise be flared, a very large reduction in CO_2-equivalent emissions would result (Scenario 18-e), because any CO_2 emissions from burning the methanol or the gas would not be a net emission. In other words, the CO_2 would be emitted anyway from gas flaring, even if the gas were not converted to methanol.

At the present time, methanol HDVs are slightly less efficient than diesel HDVs, especially in city bus driving. This condition, when combined with the emissions that result from upstream methanol processes, makes for significantly higher emissions from the methanol HDV cycle than the diesel HDV cycle, in most cases. However, in the long-run, if methanol were to be made from domestic gas in efficient plants, and if HDVs were more efficient running on methanol than on diesel fuel, the methanol HDV cycle would not produce more emissions than the diesel HDV cycle (Scenario 19-e).

Overall, the use of methanol from NG will, in the long run, provide slight to moderate reductions in total fuel-cycle, CO_2-equivalent emissions. The actual standing relative to the petroleum-fuel baseline will be determined by such things as emissions regulations, the cost and availability of NG, and the demand for fuel economy, as well as technical factors. Note, however, that a long-run methanol price that would support its large-scale production from domestic gas might also support its limited production from coal. And the overall greenhouse effect of a program using even a small amount of coal-derived methanol is likely to be negative (Scenarios 18-k and 19-g).

5.12 SCENARIOS 20 AND 21

This scenario shows that the use of methanol made from coal causes a significant increase in emissions of greenhouse gases, even if the vehicles and the coal conversion processes are very efficient. Even a combination of the most favorable assumptions -- coproduction of methanol from coal (using once-through methanol/liquid-phase methanol synthesis/integrated gasification combined cycle), very efficient methanol vehicles, and low CH_4 emissions from coal mines -- still results in an increase in greenhouse gas emissions of more than 10% for LDVs and of at least 40% for HDVs (Scenarios 20-d and 21-b). CO_2 "disposal" (for example, by injection into depleted NG fields) can reduce emissions from the coal-to-methanol cycle to below those from the petroleum cycle (Scenarios 20-e and f and 21-c and d), if it is assumed that making CO_2 and then "disposing" of it is the same as not making it in the first place.

The use of only a small amount of coal-derived methanol could undo any emissions-reductions benefit achieved by using NG-derived methanol. The greenhouse gas impacts of long-run methanol strategies should be analyzed with this fact in mind.

5.13 SCENARIO 22

Using methanol made from woody biomass that was grown using short-rotation intensive cultivation (SRIC) offers the prospect of substantially reduced greenhouse gas emissions (when compared with using petroleum fuels). In most of the following scenarios, the reduction ranges between 40% and 60%. In the most favorable scenarios, the biomethanol cycle can reduce greenhouse gas emissions by more than 70% from those in the petroleum-fuel scenario (Scenario 22-i). The most favorable scenario (22-i) includes the following:

- Fully developed, low-input, methanol-from-biomass system, where biofuels are used instead of diesel fuel in trucks and tractors (Scenario 22-b);
- No fertilizer used at all (Scenario 22-c);
- High-yield SRIC (Scenario 22-d);
- Very efficient methanol vehicles (Scenario 9-a); and
- Minimal energy embodied in capital equipment and relatively low emissions of non-CO_2 greenhouse gases from conversion facilities (Scenarios 22-a and j; note that the estimates of emissions from biomass-to-methanol facilities in Table A.1 are very uncertain).

This reduction does not count any one-time sequestering of CO_2 that would result if the SRIC plantation were to replace an ecosystem (such as cropland) that has a lower carbon content. This one-time sequestering could offset several decades of emissions from the base-case biomethanol cycle (Scenario 22-e; see App. K).

On the other hand, the advantage of methanol from biomass diminishes markedly if all the following conditions hold:

- Fertilizer is used heavily (Scenario 22-g),
- The fertilizer produces a large amount of N_2O (N_2O emissions from fertilized SRIC systems are not well known) (Scenario 22-h),
- Available estimates of the amount of energy embodied in the materials used throughout the biofuel cycle are accurate (Scenario 22-f), and
- Methanol vehicles have only a modest efficiency advantage over gasoline vehicles (Scenario 18-h).

In fact, in the worst case, which combines all the scenarios above, and with a 20-year time horizon, biomethanol provides almost no benefit when compared with the gasoline baseline (Scenario 22-j). Therefore, although biofuels provide the potential for large reductions in emissions of greenhouse gases, the reduction is not automatic. Analyses of the greenhouse impacts of biofuel programs must pay close attention to such elements as the amount of fertilizer used and the amount of energy embodied in materials.

5.14 SCENARIOS 23 AND 24

These scenarios compare emissions from CNG and LNG vehicles. The results depend on assumptions associated with the following factors:

- Thermal efficiency of the NG engine relative to the gasoline engine (Scenarios 9-b, 23-i, and 24-a and b);
- Magnitude of tailpipe CH_4 emissions -- the current database (see App. M) shows a wide range of emissions (Scenarios 23-a and 24-d and e);
- Time horizon, which determines the importance of the CH_4 emissions;
- Amount and kind of energy use to compress or liquefy gas -- a compressor located on a high-pressure transmission line has much less work to do, and so consumes less electricity and produces less greenhouse gas (Scenarios 23-b, d, e, and o);
- Range of the vehicle, which determines the size and weight of the storage tanks, which in turn affects the efficiency of the vehicle (Scenarios 23-g and q);
- Lifetime of the vehicle and the storage tanks -- a longer life results in lower lifetime-average emissions from materials manufacture and vehicle assembly (Scenario 23-c);
- Amount of energy used to recover and process NG (Scenarios 23-h, p, and s);
- Rate of leakage from the gas-distribution network (Scenarios 23-u and 24-c);
- Amount of CO emissions from the tailpipe (Scenario 23-m); and
- Other factors.

