Transportation Fuels and the Greenhouse Effect

MARK A. DELUCHI, ROBERT A. JOHNSTON, AND DANIEL SPERLING

Continued emissions of CO_2 and other "greenhouse" gases are expected to cause substantial global warming with adverse consequences for agriculture and coastal cities, yet emission of greenhouse gases has not been a criterion in evaluation of alternative transportation fuels. In this paper are evaluated emissions of CO_2, CH_4, N_2O, and other greenhouse gases from the use of gasoline and diesel fuel, electricity, methanol, natural gas, and hydrogen in highway vehicles. Emissions from initial resource extraction to end use are estimated. It is found that the use of coal to make any highway fuel would substantially accelerate greenhouse warming relative to the base-case use of petroleum. The use of natural gas as a feedstock would result in a small reduction. Significant reductions in emissions of greenhouse gases can be achieved only by greatly increasing vehicle efficiency or by using biofuels, electrolytic hydrogen, or nonfossil-fuel-based electricity as the fuel feedstock. Emissions of gases other than CO_2 are likely to contribute appreciably to the warming, but better data are needed. Full social-cost pricing of fuels and increased research and development on sustainable, environmentally sound fuels are recommended.

Long-term, global environmental concerns will play an increasingly important role in energy policy. Foremost among these concerns is the global warming caused in part by carbon dioxide (CO_2) emissions from the conversion of fossil fuels. In recent years there has been considerable interdisciplinary research on the changing atmospheric concentration of CO_2 and other greenhouse gases, the effects of anthropogenic releases of these gases on steady-state atmospheric concentrations, the climatic effects of increasing concentrations of the gases, and the consequences of a changing climate on human affairs. As documented herein, many scientists and energy analysts conclude that significant climatic change is likely and that actions should be taken to reduce the use of fossil fuels.

However, these concerns have not yet influenced actual policy formation. Few, if any, national or local energy plans explicitly recognize mitigation of the greenhouse effect as a development criterion. [In the late 1970s and early 1980s, when "synfuels" were being assessed, there was some concern about the CO_2 impact of synfuels from coal (*1–4*).] This oversight is particularly glaring in the transportation energy field, where there is a rapidly developing interest in alternatives to gasoline and diesel fuel but no systematic analyses of emissions of greenhouse gases. Indeed, policy statements and research documents on future highway transportation fuel choices, issuing from government energy organizations, automobile manufacturers, and fuel producers, totally ignore the greenhouse problem (*5–11*). Given the potential seriousness of the greenhouse effect, and the significantly different contributions of alternative fuels to climatic change, it would be unwise to make a commitment to an alternative transportation fuel without an evaluation of the greenhouse gases emitted by the production, distribution, and end use of the fuel.

In this paper are examined emissions of greenhouse gases (CO_2, CFCs, O_3, N_2O, CH_4, and H_2O) from the most prominent highway transportation energy options: petroleum, methanol, natural gas, electric vehicles, and hydrogen. It is shown that the alternatives vary widely with respect to their potential contribution to the greenhouse effect, and policy implications are briefly discussed. [An expanded version of this paper was published by the University Energy Research Group at the University of California–Berkeley (*12*). That paper should be consulted for details not provided here. For a comprehensive evaluation of alternative transportation fuels in general, including their costs and technical problems, and for support for the analytical assumptions used here, see DeLuchi et al. (*13*).]

GREENHOUSE GASES AND THE GREENHOUSE EFFECT

Carbon Dioxide

Although deforestation and other land use changes may contribute to the greenhouse effect, energy use is clearly the primary anthropogenic source of CO_2. Globally, fossil fuel burning now accounts for 56 to 94 percent of the total net CO_2 release (*14–16*)—values above 75 percent are more likely (*16*)—and will contribute an even greater share in the future.

There are many unknowns and uncertainties, which leave much room for differences of opinion about the causes and consequences of a greenhouse warming (*17–22*), but researchers are in almost unanimous agreement that if the concentration of CO_2 doubled, a substantial warming would occur. Recent data from ice-core studies appear to establish "irrefutable evidence for a fundamental link between the global climate system and the carbon cycle," and indicate that "CO_2 is a dominant climate forcing factor" (*23*). Major studies by the U.S. Department of Energy (DOE) (*18, 19*), the international Scientific Committee on Problems of the Environment (SCOPE) (*21*), the National Research Council (*24*), the Environmental Protection Agency (EPA) (*17*), the National Science Foundation [in *Nature* (*25*)], and the World Resources Institute (*26*) conclude that there is a firm basis for believing that increasing emissions of CO_2 and other trace gases will

Division of Environmental Studies, University of California–Davis, Davis, Calif. 95616.

upset the earth's radiation balance and cause a global warming of from 1°C to 5°C in the 21st century. This warming could shift global precipitation patterns, disrupt established crop-growing regions, raise sea level by approximately a meter, and eventually melt portions of the polar ice caps and threaten coastal cities worldwide with inundation.

Other Trace Gases

Several other trace gases—methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and chlorofluorocarbons (CFCs)—have a lesser, but potentially important, role in contributing to the greenhouse effect [discussions of trace gas cycles and climate can be found elsewhere (*15, 26, 27–32*)]. Current research indicates that they could be responsible for about 50 percent of the total greenhouse temperature increase 50 years from now. In this paper the greenhouse effect of emissions of CH_4 resulting from the use of transportation fuels and of N_2O from power plants is examined. The effects of O_3 and CFCs, and of other sources of N_2O, are discussed briefly later, and in more detail elsewhere (*12*).

ANALYSIS OF EMISSIONS OF GREENHOUSE GASES FROM HIGHWAY TRANSPORTATION FUELS

At present, the most commonly proposed alternatives to petroleum transportation fuels are electricity, methanol, compressed and liquefied natural gas (CNG and LNG), and hydrogen (LH_2 and hydride). In this paper is estimated the percentage change in CO_2 emissions that would result from the substitution of a mile of travel by a single-fuel, optimized alternative vehicle for a mile of travel by a heavy truck or catalyst-equipped gasoline vehicle, with concomittant substitutions along the fuel-use-to-resource-extraction chain.

Basis of Comparison

Emissions of greenhouse gases are compared on an equal work-provided basis. The petroleum fuel reference case is 1985 aggregate energy consumption (15 quads of gasoline and diesel fuel) and vehicle miles traveled (VMT) (1.78 trillion) for the entire U.S. highway fleet (*33, 34*). For methanol, natural gas, and hydrogen vehicles this 15-quad baseline is adjusted to account for the greater fuel efficiency of these vehicles, and for an increase (with methanol) or decrease (with NG and hydrogen) in energy consumption by trucks delivering highway fuels, relative to the reference case. Both aggregate CO_2-equivalent emissions, based on a complete substitution of the alternative fuel for gasoline and diesel fuel, and the percentage change in CO_2-equivalent emissions, with respect to the reference case, are presented.

For electric vehicles (EVs) only the percentage change in CO_2-equivalent emissions per mile, with respect to the petroleum fuel reference case, is presented. Because EVs do not yet perform well enough to be used in all applications, a calculation based on complete substitution of EVs for internal combustion engine vehicles (ICEVs), even if meant to show only the relative emissions of EVs in those niches in which they could compete, would be misleading. The ultimate aggregate CO_2 reduction available from the use of EVs depends on the extent to which EVs prove feasible in high-power-demand, long-range applications.

Sources of CO_2 and Trace Gases

Working backward from end use to resource extraction, five general sources of CO_2 resulting from the use of highway fuels are examined: (a) combustion of transportation fuels on the highway, including fuels used by trucks delivering liquid transportation fuels to retail outlets; (b) combustion of fuel in pipeline compressors or pumps, and in barges and trains during the wholesale transmission of fuels to the distributor; (c) CO_2 formed by the chemical reactions of fuel synthesis; (d) CO_2 formed by the use of process energy in fuel production plants; and (e) combustion of fuel in the initial extraction, preparation, and transport of the raw feedstock. CO_2 emissions are measured in gigatons (GT) (10^9 tons).

Emissions of methane from vehicles using organic fuels, and from pipeline compressors and electric power plants burning natural gas; leaks from natural gas pipelines and field recovery operations; releases from coal mining; and venting of gas associated with oil recovery are estimated. Emissions of methane from coal-fired power plants are ignored. N_2O emissions from coal and NG combustion are estimated for all of the fuel options.

