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A MULTI-COUNTRY ANALYSIS OF LIFECYCLE EMISSIONS FROM TRANSPORTATION FUELS AND MOTOR VEHICLES

Author

Delucchi, Mark

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A Multi-Country Analysis of Lifecycle Emissions from Transportation Fuels and Motor Vehicles

Mark A. Delucchi

Institute of Transportation Studies ◇ University of California, Davis
One Shields Avenue ◇ Davis, California 95616
PHONE: (530) 752-6548 ◇ FAX: (530) 752-6572
WEB: http://its.ucdavis.edu/

A MULTI-COUNTRY ANALYSIS OF LIFECYCLE EMISSIONS FROM TRANSPORTATION FUELS and MOTOR VEHICLES

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For Nissan Motor Company

Mark A. Delucchi
madelucchi@ucdavis.edu
www.its.ucdavis.edu/people/faculty/delucchi/

Institute of Transportation Studies
One Shields Avenue
University of California
Davis, California 95616

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BACKGROUND AND OVERVIEW OF NISSAN-FUNDED RESEARCH

Background

The task of developing and evaluating strategies to reduce emissions of urban air pollutants and greenhouse gases is complicated. There are many ways to produce and use energy, many sources of emissions in an energy lifecycle, and several kinds of pollutants (or greenhouse gases) emitted at each source. An evaluation of strategies to reduce emissions of greenhouse gases must be broad, detailed, and systematic. It must encompass the full "lifecycle" of a particular technology or policy, and include all of the relevant pollutants and their effects. Towards this end, Dr. Mark A. Delucchi of the Institute of Transportation Studies at the University of California, Davis (ITS-Davis) has developed a detailed, comprehensive model of lifecycle emissions of urban air pollutants and greenhouse gases from the use of variety of transportation modes. The model is called the Lifecycle Emissions Model, or LEM.

The LEM estimates energy use, criteria pollutant emissions, and CO_2-equivalent greenhouse-gas emissions from a variety of transportation and energy lifecycles. It includes a wide range of modes of passenger and freight transport, electricity generation, heating, and more. For transport modes, it represents the lifecycle of fuels, vehicles, materials, and infrastructure. It calculates energy use and all regulated air pollutants plus so-called greenhouse gases. It includes input data for up to 30 countries, for the years 1970 to 2050, and is fully specified for the United States. Full documentation of the LEM is provided in a main report and several appendices, available at Dr. Delucchi's website, www.its.ucdavis.edu/people/faculty/delucchi/.

Request for proposal from Nissan

Nissan Motor Company is interested in the lifecycle environmental impacts of motor vehicles and motor fuels. Towards this end, Nissan has funded ITS-Davis to further develop and apply the LEM to analyze lifecycle environmental impacts of motor vehicles and motor fuels. Nissan is especially interested in the longer-term options, such as hydrogen, and on impacts in countries around the world.

Products of the Nissan-funded research

With Nissan funding (and co-funding from other sources) ITS-Davis has completed several major projects and deliverables:

- Major updates and revisions to the LEM. The most significant of these revisions pertain to CO_2-equivalency factors, cultivation and land use related to biofuels, and the lifecycle of materials. The work on CO_2-equivalency factors is documented in a revised Appendix D to the LEM main report, the work on the lifecycle of materials is documented in a revised Appendix H to the LEM main report, and the work on cultivation and land use is documented in the revised LEM main report and in a revised Appendix C to the LEM main report. Other recently completed updates and revisions to the LEM include changes in the presentation of results, changes in macros that generate key tables, and changes in formatting and layout.

- Expansion of the LEM to include new pathways. Under this project the LEM has been expanded to include the complete fuel lifecycle for hydrogen derived from biomass and hydrogen derived from coal with CO_2 sequestration. These major expansions are fully incorporated in the revised LEM and are documented in the LEM main report and in a new Appendix K to the LEM main report.
- Delivery of the LEM to Nissan and provision of technical support to Nissan staff. At the beginning of this project Nissan was given a copy of the LEM and two days of intensive training in its use by Dr. Delucchi. With this final report the latest revised version of the LEM is being delivered to Nissan. Further technical support may be provided to Nissan staff in the near future.
- New sections in the LEM documentation. Four major new sections providing general background and methodological overview have been added to the LEM main report. These are: i) an extensive formal documentation of the general structure of the LEM; ii) a discussion of analytical and methodological issues in lifecycle analysis; iii) a review of the substance and applicability of ISO 14040 standards pertaining to LCA; and iv) the creation of detailed pathways diagrams. All four of these major new sections are available in the revised LEM main report and also are included in this final report (see body of final report, below and Appendix A to this report).
- Model runs and final report for Nissan. In addition to the foregoing, ITS-Davis is providing this final report which provides an overview of the LEM, pathways diagrams (Appendix A to this report), presentation of some of the important input parameters (Appendix B to this report), extensive tables of results of runs from the most recent version of the LEM, and a discussion of the results and important parameters.

Overview of this final report

General. This report provide an overview of basic assumptions and general results for all of the fuel, feedstock, and light-duty vehicle combinations treated in the LEM, and somewhat more detailed results and discussions for the longer-term advanced options, including compressed or liquefied hydrogen from natural gas, compressed or liquefied hydrogen from water via electrolysis, and liquid biofuels developed from wood, grass, or corn. It considers fuel-cell electric vehicles (FCVs) as well as internal-combustion engine vehicles (ICEVs).

Target years. The LEM has the capability of modeling lifecycle environmental impacts in any target year from 1970 to 2050. For this analysis we have estimated results for the near term (2010) and the long term (2050). (We originally proposed to run the LEM for three dates, 2005, 2020, and 2050, but for three reasons have modeled 2010 and 2050 instead: there is not enough difference between 2005 and 2020 to warrant separate runs; having three target years instead of two increases the already large number of results tables by 50%; and Nissan has the LEM and hence the capability to run any year it is interested in.)

Countries. The LEM also has the capability of modeling lifecycle environmental impacts in up to 30 countries simultaneously. For this project, we have performed lifecycle analysis for Japan, China, the U. S., and Germany, using existing data in the LEM. (We originally proposed to run the LEM for Poland, Italy, and the U. K. as well, but for several reasons we omitted them: the data for these countries are not as good as the data for China, Japan, and the U. S.; presenting results for three more countries would greatly multiply the already-large number of results tables; and Nissan has the LEM and hence the capability to run any country it is interested in.)

Results reported. The LEM produces a wide range of quantitative outputs related to lifecycle emissions from the use of alternative transportation fuels and modes. For this report we provide estimates of lifecycle CO_2-equivalent GHG emissions in grams per mile, by stage of lifecycle and fuel/feedstock/vehicle combination; emissions of pollutants from the "upstream" fuel cycle (i.e., all stages of the fuel lifecycle excluding end use) in grams per million BTU of fuel, by individual pollutant including CO_2-equivalent and fuel/feedstock combination; and emissions of pollutants from the vehicle and materials lifecycle, in grams per pound of material, by individual pollutant (including CO_2-equivalent) and vehicle type.

We discuss the key assumptions of the analysis and their impacts on the results. We pay particular attention to inputs and outputs that determine or reveal differences among countries, including kinds and sources of feedstocks for various fuel production pathways, differences in technologies, and differences in emissions regulations and fuel properties.

INTRODUCTION TO THE FINAL REPORT

Highway vehicles are a major source of urban air pollutants and so-called "greenhouse gases". In most cities throughout the world, light-duty gasoline vehicles are major sources of volatile organic compounds (VOCs), nitrogen oxides (NO_x), and toxic air pollutants, and often single largest source of carbon monoxide (CO). Heavy-duty diesel vehicles can be significant source of NO_x, sulfur oxides (SO_x), and particulate matter (PM).

These air-pollutant emissions from highway vehicles lead to serious air quality problems. Most urban areas routinely violate national ambient air quality standards and international air-quality guidelines promulgated by the World Health Organization (WHO), especially for ambient ozone and PM. Clinical and epidemiological studies have associated ambient levels of PM, O_3, and other pollutants with human morbidity and mortality (U. S. EPA, 1996a, 1996b; McCubbin and Delucchi, 1999; Rabl and Spadaro, 2000). In response to these apparently serious health effects, national and international regulatory agencies throughout the world have promulgated stringent air-quality and emissions standards.

Motor vehicles also are a major source of carbon dioxide (CO_2), the most significant of the anthropogenic pollutants that can affect global climate. In the U. S., the highway-fuel lifecycle contributes about 30% of all CO_2 emitted from the use of fossil fuels (DeLuchi, 1991). In the OECD (Organization for Economic Cooperation and

Development), the highway-fuel lifecycle contributes about one-quarter of all CO_2 emitted from the use of fossil fuels (DeLuchi, 1991; emissions in Europe are below the OECD-wide average, and emissions in the U. S. above). Worldwide, the highway fuel-lifecycle contributes about 20% of total CO_2 emissions from the use of fossil fuels – a lower percentage than in the OECD because outside the OECD relatively few people own and drive cars.

Many scientists now believe that an increase in the concentration of CO_2 and other "greenhouse" gases, such as methane and nitrous oxide, will increase the mean global temperature of the earth. In 1995, an international team of scientists, working as the Intergovernmental Panel on Climate Change (IPCC), concluded that "the balance of evidence suggests that there is a discernible human influence on global climate" (IPCC, 1996a, p. 5). According to the IPCC, in the long run this global climate change might affect agriculture, coastal developments, urban infrastructure, human health, and other aspects of life on earth (IPCC, 1996b). The most recent IPCC reports (IPCC, 2001a, 2001b) have confirmed and expanded upon these findings.

OVERVIEW OF THE LIFECYCLE EMISSIONS MODEL (LEM)

Introduction

Given the continuing problem of urban air pollution, the growing consensus that emissions of greenhouse gases will affect global climate, and the expanding role of transportation in environmental problems, it is useful to have a tool that can evaluate strategies to reduce emissions of urban air pollutants and greenhouse gases. However, the task of developing and evaluating such strategies is complicated. There are many ways to produce and use energy, many sources of emissions in an energy or materials lifecycle, and several kinds of pollutants emitted at each source. An evaluation of strategies to reduce emissions of greenhouse gases must be broad, detailed, and systematic. It must encompass the full "lifecycle" of a particular technology or policy, and include all of the relevant pollutants and their effects. Towards this end, Dr. Delucchi has developed a detailed, comprehensive model of lifecycle emissions of urban air pollutants and greenhouse gases from the use of variety of transportation modes.

A general description of "lifecycle" emissions analysis

The distinguishing feature of a "lifecycle" emissions analysis is that it estimates emissions associated with the entire "lifecycle" of a particular product, as opposed to emissions from just consumer end use. A "lifecycle" comprises all of the physical and economic processes involved directly or indirectly in the "life" of the product, from the recovery of raw materials used to make pieces of the product to recycling of the used product at the end of its life. A lifecycle analysis (LCA) of emissions formally characterizes the inputs, outputs, and emissions for each stage of the lifecycle, links the stages together, and aggregates the emission results over all of the linked stages. In essence, LCAs are input-output (I-O) analyses with emissions factors.

The basic building block in LCA is a set of energy and material inputs associated with a particular output of interest for a particular stage in a lifecycle, with emission factors attached to some of the inputs. A "lifecycle" is then a particular combination of I-O building blocks (or stages) linked together, where the output of one block (or stage) is one of the inputs to another stage, and the output of the last stage is the product or quantity of interest. A "lifecycle analysis" aggregates the emissions attached to the inputs over all of the linked stages, to produce an estimate of total emissions per unit of final product output from the lifecycle.