Most of these factors have roughly the same degree of importance, except the amount and kind of energy used to compress gas is more important, and the amount of energy used to recover and process gas is somewhat less important than most of the other factors. Thus, although previous analyses focused on tailpipe CH_4 emissions, this analysis shows that there are many other unknown variables that are at least as important.

In the best case, the use of CNG or LNG reduces greenhouse gas emissions by more than 25% when compared with the gasoline baseline and by nearly 10% when compared with the diesel-fuel baseline (Scenarios 23-v and 24-h). For this result to be realized, however, NG vehicles must be able to use lean-burn technology and still meet a NO_x standard, and compression or liquefaction stations must be located over high-pressure pipelines and use gas as a fuel. In more realistic "best-case" scenarios, NG vehicles provide a 15-20% reduction in greenhouse gas emissions.

In the worst case, emissions from NG vehicles can be up to 30% or 40% higher than emissions from gasoline or diesel vehicles (Scenarios 23-w and x and 24-i). This result occurs if NG LDVs have such a difficult time meeting the NO_x standard that they operate slightly rich and forego a higher compression ratio, which reduces efficiency and increases CO emissions (Scenario 23-n); and if they have a 350-mi instead of a 250-mi driving range, which increases the weight of the tanks and decreases the efficiency of the vehicles (Scenario 23-q); and if gas leaks from the grid are 2% instead of 0.3% (Scenario 23-u). However, the first and the last of these conditions are unlikely, and a more realistic estimate of the worst-case scenario for dedicated NG vehicles would be "no change" with respect to gasoline and diesel fuel.

If CNG is made from LNG that was made from remote NG, total fuel-cycle, CO_2-equivalent emissions are greater than in the gasoline base case (Scenario 23-r). The use of remote rather than domestic gas results in a substantial amount of extra emissions from several sources: pipeline transport to the liquefaction plant, liquefaction, transport in LNG tankers, and regasification. However, it makes much more sense to use LNG from remote gas as LNG in or near the receiving port city. In fact, the use of LNG from remote gas results in about the same emissions as the use of LNG made on site from domestic pipeline gas, because in the remote-gas case, the greater emissions from LNG transport are offset by the lower emissions from liquefaction (Scenario 23-t). (Recall that the domestic-LNG base-case here assumes that LNG is liquefied at the service station by small liquefiers; these liquefiers are less efficient than the large liquefiers used in remote-LNG projects.) Hence, if remote gas is to be used as a transportation fuel, it is best, from a greenhouse standpoint, to use it as LNG rather than CNG or methanol. (This comparison may not be completely fair, since it assumes that LNG would be used in the port city but CNG and methanol would be used inland. However, limiting the use of CNG and methanol to port cities does not significantly alter the results.) CNG or LNG, like methanol, can be made from gas that would otherwise be flared, which allows for large reductions in emissions of greenhouse gases (Scenarios 23-j and k).

5.15 SCENARIOS 25 AND 26

These scenarios test the effect of different assumptions about the following conditions:

- Source of LPG -- either NGL plants or refineries (Scenarios 25-a and b and 26-a and b),
- Efficiency of and emissions from LPG vehicles (Scenarios 9-f, 25-e and f, and 26-e through h), and
- Composition of LPG (Scenarios 25-c and d and 26-c and d).

Of these, the relative thermal efficiency of the LPG vehicle is most important factor, and the butane/propane composition of LPG is the least. Because relatively few variables were considered in these LPG scenario analyses, the difference between the best and the worst case is less for LPG vehicles than for the other alternative-fuel vehicles.

This analysis indicates that the use of LPG will reduce emissions of greenhouse gases from LDVs by 15-30% and will reduce emissions from HDVs by a slight amount (Scenarios 25-g and h and 26-i and j). The LPG fuel cycle thus consistently emits the least amount of greenhouse gases of any ICEV cycle that uses fossil fuel. There are two caveats to this conclusion, however. First, it does not necessarily apply to high levels of LPG production. Second, if the refinery energy cost of making LPG is much higher than estimated here (see App. H) and if all the LPG is made at the refinery, LPG looks less attractive (Scenarios 25-i and 26-k).

5.16 SCENARIO 27

There is no simple overall assessment of the greenhouse effect of ethanol from corn. Although the ethanol "base case" considered here shows a large increase in the amount of greenhouse gas emissions when compared with the gasoline and diesel baselines, there are many scenarios in which the increase is much less, and there are even some in which ethanol from corn actually results in a decrease. In the best case, in which corn stover is used as the process fuel, ethanol from corn can reduce greenhouse gas emissions by more than 60% (Scenarios 27-t and v). In the worst case, in which coal is used as the process fuel, emissions are more than 50% higher than they are in the petroleum-fuel cases (Scenario 27-w). The extraordinarily wide range of results is caused by the (1) variety of energy sources that can be used to provide process heat, (2) difficulty involved in allocating emissions among the multiple products of the process, (3) uncertainty involved in estimating emissions resulting from fertilizer use, and (4) uncertainty involved in estimating the energy efficiency of ethanol vehicles and ethanol production plants.

It is perhaps most important to distinguish the results by type of process fuel. Coal, NG, and corn-crop residue can all provide heat for the ethanol-production process. The combustion of corn-crop residues does not produce net CO_2, because the corn residue is either burnt or left to rot. (The removal of the residue from the field for use as a fuel does increase nutrient requirements, and this factor has been accounted for here.) Simply using corn residue instead of coal as a fuel swings the results for ethanol from moderately unfavorable to moderately favorable, all other factors being equal (Scenario 27-j). Using NG instead of coal results in about half the emissions reduction that the use of corn stover does (Scenario 27-i).