Other Conventions of Analysis

For ICEVs it is assumed that 97 percent of the carbon in the fuel used in Steps a, b, d, and e is completely oxidized to CO_2. This value is representative of the carbon oxidation efficiency of vehicles, which are the largest combustion source of CO_2 in this analysis. For EVs, estimates of CO_2 emitted per quad of energy are used (Table 1).

CH_4 emissions have been converted to "equivalent" CO_2 emissions. The authors have calculated that 75 years of 1 mass unit per year of CH_4 emissions has the same overall temperature effect (temperature increment per year multiplied by the number of years to atmospheric steady state, given 75 years of emissions) as 11.6 mass units of CO_2 emissions per year for 75 years (*12*, Appendix B). Plausible high and low CH_4/CO_2 conversion factors of 30 and 5 have been considered in the natural gas vehicle (NGV) analysis. The mass conversion factor for N_2O to CO_2 emissions is 175. N_2O emissions generally are reported in megatons (MT) (10^6 tons). All heating values are "gross" or "higher," and are consistent with values used by the U.S. Energy Information Administration (EIA).

GREENHOUSE GASES FROM PETROLEUM TRANSPORTATION FUELS (BASE CASE)

Situation in 1985

As the data in Table 1 indicate, the United States contributed nearly one-quarter of the total world production of CO_2 from fossil fuels in 1985. Fuel burned on the highways contributed almost one-quarter of the U.S. production of CO_2. When production and distribution of transportation fuels are included,

TABLE 1 CO_2 PRODUCED BY BURNING FOSSIL FUELS, U.S. AND WORLD TOTAL AND HIGHWAY TRANSPORTATION, 1985

A	B 1985		C 1985		D_1	D_2	E = $C*D_1*D_2$		F = 3.67*E		G = F/B	
Carbon-releasing energy sources	Fossil fuel energy use, quads[a] U.S.[e]	World[f]	Fossil fuel energy use, 10^9 tons (GT)[b] U.S.	World	% Mass Carbon[c]	% burnt[d]	GT of Carbon burned/yr U.S.	World	GT of CO_2 formed U.S.	World	GT CO_2 per Quad U.S.	World
Petroleum	27.4	108.2	0.70	2.75	85.0	95	0.57	2.22	2.07	8.14	0.075	0.075
Natural gas	17.2	63.6	0.37	1.37	74.5	98	0.27	1.00	0.99	3.67	0.058	0.058
Coal	17.4	86.2	0.80	4.8	50_61[g]	98	0.48	2.38	1.75	8.71	0.101	0.101
TOTALS	62.0	258.0	—	—	—	—	—	—	4.81	20.52[h]	0.078	0.080
Highway Trans.[i]	15.0	37.2[j]	0.37	0.93	86.5	94_96	0.31	0.76	1.14	2.77	0.075	0.075
% TRANSPORTATION	24.2	14.4	—	—	—	—	—	—	23.5	13.5	—	—

NOTE: Figures are rounded. GT/quad factors are adjusted to be the same for the world and the United States where input parameters are the same. Products and sums may not derive exactly from shown values. See DeLuchi et al. (*12*) for more detailed notes.

[a]Excludes nonfuel uses of resources such as oil for tar.

[b]Data used in converting quads to tons are as follows: petrolelum: 45.7 kj/g [energy/mass by fuel type weighted by world consumption figures (*35–37*)]; highway fuels: 46.7 kj/g (*35, 36, 38–40*); gasoline weighted 75 percent (*38*); natural gas: 54 kj/g, just under the gross heating value of pure methane; coal: tonnage data from EIA (*35, 37*), with nonfuel use tonnage subtracted.

[c]The mass percentage of carbon was estimated from the following data: petroleum: 80 to 89 percent C (*39, 41*); highway fuels: British gasoline, 85 to 88.5 percent C; diesel fuel, 86.5 percent C (*39*); natural gas: 90 percent CH_4, 4.5 percent C_2H_6, 3 percent C_3H_8, 1 percent C_4H_{10}, 1 percent N_2, and 0.5 percent CO_2 [as supplied by the British Gas Board (*41*)]. Additional information is available elsewhere (*40, 42*); coal: based on EIA data for coal consumption by rank, energy content of coal by country (*37*), and data from the American Society for Testing and Materials on carbon and energy content by rank (*41, 43*).

[d]Rotty and Masters (*43*) give 91.8 percent for petroleum, 98 percent for natural gas, and 98 percent for coal. Here petroleum was adjusted to 95 percent to account for use of oxidation catalysts in automobiles. Conversion efficiency of highway fuels for new 1987 cars estimated to be 99 percent on the basis of EPA emission data (*44*) [see DeLuchi et al. (*12*) for details]. Lifetime average of catalyst-equipped cars assumed to be 97 percent. U.S. fleet assumed to average 96 percent in 1985; world fleet, with a larger percentage of uncontrolled cars, assumed to average 94 percent.

[e]From EIA (*35*).

[f]World fuel-only consumption estimated by assuming that the ratio of U.S. use of fuel F to U.S. total consumption of F = world fuel use of F to world total consumption of F, using EIA data (*35*).

[g]61 percent U.S. coal; 50 percent worldwide. Fixed carbon percentages.

[h]Other estimates in the literature are 18.86 GT in 1980 (*45*), 18.2 to 23.9 GT in 1980 (*14*); 18.3 GT in 1983 [cited by Keepin et al. (*46*)]; and 19.76 GT for 1982 (*43*). See also estimates of GT CO_2/quad of fuel in Bentz and Salmon (*2*) and Marland (*4*).

[i]Excludes fuel use by off-highway and military vehicles. U.S. data from Holcomb et al. (*33*). Highway numbers are a subset of the petroleum category.

[j]Assuming that the ratio of gasoline use by automobiles to total highway fuel use for the world in 1985 equals the ratio of motor gasoline use to total highway fuel use for OECD countries in 1984 (0.773)(*38*).

the use of highway fuels accounts for about 27 percent of the U.S.-caused fossil fuel CO_2. The contribution of transportation worldwide is smaller but can be expected to grow as developing countries become more affluent.

The base case end-use emission of CO_2 from the highway fleet is thus 1.138 GT/year, at 1985 fleet efficiency and accounting for retirement of uncontrolled vehicles (see Note *d*, Table 1).

CO_2 from Oil Production and Nonhighway Product Distribution

For every unit of fuel energy delivered to a vehicle (including gasoline delivery trucks), about 0.16 unit is consumed in the production, processing, refining, and pipeline or barge transport of the highway fuel, for an overall efficiency of about 86 percent (*42*). It is assumed that 0.13 of the 0.16 unit of lost energy for every energy unit delivered to the vehicle is in combusted process fuel or material otherwise converted to CO_2, not in lost product, which does not contribute CO_2. Thus CO_2 emissions from the use of process energy in petroleum production, refining, and transmission would be 13 percent of the 1.138 GT/year produced by end use, or 0.148 GT/year (assuming that the process fuel produces CO_2 at the same GT/quad rate as do gasoline and diesel fuel).

CO_2 from Flared Natural Gas Coproduced with Petroleum

The quantity of associated gas vented or flared worldwide declined from about 4 quads in 1983 to 3.6 quads in 1984 and 3.1 quads in 1985 (*36, 37, 47*). In 1985 this energy waste was about 2.6 percent of the energy content of world production of crude oil, and 0.5 percent of the energy value of U.S. domestic oil production. In countries supplying the United States with imports, the energy value of flared gas was more than 5 percent of oil production.

Worldwide, venting and flaring will continue to decline as natural gas increases in value and is reinjected, used domestically, or exported. It is assumed that the near-term U.S. domestic production of 21 quads of oil will be associated with venting and flaring of 0.080 quad of NG (0.4 percent), and that importing 11 quads of oil will be associated with venting and flaring of 0.55 quad of gas (5 percent). The total is 0.020 quad NG/quad oil produced for U.S. consumption, on average. Thus the 17.4 quads of oil needed for the highway use chain will result in the venting or flaring of 0.3354 quad NG (assuming that highway fuels come from domestic and foreign sources in the proportion of total domestic production to total imports). Assuming that 75 percent of this is burned, the result is 0.015 GT CO_2/year, at 0.058 GT CO_2/quad NG.