Consider, for example, this simplified depiction of the lifecycle of gasoline: crude oil recovery, petroleum refining, and gasoline end use. In the first stage, fuels and materials are input to the crude-oil recovery process, which results in an output of crude oil. This crude oil output is input to the next stage, petroleum refining. (The petroleum refining stage also has other energy and material inputs.) The output of the petroleum refining stage is gasoline, which is input to the last stage, end use. At each stage, emissions are associated with the use of various inputs. Adding up the emissions associated with all of the inputs for crude oil recovery, petroleum refining, and gasoline end use gives us a picture of the "lifecycle" emissions impact of gasoline. Appendix A provides diagrammatic representations of several "pathways" in the LEM.

The Lifecycle Emissions Model (LEM) described here uses LCA to estimate energy use, criteria air-pollutant emissions, and CO_2-equivalent greenhouse-gas emissions from a wide range of energy and material lifecycles. It includes lifecycles for passenger transport modes, freight transport modes, electricity, materials, heating and cooling, and more. For transport modes, it represents the lifecycle of fuels, vehicles, materials, and infrastructure. It calculates energy use and lifecycle emissions of all regulated air pollutants plus so-called greenhouse gases. It includes input data for up to 30 countries, for the years 1970 to 2050, and is fully specified for the U. S.

The following sections give further details on the general structure of the LEM. For full documentation, see the series of reports available on the author's faculty web page (Delucchi, 2003).

Transportation lifecycles in the LEM

The LEM calculates lifecycle emissions for the following *passenger transportation modes*:

- light-duty passenger cars (internal-combustion engine vehicles [ICEVs]) operating on a range of fuel types [see below]; battery-powered electric vehicles [BPEVs]; and fuel-cell electric vehicles, with or without an auxiliary peak-power unit [FCVs];

- full-size buses (ICEVs and FCVs)

- mini-buses (albeit modeled crudely)
- mini-cars (ICEVs and BPEVs)
- motor scooters (ICEVs and BPEVs)
- bicycles
- heavy-rail transit (e.g., subways)
- light-rail transit (e.g., trolleys)

The LEM also calculates lifecycle emissions for the following *freight transport modes:*

- medium and heavy-duty trucks
- diesel trains
- tankers, cargo ships, and barges
- pipelines

Fuel and feedstock combinations for motor vehicles

For motor vehicles, the LEM calculates lifecycle emissions for a variety of combinations of end-use fuel (e.g., methanol), fuel feedstocks (e.g., coal), and vehicle types (e.g., fuel-cell vehicle). For light-duty vehicles, the fuel and feedstock combinations included in the LEM are:

Fuel --> ↓ Feedstock	*Gasoline*	*Diesel*	*Methanol*	*Ethanol*	*Methane* *(CNG, LNG)*	*Propane* *(LPG)*	*Hydrogen* *(CH2) (LH2)*	*Electric*
Petroleum	**ICEV, FCV**	**ICEV**				**ICEV**		**BPEV**
Coal	**ICEV**	**ICEV**	**ICEV, FCV**				**FCV**	**BPEV**
Natural gas		**ICEV**	**ICEV, FCV**		**ICEV**	**ICEV**	**ICEV, FCV**	**BPEV**
Wood or grass			**ICEV, FCV**	**ICEV, FCV**	**ICEV**		**FCV**	**BPEV**
Soybeans		**ICEV**						
Corn				**ICEV**				
Solar power							**ICEV, FCV**	**BPEV**
Nuclear power							**ICEV, FCV**	**BPEV**

The LEM has similar but fewer combinations for heavy-duty vehicles (HDVs), mini-cars, and motor scooters.

Fuel, material, vehicle, and infrastructure lifecycles in the LEM

The LEM estimates the use of energy, and emissions of greenhouse gases and urban air pollutants, for the complete lifecycle of fuels, materials, vehicles, and infrastructure for the transportation modes listed above. These lifecycles are constructed as follows:

Lifecycle of fuels and electricity:

- **end use**: the use of a finished fuel product, such as gasoline, electricity, or heating oil, by consumers.

- **dispensing of fuels**: pumping of liquid fuels, and compression or liquefaction of gaseous transportation fuels.

- **fuel distribution and storage**: the transport of a finished fuel product to end users and the operation of bulk-service facilities. For example, the shipment of gasoline by truck to a service station.

- **fuel production**: the transformation of a primary resource, such as crude oil or coal, to a finished fuel product or energy carrier, such as gasoline or electricity. A detailed model of emissions and energy use at petroleum refineries is included.

- **feedstock transport**: the transport of a primary resource to a fuel production facility. For example, the transport of crude oil from the wellhead to a petroleum refinery. A complete country-by-country accounting of imports of crude oil and petroleum products by country is included in the LEM.

- **feedstock production**: the production of a primary resource, such as crude oil, coal, or biomass. Based on primary survey data at energy-mining and recovery operations, or survey or estimated data for agricultural operations.

Lifecycle of materials:

- crude-ore **recovery** and finished-material **manufacture**: the recovery and transport of crude ores used to make finished materials and the manufacture of finished materials from raw materials (includes separate characterization of non-energy-related process-area emissions).

- the **transport** of finished materials to end users.

Lifecycle of vehicles:

- **materials use**: see the "lifecycle of materials".

- **vehicle assembly**: assembly and transport of vehicles, trains, etc.

- **operation and maintenance**: energy use and emissions associated with motor-vehicle service stations and parts shops, transit stations, and so on;

- **secondary fuel cycle** for transport modes: building, servicing, and providing administrative support for transport and distribution modes such as large crude-carrying tankers or unit coal trains.

Lifecycle of infrastructure:

- **energy use and materials production**: the manufacture and transport of raw and finished materials used in the construction of highways, railways, etc., as well as energy use and emissions associated with the construction of the transportation infrastructure. (Presently these are represented crudely; future versions of the LEM will have a more detailed treatment of the infrastructure lifecycle.)

Sources of emissions in LEM lifecycles

The LEM characterizes greenhouse gases and criteria pollutants from a variety of emission sources:

- Combustion of fuels that provide process energy (for example, the burning of bunker fuel in the boiler of a super-tanker, or the combustion of refinery gas in a petroleum refinery);
- Evaporation or leakage of energy feedstocks and finished fuels (for example, from the evaporation of hydrocarbons from gasoline storage terminals);
- Venting, leaking, or flaring of gas mixtures that contain greenhouse gases (for example, the venting of coal bed gas from coal mines);
- Fugitive dust emissions (for example, emissions of re-entrained road dust from vehicles driving on paved roads);
- Chemical transformations that are not associated with burning process fuels (for example, the curing of cement, which produces CO_2, or the denitrification of nitrogenous fertilizers, which produces N_2O, or the scrubbing of sulfur oxides (SO_x) from the flue gas of coal-fired power plants, which can produce CO_2);
- Changes in the carbon content of soils or biomass, or emissions of non-CO_2 greenhouse from soils, due to changes in land use.

Pollutant tracked in the LEM

The LEM estimates emissions of the following pollutants:

- carbon dioxide (CO_2)
- methane (CH_4)
- nitrous oxide (N_2O)
- carbon monoxide (CO)
- nitrogen oxides (NO_x)
- nonmethane organic compounds (NMOCs), weighted by their ozone-forming potential
- total particulate matter (PM)
- particulate matter less than 10 microns diameter (PM_{10}), from combustion
- particulate matter less than 10 microns diameter (PM_{10}), from dust
- hydrogen (H_2)
- chlorofluorocarbons (CFC-12)
- hydrofluorocarbons (HFC-134a)

- sulfur dioxide (SO_2)
- the CO_2-equivalent of all of the pollutants above

Ozone (O_3) is not included in this list because it is not emitted directly from any source in a fuel cycle, but rather is formed as a result of a complex series of chemical reactions involving CO, NO_x, and NMOCs.

The LEM estimates emissions of each pollutant individually, and also converts all of the pollutant into CO_2-equivalent greenhouse-gas emissions. To calculate total CO_2-equivalent emissions, the model uses CO_2-equivalency factors (CEFs) that convert mass emissions of all of the non-CO_2 gases into the mass amount of CO_2 with an equivalent effect on global climate. These CEFs are conceptually related, broadly, to the "Global Warming Potentials" (GWPs) used by the Intergovernmental Panel on Climate Change (IPCC). The CEFs are discussed in Appendix D of Delucchi (2003).

Material commodities in the LEM

Finally, the LEM includes the lifecycle of the following materials:

- plain carbon steel
- high strength steel
- stainless steel
- recycled steel
- iron
- advanced composites
- other plastics
- fluids and lubricants
- rubber
- virgin aluminum
- recycled aluminum
- glass
- copper
- zinc die castings
- powdered metal components
- other materials (lead)
- sodium
- sulfur
- titanium
- sulfuric acid
- potassium hydroxide
- nickel and compounds
- lithium
- cement
- concrete
- limestone

- agricultural chemicals (mainly fertilizers)

Note that recycled steel and recycled aluminum are treated as separate materials from virgin steel and virgin aluminum. In this way, the full lifecycle of materials, including recycling, is explicitly represented. Appendix H of Delucchi (2003) documents the methods and data used in to model the lifecycle of materials.

INPUTS AND OUTPUTS OF THE LEM

Major inputs to the LEM: projections of energy use and emissions

The LEM projects energy use and emissions, or changes in energy use and emissions, for the period 1970 to 2050. The user specifies any target year between 1970 and 2050, and the LEM looks up or calculates energy-use intensities, emission factors, or other data for the specified year.

There are several kinds of projections in the LEM:

- look-up tables (usually based on energy-use or emissions projections from the EIA);
- constant percentage changes per year;
- logistic functions with upper *or* lower limits; and
- logistic functions with upper *and* lower limits.

The functional forms of these projections are discussed in more detail in the Main Report of the model documentation (Delucchi, 2003).

Overview of major outputs of the LEM

The LEM produces the following tables of results, some of which are discussed in more detail the following sections:

- Emissions per mile from motor vehicles: CO2-equivalent emissions (in g/mi) by stage of fuel cycle and for the vehicle lifecycle, for all of the feedstock/fuel/vehicle combinations represented in the LEM.

- Emissions from electricity use: CO_2-equivalent emissions (in g/kWh-delivered) for different sources of electricity generation.

- Emissions from use of heating fuels: CO_2-equivalent emissions (in g/10^6-BTU-heat-delivered) for natural gas, LPG, electricity, and fuel oil.

- Summary of percent change in lifecycle g/mi emissions from alternative-fuel vehicles, relative to conventional gasoline LDVs or diesel HDVs.

- BTUs of process and end-use energy per mile of travel by stage of lifecycle, for different feedstock/fuel/vehicle combinations.

- Breakdown of energy use by type of energy (e.g., diesel fuel, natural gas, propane), stage of lifecycle, and feedstock/fuel combination.

- Vehicle characteristics: input data and results regarding vehicle weight and energy use.

- Emissions from EVs, by region: a macro runs the model for regional data for EV recharging and prints the g/mi results for up to six different regions.

- Emissions by IPCC sector: The g/mi results for vehicles are mapped into the IPCC sectors used in GHG accounting (e.g., "energy/road transport," "energy/industry," "land-use/forestry").

- Emissions by geographic sector: The g/mi results for vehicles are mapped into a geographic framework that distinguishes in-country from outside-of-country emissions.

- Emissions by individual pollutant: one set of tables reports emissions of each individual pollutant (not weighted by CO_2-equivalency factors) for each stage of the upstream fuel cycle for each feedstock/fuel. Another table does the same for vehicle manufacture and assembly.

- CO_2-equivalent emissions by pollutant: a tabular summary of the contribution of each pollutant to upstream fuel cycle CO_2-equivalent emissions.

- Emissions from complete transportation scenarios: a table of results that shows g/passenger-mi emissions from a user-specified mix of travel by conventional motor vehicles, alternative-fuel vehicles (including electric vehicles), mini-cars, scooters, buses, trolleys, subways, bicycles, and walking.

- Emissions from other countries: the LEM can be programmed to calculate all results for the characteristics of any of up to 30 different countries. Separate data files exist within the LEM for each of the countries.

In the following sections we discusses the major outputs of the LEM in more detail.