Many other variables are quite important. Using very efficient corn-to-ethanol conversion technologies can substantially reduce emissions from the base-case level (Scenario 27-g). Because much of the heat required in an ethanol plant is for drying the wet by-products of the distillation process, not drying these by-products can greatly reduce energy requirements and hence greenhouse gas emissions (Scenario 27-k). (This scenario is practical only when the wet slop can be used as a feed at the site of ethanol production.) Reducing the use of fertilizer reduces emissions from fertilizer manufacture and from denitrification and nitrification of nitrogenous fertilizers to N_2O and NO_x. For example, "low-input" agriculture, in which fertilizer use is only 30% of the base-case level, greatly reduces total fuel-cycle, greenhouse-gas emissions; in fact, emission levels are below the level of those from the gasoline base-case vehicle (Scenario 27-b). Even at the base-case level of fertilizer use, the uncertainty in the level of N_2O emissions alone has a considerable effect on the results (Scenario 27-a). N_2O emissions from corn fields need to be better documented. As with all the alternative-fuel cycles, the efficiency of the alternative-fuel vehicle relative to the gasoline or diesel vehicle is quite important. In the case of LDVs, the potential relative efficiency gain may be constrained by the tight NO_x standards of the new Clean Air Act Amendments (App. B).

The corn-to-ethanol process results in products other than ethanol; consequently, greenhouse gas emissions per unit of ethanol depend on how one allocates the total emissions of the corn-conversion process among the products. The difficulty of allocating emissions is discussed in App. K. Results show that allocation is very important. In the base case, emissions from the manufacture of the products replaced by the by-products of the corn-to-ethanol process (e.g., soybeans replaced by distillers' dried grains and solubles, or DDGS) are deducted from total emissions from corn farming and conversion. The remaining emissions are assigned to ethanol. However, if emissions are allocated to all products (ethanol, DDGS, corn oil, etc.) on the basis of their value or energy content, then the corn-to-ethanol cycle produces less CO_2-equivalent emissions than does the gasoline cycle (Scenario 27-f). Uncertainty in assigning by-product credits has as much of an effect on emissions as does switching from coal to corn stover.

Yet another important and uncertain variable in the corn-to-ethanol cycle is the amount of emissions from the manufacture and assembly of materials used to make farm equipment and the corn-to-ethanol plant itself. It appears that a large amount of energy is embodied in the materials used to make ethanol production facilities and farm equipment (Table K.7) -- much more than is embodied in the facilities and equipment used in the gasoline cycle, on a Btu of embodied energy/Btu of product basis. If emissions from the manufacture and assembly of these materials are counted, fuel-cycle emissions increase considerably (Scenario 27-m). These sources, too, need to be better documented.

Finally, if the corn grown to produce ethanol were to replace rangeland, CO_2 would be emitted from the soil, because frequently disturbed agricultural soils contain less carbon than rangeland soils (Table K.12). This emission can actually be equivalent to several years of total CO_2-equivalent emissions from the entire ethanol-to-corn cycle (Scenario 27-o).

The general message of these corn-to-ethanol scenarios is that one can pick values for a set of assumptions that will support virtually any conclusion about the impact of the corn-to-ethanol cycle on global warming.

5.17 SCENARIO 28

Generally, the discussion for Scenario 22 (methanol from wood) applies to this scenario, which tests ethanol from wood. The most important difference is that the ethanol process produces excess electricity for sale. This situation results in a substantial emissions credit, which makes overall emissions from the wood-to-ethanol cycle lower than those from the wood-to-methanol cycle. For example, the best case for ethanol from wood (Scenario 28-l) is much better than the best case for methanol from wood (Scenario 22-i); in fact, it provides the largest percentage reduction in total fuel-cycle emissions of any alternative examined here (because of the large electricity-generation credit). Nevertheless, the variables important in the methanol case -- intensity of fertilizer use, use of biofuels in trucks and tractors, vehicle efficiency, and yield per acre -- are important in the ethanol case, and for the same reasons. As in the methanol case, the values for these variables can be chosen to produce relatively unfavorable results (Scenario 28-m).

The result for ethanol from wood spans a huge range, from the virtual elimination of all greenhouse gases to no change relative to the gasoline base case. This range illustrates, once again, the dramatic effects that can result if assumptions about emissions of non-CO_2 greenhouse gases, the time horizon, and the cumulative force of many independent assumptions are all either favorable or unfavorable.

5.18 SCENARIO 29

The effect of EVs can range from a moderate increase to nearly complete elimination of greenhouse gas emissions, depending on assumptions about the mi/kWh efficiency of the vehicle, the efficiency of electricity generation, the emissions from electricity generation, and the kind of fuel used to generate electricity.

The most important factor is the kind of fuel that is used to generate the electricity used to recharge the EVs. The use of coal-based power can cause a slight increase to a large decrease in CO_2-equivalent emissions (when compared with the gasoline baseline), depending primarily on the efficiency of the power plants and the vehicles (Scenarios 29-p, q, and r). The use of NG-based power allows for a moderate to very large reduction in fuel-cycle emissions (Scenarios 29-u, v, and w), because of NG's lower carbon/Btu content. In fact, highly efficient battery-powered EVs, using electricity generated by highly efficient combined-cycle or intercooled steam-injected gas turbines (Williams and Larson, 1989) or by NG fuel cells, offer the largest reduction of any fossil-fuel-based option examined in this analysis (Scenarios 29-v and w). The use of solar or nuclear power virtually eliminates all fuel-cycle greenhouse gas emissions other than those associated with vehicle manufacture (Scenarios 29-m, n, and o). Note the efficiency of uranium mining and enrichment has no appreciable effect on the results, mainly because the amount of upstream emissions from the nuclear power cycle is not very large in the base case.