CH_4 Emissions

From Vehicles

Available data on methane emissions from highway vehicles indicate a lifetime average of 0.08 g/mi for diesel vehicles and gasoline passenger cars, and 1.0 g/mi for gasoline trucks (*12*, Table 2). Multiplying these rates by the 1.78 trillion miles traveled in 1985 results in 0.000241 GT CH_4, or 0.003 GT CO_2 equivalent.

Vented Associated Natural Gas

From the preceding, 0.089 quad of associated NG is assumed to be flared in the production of oil used by the highway transportation sector. This is 0.0019 GT NG, or 0.022 GT CO_2 equivalent.

N_2O Emissions from Oil Refineries

About 0.03 MT N_2O is emitted per quad of oil burned (*48–50*). Assuming 1.95 quads of oil burned in refineries and in transport, and given a N_2O:CO_2 conversion factor of 175, 0.010 GT CO_2 equivalent of N_2O would be emitted.

Total CO_2-Equivalent Emissions from Gasoline and Diesel Vehicles

The total is calculated as follows:

1.138 (CO_2 from vehicles) +
0.003 (CH_4 from vehicles) +
0.148 (CO_2 from fuel production and transmission) +
0.015 (CO_2 from flaring of associated CH_4) +
0.022 (CH_4 from venting of associated CH_4) +
0.010 (N_2O from use of process fuel) =
1.336 GT/year

GREENHOUSE GASES FROM ELECTRIC VEHICLES

In this section the CO_2 emissions of power plants supplying EVs are estimated for two scenarios. In the base case it is assumed that no new capacity is required and that the electricity demand by EVs is sufficiently widespread that, nationally, fuel inputs, including nonfossil sources such as nuclear and hydropower, are used in the proportion that they are being used currently by electricity producers. In the second scenario it is assumed that new generating capacity is required, and emissions from new coal and NG power plants are estimated.

CO_2 Emissions from Power Plants, No New Capacity Required (Scenario 1)

Assume that X quads per year are consumed by petroleum-fueled vehicles in those applications suited for EVs. Considering the entire fuel-production and end-use chain, this would have resulted in 0.0891X GT of CO_2-equivalent emissions (recall that 15 quads resulted in 1.336 GT CO_2).

On the basis of vehicle tests and other efficiency estimates discussed in Appendix A of DeLuchi et al. (*12*) it is assumed that an optimally efficient (from an economic standpoint) electric car, van, or light truck is three times more efficient, including recharging, than an optimally efficient ICE version of the same vehicle. Given this, and the EIA's estimate (*51*) that in 1985 power plants were 30.2 percent efficient on average in converting input energy to electricity available at the outlet, including transmission losses and energy used internally by electricity plants, 1.104X quads would have to burned in power plants to supply the energy needed for EVs to displace the X quads of gasoline and diesel fuel.

The percentage shares of each fuel input to U.S. power plants in 1985 were as follows: coal, 56.0 percent; nuclear, 16.0 percent; NG, 12.0 percent; hydro and other, 11.9 percent; and oil, 4.1 percent. The 1.10X quads would therefore comprise 0.618X quad of coal, 0.132X quad of natural gas, and 0.0453X quad of oil. The remainder of the total input would be from the non-CO_2-producing sources, mainly nuclear and hydro.

Multiplying the estimate of CO_2/quad of fuel in Table 1 by the corresponding amount of each fuel input to electricity production (and, of course, assuming 0 GT CO_2/quad of nuclear, hydro, and other power) and summing yield 0.0735 GT of CO_2/year. It is assumed that 4 percent more CO_2, or 0.00294X GT/year, would be produced by the initial mining, processing, and distribution of the input fuels.

CH_4 and N_2O Emissions

CH_4 from NG Use

Assuming that 3 percent of the 0.132X quad of NG used in electricity plants is not burnt, and is released as methane, and that an additional 3 percent of the delivered gas is lost through pipelines and in field operations (see later section on Natural Gas Fuels), 0.00792X quad of CH_4, or 0.000167X GT CH_4 would be emitted (1 GT contains about 47.5 quads), the equivalent of 0.00193X GT of CO_2.

CH_4 from Coal Use

One source (*30*) cites five estimates of emissions of CH_4 from coal mining, ranging from 30 tg/year to 100 tg/year, with most around 35 tg/year (0.038 GT/year). This indicates an emission rate of about 0.0005 GT CH_4/quad of coal produced. Given the estimate of 0.618X quad of coal required, 0.00358X GT CO_2 equivalent would be emitted.

N_2O Emissions from Coal Use

Estimates of N_2O production from worldwide coal combustion range from 0.03 MT N_2O/quad of coal to 0.10 (*48–50, 52*). Here it was assumed to be 0.055 MT/quad. Total CO_2-equivalent emissions would be 0.00595X GT.

Total CO_2-Equivalent Emissions from EVs

The total is calculated as follows:

0.07350X (CO_2 from power plants) +
0.00294X (CO_2 from feedstock recovery) +
0.00193X (CH_4 from leaks and stacks) +
0.00358X (CH_4 from coal mining) +
0.00595X (N_2O from coal combustion) =
0.0879X GT/year

This is a 1 percent decrease from the 0.0891X GT/year emitted by gasoline and diesel fuel use in applications in which EVs are feasible.

New Power Plant Capacity Required (Scenario 2)

New Coal Plants

Assuming that new coal plants will have a conversion efficiency of 38 percent (*53, 54*), and that electricity distribution losses are 6 percent (*51*), and given 0.101 GT CO_2/quad coal, CO_2 production would be (X/3)/0.36(0.101 GT CO_2/quad) = 0.0935X GT CO_2. The authors increase this by 4 percent to account for CO_2 released by the energy used in coal mining and delivery.

CH_4 and N_2O emissions associated with the mining and burning of 0.926X quad of coal would be responsible for 0.00891X (N_2O) and 0.00537 (CH_4) GT CO_2-equivalent emissions, applying the emission rates and conversion factors discussed previously. The grand total would be 0.112X GT, 26 percent more than the amount emitted by petroleum-fueled vehicles in the base case.

New Natural Gas Plants

Assuming an electricity generation and distribution efficiency of 36 percent, the CO_2 production by an EV fleet using power generated from natural gas would be (0.926X quad) (0.058 GT/quad) = 0.0537 GT CO_2. On the basis of data cited hereafter in the natural gas vehicle analysis, it was assumed that an additional 0.08 unit of CO_2 is produced by pipeline compressors and field recovery equipment for each unit produced by the power plant. This amounts to 0.00429X GT CO_2. The CO_2 equivalent of the 3 percent unburnt methane from utilities and 3 percent methane leaks from pipelines would be about 0.0136 GT. N_2O emissions, at 0.007 MT/quad of NG (see natural gas vehicle analysis), would amount to 0.00113 GT CO_2 equivalent. The total would be 0.0727X GT CO_2-equivalent emissions per year, an 18 percent reduction from the petroleum-fuel base case.

GREENHOUSE GASES FROM METHANOL FUELS

Methanol can be made from many feedstocks including coal, natural gas, organic wastes, crops, and wood products. In this section the authors first estimate greenhouse emissions from end use and fuel transportation, because these do not depend on the feedstock. Then the emissions attributable to coal- and natural gas–based production methods are examined in turn. Biomass, which can be made into other fuels besides methanol, is treated in a separate section.

CO_2 Emissions from End Use

Assuming that methanol vehicles are 13 percent more efficient than gasoline vehicles, and just as efficient as diesel fuel vehicles, the 13 quads of gasoline and 2 quads of diesel fuel consumed annually on the highways would be replaced by 13.5 quads of methanol. The authors increase this to 13.6 quads to account for the greater energy use of methanol delivery trucks (*13*). It is assumed that delivery of fuel from the fuel station to the vehicle is 100 percent efficient.

At 22.5 kj/g, this would be 0.702 GT/year of methanol. Methanol is 37.5 percent carbon by weight, so the methanol used in a year for the highway fleet would contain 0.263 GT carbon. With 97 percent oxidation the result is 0.935 GT of CO_2 per year. This reduction in CO_2 output relative to gasoline and diesel fuel use (1.138 GT/year) is primarily due to the lower carbon-to-hydrogen ratio of methanol.