Emissions per mile from the use of conventional and alternative transportation fuels for motor vehicles

The LEM estimates CO_2-equivalent emissions per mile for the motor-vehicle transportation fuel and feedstock combinations shown above. For baseline petroleum fuels (gasoline and diesel fuel), the results are reported as grams of individual gases or CO_2-equivalent emissions from each stage of the lifecycle of fuels. The lifecycle of fuels also include the manufacture and assembly of materials for vehicles, per mile of travel by the vehicle. For the alternative fuel vehicles, the results are reported in grams/mile as for gasoline and diesel vehicles, and also as a percentage change relative to the petroleum-fuel gram-per-mile baseline.

Emissions per energy unit from the use of electricity, and from end-use heating

The LEM calculates grams of individual gases and grams of CO_2-equivalent emission from the entire fuel cycle, per kWh of electricity delivered to end users. It analyzes coal, residual fuel oil, natural gas, methanol, nuclear, and hydro power plants, individually or in any combination. The analysis covers emissions from all stages of the fuel cycle, from feedstock recovery to scrubbing sulfur from flue gas to transmitting power via high-voltage lines, which can produce N_2O. The estimates of emissions of NO_x and SO_x account for the phase-in and effectiveness of emission controls. The gram/kWh emissions can be estimated for any power-plant efficiency, fuel mix, emission-control scenario, and time horizon.

The LEM also estimates lifecycle emissions from the use of NG, LPG, fuel oil, and electricity for space heating and water heating, in grams CO_2-equivalent emissions per 10^6 BTU of heat delivered.

Results by emissions sector or stage of lifecycle

The LEM organizes lifecycle emissions in several ways. **First**, it presents emissions by *stage of the lifecycle:*

- vehicle operation (fuel)
- fuel dispensing
- fuel storage and distribution
- fuel production
- feedstock transport
- feedstock and fertilizer production
- CH_4 and CO_2 gas leaks and flares
- emissions displaced by coproducts
- vehicle assembly and transport
- materials in vehicles
- lube oil production and use
- refrigerant (HFC-134a) use

Second, the LEM maps the results calculated by “stage” of the lifecycle (e.g., petroleum refining) into the *emissions sectors used in the IPCC greenhouse-gas emissions-accounting* frameworks. In the following table, the IPCC sectors are underlined, and the LEM stages that are mapped into each IPCC sector are in italics below the pertinent IPCC sector:

IPCC energy/road transport: fuels	
LEM: Vehicle operation, fuel	Note: This mapping includes credits for plant uptake of CO_2. Changes in soil and plant carbon are in "Land-use/forestry/agriculture".
IPCC energy/industry: fuels	
LEM: Fuel dispensing	
LEM: Fuel storage and distribution	
LEM: Fuel production	
LEM: Feedstock transport	
LEM: Feedstock, fertilizer production	
LEM: CH_4 and CO_2 gas leaks, flares	Note: related to fuel production and use.
IPCC energy/industry: materials, vehicles	
LEM: Vehicle assembly and transport	
LEM: Materials in vehicles	
LEM: Lube oil production and use	
LEM: Refrigerant (HFC-134a)	
IPCC land-use/forestry/agriculture	
LEM: Land use changes, cultivation	Note: this does not include any energy-related emissions (e.g., from fuel use by tractors).
Not mapped to IPCC sectors:	
LEM: Emissions displaced by coproducts	
LEM: Road dust, brake dust, tirewear PM	

Third, the LEM maps the CO_2-equivalent emission results into six *geographic sectors*:

- the energy/road transport sector of the designated consuming country (the country selected for analysis; e.g., the U. S.);
- the energy/industry sector of the designated consuming country;
- the energy/industry sector of a selected major exporter (e.g., Canada) to the designated consuming country;
- the energy/industry sector of a second major exporter;
- international transport; and
- the rest of the world.

This mapping reveals how policies in one country affect emissions in other countries. International transport is a separate source because in the IPCC accounting it is not assigned to any country.

The mapping into geographic sectors is based on part on the LEM's representation of trade between major producing countries and designated consuming and target countries. Trade between countries is discussed in the section "Analysis of emissions from countries other than the U. S."

Analysis of emissions from complete transportation scenarios

The LEM estimates total average emissions per passenger-mile and per freight ton-mile from a complete transportation scenario. A complete transportation scenario includes passenger transport and freight transport by all possible modes, where the modal shares and other characteristics of the modes are specified by the user.

The passenger travel modes that can be characterized in a transportation scenario are:

- conventional motor vehicles,
- alternative-fuel vehicles (including electric battery and fuel-cell vehicles)
- mini-cars (conventional and alternative-fuel)
- scooters
- buses (conventional and alternative-fuel)
- trolleys
- subways
- bicycles and walking

The freight modes that can be characterized in a complete transportation scenario are:

- heavy-duty and medium–duty trucks (conventional and alternative-fuel)
- rail
- cargo ship, tanker, and barge
- pipeline

To create a scenario, the user specifies the distribution of passenger miles of travel over all passenger transport modes and the distribution of freight ton-miles of travel over all freight transport modes. The user also specifies the passenger occupancy and in some cases the energy-use efficiency of each mode. With these data, the LEM calculates average CO_2-equivalent lifecycle emissions per passenger mile and freight ton-mile for the scenario.

ANALYSIS OF EMISSIONS FOR COUNTRIES OTHER THAN THE U. S.

Background

The LEM originally was constructed and specified for the U. S. only. Starting in the late 1990s it was extensively revised to be able to estimate lifecycle emissions from the use of energy and materials in countries other than the U. S. Data sets for countries other than the U. S. were created for the most important parameters in the model. Now, the LEM can estimate lifecycle emissions from the use of transportation fuels, transport modes, electricity, and heat in any one of up to 30 countries. The user specifies a country (which I will refer to as a "consuming" or "target" country), and the LEM looks up the corresponding data sets and uses them in the active calculations.

In the LEM, the calculation of end-use emissions from transportation, electricity, and heat involves hundreds of parameters. There are parameters for the inputs and outputs of fuel-conversion processes (e.g., crude oil refining to gasoline), the efficiency of fuel use by motor vehicles (e.g., fuel economy in urban driving), emissions from motor vehicles (e.g., g/mi of particulate matter), and so on. If one had unlimited time and resources, one would have country-specific values for every parameter in the model. For example, there would be a unique set of emission factors for each country, because combustion technology, regulations, and emission controls vary from country to country. However, because I do not have unlimited time and resources, I have developed country specific-values for only the most important parameters. For these relatively important parameters, the LEM has 30 values or sets of values – one for each country.

For most parameters, however, the LEM does not have country-specific data sets. For example, as a general rule, I have assumed that fuel qualities (apart from sulfur content), CO2-equivalency factors (similar to IPCC "Global Warming Potentials"), land-use impacts (e.g., changes in carbon storage due to cultivation), and the energy intensity and emissions of new technologies (e.g., the energy use of facilities that produce diesel-like fuel via the Fischer-Tropsch process, or emissions from natural-gas motor vehicles *relative* to emissions from gasoline vehicles) are the same in all countries. For these parameters, the LEM uses either generic technology values (e.g., the parameters that specify inputs and outputs for converting natural gas to hydrogen are based on a generic technological specification, not on country-specific inputs and outputs), or values specific to the U. S. (e.g., the travel distances for trucks distributing finished motor fuels are based on U. S. data, regardless of whether the U. S. data are appropriate for any particular country). I believe that most of the *non*-country-specific technologically generic assumptions are reasonable for all countries. Some of the U .S.-based assumptions are likely to be inaccurate for other countries, but because most of these parameters are relatively unimportant (in the sense that changes in the value of the parameter have a relatively minor impact on total estimated lifecycle emissions), the inaccuracies generally are relatively unimportant.

Data specific to "consuming" countries

The LEM has the following parameters specific to designated target or "consuming" countries:

DATA CATEGORY	**COUNTRY-SPECIFIC PARAMETERS**
Motor-vehicle fuel use (light-duty and heavy-duty vehicles)	City fuel economy, highway fuel economy, and city-driving fraction of total VMT, by vehicle type (light-duty vehicles, heavy-duty trucks, and buses).
Motor-vehicle emissions (light-duty and heavy-duty vehicles)	Emissions by pollutant, model year, and vehicle type (light-duty vehicles and heavy-duty vehicles) (exhaust emissions, evaporative emissions, and road-dust, brakewear, and tailpipe PM).
Motor scooters	Fuel economy and emissions by pollutant, relative to US values.
Mini cars (up to 500 kg)	Fuel economy and emissions by pollutant, relative to US values.
Motor vehicles (all types)	Lifetime to scrappage.
Rail transit (heavy rail and light rail)	Passenger load/passenger-capacity factors; BTUs/capacity-mile for traction energy; BTUs/capacity-mile for station energy; energy for construction relative to energy for traction.
Evaporative emissions	g/gal emissions from refueling and fuel marketing, in a base year; annual rate of change of g/gal emissions

Electricity generation and distribution efficiency	Generation efficiency in a base year, by type of fuel; percent change in generation efficiency per year, by type of fuel; electricity distribution efficiency in a base year; annual percentage change in distribution efficiency
Electricity generation fuel mix for specific end uses of electricity	Mix of sources used to generate electricity (coal, oil, gas boiler, gas turbine, nuclear, hydro, other), specified separately for: EV recharging, crop-ethanol production, biomass-ethanol production, operation of rail transit, water electrolysis (for hydrogen production), and generic power. (For generic power, data are base year generation by type in gWh, and percentage change per year in absolute generation.)
Electricity generation emissions	Efficiency of emission controls, by pollutant, relative to US values.
Diesel fuel sulfur	Sulfur content (ppm) for various years between 1970 and 2050, for highway, offroad, and heating fuels.
Other fuel quality	Sulfur content of coal and various petroleum products, relative to that in the U. S..
Material flows	Imports of materials by producing region (the major material producing and exporting regions of the world) and by material (iron, aluminum, plastics, and “other materials”); transport distances between producing and consuming countries; transport modes (ship or other) by producing region.
Oil flows	Imports of petroleum by producing region (the major oil producing and exporting regions of the world) and by kind of petroleum (crude oil, light petroleum products, heavy petroleum products); transport distances between producing and consuming countries; transport modes (ship or other) by producing region.
Coal flows	Imports of coal by producing region (the major coal producing and exporting regions of the world); transport distances between producing and consuming countries; transport modes (ship or other) by producing region.
Natural-gas flows	Imports of natural gas by producing region (the major gas producing and exporting regions of the world) and product (natural gas by pipeline, liquefied natural gas, and natural-gas-derived liquids); transport distances between producing and consuming countries; transport modes (pipeline or ship) by producing region.
Natural gas losses	Leakage from domestic distribution systems (percent of

	end use consumption).
Motor-vehicle flows	Imports of motor vehicles by producing region (the major-vehicle producing and exporting regions of the world) and type of vehicle (heavy-duty or light-duty); transport distances between producing and consuming countries; transport modes (ship or other) by producing region.
Uranium production and enrichment	Production of uranium by country; imports of enriched uranium (as "separative work units" [SWUs] by producing region (the major SWU-producing-countries of the world); SWUs per MWh generated; tons of enriched uranium per GWh generated.
Crop production and fertilizer use	Harvest yield in base year and annual change in harvest yield, by crop type; rate of nitrogen loss, by crop type; fraction of residue burned, by crop type; energy intensity of N-fertilizer production relative to U. S; distribution of land types displaced, by crop type.
Corn-ethanol production	Total energy requirement (BTUs-process-fuel/gal-ethanol); electricity use (kWh/gal); type of process fuel (coal, oil, gas, biomass).
Nitrogen deposition	Distribution of land types affected by deposition, by country; deposition of N onto agricultural land, by country.
Multi-modal emissions	Parameters for the estimation of emissions per passenger-mi and emissions per ton-mi (for use in the analysis of the impacts of multi-modal transportation policies): vehicle occupancy by mode (passenger cars, motor-scooters, mini-cars, bicycles, minibuses, and buses); passenger-load/passenger-capacity fractions for rail heavy and light rail; passenger-miles of travel by mode (light-duty vehicles, buses, minibuses, minicars, and motor scooters [including a wide range of alternative fuels and electric vehicles], heavy rail, light rail, bicycling, and walking); tons and miles of travel by freight mode (large and medium diesel, CNG, and ethanol trucks, diesel trains, cargo ships, tankers, barges, and pipelines).