The use of biomass-derived electricity could have a wide range of effects, depending on the amount of acreage fertilized and the amount of fertilizer used, the amount of N_2O evolved from fertilizer, the amount of energy embodied in equipment and facilities, the efficiency of power generation, the efficiency of vehicles, land use effects, and other factors. In the best case, if trees permanently replaced crops or grasses, the one-time increase in the standing stock of carbon (CO_2) would offset decades of fuel-cycle emissions. In the worst case, under the short-term horizon, fuel-cycle CO_2 emissions would actually be the same as those from a gasoline vehicle, in large part because of the extremely high level of emissions of non-CO_2 greenhouse gases from feedstock production.

Emissions from the use of EVs depend on the actual mix of fuels used to generate the electricity that would not have been generated had there been no EV program. This mix depends on the cost and availability of fuels, environmental regulations, reliability of power plants, and other factors, all of which are difficult to project. To give an idea of how this mix, and thus emissions from power plants, can vary, I show the emission results for the average power mixes used in five major U.S. cities (Scenarios 29-h through l). (The "average" power mix in a city or region is based on total electricity generation, for all end uses, in a year.) The actual marginal or specific mix used by EVs, however, will almost certainly not be the same as the average or all-purpose mix in these cities. In all five cities, EVs offer a moderate to large reduction in greenhouse gas emissions, primarily because of the relatively light use of coal in this scenario.

When a fossil fuel is used to generate electricity, overall emissions are determined by the efficiency of the EV. The overall efficiency of the vehicle is a function of the weight of the vehicle and the efficiency of the battery, recharger, and drivetrain. The weight of the vehicle is a function of drivetrain and battery technology and vehicle range, and the efficiency of the components is a function of technology and how the vehicle is used. For example, the use of Pb/acid rather than Na/S batteries greatly increases emissions of greenhouse gases (Scenario 29-d), because Pb/acid batteries are much heavier and are recharged much less efficiently. In fact, the difference in recharging efficiency (75% versus 92%) is the main cause of the increase, because fuel-cycle emissions are proportional to the efficiency of recharging. Conversely, lightweight, aerodynamic EVs (like the GM Impact) with very efficient powertrains and efficient batteries significantly reduce emissions of greenhouse gases (Scenario 29-a).

Greenhouse gas emissions from the EV cycle are related to how the vehicle is used. In the base case, I assume that EVs are used only in city driving. If EVs are used in highway driving as well, their efficiency advantage relative to gasoline vehicles declines, because gasoline vehicles are more efficient in highway driving than in city driving, whereas EVs are not (see App. B). This large drop in efficiency substantially increases greenhouse gas emissions (Scenario 29-c). Also, if EVs are consistently recharged after only shallow discharges, the efficiency of the battery can be substantially degraded, which causes a large increase in greenhouse gas emissions (Scenario 29-e).

Emissions from the use of EVs are an indirect function of the range of the vehicle. The longer the range is, the heavier the battery is and the lower the overall efficiency is. Increasing or decreasing the range by 50 miles results in a change of almost 10 percentage points in emissions from the EV relative to the gasoline vehicle (Scenarios 29-y and z).

In the base case, the amount of N_2O formed by the corona discharge from high-voltage power lines is too small to significantly affect the results. However, if the high-end estimate of N_2O from this source is accurate (App. N), electricity transmission becomes a nontrivial source of greenhouse gas emissions (Scenario 29-aa). This source of N_2O needs to be investigated further.

For most of the variables examined here, a change in value changes the amount of overall greenhouse gas emissions proportionately. Thus, combinations of changes in these variables, all in the same direction (i.e., favorable or unfavorable), can have an enormous effect on the overall result. For example, if EVs were to use Pb/acid technology, be used in combined city/highway driving, and be recharged after shallow discharges (an unlikely combination, to be sure), they would cause a huge increase in greenhouse gas emissions, given the base-case marginal power mix (Scenario 29-g). On the other hand, the use of the best EV technology, together with a long EV life (Scenario 29-b), would greatly reduce greenhouse gas emissions (Scenario 29-f). The gap between these best and worst cases is more than 100 percentage points.

In conclusion, the overall standing of EVs hinges on two classes of variables that are very hard to project: the marginal mix of power used to recharge vehicles and the technology and use characteristics of the vehicles (including their range). These factors must be considered in any analysis of the greenhouse impact of EV policies.

5.19 SCENARIO 30

This hydrogen-in-ICEVs scenario illustrates the importance of considering emissions from the entire nuclear fuel cycle as opposed to just those emissions from the tailpipe. Hydrogen vehicles themselves produce virtually no greenhouse gases, and hydrogen transport is virtually free of emissions, but the production and compression or liquefaction of hydrogen consumes a large amount of electricity. In fact, coal-fired power plants providing power to hydrogen liquefiers will by themselves emit about as much greenhouse gas as does the entire gasoline production-and-use cycle (Scenario 30-e).

Very efficient enrichment technologies, such as laser-isotope separation, use much less electricity than does gaseous diffusion and noticeably reduce total life-cycle, CO_2-equivalent emissions from nuclear-electrolytic-hydrogen vehicles (Scenarios 30-c and g). More dramatic results would occur if nuclear power (rather than the U.S. year-2000 mix, dominated by coal) were used to liquefy hydrogen; emissions of greenhouse gases would decline substantially (Scenario 30-f). Combining all-nuclear liquefaction with advanced enrichment technology virtually eliminates greenhouse gas emissions -- any emissions that would remain would be a result of the manufacture and assembly of materials for the vehicle. At this point, nuclear-electrolytic hydrogen would fulfill its promise.