CH_4 Emissions from Methanol Vehicles

The few data available on methane emissions from methanol vehicles [0.06 g/mi by a prototype Ford Escort wagon (*55*)] indicate that they emit about as much as do available gasoline vehicles. A total of 0.003 GT CO_2-equivalent emissions were therefore assumed.

CO_2 from Nonhighway Transportation of Methanol

Because methanol is twice as bulky and heavy as gasoline per energy unit, the shipment of an energy unit of methanol would require more fuel and thus produce more CO_2—in most cases almost twice as much—as the movement of gasoline or diesel fuel. Assuming that methanol transport is 98 percent efficient (*42*), an additional 0.02 unit of fuel would be needed for the transport of each unit consumed in end use. CO_2 production thus would be 0.019 GT/year.

Methanol from Coal

CO_2 from Fuel Used in Coal Mining and Delivery

0.014 unit of process energy is required for each energy unit of coal mined (*42*). This results in about 0.03 unit for each unit of methanol burned on the highways. It is assumed that the energy used in delivering coal to the conversion plant is included in this estimate and that the process fuel would be methanol. The CO_2 production would therefore be 0.03 × 0.935 GT/year = 0.028 GT/year.

CO_2 from Conversion of Coal to Methanol

Gasification The total amount of carbon that must be made available for methanol manufacture would be 0.263 GT/year for end use, plus 5 percent of this for transmission and feedstock recovery, equaling 0.276 GT carbon/year.

The initial gasification of coal in methanol conversion produces gas with an H_2:CO:CO_2 ratio of about 0.68:1.00:0.205 (*56, 57*). In the next stage, the H_2:CO ratio is shifted to 2:1 by adding H_2 and removing CO at a 1:1 ratio. With these relationships it can be calculated that the 0.276 GT of carbon needed per year for methanol fuel would result in 1.166 GT CO_2/year being released from coal conversion (*12*).

Process Energy Used by Coal-to-Methanol Plants Available data indicate a process fuel requirement of 22 percent of the output methanol energy (*58, 59*). Therefore, if 14.3 quads of methanol must be produced to fuel the highway fleet, transport methanol, and mine coal, then 3.1 quads of coal energy would be devoted to producing electricity and steam for coal-to-methanol plants, which at 0.101 GT CO_2/quad coal would produce 0.313 GT CO_2.

CH_4 from Coal Mining

Because about 25 quads of coal are required in this methanol scenario, 0.0125 GT methane would be released, using the 0.0005 GT CH_4/quad rate from the EV section. This is a substantial release, the equivalent of 0.145 GT CO_2.

N_2O from Coal Used to Generate Steam

Given an emission rate of 0.055 MT N_2O/quad of coal (see EV analysis), and assuming that this applies to all the 3.1 quads of coal used to generate process energy, 0.030 quad CO_2 equivalent would be produced.

Total CO_2-Equivalent Emissions from Methanol Vehicles, Coal Feedstock

The grand total is calculated as follows:

0.935 (CO_2 from vehicles) +
0.003 (CH_4 from vehicles) +
0.047 (CO_2 from fuel transport and coal recovery) +
1.479 (CO_2 from conversion of coal to methanol) +
0.145 (CH_4 from coal mining) +
0.030 (N_2O from coal combustion) =
2.639 GT/year

This would be a 98 percent increase over the 1.336 GT/year released in the petroleum fuel base case. It has been calculated elsewhere (*12*) that even if the efficiency of conversion of coal carbon to methanol were increased 30 percent, and greenhouse gas emissions from all processes were reduced accordingly, the net result would still be a 51 percent increase in emissions of CO_2-equivalent gases.

Methanol from Natural Gas

Manufacture and Transport of Methanol

Conversion of Natural Gas to Methanol The initial reforming of natural gas ($CH_4 + H_2O \rightarrow CO + 3H_2O$) produces a gas with a 3:1 hydrogen (as H_2)-to-carbon ratio (*59, 60*). Because methanol synthesis requires a 2:1 ratio, the reformed gas is actually carbon deficient, and so carbon conversion efficiency is relatively high: about 91 percent is converted to carbon in methanol (Jerome Trumbley, Celanese Corp., 1987, unpublished data). This indicates that only 0.10 carbon unit of CO_2 is emitted for each unit of methanol produced.

Process Energy and Other Considerations More process energy is required to run a methanol plant than is provided by combustion of purge gas and recycling of waste heat. It is assumed that this additional process fuel is methanol and is 10 percent of the energy content of the methanol produced by the plant. The total CO_2 from process energy and purge gas would be $0.20 \times 0.935 = 0.187$ GT CO_2.

As a check on their assumptions about process energy and carbon conversion, the authors have estimated that the overall thermal efficiency implied is 70.5 percent, which is consistent with values in the literature (*12*).

CO_2 from Recovery and Initial Shipping of Natural Gas

Because methanol plants would be located close to gas fields, gas would not be transported far, and so the energy used in gas transmission probably would amount to no more than 1 percent of the output. Gas recovery and processing require about 5 percent of the energy withdrawn from the reservoir (see data in the section on natural gas fuel). Combining these figures, about 0.06 unit of gas would be consumed for each unit delivered to the plant. Thus 0.06×19.7 (from the preceding discussion) = 1.18 quads of CH_4 burned in field plant equipment and in pipeline compressors, and about 0.069 GT CO_2 produced per year.

CH_4 Leaks

Data cited hereafter indicate that the amount of gas lost in recovery and transmission is 3 to 4 percent of the amount delivered. It is assumed that transmission losses are negligible for the short distances from field to methanol plant. Losses during recovery are assumed to be 1.5 percent of the amount delivered to the plant, or $0.0175 \times 19.7 = 0.34$ quad. This is equivalent to 0.084 GT CO_2.

N_2O emissions from methane conversion appear to be negligible (*12*).

Total CO_2-Equivalent Emissions from Methanol Vehicles, Natural Gas Feedstock

The total is calculated as follows:

0.935 (CO_2 from vehicles) +
0.003 (CH_4 from vehicles) +
0.018 (CO_2 from methanol transmission) +

0.187 (CO_2 from natural gas–to–methanol) +
0.069 (CO_2 from natural gas production and transmission) +
0.084 (CH_4 losses) =
1.296 GT/year CO_2

This would represent a 3 percent decrease from the base case of gasoline and diesel fuels.

GREENHOUSE GASES FROM NATURAL GAS FUELS

CO_2 Emissions from NGVs

Available data indicate that 13.5 quads of CNG, or 13.1 quads of LNG, could replace the 15 quads of diesel fuel and gasoline currently consumed on the highways, assuming that NG would be no more efficient than diesel fuel in compression ignition engines (*13*). A further 0.8 percent reduction in energy use due to the elimination of truck distribution of highway fuels (*13*) is assumed. Assuming that NG is pure methane, and that oxidation is 97 percent complete, if CNG vehicles replaced all gasoline and diesel fuel vehicles, a total of 0.769 GT/year of CO_2 would be produced. With an all-LNG fleet, 0.746 GT/year would be produced.

CO_2 Emissions from Compression or Liquefaction of Natural Gas

There are reasonably good data indicating that compression of natural gas to 3,000 psi requires about 0.04 mmBtu of electricity for every mmBtu of gas produced. Compressors typically use electricity. If future electricity production and distribution are 36 percent efficient, the extra energy required at the compressor would result in 0.11 unit of fuel being burned at the power plant for each unit delivered to vehicles, and thus 0.085 GT CO_2, assuming natural gas is the feedstock for electricity generation.

Liquefaction at the service station by small, self-powered, skid-mounted units requires about 0.21 mmBtu of gas for every mmBtu of LNG produced. On-site liquefiers use natural gas as the process energy.

It is assumed that delivery from the compressor to the CNG vehicle is 100 percent efficient. Vaporization losses in the transfer and storage of LNG are on the order of 2 percent. It is assumed that all vaporized LNG is returned to the liquefier, the effect of which is to increase the energy requirements of liquefaction per unit of LNG energy actually delivered to the vehicle. Thus the final amount of liquefaction energy required is 0.21 unit to liquefy one unit of LNG on the first pass plus $0.02 \times 0.21 = 0.004$ unit of energy to reliquefy the vaporized LNG. (Only two passes were assumed, and the 2 percent of the reliquefied gas that vaporizes was ignored.) The result is $0.214 \times 0.746 = 0.160$ GT CO_2.