Appendix B of this report documents some of the country-specific parameter values.

Representation of producing countries

The preceding section describes data sets specific to the target or consuming countries. Among the country-specific parameters listed in that table are several that describe imports of fuels or materials for consuming countries. For each consuming country and fuel or material commodity, the user specifies the fraction imported from each of the major producing regions of the world. For example, for any consuming country (say, Japan), one specifies the amount of crude oil imported from the major crude-oil producing and exporting regions of the world (the Persian Gulf, Indonesia, and so on).

Important energy-use and emissions parameters are specified for each producing region. For example, the energy intensity of petroleum refining is specified for each major petroleum-product-exporting region, and venting and flaring of associated gas is specified for each major crude-oil-producing region. The shipping distance between producing regions and designated end-use consuming (target) countries also is specified. The energy, emissions, and distance parameters for each producing region are weighted according to the region’s contribution to the total consumption of the designated or “target” country.

The LEM represents producing regions and flows between producing regions and consuming countries for two reasons: 1) to properly represent differences in energy intensity and emission factors from one region to the next; and 2) to allow users to separate “domestic” emissions, associated with the designated consuming country, from foreign emissions. This second purpose can be useful in national GHG accounting inventories.

In the LEM, the commodities exported from producing regions to consuming countries are crude oil, petroleum products, natural gas (including liquefied natural gas), natural-gas liquids, coal, uranium, SWUs, vehicles, steel and iron, aluminum, plastics, and other materials. The producing regions vary by commodity, of course, and are those that actually account for the bulk of the production of the commodity in the world today. The following table lists the key producing regions and the commodities produced in each region.

Producing region or country	Commodity produced
U. S.	all
Canada	all except SWUs
Japan	SWUs, MVs, all materials
N. Europe	all except MVs, uranium
S. Europe	petroleum products, NG, NGTLs, all materials
Former Soviet Union	all except MVs
China	coal, SWUs
Korea	MVs, materials

Asian Exporters	all except SWUs, uranium, MVs
Venezuela	petroleum products, crude oil
North Africa (Algeria, Libya)	petroleum products, crude oil, NG, NGTLs
Nigeria	petroleum products, crude oil, NG (LNG)
Indonesia	coal, petroleum products, crude oil, NG, NGTLs
Persian Gulf	petroleum products, crude oil, NG, NGTLs
Malaysia	NG (LNG)
Caribbean Basin	petroleum products, crude oil, coal, NG (LNG)
Other	all
Mexico	crude oil, NG, NGTLs, MVs
France	SWUs, MVs
Germany	MVs, materials
Other Europe	MVs
Australia	coal, uranium, NG (LNG)
Colombia	coal
Poland, Czech Republic	coal
South Africa	coal, uranium
Other Middle East	crude oil
Other Africa	crude oil
Target developed (domestic)	all
Target LDC (domestic)	all
International transport	all except SWUs, uranium

In this table, "all" commodities are crude oil, petroleum products, natural gas (NG) including liquefied natural gas (LNG), natural-gas liquids (NGTLs), coal, separative work units (SWUs; for enriching uranium), uranium, motor vehicles (MVs), steel and iron, aluminum, plastics, and other materials, and "all materials" are steel and iron, aluminum, plastics, and other materials. Note that the "target developed" and "target LDC" categories are used to account for domestic production in target countries that are not part of any of the major producing regions.

For each commodity produced and traded in the LEM, there are parameters that are relevant to the estimation of lifecycle energy use and emissions and specific to each producing region. The following table shows commodities produced and traded in the LEM, and the corresponding energy use and emissions parameters specified for the commodity and producing region:

Commodity produced	Energy and emission parameters for producing regions

crude oil	Amount of oil recovery onshore, offshore, and from unconventional reserves; energy intensity of oil recovery for onshore, offshore, and unconventional production; venting and flaring of associated gas; CO_2 and SO_2 emissions from oil production; emissions associated with using concrete to plug oil wells.
petroleum products	Energy intensity of petroleum refining; mix of fuels used by petroleum refineries; electricity generation mix for petroleum refineries; sulfur content of fuels.
natural gas	Energy intensity of gas production; energy intensity of gas transmission; leakage from gas recovery, processing and transmission; CO_2 and SO_2 emissions from oil production; emissions associated with using concrete to plug oil wells.
NGTLs	Energy intensity of natural-gas-to-liquids (NGTL) production.
coal	Energy intensity of coal production; amount of production from underground and surface mines; methane emissions from underground and surface mines; fate of methane emissions from coal mining.
materials	Energy intensity of materials production.
vehicles	Energy intensity of vehicle assembly; electricity generation mix for vehicle assembly.
uranium	Energy intensity of uranium production.
SWUs	SWU production by gas diffusion, centrifuge, and laser-based technologies; electricity requirements of each production technology.

The values of these parameters are given and documented in the Main Report of Delucchi (2003).

COMPARISON OF THE LEM WITH OTHER RECENT LC MODELING EFFORTS

The structure and coverage of the LEM can be compared with that of several other recent transportation fuelcycle or lifecycle modeling efforts:

Project	**GM -ANL U. S.**	**GM –LBST Europe**	**MIT 2020**	**EUCAR**	**LEM**
Region	North America	Europe	based on U. S. data	Europe	multi-country (primary data for U. S.; other data for up to

					30 countries)
Time frame	near term (about 2010)	2010	2020	2010 and beyond	any year from 1970 to 2050
Transport modes	LDV (light-duty truck)	LDV (European mini-van)	LDV (mid-size family passenger car)	LDVs (compact 5- seat European sedan)	LDVs, HDVs, buses, light-rail transit, heavy-rail transit, minicars, scooters, offroad vehicles
Vehicle drivetrain type	ICEVs, HEVs, BPEVs, FCEVs	ICEVs, HEVs, FCEVs	ICEVs, HEVs, BPEVs, FCEVs	ICEVs, HEVs, FCEVs	ICEVs, BPEVs, FCEVs
Motor fuels	gasoline, diesel, naptha, FTD, CNG, methanol, ethanol, CH2, LH2, electricity	gasoline, diesel, naptha, FTD, CNG, LNG, methanol, ethanol, CH2, LH2	gasoline, diesel, FTD, methanol, CNG, CH2, electricity	gasoline, diesel, FTD, CNG, ethanol, FAME, DME, naptha, methanol, CH2, LH2	gasoline, diesel, LPG, FTD, CNG, LNG, methanol, ethanol, CH2, LH2, electricity
Fuel Feedstocks	crude oil, natural gas, coal, crops, ligno-cellulosic biomass, renewable and nuclear power	crude oil, natural gas, coal, crops, ligno-cellulosic biomass, waste, renewable and nuclear power	crude oil, natural gas, renewable and nuclear power	crude oil, natural gas, coal, nuclear, wind. sugar beets, wheat, oil seeds, wood	crude oil, natural gas, coal, crops, lignocellulosic biomass, renewable and nuclear power
Vehicle energy-use modeling, including drive cycle	GM simulator, U. S. combined city/ highway driving	GM simulator, European Drive Cycle (urban and extra-urban driving)	MIT simulator, U. S. combined city/ highway driving	Advisor (NREL simulator), New European Drive Cycle	simple model based on SIMPLEV-like simulator, U. S. combined city/highway driving
Fuel lifecycle	GREET model	LBST E^2 I-O model and data base	literature review	LBST E^2 I-O model and data base (review & update of GM et al. [2002])	detailed internal model
Vehicle lifecycle	not included	not included	detailed literature review and analysis	not included	internal model based on detailed literature review and analysis

GHGs [CEFs]	CO_2, CH_4, N_2O [IPCC] (other pollutants included as non-GHGs)	CO_2, CH_4, N_2O [IPCC]	CO_2, CH_4 [IPCC]	CO_2, CH_4, N_2O [IPCC]	CO_2, CH_4, N_2O, NO_x, VOC, SO_x, PM, CO, H_2, HFCs, CFCs [own CEFs, also IPCC CEFs]
Infrastructure	not included	not included	not included	not included	crude representation
Price effects	not included	not included	not included	not included	a few simple quasi-elasticities
Reference	GM, ANL et al. (2001)	GM et al. (2002a, 2002b, 2002c)	Weiss et al. (2000)	Concawe et al. (2004)	Delucchi (2003)

Project	**ADL AFV LCA**	**EcoTraffic**	**CMU I-O LCA**	**Japan CO2 from AFVs**	**LEM**
Region	United States	generic, but weighted towards European conditions	United States	Japan	multi-country (primary data for U. S.; other data for up to 30 countries)
Time frame	1996 baseline, future scenarios	between 2010 and 2015	near term	near term?	any year from 1970 to 2050
Transport modes	subcompact cars	LDVs (generic small passenger car)	LDVs (midsize sedan)	LDVs (generic small passenger car)	LDVs, HDVs, buses, light-rail transit, heavy-rail transit, minicars, scooters, offroad vehicles
Vehicle drivetrain type	ICEVs, BPEVs, FCEVs	ICEVs, HEVs, FCEVs	ICEVs	ICEVs, HEVs, BPEVs	ICEVs, BPEVs, FCEVs
Motor fuels	gasoline, diesel, LPG, CNG, LNG, methanol, ethanol, CH2, LH2, electricity	gasoline, diesel, FTD, CNG, LNG, methanol, DME, ethanol, CH2, LH2	gasoline, diesel, biodiesel, CNG, methanol, ethanol	gasoline, diesel, electricity	gasoline, diesel, LPG, FTD, CNG, LNG, methanol, ethanol, CH2,

					LH2, electricity
Fuel feedstocks	crude oil, natural gas, coal, corn, ligno-cellulosic biomass, renewable and nuclear power	crude oil, natural gas, ligno-cellulosic biomass, waste	crude oil, natural gas, crops, ligno-cellulosic biomass	crude oil, natural gas, coal, renewable and nuclear power	crude oil, natural gas, coal, crops, lignocellulosic biomass, renewable and nuclear power
Vehicle energy-use modeling, including drive cycle	Gasoline fuel economy assumed; AFV efficiency estimated relative to this	Advisor (NREL simulator), New European Drive Cycle	Gasoline fuel economy assumed; AFV efficiency estimated relative to this	none; fuel economy assumed	simple model based on SIMPLEV-like simulator, U. S. combined city/highway driving
Fuel lifecycle	Arthur D. Little emissions model, revised	literature review	own calculations based on other models (LEM, GREET..)	values from another study	detailed internal model
Vehicle lifecycle	not included	not included	Economic Input-Output Life Cycle Analysis software (except end-of-life)	detailed part-by-part analysis	internal model based on detailed literature review and analysis
GHGs [CEFs]	CO_2, CH_4, [partial GWP] (other pollutants included as non-GHGs)	none (energy efficiency study only)	CO_2, CH_4, N_2O? [IPCC] (other pollutants included as non-GHGs)	CO_2	CO_2, CH_4, N_2O, NO_x, VOC, SO_x, PM, CO, H_2, HFCs, CFCs [own CEFs, also IPCC CEFs]
Infra-structure	not included	not included	not included	not included	crude representation
Price effects	not included	not included	not included (fixed-price I-O model)	not included	a few simple quasi-elasticities
Reference	Hackney & de Neufville (2001)	Ahlvik and Brandberg (2001)	MacLean et al. (2000)	Tahara et al. (2001)	Delucchi (2003)