The analysis for solar-electrolytic hydrogen would be similar, except that in all cases, the use of solar power produces less greenhouse gas than does the use of nuclear power.

5.20 SCENARIO 31

This fuel-cell scenario examines the results of using more efficient processes to produce the methanol used in fuel-cell vehicles. The use of more efficient gas-conversion technology, or OTM/LPM/IGCC coproduction of methanol and electricity from coal, further reduces emissions of greenhouse gases by 10 to 20 absolute percentage points.

Although fuel-cell vehicles using methanol made from NG offer a substantial reduction in emissions of greenhouse gases when compared with current gasoline LDVs, this reduction is much less than that provided by hydrogen- or biomethanol-powered fuel-cell vehicles. Moreover, any increase in vehicle miles traveled will, in the long run, reduce the large per-mile reduction in emissions available with NG-derived methanol, so that even NG/methanol-powered fuel cell vehicles will not be a long-run solution to the greenhouse problem. Furthermore, by the time fuel-cell vehicles would be common, methanol would probably be made, in part, from coal, and fuel-cell vehicles using methanol from coal offer little or no greenhouse benefit at all. Consequently, vehicles using methanol fuel cells would offer substantial long-term reductions in emissions of greenhouse gases only if biomass were used as the feedstock.

Biomass could be made into hydrogen as well as into methanol (DeLuchi, Larson, and Williams, 1991). However, the biomass-to-hydrogen fuel cycle could produce more emissions than the biomass-to-methanol fuel cycle, because of the potential for substantial CO_2-equivalent emissions to result from the use of fossil electricity to compress or liquefy hydrogen. These emissions might erase the efficiency and emissions advantage of the biomass-to-hydrogen fuel cycle. However, if solar or biomass power were used to compress or liquefy hydrogen, the hydrogen cycle would probably be superior to the methanol cycle.

6 CONCLUSIONS

6.1 TRANSPORTATION SECTOR CONCLUSIONS

6.1.1 Coal

In most cases, CO_2-equivalent emissions from the transportation sector increase when coal is used (1) to produce methanol, hydrogen, or SNG for ICEVs (see DeLuchi et al., *Transportation Fuels and the Greenhouse Effect*, 1987, for analyses of hydrogen and SNG from coal); (2) to produce electricity for battery-powered EVs; or (3) as a process fuel in the corn-to-ethanol fuel cycle. Even when the most efficient way of producing methanol from coal is used (OTM/LPM/IGCC; see App. J), the result is still a considerable increase in emissions of greenhouse gases over those that result from the current gasoline production and use cycle. The use of coal as a process fuel in the ethanol-from-corn cycle also contributes substantially to total fuel-cycle emissions.

The only way (other than CO_2 disposal in, for example, depleted NG reservoirs) to use coal as a primary energy source in the transportation sector without causing an increase in greenhouse gas emissions is to greatly increase the overall energy efficiency of the entire transportation fuel cycle. This goal can be accomplished by using coal-derived methanol in fuel-cell vehicles (which are roughly twice as efficient as ICEVs) or by using coal in very efficient, low-polluting power plants, such as fuel cells, to produce electricity for very efficient battery-powered EVs. The acceptable use of coal, then, is linked to the development of advanced electric and fuel-cell vehicles. Even in these cases, coal provides an actual reduction in greenhouse gas emissions only in the very best case for coal-based power plants and EVs. (Coal use with CO_2 disposal also reduces CO_2 emissions, but CO_2 that is disposed of is not the same as CO_2 that was not generated in the first place.)

6.1.2 Natural Gas

Slight to moderate reductions in CO_2-equivalent emissions result from (1) using NG to produce methanol, CNG, or LNG for alternative-fuel vehicles or electricity for EVs; (2) using NG as a process fuel in the corn-to-ethanol cycle; or (3) using NG liquids to make LPG. The reductions are, in most cases, less than 25% of current per-mile emissions from the use of gasoline and diesel fuel. In the long run, such moderate reductions would do little more than help keep the emissions level steady for a few years as vehicle miles traveled increase. In many cases, then, NG could act as a transitional fuel or feedstock in a strategy designed to control emissions of greenhouse gases, but it cannot be viewed as a long-run solution. The main exception to this general conclusion would be to use NG in very efficient, low-polluting advanced gas turbines or fuel cells that provide power for very efficient EVs. In the best case, this use of NG would greatly reduce per-mile emissions of greenhouse gases from motor vehicles.

6.1.3 Improved Fuel Economy

Improving fleet-average fuel economy does reduce total fuel-cycle emissions of greenhouse gases from motor vehicles. However, emissions of greenhouse gases from motor vehicles are not linearly related to fuel economy, primarily because tailpipe emissions of non-CO_2 greenhouse gases are not related to fuel economy. In other words, a doubling of fuel economy reduces fuel-cycle emissions of greenhouse gases by less than a factor of two. The reason that tailpipe emissions of greenhouse gases are not related to fuel economy is because the emission standards for vehicles are specified in terms of grams per mile of travel, not grams per gallon or Btu of fuel. By contrast, emission standards for power plants are in grams per Btu of fuel input. Thus, improving fuel efficiency is a more effective greenhouse gas control strategy for power plants than for motor vehicles.