CO_2 Emissions from Distribution and Production of Gas

Additional NG is used in transporting and recovering the gas itself, and the use of this gas produces CO_2. In this section an estimate is made of the amount of gas consumed during the entire resource-recovery-to-end-use process, which may be thought of as the total amount of natural gas removed from deposits less any fuel losses. [Lost gas is not burned, and thus does not produce CO_2, although it does contribute directly to the greenhouse effect. This direct contribution of methane is estimated separately. Also, the energy used to recover and ship gas that is eventually lost does produce CO_2. This is included in the total energy consumption figures used for pipelines and field operations.]

Transmission

In 1985, 0.53 trillion cubic feet (TCF) of gas was consumed in compressors and 17.79 TCF of gas was consumed by all end users, including the gas used in the compressors but excluding losses (*51*). Thus the ratio of ultimately combusted energy into the pipeline to useful energy out (i.e., energy that could reach the CNG or LNG station inlet, where it would be compressed or liquefied), excluding losses, is $[17.79/(17.79 - 0.53)] = 1.03$. This indicates a 97 percent efficiency.

Production

In 1985, 0.87 TCF was used by field-gathering and processing-plant equipment to produce 16.95 TCF of gas, including process fuel and lost gas (*51*). Data cited hereafter indicate that this loss is as high as 2 percent of produced gas. Therefore the ratio of gas withdrawn from the reservoir to gas put into the pipeline, excluding losses, is $[16.95 - (0.02 \times 16.95)]/[16.95 - 0.87 - (0.02 \times 16.95)] = 1.055$.

Total

The product of the production and transmission factors is $1.03 \times 1.055 = 1.0867$, which indicates 0.0867 unit of CO_2 produced by field operation and pipeline compressor for every unit produced by end use (including service stations). The result is thus $0.0867 \times 1.11 \times 0.769 = 0.074$ GT CO_2/year for CNG, and 0.078 GT/year for LNG.

CH_4 Emissions

Vehicles, Pipeline, and Field Equipment

Light-duty natural gas vehicles emit 0.08 to 2.5 g/mi methane (*61–64*); a value of 1.2 g/mi was used. Proceeding as was done earlier in the calculation for petroleum-fueled vehicles gives 0.00235 GT/year CH_4, or 0.027 GT/year CO_2-equivalent emissions.

Emissions of unburnt methane from pipeline compressors and plant machinery would be about 8.5 percent of the 0.027 GT figure, because gas use in these applications is only about 8.5 percent of end use $[(0.53 + 0.87)/(17.79 - 0.53 - 0.87)]$, or 0.002 GT CO_2 equivalent.

Leaks

Available data indicate that about 3 percent of the amount of gas delivered to users is lost during recovery and transportation (*30, 51*). Using the multiplicative factors derived earlier, 16.3 quads ($1.055 \times 1.03 \times 1.11 \times 13.5$) of NG would have to be produced to fuel the CNG fleet, and 17.3 quads for LNG

vehicles. Three percent of 16.3 and 17.3 is 0.49 and 0.52 quad, respectively, or about 0.0105 GT (using 0.50 quad). The CO_2 equivalent would be 11.6 times this, or 0.122 GT. (It is assumed that this is methane that would not have leaked from natural formations had it not been withdrawn and transported.) A negligible amount of methane would be lost from venting LNG tanks (*12*).

N_2O Emissions from Electricity Production

N_2O production from natural gas combustion is on the order of from 0.0055 to 0.01 MT/quad of NG, an order of magnitude lower than production from coal (*49, 52*). About 1.5 quads of gas would be burned to produce the electricity needed to compress the gas for the highway fleet, resulting in about 0.002 GT CO_2-equivalent emissions of N_2O.

Total CO_2-Equivalent Emissions from Natural Gas Vehicles

The grand total is calculated as follows:

CNG		*LNG*
0.769	(CO_2 from vehicles) +	0.746
0.027	(CH_4 emissions from vehicles) +	0.027
0.085	(CO_2 from compression/ liquefaction) +	0.160
0.074	(CO_2 from NG production and transmission) +	0.078
0.002	(CH_4 from pipeline and field equipment) +	0.002
0.122	(CH_4 losses) +	0.122
0.002	(N_2O from NG power plants) =	–
1.081	GT/year	1.135 GT CO_2/year

CNG vehicles would offer a reduction of 19 percent in emissions of greenhouse gases relative to gasoline and diesel fuels. The reduction with LNG vehicles would be 15 percent.

This estimate is moderately sensitive to the value of the CH_4-to-CO_2 conversion factor, which could range plausibly between 5 and 30. If 5 is used, rather than 11.6, the result is more substantial reductions of 25 and 21 percent. On the other hand, if a conversion factor of 30 is used, there will be a 4 percent decrease with CNG, and no change with LNGVs, relative to the (modified) base case (*12*).

GREENHOUSE GASES FROM USE OF BIOFUELS

In general, the carbon released by the combustion of a biofuel was removed from the atmosphere earlier by a plant, and thus the CO_2 formed by combustion about equals the CO_2 removed. However, as shown hereafter, it is still possible that the production and use of a biofuel would release net CO_2, relative to what would have occurred had the biofuel not been made.

Bioenergy Crops Replace a Forest

The difference between the amount of forest carbon released as a result of clearing a forest and the order-of-magnitude-smaller amount of carbon fixed in crops (*65*) constitutes a one-time net emission of CO_2. In addition, there would be a release of CO_2 from the soil as a result of the clearing (*40, 65*) and a large release of N_2O (*66*).

Biofuels from Waste

There is some support for the hypothesis that the long-term, steady-state rate of accumulation of carbon in organic waste material substantially exceeds the rate of its oxidation, resulting in the net removal of carbon from the atmosphere (*67, 68*). If this is the case, the production of biofuels would reduce the net withdrawal of CO_2 from the global cycle by humans and so cause an increase in the concentration of CO_2.

In conclusion, the use of biofuels would not contribute to the greenhouse effect, unless forest land were cleared to plant biomass feedstock, or waste products were used that otherwise would not have oxidized.

GREENHOUSE GASES FROM HYDROGEN FUELS

Hydrogen can be made by splitting water (electrolysis), steam-gasifying coal, steam-reforming natural gas, or partially oxidizing oil. It is likely that electrolytic hydrogen will not be produced commercially from fossil-fuel-based electricity because it is generally cheaper and more efficient to make hydrogen directly from fossil fuels than to use fossil fuels to make electricity to split water. Thus electrolytic hydrogen probably will be made from nonfossil electricity sources and will not contribute to the greenhouse effect.

Of the three fossil fuel feedstocks for hydrogen, only coal would be available in the long term in the United States. Elsewhere, the authors have estimated emissions of greenhouse gases from the mining of coal and its conversion to hydrogen (for use in transporting hydrogen and by hydride and LH_2 vehicles) and from the use of coal-based electricity for hydrogen liquefaction and compression (*12*). Because hydrogen is the least promising near-term alternative fuel, the calculations are omitted here. The results of the analysis follow:

Hydride Vehicles		*LH_2 Vehicles*
1.419	(CO_2 from coal gasification) +	1.155
0.946	(CO_2 from process energy) +	0.770
0.074	(CO_2 from coal-power for compression/liquefaction) +	0.981
0.141	(CH_4 from coal mining) +	0.167
0.097	(N_2O from coal combustion) =	0.167
2.677	GT	3.240 GT

These represent increases of 100 percent (hydride vehicles) and 143 percent (LH_2 vehicles) with respect to current emissions from petroleum use.

EFFECT OF TRACE GAS EMISSIONS NOT ESTIMATED

Emissions of CFCs and ozone precursors, and N_2O emissions from vehicles, may contribute to the greenhouse effect of transportation fuels. At present, though, there are not enough data to quantify these effects for all of the alternatives. The possible greenhouse role of gases and sources not treated in the quantitative analysis is discussed here.