The terms in the model comparison table are defined as follows:

Region	The countries or regions covered by the analysis.
Time frame	The target year of the analysis.
Transport modes	The types of passenger transport modes included. LDVs = light-duty vehicles, HDVs = heavy-duty vehicles.
Vehicle drivetrain type	ICEVs = internal combustion-engine vehicles, HEVs = hybrid-electric vehicles (vehicles with an electric and an ICE drivetrain), BPEVs = battery-powered electric vehicles (BPEVs), FCEVs = fuel-cell powered electric vehicles.
Motor fuels	Fuels carried and used by motor vehicles. FTD = Fischer-Tropsch diesel, CNG = compressed natural gas, LNG = liquefied natural gas, CH2 = compressed hydrogen, LH2 = liquefied hydrogen, DME = dimethyl ether, FAME = fatty acid methyl esters.
Fuel feedstocks	The feedstocks from which the fuels are made.
Vehicle energy-use modeling	The models or assumptions used to estimate vehicular energy use (which is a key part of fuelcycle CO_2 emissions), and the drive cycle over which fuel usage is estimated (if applicable).
Fuel lifecycle	The models, assumptions, and data used to estimate emissions from the lifecycle of fuels.
Vehicle lifecycle	The lifecycle of materials and vehicles, apart from vehicle fuel. The lifecycle includes raw material production and transport, manufacture of finished materials, assembly of parts and vehicles, maintenance and repair, and disposal.
GHGs and CEFs	The pollutants (greenhouse gases, or GHGs) that are included in the analysis of CO_2-equivalent emissions, and the CO_2-equivalency factors (CEFs) used to convert non-CO_2 GHGs to equivalent amount of CO_2 (IPCC = factors approved by the Intergovernmental Panel on Climate Change [IPCC]; LEM CEFs are those derived in Appendix D of Delucchi [2003]).
Infrastructure	The lifecycle of energy and materials used to make and maintain infrastructure, such as roads, buildings, equipment, rail lines, and so on. (In most cases, emissions and energy use associated with the construction of infrastructure are small compared with emissions and energy use from the end use of transportation

	fuels.)
Price effects	This refers to the relationships between prices and equilibrium final consumption of a commodity (e.g., crude oil) and an "initial" change in supply of or demand for the commodity or its substitutes, due to the hypothetical introduction of a new technology or fuel.

Note that the study by EcoTraffic (Ahlvik and Brandberg, 2001) provides a good comparison of their work with the GM WTW U. S. (GM et al., 2001), the MIT 2020 (Weiss et al. 2000), and several other studies.

Among the tools used in the studies in the table above, those used in the GM WTW studies are most similar to those used in the transportation fuel lifecycles of the LEM. In particular, the GREET model is similar to the fuel lifecycle parts of the LEM. (See Wang [1999] for documentation of the GREET model.) Even so, there are significant differences. Generally, the LEM is broader in scope than the GM studies: it covers more countries, wider time frames, more transport modes, more pollutants, more aspects of the lifecycle (such as materials), and more relevant effects (such as price effects). One significant exception is that the GM studies, and several other studies listed in the table above, include one vehicle type (hybrid EVs) and some fuel pathways (such as fuels from waste) that are not included in the LEM.

My examination of the available documentation for the GREET model and the LBST E^2 I-O model (used in the GM WTW European study) indicates that, apart from the differences noted in the table above, the fuel lifecycle parts of the LEM are in some cases more detailed than are the GREET and E^2 models. For example, the LEM includes a more detailed carbon tracking (apportioning carbon between fuel, lubricating oil, biomass and non-biomass components) than do other models. More significantly, the LEM has a more comprehensive and detailed treatment of emissions associated with cultivation, land-use change, the nitrogen cycle, and particulate matter. The LEM also uses complete, detailed input-output relationships, usually based on primary data (rather than secondary citation of literature), for most lifecycle stages.

Note that the comparison above covers only major, original, recent analyses of lifecycle emissions from a wide range of alternative transportation fuels. It does not include the following:

- older LCAs of alternative transportation fuels (see DeLuchi [1991] for a discussion of studies done before 1990, and Wang [1999] for a discussion of studies done in the 1990s);
- studies that are entirely derivative;
- studies of a single fuel or narrow range of transportation fuels;
- studies that focus mainly on the lifecycle of the automobile as opposed to automotive fuels (e.g., Sullivan et al., 1998; see Appendix H of Delucchi [2003] for more discussion pertinent to these analyses);

- LCAs not directly related to transportation (of which there area great many, for a wide range of non-transportation products and system, including power generation, building materials, and more).

It should be emphasized that many of these studies, and particularly some of those that focus on a single fuel or a narrow range of fuels, are of high quality. I have omitted them only to keep the comparison manageable. It is also worth noting that many of the non-transportation LCAs and some of the transportation LCAs follow guidelines established by the International Organization for Standardization (ISO). The general applicability ISO guidelines are discussed briefly in a separate section below.

METHODS AND ANALYTICAL ISSUES IN LCA

General method of estimation of lifecycle-CO_2 emissions from transportation systems in the LEM

As discussed above, basic outputs of the LEM include lifecycle CO_2-equivalent emissions per mile of travel by transportation modes or per pound of material produced (g/mi or g/lb). Appendix H of Delucchi [2003] documents the calculation of g/lb emissions from the lifecycle of materials. Here I present the basic methods used to calculate g/mi emissions from the lifecycle of transportation fuels.

Generally, the LEM calculates grams of CO_2-equivalent emissions from stage *S* (e.g., oil recovery) of the lifecycle of end-use fuel X (the fuel of interest; e.g., motor gasoline), per mile of travel, by multiplying emissions per energy unit of X by energy use per mile:

$$GHGMI_{S,X} = GHGBTU_{S,X} \cdot M_X \qquad \text{eq. 1a}$$

where:

$GHGMI_{S,X}$ = CO_2-equivalent emissions of GHGs from stage *S* of the lifecycle of fuel *X*, in grams per vehicle mile of travel
$GHGBTU_{S,X}$ = CO_2-equivalent emissions of GHGs from stage *S* of the lifecycle of fuel *X*, in grams per million BTU of *X* made available to end users (discussed below)
M_X = fuel *X* available to the transportation sector, in 10^6 BTUs per vehicle mile of travel (elaborated in the Main Report of Delucchi [2003])
Subscript *S* = stages of the lifecycle (feedstock recovery, feedstock transport, etc.; see the list earlier in this report)
Subscript X = fuel (or commodity) whose lifecycle is being analyzed (see the table earlier in this report)

Strictly speaking the method of equation 1a applies only to "upstream" or non-end use stages of the lifecycle. CO_2-equivalent emissions from end-use of fuels by vehicles are calculated with a slightly different method, not presented here.

Emissions over the entire lifecycle of *X* are simply the sum of g/mi emissions for each stage:

$$GHGMI_X = \sum_S GHGMI_{S,X} \qquad \text{eq. 1b}$$

CO_2-equivalent emissions per energy unit of fuel *X* delivered to end users – the parameter GHGBTU – are calculated by multiplying inputs to stage *S* per unit of final output of the fuel of interest X by CO_2-equivalent emissions from the use of the inputs. Thus, the heart of the LEM is essentially an engineering input-output model with emission factors. Formally:

$$GHGBTU_{S,X} = \sum_I IO_{I,S,X} \cdot CEEF_I \qquad \text{eq. 1}$$

where:

$IO_{I,S,X}$ = input of quantity *I* to stage *S* of the lifecycle of fuel *X* per BTU of *X* delivered to end users (the units of the inputs – lbs, BTUs, etc. – vary with the type of input) (discussed further below)

$CEEF_I$ = CO_2-equivalent emissions of GHGs per unit of input *I*

Subscript *I* = quantities input to stages of lifecycles (includes energy commodities, such as coal, oil, and natural gas; chemicals, and more; see discussions of specific lifecycles throughout the Main Report of Delucchi [2003])

Input/output ratios (parameter IO) are discussed throughout this documentation. Typically they are not specified as such but rather are the result of further calculations within the LEM.

CO_2-equivalent emissions (CEEF) are calculated as the product of a CO_2-equivalency factor (CEF) and emissions of individual pollutants *P*, summed over all P:

$$CEEF_I = \sum_P EF_{P,I} \cdot CEF_P \qquad \text{eq. 1d}$$

where:

$EF_{P,I}$ = the emission factor for pollutant *P* and input *I:* grams of pollutant *P* per unit of input *I* (discussed below)

CEF_P = CO_2-equivalency factor for pollutant *P* (discussed in Appendix D of Delucchi [2003])

Subscript P = individual pollutants tracked in the LEM (CH_4, N_2O, etc; see the list earlier in this report)

The emission factors *EF* generally are calculated directly from primary inputs to the LEM. These primary emission-factor inputs are taken from a wide variety of primary sources, such as the EPA's compilation of emission factors known as AP-42. (See the discussion of individual lifecycles in Delucchi [2003] for details.) Emissions of CO_2 are a special case, because these emissions are calculated based on carbon contents (rather than specified by the user) and because the CEF for CO_2 is 1.0. Formally, emissions of CO_2 are calculated on the basis of a complete carbon balance for any input *I*:

$$EF_{CO2,I} = \left(CC_I - C_{NONCO2,I}\right) \cdot \frac{MW_{CO2}}{MW_C} \qquad \text{eq. 1e}$$

where:

CC_I = the carbon content of input *I* (grams of C per unit of *I*; these are specified in DeLuchi [1993] and Delucchi [2003])

$C_{NONCO2,I}$ = carbon in input *I* that ends up in any form other than CO2 (based on calculations of the carbon content of non-CO_2 gases and other carbon sinks; most of these further calculations are presented in this documentation)

MW_{CO2} / MW_C = the ratio of the molecular weight of CO_2 to that of C (3.664)

The carbon-balance calculations also properly distinguish biogenic from fossil-fuel carbon for the purpose of determining "net" emissions to the atmosphere.

The summary calculations presented above provide a general outline of some of the main algorithms within the LEM. There are of course many variations on the methods presented above, considerable further elaborations (especially in the case of calculating input/output ratios), and a number of important cases where entirely different algorithms are used (e.g., the calculation of CO_2-equivalent emissions related to changes in land-use in the lifecycle of biofuels). Most of these are discussed Delucchi (2003). Finally, additional methodological considerations, such as "own-use" of fuel, also are discussed in Delucchi (2003).

Note on structural circularity. All of the major lifecycle calculations within the LEM are circular: every lifecycle is related structurally to every other lifecycle. For example, the calculation of lifecycle emissions associated with the use of coal calls on the calculation of lifecycle emissions associated with the use of natural gas, but also vice versa: the natural-gas lifecycle calls on the coal lifecycle. This structural circularity connects most lifecycles. The model resolves these circularly related equations by iterative calculations using convergence algorithms internal to the spreadsheet program. This structural circularity is an proper representation of the real world and is a methodological advantage of the LEM over models that lack such structure.

Overview of basic analytical issues in LCA

As mentioned above, transportation LCAs, and indeed all LCAs as done today, are essentially linked input-output building blocks with emission factors. From this simple description we can identify several basic analytical issues in LCA:

i) <u>detail:</u> the appropriate "grain" or level of detail of the building blocks and the appropriate number of building blocks (e.g., in the case of petroleum refining, should one represent the entire petroleum-refining sector of the economy, or specific petrochemical processes within refineries);

ii) <u>scope:</u> the boundaries or extensiveness of the system of blocks that represent the lifecycle (e.g., in an analysis of transportation fuels, whether to include materials used in the construction of petroleum refineries);

iii) <u>structure:</u> the mathematical representation of building blocks and the nature of the I-O relationships between building blocks (e.g., fixed versus dynamic I-O ratios for building blocks).