6.1.4 Woody Biomass

The production of alcohol fuels, SNG, or electricity from woody biomass can greatly reduce emissions of greenhouse gases. In the best cases, the use of wood-based fuels can virtually eliminate these emissions. In fact, if wood plantations are established on marginal cropland, the initial buildup of carbon (from atmospheric CO_2) in the biomass will offset decades of CO_2-equivalent emissions from the production and use of biofuels, including emissions from the manufacture of materials for conversion plants, farm equipment, and motor vehicles (see App. K). Thus, with the right land-use policy, an energy-efficient, biofuels-from-wood program that uses little or no fertilizer will result in zero net emissions of greenhouse gases for decades. This potential to mitigate transportation's contribution to the greenhouse problem is a major attraction of biofuels made from wood.

On the other hand, if wood plantations require a lot of fertilizer, and if the manufacture of materials and equipment results in substantial emissions of greenhouse gases (and if other unfavorable conditions hold), then the biofuel cycles will provide no more than modest reductions -- and perhaps even no reduction at all -- in greenhouse gas emissions.

Overall, the wide range of possible outcomes for biofuels show that analysts must pay serious attention to (1) emissions from the use of "embodied" energy (e.g., energy used to make fertilizer, buildings, and equipment), (2) emissions of non-CO_2 greenhouse gases that result from combustion (e.g., NO_x from the tailpipe), (3) emissions of greenhouse gases that do not result from combustion (e.g., N_2O from nitrification of fertilizer), and (4) changes in land use. An analysis that focuses only on emissions of CO_2 that result from combustion can miss all these other sources and seriously misrepresent the greenhouse impact of the biofuel cycle.

6.1.5 Solar and Nuclear Energy

The use of solar energy to make electricity for battery-powered EVs or hydrogen for fuel cell vehicles nearly eliminates emissions of greenhouse gases, as long as the solar energy is used throughout most of the fuel cycle. Solar energy is the most attractive supply-side option for reducing emissions of greenhouse gases.

The use of nuclear power to make electricity or hydrogen also greatly decreases emissions of greenhouse gases, but not as much as solar power (given current gaseous-diffusion uranium-enrichment technology). The use of more efficient uranium-enrichment technologies, such as the gas centrifuge or the laser isotope separation technique, would make greenhouse gas emissions from the nuclear fuel cycle comparable with those from the solar fuel cycle.

The stipulation that nonfossil energy be used throughout the fuel cycle and not just to make the primary energy carrier has an important relationship to total emissions. In fact, as shown in the hydrogen scenario analyses (Table 12), emissions from the use of energy for some upstream processes, such as hydrogen liquefaction, can be nearly as large as total emissions from the gasoline fuel cycle.

6.1.6 Non-CO_2 Greenhouse Gases

This analysis shows that non-CO_2 greenhouse gases -- CH_4, N_2O, NO_x, CO, and NMOCs -- play a surprisingly important role in total greenhouse gas emissions. These gases dominate the ethanol-from-wood cycle and are a major part of the other biofuel cycles. They constitute a large part of total CO_2-equivalent emissions from fossil-fuel-based cycles -- more than 30%, in the case of CNG. The contribution of non-CO_2 greenhouse gases also determines how an alternative fuel ranks relative to petroleum fuel over different time horizons: the larger its contribution of non-CO_2 greenhouse gases is to total emissions, the better the alternative is in the longer run, because as time passes, the non-CO_2 gases are down-weighted in their contribution to total emissions relative to CO_2.

Emissions of non-CO_2 greenhouse gases depend on the type of fuel, energy technology, and emission control technology used. It follows that the specific assumptions about these parameters are thus quite important. For example, because NG-driven engines emit much more CH_4 than do NG-driven turbines, assumptions about the fraction of pipeline compressors that are driven by engines rather than by turbines can have a nontrivial effect on CO_2-equivalent emissions from NG fuel cycles. Another example is gasoline-fueled farm equipment, which emits huge amounts of CO. Thus, the use of gasoline on a farm can also contribute a nontrivial amount of CO_2-equivalent emissions. Emissions of NO_x and CH_4 from NG-to-methanol plants, coal-to-methanol plants, wood-to-fuel plants, and corn-to-ethanol plants might also be important; they need to be measured accurately to find out.

If the IPCC's estimate of the global warming potential of NO_x is accurate (Table 8), in many cases, NO_x emissions alone account for a substantial fraction of total fuel-cycle, CO_2-equivalent emissions. For example, diesel HDVs in Europe are projected to emit such large quantities of NO_x that in the short term (20 years), these NO_x emissions will contribute more to global warming than all the other greenhouse gases, including CO_2, combined. Preliminary results such as these indicate the importance of accurately calculating the global warming potential of non-CO_2 greenhouse gases.

6.1.7 Comparative Efficiency of Alternative Fuel Vehicles

The efficiency of alternative-fuel ICEVs relative to gasoline and diesel vehicles is an important factor in total fuel-cycle emissions of greenhouse gases. For example, there is a large difference in the amount of total fuel-cycle, CO_2-equivalent emissions generated when an ethanol vehicle is 28% more efficient than a comparable gasoline vehicle and when an ethanol vehicle is only 9% more efficient. However, projecting the in-use fuel efficiency of alternative-fuel vehicles is a complicated task. It requires an analysis of the interaction of the cost of efficiency-improving technologies and the gains provided by these technologies with emission standards, vehicle performance, and consumer demand for efficiency.

In the alternative-fuel community, most of the debate about fuel efficiency has focused on the technical potential for efficiency gains. Unfortunately, there has been little discussion of some equally important issues. For example, how will tailpipe emission standards constrain potential efficiency gains? How will consumers respond to the greater cost of improved efficiency, which will result in higher vehicle prices or reduced performance? Is it reasonable to expect that manufacturers will offer and that consumers will buy all the cost-effective, efficiency-maximizing technologies and designs available?