CFCs

The various CFC compounds are among the most potent of the greenhouse gases. However, the only significant source of

CFCs from highway vehicles is the air conditioning systems of scrapped automobiles. Because this contribution is independent of the fuel used, accounting for CFC emissions here would increase the total emission of greenhouse gases by the same amount for all of the alternatives, and thus would not affect absolute differences in emissions of greenhouse gases or the ranking of the alternatives.

Ozone

Ozone formation in the boundary layer due to vehicular emissions depends in large part on the quantity and reactivity of hydrocarbon emissions. [The boundary layer, sometimes called the mixed layer, is generally the first 2 km of the atmosphere. It is separated from the overlying free troposphere by a temperature inversion that prevents mixing of the contents of the boundary layer with those of the free troposphere.] Current indications are that emissions from gasoline and diesel vehicles have the greatest ozone-formation potential of the fuels considered here, followed by methanol, natural gas, electricity (assuming nighttime battery recharging), and hydrogen vehicles.

Unfortunately, differences in the ozone-formation potentials of the fuels have not yet been satisfactorily quantified. Furthermore, there is disagreement in the literature about the extent to which ground-level sources of ozone precursors ultimately affect ozone concentration above the boundary layer in the free troposphere, where ozone has the greatest impact on climate (*27, 29, 69*). Finally, the effect on climate of changes in the concentration of ozone is not well characterized (*27, 29–31, 69*). These uncertainties make it difficult to infer the climatic effect of changes in emissions of ozone precursors in the boundary layer.

N_2O

From Vehicles

Data on N_2O emissions from gasoline-burning vehicles are available, but there are no data for N_2O emissions from alternative-fueled vehicles. N_2O emissions from gasoline-fueled automobiles depend significantly on the type of catalyst, rather than on total NO_x emissions or fuel nitrogen content. Cars without catalytic converters produce essentially no net N_2O.

Data on N_2O emissions from highway vehicles have been tabulated elsewhere (*12*, Table 3). Those data showed that N_2O emissions from cars with three-way catalysts are much higher than emissions from cars without catalysts but still relatively low—on the order of 0.02 GT CO_2 equivalent for the whole fleet in 1985 assuming replacement of uncontrolled passenger cars. It thus appears that N_2O from petroleum-fueled vehicles is relatively unimportant. N_2O emissions from alternative fuels will depend primarily on the composition of catalysts optimized for particular fuels. Such catalysts have not been developed. However, given the likelihood that N_2O emissions from petroleum vehicles are small (less than 2 percent of total CO_2-equivalent emissions calculated here), and that N_2O emissions from alternative-fueled vehicles would be of the same order of magnitude, quantification of N_2O emissions from alternative-fueled vehicles is not likely to change the findings.

From Other Sources

See DeLuchi et al. (*12*) for a discussion of N_2O emissions from coal gasification, NG reforming, and the corona discharge from power lines.

FINDINGS

The fuels reviewed in this paper are ranked in Table 2 by CO_2-equivalent emissions. The major findings follow.

TABLE 2 SUMMARY OF EMISSIONS OF GREENHOUSE GASES FROM ALTERNATIVE VEHICULAR FUELS, INCLUDING PRODUCTION, DISTRIBUTION, AND END USE OF FUEL[a]

Fuel/Feedstock	Total CO_2-Equivalent Emissions (GT/yr)	Change per Mile, Relative to Petroleum (%)
EVs from nonfossil electric[b]	0	−100
Hydrogen from nonfossil electric	0	−100
CNG/LNG/methanol from biomass[c]	0	−100
2 × fleet efficiency, to 29 mpg, petroleum	0.668	−50
CNG from natural gas	1.081	−19
EVs from new natural gas plants	–[d]	−18
LNG from natural gas	1.135	−15
Methanol from natural gas	1.293	−3
EVs from current power mix[e]	–[d]	−1
Gasoline and diesel from crude oil[f]	1.336	–
EVs from new coal plants	–[d]	+26
Methanol from coal, 30 percent increased efficiency	2.013	+51
Methanol from coal, baseline	2.639	+98
Hydride from coal	2.677	+100
LH_2 from coal	3.240	+143

[a]Excludes CFCs, O_3, and vehicular N_2O. CH_4 and N_2O multiplied by 11.6 and 175, respectively, to convert to CO_2 with same temperature effect, on a mass basis.
[b]Ignores greenhouse gases from energy used to mine and transport uranium for nuclear power.
[c]Assumes biofuels used for process energy. Ignores greenhouse gases from soil or from changes in land use.
[d]Aggregate CO_2-equivalent emissions depend on the level of penetration assumed possible for EVs.
[e]Ignores greenhouse gases from energy used to mine and transport uranium, N_2O emissions from NG and petroleum power plants, and CH_4 emissions from petroleum and coal power plants.
[f]Petroleum fuel baseline assumes 1985 total VMT and efficiency.

1. The use of coal to produce methanol, hydrogen, or synthetic natural gas would increase CO_2-equivalent emissions from the transportation sector considerably, even if conversion efficiencies were greatly improved. If the electricity to charge battery-powered electric vehicles came from new coal plants, the net result would be a moderate increase in CO_2-equivalent emissions. In all cases, the release of methane from coal mining and the production of N_2O from coal combustion would contribute significantly to the greenhouse effect of using coal as a transportation fuel feedstock.

2. The use of natural gas to produce CNG, LNG, or electricity for EVs would result in only slight to moderate reductions in CO_2-equivalent emissions. The use of natural gas as feedstock for methanol would result in approximately the same CO_2-equivalent emissions as result from using petroleum fuels.

In general, the reduction in CO_2-equivalent emissions with NG is not as great as might be expected, given the low carbon-to-hydrogen ratio of methane and the high efficiency of NGVs and methanol vehicles, because the greenhouse effect of methane emissions from vehicles and pipelines is significant when expressed in CO_2-equivalent units. Reducing leaks of methane from pipelines, storage facilities, and production operations could significantly reduce the greenhouse effect of using natural gas.

In light of the growing enthusiasm for methanol as a replacement for petroleum in transportation (*6, 8, 70, 71*), an important finding of this research is that a commitment to methanol from natural gas in the near term, and from coal in the long term, would worsen the threat of climatic change. Emissions of greenhouse gases would continue unabated in the near term, and increase substantially in the long term, relative to the petroleum-fuel base case.

3. Improving average fleet efficiency would reduce CO_2 emissions proportionately and is a viable strategy for addressing the greenhouse effect in transportation. An improvement of the average efficiency of the whole U.S. fleet, including trucks and buses, from 14.5 (in 1985) to 29 mpg would reduce CO_2 emissions by 50 percent.

4. There are two fuel feedstock options that do not produce net CO_2: biomass and nonfossil electricity. The use of biofuels would not release net CO_2 unless forests were cleared to plant feedstock crops or biomass was used that otherwise would have been a carbon sink. Biomass can be converted to alcohol or synthetic natural gas and thus could be used to fuel methanol or natural gas vehicles. Electricity from nuclear, solar, hydro, or geothermal power could supply EVs or be used to split water to make hydrogen fuels.

5. N_2O emissions from vehicles appear to be primarily a function of the chemical composition and age of the catalytic converter. The few data available indicate that N_2O emissions from gasoline vehicles with three-way catalytic converters are relatively unimportant.

Lack of data on the ozone-formation potential of reactive hydrocarbon and NO_x emissions from alternative fuels, on the movement of ozone and ozone precursors to the upper and middle troposphere, and on the steady-state climatic response to changes in the distribution of ozone precludes quantitative estimates of the greenhouse effect of emissions of ozone precursors from highway vehicles.

RECOMMENDATIONS AND DISCUSSION

This analysis has shown that substantial long-term reductions in CO_2-equivalent emissions from the transportation sector can be accomplished only through the use of high-efficiency vehicles, biofuels for NGVs and methanol vehicles, or nonfossil electricity for hydrogen and electric vehicles. From a greenhouse perspective, the policy question is thus: What is holding these options back, and what can be done to encourage their adoption?