The issues outlined above are widely recognized in the literature on LCA (see for example the recent articles by Rebitzer et al. [2004] and Pennington et al. [2004]). Many discussions in the literature focus on the trade-off between detail and extensiveness, typically manifested in the choice between detailed engineering-type process-specific LCAs of limited extensiveness and extensive economy-wide I-O type analyses of limited detail. (For an example of the latter, see Matthews and Small [2001].) There has, however, been virtually no in-depth discussion of the question of fixed versus dynamic I-O ratios. In a later section of this documentation I will address this issue in some depth. In the following section I discuss specific issues of detail, scope, and structure in the LEM.

Issues concerning the detail, scope, and structure of the LEM

An ideal analysis of life cycle emissions and energy use would include all energy-consuming and pollutant-emitting processes and all pollutants in complete and correct detail. With respect to this ideal, the LEM falls short in several ways. In addition, although most parts of the LEM contain reasonably detailed representations, there are a few important simplifications that can lead to misleading or internally inconsistent results.

• The LEM does not include at least two major kinds of air pollution: emissions of particulate matter dust from some sources (e.g., dust from agricultural operations or coal mining [however, dust from roadways *is* included), and emissions of volatile organic compounds from biomass (e.g., terpenes from trees used in short-rotation intensive cultivation). Inclusion of these sources of pollutant could change the relative attractiveness of different life cycles.

• Although it includes emissions associated with materials manufacture and assembly for vehicles, trains, and ships, it does not include emissions associated with materials used for large construction projects such as power plants and refineries. It is possible, albeit in my view in unlikely, that in some lifecycles this omitted source of emissions might be unlikely.

- Generally, the model uses average rather than "marginal" emission-reduction factors. For example, the model calculates the average emissions for all coal-fired boilers used in industry, on the basis of the projected extent and effectiveness of emission controls. It does not distinguish industries or processes in which all boilers will be controlled from industries or processes in which few boilers will be controlled. This results in an overestimate of emissions from new sources, which are required to meet New Source Performance Review Standards, and an underestimation of emissions from old sources not subject to emission controls.
- A few important parameters are not projected year-by-year through 2050, as are many unimportant parameters are, but rather are fixed at year 2000 values.
- The calculation of second-order energy use and emissions related to the manufacture and servicing of transportation modes (trains, ships, trucks, and pipelines) also is an input rather than a calculated parameter, and might in fact be inconsistent with other calculations in the analysis.
- For the most part the LEM assumes fixed rather than dynamic I-O ratios. As discussed in the next section, I-O ratios generally are not fixed, but rather vary as some function of the assumed changes in the level of use of the product whose lifecycle is being modeled ("the product of interest"). The ultimate driver of the variation in I-O ratios is changes in the prices of important commodities, changes which are related to changes in the level of use of the product of interest. Hence, in principle, dynamic I-O ratios could be represented by the use of price elasticities, which show how the use of major commodities changes with changes in prices. The LEM uses a few quasi price elasticities, mainly as regards the marketing of the co-products of some production processes (e.g., the marketing of the co-products of corn-to-ethanol conversion).

Focus on the question of dynamic versus fixed I-O ratios

LCAs that I am aware of, including economic I-O LCAs, have assumed *fixed* I-O ratios. Many LCAs, and all economic I-O LCAs, acknowledge this assumption, but none discuss it or justify it any length. In this context, "fixed" I-O ratios mean that ratios of input quantities to output quantities, at every stage, from intermediate production to final demand, do *not* change as a result of the posited changes in the final output of the product whose lifecycle is being analyzed. The meaning of this is best illustrated by an example.

Consider a lifecycle analysis of motor gasoline, in which we wish to estimate the lifecycle impacts of using more or less motor gasoline than in some baseline. To assume fixed I-O ratios means, for example, to assume that the ratio of crude oil input to refinery outputs of each petroleum product, or the ratio of crude oil input to total power-plant output of electricity, or the ratio of gasoline use to vehicle-miles of travel, are constant regardless of the level of motor-gasoline use. Given this characterization, the methodological question can be put succinctly: are these reasonable assumptions?

In the real world, I-O ratios are *not* actually fixed, but rather are a function of changes in prices – changes which are associated with the change in final output (of the product of interest) that is at least implicitly posited in any LCA. Let us focus again on transportation LCAs. Any action regarding transportation – for example, a vehicle production mandate by government, a public subsidy to fuels, or a market decision by a private company to make a new kind of diesel fuel – will affect the prices of globally important commodities, such as oil, natural gas, or steel. The effects on the prices of these commodities ultimately will affect emissions, which are what lifecycle emissions models wish to estimate. As a result, transportation LCAs that assume fixed rather than dynamic I-O ratios mis-estimate the emissions of interest.

In general, actions may affect prices directly, for example by changing tax rates, or indirectly, by affecting the supply of or demand for commodities used in transportation. In an integrated and complex global economy, changes in the prices of important commodities ultimately will affect production and consumption of all commodities in all sectors throughout the world. In the final equilibrium of prices and quantities, there will be a new global pattern of production and consumption. This pattern will be different from what would have obtained had prices been fixed. Associated with this new pattern of production and consumption (arising from dynamic prices) will be a new pattern of emissions of air pollutants. The difference between the global emissions pattern associated with the transportation action being evaluated and the global emissions pattern without the action (in a world of dynamic prices) may be said to be the "emissions impact" of the action being evaluated. This emissions impact will differ from that obtained when we assume that prices are fixed, because the pattern of production and consumption assuming fixed prices will differ from that assuming dynamic prices.

Returning to our gasoline example, *any* action that affects gasoline use is likely to affect the price of gasoline and by extension the price of crude oil. In turn, changes in the price of gasoline will have a direct affect on transportation choices and hence on transportation-related emissions. Furthermore, changes in the price of crude oil will affect the consumption not only of crude oil but of the products of, substitutes for and complements of crude oil and petroleum products as well. These large-scale changes in prices of major commodities will reverberate throughout the world economy, affecting the production of important raw materials (such as ores) and finished products (such as metals). These changes in production will result in changes in emissions.

The reasoning outlined above suggests that any real-world action that is the ostensible object of an LCA (such as a policy that affects motor-gasoline use) is likely to affect prices and hence ultimately likely to make the standard assumption of fixed I-O ratios invalid. (See Delucchi [2002] for further discussion.)

Applicability of International Organization for Standardization (ISO) 14040 standards

As mentioned above, the International Organization for Standardization (ISO) has established guidelines for conducting LCA. The ISO guidelines for LCA are laid out in ISO standards 14040 to 14049 (see the ISO web site, www.iso.ch/iso/en/iso9000-14000/iso14000/iso14000index.html). The specific standards are:

Title	Year	Description
ISO 14040: 1997	1997	Environmental management – Life cycle assessment – Principles and framework. (General principles and methodological requirements.)
ISO 14041: 1998	1998	Environmental management – Life cycle assessment – Goal and scope definition and inventory analysis.
ISO 14042: 2000	2000	Environmental management – Life cycle assessment – Life cycle impact assessment. (Guidance on conducting the actual life-cycle assessment.)
ISO 14043: 2000	2000	Environmental management – Life cycle assessment – Life cycle interpretation. (Guidance on interpreting the results of the analysis.)
ISO/Technical report 14047: 1997	Post 2002?	Environmental management – Life cycle assessment – Examples of application of ISO 14042.
ISO/Technical report 14048: 2002	2002	Environmental management – Life cycle assessment – Data documentation format. (Information regarding the formatting of data to support life cycle assessment.)
ISO/Technical report 14049: 2000	2000	Environmental management – Life cycle assessment – Examples of application of ISO 14041 to goal and scope definition and inventory analysis.

A number of articles and reports discuss ISO 14040 standards or LCA applications that are consistent with ISO 14040 standards. For example, Rebitzer et al. (2004) and Pennington et al. (2004) provide recent comprehensive reviews of methods, data, and applications in LCA, with reference to ISO guidelines. Weidema (2001) discusses the proper handling of joint production (sometimes known as "co-product allocation") with specific reference to the methods of ISO 14041. There also are many commercial database and inventory tools that follow ISO 14040 protocols.

ISO guidelines and transportation LCAs. In principle, there are three ways in which the ISO 14040 guidelines and database tools might be useful in lifecycle of analyses of CO_2-equivalent emissions associated with policies directed towards alternative transportation options. First, they might provide guidance concerning conceptual and methodological issues, such as those concerning system boundaries and joint production. However, in this respect it appears that the ISO 14040 guidelines and tools may reflect but usually do not themselves advance the state of the art, and as a result have no advantage over models, such as the LEM, which have undertaken original (albeit limited) explorations of conceptual and methodological issues. For example, the first version of the LEM (DeLuchi, 1991, 1993) addressed several conceptual and methodological issues in fuelcycle analysis independently of and in some instances prior to treatment by ISO 14040, including: joint production (also known as "co-production;" e.g., the production of ethanol and feed from inputs of corn and other items); system boundaries (e.g., whether to include, in analyses of alternative transportation fuels, inputs and outputs associated with infrastructure, buildings, and maintenance and repair); "own-use" (e.g., the use of diesel fuel by trucks delivering diesel fuel to service stations in the lifecycle of diesel fuel); and nth-order indirect effects (e.g., the lifecycle of natural gas used to recover crude oil made into diesel fuel used to transport coal to power plants that provide electricity to petroleum refineries that make gasoline).

Second, ISO 14040-based tools and databases might provide input-output or emission-factor data relevant to transportation LCAs. This indeed can be case, and in the development of the LEM I have consulted these databases whenever they have been publicly available (e.g., National Renewable Energy Laboratory, 2003). However, my experience has been that those ISO-14040-based database tools per se, and per force, do not develop original data from primary sources (such as actual experiments, or analyses of primary survey data) but rather rely on data developed by others – including, in some cases, original estimates developed in the documentation for earlier versions of the LEM.

Third, the ISO 14040 guidelines can provide a common template for organizing, presenting, and interpreting LCAs. However, ISO 14040 formats appear to be most suited to multi-media, multi-pollutant, multi-denominated (i.e., *not* reduced to a single common metric) outputs of industrial processes. By contrast, LCAs of CO_2-equivalent emissions from transportation alternatives report single-media, multi-pollutant, single-metric outputs of public transportation policies. There is no particular advantage to shoe-horning the outputs of the transportation LCAs into ISO 14040 formats.

In summary, LCAs of CO_2-equivalent emissions from transportation alternatives have developed independently of the multi-media, multi-pollutant, multi-metric LCAs of industrial processes that ISO 14040 targets. Although ISO 14040 guidelines and databases can inform transportation LCAs, it is at least as likely that the methods and original data estimates of the more academically advanced transportation models would inform the more applied, commercial world of ISO 14040.

DISCUSSION OF RESULTS FROM THE LEM

Energy efficiency and emissions of vehicles.

Vehicle energy use is one of the most important calculated parameters in the LEM, because it linearly determines fuel cycle emissions of CO_2. In the LEM, the energy use of a vehicle is determined by the mi/BTU energy-conversion efficiency of the AFV engine or powertrain relative to that of the baseline gasoline or diesel vehicle, the weight of the vehicle, and other parameters. The weight of a vehicle, in turn, is a function of the driving range, the characteristics of the fuel storage systems, and other factors. Of these parameters, the energy-conversion efficiency of the powertrain is the most important because it directly determines vehicle energy use. Driving range and vehicle weight are less important because they affect vehicle energy use only indirectly. (Over the typical range of variation of both driving range and fuel-storage characteristics, the fuel cycle CO_2-equivalent emissions vary by only 1-2%.)

The input parameters for the calculation of vehicle energy use are discussed in the Main Report of Delucchi (2003). The calculated weight results are shown in Table Y-10b, and the calculated overall efficiency and fuel-use results are shown in Table Y-11. Compared with analysis in DeLuchi (1991), the efficiency of the EV relative to efficiency of the baseline gasoline vehicle has increased, and as a result fuel cycle GHG emissions from EVs are significantly lower.