As discussed in App. B, tighter emission standards may preclude the use of some efficiency-improving technologies. For example, the use of lean-burn technology, which greatly improves the thermal efficiency of an engine, renders a NO_x reduction catalyst almost useless. Therefore, lean-burn vehicles will probably not be able to meet the 0.4 g/mi NO_x standard to be phased in under the new Clean Air Act Amendments. Without this lean-burn option, alternative-fuel vehicles will probably not be more than 20% more efficient than gasoline vehicles.

Furthermore, some of the technologies used to improve the efficiency of alternative-fuel vehicles could be applied, to some degree, to gasoline vehicles. For example, Toyota Motor Corp. (1989, p. 49) believes that lean-burn gasoline technology "will be very important in the near future." If both lean-burn gasoline vehicles and alternative-fuel vehicles will be able to meet the 0.4 g/mi NO_x standard, the alternative-fuel vehicles will have less of an efficiency advantage over the gasoline vehicles. Nevertheless, research to date suggests that it will be quite difficult for lean-burn gasoline vehicles to achieve the 0.4 g/mi NO_x in-use standard (Held et al., 1990; Diwell et al., 1988); certainly, it will be more difficult for them than for most alternative-fuel vehicles.

It may also be possible to increase the compression ratio of gasoline vehicles by making commercial gasoline more knock resistant. However, it is not likely that the compression ratio can be increased to anywhere near the level achievable with alternative fuels.

Even if emission standards do not constrain efficiency improvements, vehicles may still not be as efficient as technically possible, because consumers may not demand the highest efficiency attainable. In the first place, very high levels of efficiency may not be cost effective according to a rational social-cost accounting standard. Even if very high levels of efficiency were cost effective, however, consumers might still not be interested. Efficiency, in the auto industry and elsewhere, has been difficult to sell. However, the efficiency situation is somewhat different for alternative-fuel vehicles than gasoline vehicles. Higher efficiency does more than just reduce fuel cost; it increases the range of the vehicle or reduces the volume of fuel storage. These benefits are less important in gasoline vehicles, which have small fuel tanks and long driving ranges to begin with. Nevertheless, the conclusion remains that to make reasonable claims about what kind of alternative-fuel ICEVs will actually be sold and used, one first must analyze how consumers will trade off efficiency with cost and performance.

6.1.8 Comparative Efficiency of Electric Vehicles

The in-use efficiency of EVs relative to gasoline vehicles is an important factor in overall greenhouse gas emissions from the use of EVs. The relative efficiency of EVs is especially difficult to estimate, because it is a function not only of the type of battery and powertrain technology but also of how the vehicle is driven. Electric powertrains are much more efficient than ICEV powertrains under any circumstance, but their advantage is much greater in city driving than in highway driving. Furthermore, some types of batteries become less efficient if they are repeatedly recharged after shallow discharges (DOE, *Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector, Technical Report Four: Vehicle and Fuel Distribution Requirements*, 1990). Thus, an EV that is recharged every night after relatively short highway trips will fare much worse, relative to the ICEV it replaces, than will an EV that is recharged after a week's worth of stop-and-go driving. Compounding this uncertainty is the fact that there are so many battery and powertrain technologies available for EVs. Consequently, to pinpoint the impacts of EVs on global warming, one must project how the EVs will be used, what technologies they will use, and what fuels will be used to recharge them.

6.1.9 Upstream Energy Use

The amount and type of energy used by upstream processes are important factors in determining total emissions from most transportation fuel cycles. The use of energy by upstream processes, like the use of fuel by vehicles, is governed by political and economic forces. For example, the amount and kind of energy used to make a barrel of gasoline depends on the amount of gasoline being made from a barrel of crude, composition of the crude, desired composition of the gasoline, particular refining technologies used, emission standards for refineries, and other factors. The composition of gasoline, in turn, is determined by both consumer demand and environmental and safety regulations.

Similarly, the amount and type of energy used by power plants to produce electricity is a very important factor in determining CO_2-equivalent emissions from the use of EVs. A mix that relies heavily on old coal-fired plants gives radically different results than a mix relying on NG fuel cells. To project which power plants will be used to provide the marginal power demanded by EVs, one must consider such factors as the age, reliability, fuel costs, emissions, maintenance costs, capacity factors, and location of available power plants.

6.1.10 Summary

This analysis shows that the use of any fossil fuel feedstock to make any transportation fuel will not significantly reduce emissions of greenhouse gases as long as the transportation fuel is used in an ICEV. However, the use of NG as the ultimate energy source for battery-powered or fuel-cell-powered electric-motor-driven vehicles can greatly reduce emissions of greenhouse gases. Still larger reductions can be achieved by the use of nonfossil fuels (biofuels and hydrogen) in ICEVs. The biggest reductions in emissions of greenhouse gases can be achieved by the use of nonfossil fuels with electric-motor-driven vehicles. In summary, the ranking from best to worst is as follows:

1. Nonfossil fuels with electric-motor-driven vehicles,

2. Nonfossil fuels with ICEVs,

3. Fossil fuels with electric-motor-driven vehicles, and

4. Fossil fuel with ICEVs.

Even though in the near term, the use of alternative fuels does not greatly reduce emissions of greenhouse gases, it can be a first step in a path that leads to ultra-low emissions. The key is to switch from fossil fuel feedstocks like NG to nonfossil feedstocks such as biomass and solar energy and to switch from ICEVs to electric-motor-driven vehicles. Many paths are possible; some of these follow:

- From NG-derived methanol in ICEVs to wood-derived methanol in ICEVs, then to wood-derived methanol in fuel-cell vehicles;

- From corn-derived ethanol using coal as a process fuel to corn-derived ethanol using corn stover as a process fuel, then to wood-derived ethanol;

- From NG to solar-electrolytic hydrogen in ICEVs (this path could begin with the addition of hydrogen to NG);

- From battery-powered EVs using coal-based power to battery-powered EVs using biomass and solar power; or

- From a mix of CNG vehicles and battery-powered EVs to compressed-hydrogen fuel-cell vehicles, which use a fuel cell to link CNG-like fuel storage and refueling technology with an electric powertrain.