Further improvements in vehicular efficiency are being stalled primarily by low world oil prices and consumer demand for larger cars. Biofuels are very expensive and could not supply even one-half of total demand for highway fuels, at current fleet efficiency. Solar energy is very expensive (on a private cost basis), and nuclear energy is expensive and politically unpopular. Electric vehicles do not perform well enough to be used in all highway applications; hydrogen vehicles do but are very expensive (on a private cost basis), and fuel storage is still problematic. In a nutshell, current petroleum fuels are relatively cheap, 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 (full economic) cost, not at their private cost. Gasoline is currently the cheapest transportation fuel on a private cost basis, but the external costs of gasoline use, from air pollution to the cost of defending oil fields in the Middle East, are large. The authors have estimated elsewhere (*13*) that if the external costs of gasoline and diesel fuel use are at the high end of a plausible range, and the private costs of hydrogen or electric vehicles, using solar power (with essentially no external costs), are at the low end of a plausible range, the use of hydrogen and electric vehicles, where their performance is acceptable, is more economically efficient. That analysis did not attempt dollar estimates of the effects of emissions of greenhouse gases on world climate, or of the effects of policing the Middle East in the event of large-scale conflict.

Second, research and development (R&D) should be directed at fuel and vehicle combinations with low external costs, especially those that do not produce CO_2 or exacerbate global tensions, because these external costs are difficult to estimate but probably very large. For electric vehicles, this means R&D 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 LH_2 vehicles, making the handling of LH_2 boil-off safe, and reducing storage costs for both hydride and LH_2 vehicles.

For fuels, R&D money should be spent on sustainable, clean, non-CO_2-producing technologies that have received comparatively little funding but are technically feasible and have the potential to supply a large portion of U.S. energy consumption. This indicates that the government should generously support solar energy R&D and stimulate production with large purchases. [Federal R&D support for nuclear fission, fusion, and breeder reactors has been at least an order of magnitude larger than support for solar alternatives (*72, 73*). Hydropower is a relatively mature technology and will not contribute an appreciably larger share of energy supply in the future. Therefore long-range strategies aimed at reducing CO_2 from the transportation sector, and indeed from all energy sectors, should focus on reducing costs of solar and renewable technologies.]

Proper pricing of petroleum fuels will encourage efficiency improvements and reduce CO_2 emissions proportionately, and increase national efficiency of resource use. Proper pricing combined with increased R&D on solar energy production and hydrogen and electric vehicles will hasten the efficient adoption of sustainable, environmentally sound, non-CO_2-producing transportation options.

REFERENCES

1. *Carbon Dioxide Accumulation in the Atmosphere, Synthetic Fuels, and Energy Policy.* Committee print. Committee on Governmental Affairs, U.S. Senate, 1979.
2. E. J. Bentz and E. J. Salmon. *Synthetic Fuels Technology Overview, with Health and Environmental Impacts.* Ann Arbor Science, Ann Arbor, Mich., 1981.
3. *To Breathe Clean Air.* National Commission on Air Quality, Washington, D.C., 1981.
4. G. Marland. The Impact of Synthetic Fuels on Global Carbon Dioxide Emissions. In *Carbon Dioxide Review: 1982* (W. Clark, ed.), Clarendon Press, New York, 1982, pp. 406–410.
5. T. J. Feaheny. Nonpetroleum Vehicular Fuels. In *Nonpetroleum Vehicular Fuels III,* Institute of Gas Technology, Chicago, Ill., 1983, pp. 109–114.
6. R. J. Nichols. Fuels of the Future. Presented at the Energy 2000 Conference, Toronto, Canada, Nov. 1985.
7. *Energy Development Report.* California Energy Commission, Sacramento, 1986.
8. B. D. McNutt and E. E. Ecklund. Is There a Government Role in Methanol Market Development? SAE Technical Paper 861571. Society of Automotive Engineers, Warrendale, Pa., 1986.
9. *LNG/LPG/CNG/Methanol/Hydrogen Trade-offs Study.* ST/ESCAP/491. Economic and Social Commission for Asia and the Pacific, United Nations, May 1987.
10. *Alternative Transport Fuels from Natural Gas: Discussion Draft.* Energy Department, The World Bank, Washington, D.C., 1987.
11. *Energy Security.* DOE/S-0057. U.S. Department of Energy, March 1987.
12. M. A. DeLuchi, R. Johnston, and D. Sperling. *Transportation Fuels and the Greenhouse Effect.* Research Report UER-182. University Energy Research Group, University of California, Berkeley, Dec. 1987.
13. M. A. DeLuchi, D. Sperling, and R. A. Johnston. *A Comparative Analysis of Future Transportation Fuels.* Research Report UCB-ITS-RR-87-13. Institute of Transportation Studies, University of California, Berkeley, Oct. 1987.
14. G. M. Woodwell et al. Global Deforestation: Contribution to Atmospheric Carbon Dioxide. *Science,* Vol. 222, No. 4628, Dec. 9, 1983, pp. 1081–1086.
15. H. A. Mooney, P. M. Vitousek, and P. Matson. Exchange of Materials Between Terrestrial Ecosystems and the Atmosphere. *Science,* Vol. 238, No. 4829, Nov. 13, 1987, pp. 926–932.
16. R. P. Detwiler and C. A. S. Hall. Tropical Forests and the Global Carbon Cycle. *Science,* Vol. 239, Jan. 1, 1988, pp. 42–47.
17. S. Seidel and D. Keyes. *Can We Delay a Greenhouse Warming?* Environmental Protection Agency, Washington, D.C., Nov. 1983.
18. M. C. MacCracken and F. M. Luther, ed. *Detecting the Climatic Effects of Increasing Carbon Dioxide.* DOE/ER-0235. Carbon Dioxide Research Division, U.S. Department of Energy, 1985.
19. M. C. MacCracken and F. M. Luther, eds. *Projecting the Climatic Effects of Increasing Carbon Dioxide.* DOE/ER-0237. Carbon Dioxide Research Division, U.S. Department of Energy, 1985.
20. J. Trabalka, eds. *Atmospheric Carbon Dioxide and the Global Carbon Cycle.* DOE/ER-0239. Carbon Dioxide Research Division, U.S. Department of Energy, Dec. 1985.
21. B. Bolin et al., eds. *SCOPE 29: The Greenhouse Effect, Climatic Change, and Ecosystems.* John Wiley and Sons, New York, 1986.
22. H. W. Ellsaesser et al. Global Climatic Trends as Revealed by the Recorded Data. *Reviews of Geophysics,* Vol. 24, No. 4, 1986, pp. 745–792.
23. E. Sundquist. Ice Core Links CO_2 to Climate. *Nature,* Vol. 329, No. 6138, Oct. 1, 1987, pp. 389–390.
24. National Research Council (1983). *Changing Climate: Report of the Carbon Dioxide Assessment Committee,* Executive Summary, National Academy Press, Washington, D.C.
25. Energy Efficiency May Help. *Nature,* Vol. 307, Jan. 12, 1984, p. 101.
26. I. Mintzer. *A Matter of Degrees: The Potential for Controlling the Greenhouse Effect.* Research Report 5. The World Resources Institute, Washington, D.C., April 1987.
27. V. Ramanathan et al. Trace Gas Trends and Their Potential Role in Climate Change. *Journal of Geophysical Research,* Vol. 90, No. D3, June 20, 1985, pp. 5547–5566.
28. W.-C. Wang and G. Molnar. A Model Study of Greenhouse Effects Due to Increasing Atmospheric CH_4, N_2O, CF_2Cl_2, and $CFCl_3$. *Journal of Geophysical Research,* Vol. 90, No. D7, Dec. 20, 1985, pp. 12791–12980.
29. W.-C. Wang, D. Wuebbles, and W. M. Washington. Potential Climatic Effects of Perturbations Other Than Carbon Dioxide. In *Projecting the Climatic Effects of Increasing Carbon Dioxide* (M. C. MacCracken and F. M. Luther, eds.), DOE/ER-0237. U.S. Department of Energy, Dec. 1985, pp. 191–236.
30. H. J. Bolle, W. Seiler, and B. Bolin. Other Greenhouse Gases and Aerosols. In *The Greenhouse Effect, Climatic Change, and Ecosystems.* (B. Bolin et al., eds.), John Wiley and Sons, New York, 1986, pp. 157–203.
31. R. E. Dickinson and R. J. Cicerone. Future Global Warming from Atmospheric Trace Gases. *Nature,* Vol. 319, Jan. 9, 1986, pp. 109–114.
32. Greenhouse Role of Trace Gases. *Science,* Vol. 231, No. 4743, March 14, 1986, p. 1233.
33. M. C. Holcomb, S. D. Floyd, and S. L. Cagle. *Transportation Energy Book,* 9th ed. Oak Ridge National Laboratory, Tennessee; U.S. Department of Energy, April 1987.
34. *Statistical Abstract of the United States: 1987,* 107th ed. Bureau of the Census, U.S. Department of Commerce, 1987.
35. *Annual Energy Review 1985.* DOE/EIA-0384(85). Energy Information Administration, U.S. Department of Energy, May 1986.
36. *International Energy Annual 1985.* DOE/EIA-0219(85). Energy Information Administration, U.S. Department of Energy, Oct. 1986.
37. *International Energy Annual 1986.* DOE/EIA-0219(86). Energy Information Administration, U.S. Department of Energy, Oct. 1987.
38. *Energy Statistics and Main Historical Series.* Organisation for Economic Cooperation and Development, International Energy Agency, Paris, France, 1986.
39. J. W. Rose and J. R. Cooper. *Technical Data on Fuel.* John Wiley and Sons, New York, 1977.
40. I. Campbell. *Energy and the Atmosphere: A Physical Chemical Approach,* 2nd ed. John Wiley & Sons Ltd, Chichester, England, 1986.
41. W. Francis and M. C. Peters. *Fuels and Fuel Technology, A Summarized Manual.* Pergamon Press Ltd., Oxford, England, 1980.
42. *Assessment of Methane-Related Fuels for Automotive Fleet Vehicles.* Energy Conservation Directorate, The Aerospace Corporation, 1982, Vols. 1–3. NTIS DOE/CE/50179-1.
43. R. M. Rotty and C. D. Masters. Carbon Dioxide from Fossil Fuel Combustion: Trends, Resources, and Technological Implications. In *Atmospheric Carbon Dioxide and the Global Carbon Cycle* (J. R. Trabalka, ed.), DOE/ER-0239, Carbon Dioxide Research Division, U.S. Department of Energy, Dec. 1985, pp. 63–80.
44. *1987 Test Car List—Passenger Cars.* Environmental Protection Agency, Ann Arbor, Mich., Feb. 24, 1987.
45. J. Watts. The Carbon Dioxide Question: Data Sampler. In *Carbon Dioxide Review: 1982* (W. Clark, ed.), Clarendon Press, New York, 1982, pp. 429–469.
46. W. Keepin, I. Mintzer, and L. Kristoferson. Emission of CO_2 into the Atmosphere. In *SCOPE 29: The Greenhouse Effect, Climatic Change, and Ecosystems.* (B. Bolin et al., eds.), John Wiley and Sons, New York, 1986, pp. 35–91.
47. *International Energy Annual 1984.* DOE/EIA-0219(84). Energy Information Administration, U.S. Department of Energy, Oct. 1985.
48. W. M. Hao et al. Sources of Atmospheric Nitrous Oxide from Combustion. *Journal of Geophysical Research,* Vol. 92, No. D3, March 20, 1987, pp. 3098–3104.
49. M. Kavanaugh. Estimates of Future CO, N_2O, and NO_x Emissions from Energy Combustion. *Atmospheric Environment,* Vol. 21, No. 3, 1987, pp. 463–468.