The calculated g/mi emissions are shown in Tables Y-12a. For economy of presentation, all of these results are shown for the U. S. 2010 case only.

Energy intensity of fuel cycles and kinds of process fuel used

Table Y-13a presents the new calculated energy intensities by stage of the fuel cycle, in BTUs of process energy used at each stage per BTU of fuel made available to end users. (For economy of presentation, this result is shown for the U. S. in 2010 only.) The most significant parameters are those relating to the energy requirements of fuel production (e.g., methanol production from natural gas); less significant are those relating to the energy requirements of fuel and feedstock transport.

Table Y-13b shows BTUs of process energy consumed per vehicle mile of travel.

Variation in the mix of process fuels (not presented here) typically has only a minor effect on fuel cycle CO_2-equivalent emissions. An example of an exception is whether coal or natural gas is used to provide process heat at corn-to-ethanol plants.

Leaks of methane and CO_2

As discussed in the Main Report of Delucchi (2003), the data and methods used to estimate leaks from natural-gas systems, venting and flaring of gas associated with oil production, and methane emissions from coal mines have been completely revised. As a result, calculated venting and flaring emissions from oil wells have increased by a minor amount, calculated leaks from natural-gas systems have increased substantially, and calculated emissions from coal mining have decreased substantially, compared with the results reported in DeLuchi (1991). Table 24 in the Main Report (Delucchi, 2003) shows parameters in the estimation of leaks from coal mining, and Table 28 in the Main Report shows parameters in the estimation of leaks from NG systems.

The increase in the calculated leakage rate from NG systems (compared with the value in DeLuchi [1991]) increases fuel-cycle emissions by about 7 g/mi, or 2%. The decrease in calculated methane emissions from coal mining decreases CO_2-equivalent emissions from the coal-to-electricity fuel cycle by about 2%.

Leaks of hydrogen

The LEM, unlike other lifecycle models, estimates leaks from hydrogen stations, vehicles, and pipelines, and accounts for the climate effect of hydrogen leaks on concentrations of methane and tropospheric ozone. The following table shows the CO_2-equivalent gram/mile fuelcycle emissions (not including emissions from the lifecycle of materials or vehicles) without and with a CEF for hydrogen, and the resulting percentage increase in fuelcycle emission, for conditions in the U. S. (number before the comma is without CEF for H_2, number after the comma is with CEF):

	Light-duty FCEV (H_2/water)	Light-duty FCEV (H_2/NG)	Heavy-duty ICE (H_2/NG)
Compressed H_2	42.8, 44.5 (4.0%)	197, 198 (0.4%)	2497, 2507 (0.4%)
Liquefied H_2 (central.)	116.2, 119.2 (2.6%)	273, 276 (0.9%)	3345, 3375 (0.9%)

The increase in the CO_2-equivalent emissions due to assigning a non-zero CEF to hydrogen, compared with a CEF of zero, ranges from less than 1% in the case of vehicles using compressed hydrogen made from natural gas, to 3-4%, in the case of vehicles using liquid hydrogen made from electrolysis of water. The use of liquefied rather than compressed hydrogen results in higher leakage, and hence higher CO_2-equivalent emissions, because of boil-off losses associated with liquid-fuel transfers. The use of hydrogen made from water rather than from natural gas results in higher hydrogen leakage, and hence higher CO_2-equivalent emissions, because of the assumption that there are hydrogen pipelines in the case of hydrogen from water but not in the case of hydrogen from natural gas.

This analysis has explicit estimates of leakage from vehicular storage and fuel systems, fuel-cell stacks, fuel dispensing, other liquid-fuel transfers, pipeline distribution, pipeline transmission, and pipeline compressors. However, there are very few data on hydrogen leakage rates, and our assumptions may be substantially wrong. Note, too, that as regards comparing lifecycle GHG emissions from hydrogen fuel-cell vehicles with lifecycle GHG emissions from fossil-fuel internal-combustion-engine vehicles, we have not included emissions of hydrogen from the incomplete combustion of fossil fuels. We do not know the magnitude of this source, and hence do not know how the omission might affect the comparison.

Electricity generation: efficiency and mix of fuels,

The LEM projects the efficiency of electricity generation and the mix of fuels used for generic national power. Tables Y-15a and Y-15b show the projected efficiencies and fuel mixes. The efficiency of power generation and the mix of fuels used are important in lifecycles (such as battery electric vehicles) that have a significant electricity input.

Grams emitted per 10^6 BTU of fuel delivered to end users, by stage and feedstock/fuel combination.

Table Y-16 shows the calculated CO_2-equivalent emissions per unit of energy delivered to end users, by stage of the fuel cycle and feedstock/fuel combination. These results are useful mainly for the purpose of estimating emissions from the "upstream" portion of fuel lifecycles (i.e., the entire lifecycle except end use). For example, one can use the g/10^6-BTU results for the NG fuel cycle to estimate emissions from the use of NG for home heating. (One still must estimate emissions from final end-use combustion of the gas in the home, of course.) These results are shown for all countries and analysis years.

Table Y-18 shows the calculated emissions per unit of energy delivered to end users, by individual pollutant (without CO_2-equivalency weights) and feedstock/fuel combination. For economy of presentation, these results are shown for the U. S. 2010 case only. The importance of upstream emissions of individual pollutants can be understood better by relating these emissions to end use, which is done in the next section.

Upstream fuel cycle and material lifecycle emissions expressed relative to end-use emissions.

One can gain a better understanding of the magnitude of emissions from the upstream fuelcycle and emissions from the materials lifecycle by expressing them relative to end-use emissions from vehicles. Thus, Table Y-25 expresses upstream emissions of each pollutant as a percentage of end-use vehicular emissions of the pollutant (for the U. S. 2010 case) and Table Y-27 expresses emissions from the materials lifecycle and vehicle assembly and transport as a percentage of end-use vehicular emissions (also for the U. S. 2010 case).

These percentages are interesting in several respects. In all cases, upstream and materials-lifecycle emissions of CH_4 and SO_X equal or exceed vehicular emissions, usually by a wide margin. In most cases, upstream emissions of PM (BC+OM) exceed vehicular emissions. (A significant exception is that PM emissions from the materials lifecycle for HDDVs are a small fraction of PM emissions from HDDVs.) This is significant because all three are potent greenhouse gases, and because on a per-kg basis SO_X and PM are the most damaging of all urban pollutants (Delucchi, 2000).

Upstream fuelcycle emissions of CO and N_2O are relatively minor in the fossil-fuel lifecycles, but significant in the biofuel lifecycles. In the case of N_2O, the large emissions are due to the fixation of N or the use of N fertilizer. Material lifecycle emissions of CO and N_2O are relatively small compared with end-use vehicle emissions. Upstream and material-lifecycle emissions of NO_X and NMOCs generally are significant fractions of vehicular emissions, and in some fuel cycles (e.g., ethanol) exceed vehicular emissions. Upstream CO_2, NO_X, and CO_2-equivalent emissions are large in those fuel cycles in which fuel production is relatively energy intensive (such as ethanol, methanol, and hydrogen from natural gas).

My findings with regard to emissions of CO, NO_X, CH_4, and SO_2 from the "upstream" (or well-to-tank) lifecycle of fuels, expressed as a percentage of end-use (vehicular emissions), are similar to those in Van Mierlo et al. (2004). However, Van Mierlo et al. (2004) estimate lower upstream CO_2 and higher upstream NMOC emissions.

My findings with regards to emissions from the lifecycle of materials used in vehicles (Table Y-27) are similar to those in Maclean and Lave (1998) and Tahara et al. (2001). For example, Tahara et al. (2001) estimate that the lifecycle of automotive materials emits about 1.6 lbs of CO_2 per lb of vehicle, and that assembly emits about 1.0 lbs of CO_2 per lb of vehicle. I estimate that the lifecycle of materials emits about 1.5 lbs of CO_2 per lb of vehicle, and that assembly emits about 0.3 lbs of CO_2 per lb of vehicle. It is possible that my estimate of assembly energy do not account adequately for energy used to assemble parts at establishments not included in the automotive manufacturing sector.

Gram-per-mile emissions by vehicle/fuel/feedstock combination, and stage of the fuel cycle.

Table Y-19 presents the final g/mi results by vehicle/fuel/feedstock, and stage of the fuel cycle. The results are presented for all LDVs, all countries, and all analysis years.

Comparison of results with IPCC GWPs versus with CEFs estimated here

As indicated by eq. 1d, CO_2-equivalency factors (CEFs), which convert gases other than CO_2 to the amount of CO_2 with some equivalent effect on climate or the global economy, are an integral part of the calculation of CO_2-equivalent lifecycle emissions. Appendix D of the LEM main report documents the development of the CEFs used in the LEM (hereinafter referred to as "LEM CEFs"). As noted in Appendix D, the LEM CEFs differ in a number of important respects from the widely used CEFs – called "Global Warming Potentials," or GWPs – adopted by the Intergovernmental Panel on Climate Change (IPCC). The most important difference is that the IPCC has not formally estimated CEFs (qua GWPs) for CO, NMOCs, NO_X, SO_X, PM and H_2 (apart from accounting for the effect of CO and C in NMOCs oxidizing to CO_2), whereas we have (see Appendix D of the LEM documentation for details):

Pollutant	Our CEFs (yr. 2030)	IPCC 100-yr. GWPs
NMOC-C	3.664	3.664
NMOC-$0_3/CH_4$, SOA	3	not estimated
CH_4	14	23
CO	10	1.6
N_2O	300	296
NO_2	-4	not estimated
SO_2	-50	not estimated
PM (black carbon)	2,770	not estimated
CFC-12	13,000	8,600
HFC-134a	1,400	1,300
PM (organic matter)	-240	not estimated
PM (dust)	-22	not estimated
H_2	42	not estimated
CF_4	41,000	5,700
C_2F_6	92,000	11,900
HF	2000	not estimated

In addition, the IPCC GHG accounting methods ignore temporary carbon sequestration or emission due to changes in land use, whereas we do not. As we discuss below, the use of IPCC GWPs and methods rather than the LEM CEFs eliminates significant CO_2-equivalent emissions related to changes in land use.

How important are the differences between the LEM CEFs and the IPCC GWPs? In this section, we compare results from the LEM using LEM CEFs with results using IPCC GWPs, for a selected number of fuel lifecycles.

Results for the U. S. Table Y-28A presents this comparison for the U. S, for the year 2010. The table shows the percentage change in the g/mi emissions going from the IPCC g/mi results to the LEM CEF g/mi results, and two different measures of the percentage change in emissions relative to gasoline. As one would expect, there are significant differences in using IPCC GWPs rather than LEM CEFs in those cases where there are significant differences in emissions of the pollutants for which LEM CEFs differ significantly from IPCC GWPs – PM, SO_2, and (perhaps surprisingly) CO – or else significant emissions associated with changes in land use (which are counted in the LEM CEF case but not in the IPCC GWP case).

Three of the four lifecycles in which the differences between the IPCC-GWP results and the LEM-CEF results are large – diesel ICEVs, corn ethanol, and cellulosic ethanol – all involve significant emissions of PM or CO. The significant differences between the LEM CEF case and the IPCC GWP case for corn ethanol and cellulosic ethanol are due also to the different treatment of emissions related to changes in land use. This is discussed more in the next section.

The other lifecycle for which LEM CEFs and IPCC GWPs differ significantly is that of battery EVs using coal-based electricity. In this case, SO_2 emissions make lifecycle CO_2-equivalents significantly *lower* when using LEM CEFs as opposed to IPCC GWPs because the LEM CEF for SO_2 is negative. In fact, in the case of battery EVs from coal, pollutant-by-pollutant tests indicate that nearly 100% of the difference between the results with LEM CEFs and the results with IPCC GWPs is due to SO_2. PM emissions don't matter at all in this case because U.S. power plants are estimated to emit very low levels of PM in 2010, and because PM from coal boilers – unlike PM from diesel fuel – contains relatively little black carbon.