The extent and timing of these transitions will depend on many economic and regulatory factors. In general, switches will occur when nonfossil feedstocks and electric motors become economically competitive or are mandated, directly or indirectly. An example of an indirect mandate would be a zero-emissions tailpipe standard.

6.2 OVERALL CONCLUSIONS FOR TRANSPORTATION AND ELECTRICITY

This analysis has three main messages. First, for most energy options, emissions of CO_2 from fuel combustion account for the bulk of total greenhouse gas emissions. It thus is very important to estimate as accurately as possible the two main determinants of combustion emissions of CO_2: the carbon content of fuels (in grams per Btu) and the efficiency of fuel use (in Btu per mile or Btu per kilowatt).

The second conclusion is that CO_2 is not the only greenhouse gas of interest and combustion is not the only source of greenhouse gases. Emissions of CH_4, CO, N_2O, NO_x, and NMOCs, from both combustion and noncombustion sources, can be responsible for a large part of the total global warming potential of energy use. In some cases, non-CO_2 greenhouse gases are collectively more important than CO_2, and there are even cases in which an individual non-CO_2 gas is more important than CO_2. Analyses of energy options and the greenhouse effect must examine all greenhouse gases and all sources of emissions.

The third and most interesting point from an analytical standpoint is that the details matter a lot. The overall g/mi or g/kWh results are determined by hundreds of specific assumptions about such factors as the chemical composition of fuels, the stringency of emission standards, the types of emission control technologies used, how vehicles are used, where primary feedstocks come from, where fuels are produced and used, what kinds of engines or motors and fuels are used by fuel-processing equipment, and how much fertilizer is used to grow biomass. For most energy options, assumptions about these factors can be chosen to produce results with a wide range -- from very favorable to unfavorable.

In turn, virtually all of these factors depend on political, social, and economic forces: energy prices, environmental policies, the distribution and availability of land and other resources, government support for new technologies, consumer preferences, and so on. Ultimately, then, to model emissions of greenhouse gases from the use of energy, one must analyze the broader context in which energy is produced and used. Further work on greenhouse gas emissions from the use of energy should not just refine engineering estimates of energy efficiency and emission factors but should also address these larger social, political, and economic issues.

6.3 POLICY RECOMMENDATIONS FOR TRANSPORTATION

This analysis has shown that large, long-term reductions in CO_2-equivalent emissions from the transportation sector can be accomplished best by using fuels derived from biomass or nonfossil electricity to charge battery-powered EVs or make hydrogen for ICEVs or fuel-cell-powered EVs. From a greenhouse perspective, the policy question is: "What is holding these options back, and what can be done to encourage their adoption?"

Biofuels and solar energy are expensive on a private-cost basis, and nuclear energy is expensive and politically unpopular. Battery-powered EVs do not perform well enough to be used in all highway applications; hydrogen-powered ICEVs or fuel-cell vehicles do but are relatively expensive on a private-cost basis, and fuel storage is still problematic. In summary, current petroleum fuels are relatively cheap and alternative non-CO_2-producing fuels are relatively costly on a private-cost basis, and some alternative vehicular technologies have performance drawbacks. Thus, two kinds of policies are needed to address these problems.

First, fuels and technologies should be priced at their social or full economic cost and not at their private cost. Gasoline is currently the cheapest transportation fuel on a private-cost basis, but the external cost of gasoline use, which includes the effects of air pollution and greenhouse gas emissions and the cost of defending oil fields in the Middle East, is probably very large. On the other hand, the use of solar power or solar-derived hydrogen has only a small external cost. Thus, if the external cost of gasoline and diesel fuel use is at the high end of a plausible range, and the private cost of electric or hydrogen vehicles using solar power (with essentially no external costs) is at the low end of a plausible range, the use of electric and hydrogen vehicles (where their performance is acceptable) may be more economically efficient from the standpoint of society.

Second, research and development (R&D) should be directed at fuel and vehicle combinations with low external costs, especially those that do not produce greenhouse gases or exacerbate global tensions, since these external costs are difficult to estimate but may be large. For EVs, R&D should be aimed at increasing the energy density and power of batteries, reducing battery cost, and reducing recharging time without sacrificing battery performance and life. For hydrogen vehicles, R&D should focus on increasing the mass-energy density of hydrides, reducing the desorption temperature of hydrides, increasing the no-vent period for liquid hydrogen (LH_2) vehicles, making the handling of LH_2 boil-off safe, and reducing storage costs for both hydride and LH_2 vehicles. Work on hydrogen-powered fuel-cell vehicles, which combine the best attributes of hydrogen and electric vehicles, should be greatly expanded.

Today the United States provides only modest support for the development of solar technologies and EVs, and next to no support for the development of hydrogen and fuel-cell vehicles. Considering that both these technologies are very benign environmentally and quite promising technically, this lack of support is short-sighted.

Proper pricing of petroleum fuels will encourage efficiency improvements and reduce CO_2-equivalent emissions and increase the efficiency with which the nation uses resources. Proper pricing combined with increased R&D on solar energy production and electric and hydrogen vehicles will hasten the efficient adoption of sustainable, environmentally sound, non-CO_2-producing transportation options. We should begin on this path today.

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