50. R. F. Weiss and H. Craig. Production of Atmospheric Nitrous Oxide by Combustion. *Geophysical Research Letters,* Vol. 3, No. 12, Dec. 1976, pp. 751–753.
51. *Annual Energy Outlook 1985.* DOE/EIA-0383(85). Energy Information Administration, U.S. Department of Energy, Jan. 1986.
52. D. Pierotti and R. A. Rasmussen. Combustion As a Source of Nitrous Oxide in the Atmosphere. *Geophysical Research Letters,* Vol. 3, No. 5, May 1976, pp. 265–267.
53. Gilbert Associates. *Development Plan for Advanced Fossil Fuel Power Plants.* EPRI CS-4029. Electric Power Research Institute, Palo Alto, Calif., May 1985.
54. Encor America, Inc. *Proceedings: 1985 Heat Rate Improvement Workshop.* EPRI CS-4736. Electric Power Research Institute, Palo Alto, Calif., Sept. 1986.
55. R. J. Nichols et al. Ford's Development of a Methanol-Fueled Escort. *Proc.,* 75th Annual Meeting, Air Pollution Control Association, New Orleans, La., June 20–25, 1982.
56. Fluor Engineers and Constructors, Inc. *Economic Evaluation of the Coproduction of Methanol and Electricity With Texaco Gasification Combined-Cycle Systems.* EPRI-AP 2212. Electric Power Research Institute, Palo Alto, Calif., 1982.
57. L. H. Cohen and H. L. Muller. Methanol Can Not Economically Dislodge Gasoline. *Oil and Gas Journal,* Jan. 28, 1985, pp. 119–124.
58. Fluor Engineers and Constructors, Inc. *An Engineering Evaluation of Texaco Gasification and ICI Methanol Synthesis.* EPRI AP-1962. Electric Power Research Institute, Palo Alto, Calif., 1981.
59. J. K. Paul. *Methanol Technology and Application in Motor Fuels.* Noyes Data Corporation, Park Ridge, N.J., 1978.
60. Jack Faucett Associates. *Methanol Prices During a Transition.* Draft Report. Environmental Protection Agency, Ann Arbor, Mich., Sept. 12, 1986.
61. T. J. Penninga. *Evaluation of the Impact on Emissions and Fuel Economy of Converting Two Vehicles to Compressed Natural Gas Fuel.* Test and Evaluation Branch, Environmental Protection Agency, Ann Arbor, Mich., June 1981.
62. R. L. Bechtold and T. J. Timbario. *The Status of Gaseous Fuels for Use in Highway Transportation, A 1983 Perspective.* DOE/CS/56051-10. Office of Vehicle and Engine R&D, U.S. Department of Energy, Nov. 1983.
63. Swain et al. Methane Fueled Engine Performance and Emissions Characteristics. *Proc.,* 18th Intersociety Energy Conversion Engineering Conference. American Institute of Chemical Engineers, New York, 1983, pp. 626–629.
64. T. G. Adams. The Development of Ford's Natural Gas Powered Ranger. SAE Paper 852277. Society of Automotive Engineers, Warrendale, Pa., 1985.
65. B. Bolin. How Much CO_2 Will Remain in the Atmosphere? In *SCOPE 29: The Greenhouse Effect, Climatic Change, and Ecosystems,* (B. Bolin et al., eds.), John Wiley and Sons, New York, 1986, pp. 93–155.
66. W. B. Bowden and F. H. Bormann. Transport and Loss of Nitrous Oxide in Soil Water After Forest Clear-Cutting. *Science,* Vol. 233, No. 4766, Aug. 22, 1986, pp. 867–869.
67. J. S. Olson. Earth's Vegetation and Atmospheric Carbon Dioxide. In *Carbon Dioxide Review: 1982* (W. C. Clark, ed.), Oxford University Press, New York, 1982, pp. 388–398.
68. A New Term in the Global Carbon Balance. *Nature,* Vol. 322, July 3, 1986, p. 19.
69. P. J. Crutzen and L. T. Gidel. A Two-Dimensional Photochemical Model of the Atmosphere 2: The Tropospheric Budgets of the Anthropogenic Chlorocarbons CO, CH_4, CH_3Cl, and the Effect of Various NO_x Sources on Tropospheric Ozone. *Journal of Geophysical Research,* Vol. 88, No. C11, Aug. 20, 1983, pp. 6641–6661.
70. C. Gray and J. Alson. *Moving America to Methanol.* University of Michigan Press, Ann Arbor, 1985.
71. *Methanol—Fuel of the Future:* Hearing on H.R. 3355 Before the Subcommittee on Fossil and Synthetic Fuels of the House Committee on Energy and Commerce, 99th Congress, Nov. 20, 1985.
72. B.W. Cone et al. *An Analysis of Federal Incentives Used to Stimulate Energy Production.* PNL-2410 REV II. Battelle Memorial Institute; Division of Conservation of Solar Applications, U.S. Department of Energy, Feb. 1980.
73. R. H. Heede, R. E. Morgan, and S. Ridley. *The Hidden Costs of Energy.* The Center for Renewable Resources, Washington, D.C., 1985.