The case of diesel ICEVs warrants further comment. In this case, the impact of switching from LEM CEFs to IPCC GWPs depends almost entirely on emissions of PM from diesel LDVs relative to emissions of PM from gasoline LDVs. The LEM assumes that diesel LDV model years prior to 2005 have an order of magnitude larger PM emissions, but that model years 2005 and later have only twice the PM emissions of gasoline LDVs. In the cases analyzed here, diesel LDVs are estimated to be model year 2005, and hence to have relatively low PM emissions. Thus, in the cases presented here the difference between IPCC GWPs and LEM CEFs is only modest, albeit not trivial. However, if diesel LDV PM emissions are at least an order of magnitude higher than gasoline LDV PM emissions, then switching from IPCC GWPs to LEM CEFs changes the results for diesel vehicles from a significant reduction in lifecycle emissions compared with gasoline to a significant increase. In this case, whether or not one accounts for the warming impact of PM has a decisive impact on the overall attractiveness of diesel relative to gasoline. Of course, if one assumes that PM emissions from diesel LDVs are the *same* as PM from gasoline LDVs, then the LEM CEFs give roughly the same results as do the IPCC GWPs.

In all other cases analyzed, with one modest exception, the difference between using IPCC GWPs and LEM CEFs is relatively small. The modest exception is that in the case of FCEVs using hydrogen from water, life-cycle emissions are slightly higher with LEM CEFs than with IPCC GWPs. This is because a water-to-hydrogen system leaks modest amounts of hydrogen, which has a non-trivial impact on climate that is accounted for by LEM CEFs but not by IPCC GWPs. (Impacts of leaks of hydrogen are discussed further in section "Leaks of hydrogen" of this report.) However, this difference in lifecycle emissions does not materially affect the attractiveness of this hydrogen pathway compared with gasoline, because emissions are much lower than with gasoline regardless of the CEFs used.

<u>Results for other countries.</u> Parts B, C, and D of Table Y-28 show the comparison of LEM CEFs with IPCC GWPs for Japan, China, and Germany, again for the year 2010. The comparison for Japan is qualitatively similar to the comparison for the U. S. just discussed. Although there are major differences between total lifecycle emissions in Japan versus in the U. S., what is of interest here are emissions with LEM CEFs versus emissions with IPCC GWPs, and *those* differences vary far less from country to country

than do differences in absolute or total emissions. In this respect, only two differences between the results for Japan and the results for the U. S. are notable. First, there is less difference between gasoline and battery EVs using coal-based power in Japan than there is in the U. S, because coal in Japan is assumed to have less sulfur than in the U. S., and because coal-fired power plants in Japan are assumed to have tighter SO_2 emission controls than in the U. S. This results in lower SO_2 emissions in Japan and hence less of an effect due to the CEF for SO_2.

Second, hydrogen losses from the water-to-hydrogen system are more pronounced in Japan than in the U. S., and as a result whether or not one includes a CEF for hydrogen has a greater impact in Japan than in the U. S. However, the attractiveness of hydrogen relative to gasoline remains qualitatively the same in both countries regardless of the CEFs used.

The results for China (Y-28C) are interesting in several respects. First, in China the use of LEM CEFs rather than IPCC GWPs has an especially significant effect on lifecycle emissions of diesel fuel, cellulosic ethanol, and battery EVs from coal. In the case of diesel fuel, this is because the projected continued large emissions of PM from diesel-fuel vehicles in China. In the case of cellulosic ethanol, it is because of significant emissions related to changes in land use, counted in the LEM CEF case but not the IPCC GWP case. In the case of battery EVs from coal, it is because of the high level of SO_X emissions from power plants in China, which as mentioned above serve to significantly decrease lifecycle emissions in the LEM CEF case compared to the IPCC GWP case.

The results for Germany, shown in Table Y-28D, are sufficiently similar to the results already shown (especially to those for the U. S.) that no further discussion is warranted.

Notes on results for China. Kreucher et al. (1998) have estimated emissions of CO_2, SO_2, NO_x, CO, THC, and PM from the lifecycle of fuels and vehicles for several coal-based feedstock/fuel/vehicle combinations in China: coal to gasoline or methanol, coal to electricity, coal or coke-oven gas to methanol, byproducts to methanol, and (for comparison) crude oil to gasoline or diesel fuel. For these combinations, they show upstream fuelcycle emissions of each pollutant assuming state-of-the art emission factors, and also assuming EPA's AP-42 emission factors. We can compare our estimates of upstream fuelcycle emissions (in g/million BTU) with theirs for oil-to-gasoline, oil-to-diesel, coal-to-methanol, and gas-to-methanol. All of our upstream emission factors (all pollutants, all fuelcycles) are higher (in some cases, several-fold higher) than the "state-of-the-art" emission factors of Kreucher et al. (1998). Moreover, our estimates for CO_2, CO, NO_x, and (we infer) CH_4 in all cases are higher than the "EPA AP-42" emission factors of Kreucher et al. (1998). Our estimates of PM emissions lie between the Kreucher et al. (1998) "state-of-the-art" and "EPA AP-42") cases. We cannot readily explain the differences between the sets of estimates.

Comparison of results using IPCC methods for estimating emissions from land-use changes with results using our methods.

Our methods for estimating GHG emissions related to land-use changes are similar to those outlined by the IPCC (1997, chapter 5) except for this key difference: we use a time-varying discount rate with a very long time horizon (see Appendix D) whereas the IPCC apparently assumes a zero discount rate but suggests using a 100-year time horizon (e.g., IPCC, 1997, pp. 5-34 and 5-35). As discussed in Appendix D of Delucchi (2003), the value of the discount rate can have a significant effect on estimated CEFs. In this section, we will show that value of the discount rate also can have a significant effect on estimated GHG emissions related to land-use changes.

The Main Report of Delucchi (2003) provides a brief discussion of how the discount rate (and time horizon) affect GHG emissions related to land-use changes. Our methods and the IPCC methods both assume that any initial change in land use – say, the clearing of forest to plant crops – eventually is reversed when the program that gave rise to the initial change (planting crops, in our example here) is abandoned. Following abandonment, the carbon content of the soils and biomass begins a gradual return to the original values (in our example, those of a forest). If the discount rate is zero and the carbon content after reversion is the same as the original carbon content (and if the complete reversion occurs within the time horizon – 100 years in the IPCC recommendations), then the *net* carbon emission due to the program is zero. However, if the discount rate is not zero, then the present value of the future carbon gain following reversion is less than the value of the carbon loss at the start of the program, resulting in a non-zero net emission due to the program.

As shown in the LEM main report, emissions related to changes in land use can be significant in biofuel lifecycles. As a result, whether one uses the LEM CEFs (which incorporate a non-zero discount rate, and hence count emissions related to land-use changes) or the IPCC GWPs (which ignore emissions related to changes in land use) can have a big impact on absolute and relative emissions in biofuel lifecycles. Indeed, much of the difference between the LEM CEF results and the IPCC GWP results for biofuel lifecycles in Tables Y-28 A, B, C, and D are due to just this difference in the treatment of emissions related to changes in land use.

Uncertainty in important parameter values

All parameter values are uncertain to some degree. In some cases, the uncertainty is great enough, and the parameter values important enough, to significantly affect the certainty of the overall results. The most important uncertainties in this analysis are:

- The CO_2-equivalency factors (CEFs) for all non-CO_2 greenhouse gases. The uncertainty in the CEFs for CH_4, N_2O, N (as NO_x, or nitrogen in fertilizer), SO_2, and PM can have a significant effect on the overall results. The uncertainty in the CEFs for CO and NMOCs is less important: varying these CEFs over their likely range of values does not significantly affect the results. See Appendix D of Delucchi (2003) and the comparison of our CEFs with IPCC GWPs in this report for further discussion.
- Efficiency of end use. In all fuel cycles, the efficiency of energy end use is important and still uncertain. In particular, in the EV cycle, the major uncertainty remains the relative energy use of EVs (both BPEVs and FCEVs) although the new energy-use model described briefly in Appendix G of Delucchi (2003) has helped to narrow that uncertainty. The effect of the mix of fuels used to generate power is reasonably well reflected in the regional results.

There also is non-trivial uncertainty in the composition and cycle life of batteries for EVs. The cycle life is important because the shorter the cycle life (in miles of travel), the higher the g/mi lifetime emissions.

- The evolution of fuel-production technology. Generally, I have assumed that production processes will continue to get more efficient, and gradually switch from high-emitting to low-emitting process fuels. Historically there is some justification for these assumptions. For example, in the 1980s, high fuel prices led to considerable improvements in the fuel efficiency of corn-to-ethanol conversion processes, and environmental and other considerations spurred a switch from coal to natural gas. It is not clear, however, to what extent these trends can be expected to continue. And the problem of prediction is even more difficult for those technologies, such as wood-to-ethanol, that are still being developed.
- Emissions related to changes in cultivation and land use. In the biomass fuel cycles, the most uncertain and important parameters, aside from those mentioned above, are those that represent which land uses (e.g., forests, pasture land, or agricultural land) are replaced by which energy crop systems (corn, soybeans, switchgrass, or SRIC trees), and those pertaining to N_2O emission related to nitrogen fertilizer inputs. In some cases (e.g., the biodiesel fuel cycle), uncertainty regarding N inputs can have an enormous impact on fuel cycle CO_2-equivalent emissions.
- The effect of quantity changes on prices and hence demand and, ultimately, supply in other markets. In a few instances I account, crudely, for economic effects in the markets for products related to the co-products of fuel cycles (e.g., in markets for electricity affected by the generation of power from excess lignin in biomass-to-ethanol plants). The values of these parameters are uncertain and can significantly affect fuelcycle CO_2-equivalent emissions. (See the longer discussion above, and the exploratory discussion in Delucchi [2002].)

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Appendix A: Energy use and emissions from the lifecycle of diesel-like fuels derived from biomass (20 pp.)
Appendix B: Data for other countries (81 pp.)
Appendix C: Emissions related to cultivation and fertilizer use (73 pp.)
Appendix D: CO_2-equivalency factors (115 pp.)
Appendix E: Data on methane emissions from natural gas production, oil production, and coal mining (24 pp.)
Appendix F: Emissions of nitrous oxide and methane from alternative fuels for motor vehicles and electricity-generating plants in the U. S. (74 pp.)
Appendix G: Parameters calculated with the EV and ICEV energy-use and lifecycle-cost model (8 pp.)
Appendix H: The lifecycle of materials (103 pp.)
Appendix J: Emission factors for heavy-duty diesel vehicles (~ 25 pp.)
Appendix Y: Some results from the LEM (~ 50 pp.)
Appendix Z: References to the Main Report (47 pp.)

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TABLE Y-10B. CALCULATED VEHICLE WEIGHT OF FUEL, FUEL STORAGE, AND ICE VEHICLES (U. S. 2010)

	Gas-oline	Diesel	Soy-diesel	Diesel mix	MeOH	CNG	LNG	CH2	LH2	Ethanol	LPG
Weight of fuel, LDVs (lbs)	90.5	87.0	n.a.	n.a.	122.1	51.6	61.3	13.9	17.1	116.9	64.8
Weight of fuel, HDVs (lbs)	1,400	1,284	1,613	1,281	2,237	1,000	1,092	241	302	1,863	1,267
Weight of fuel-storage system, LDVs (lbs)	36.5	35.1	n.a.	n.a.	44	232	98	167	102	42	86
Weight of fuel-storage system, HDVs (lbs)	252	231	290	231	358	3,219	1,256	2,072	1,206	298	951
Weight of vehicle without fuel, tank, payload, LDVs (lbs)	3,219	3,328	n.a.	n.a.	3,223	3,234	3,222	3,224	3,218	3,222	3,221
Weight of vehicle without fuel, tank, payload, HDVs (lbs)	31,279	31,485	31,524	31,265	31,373	31,536	31,348	31,345	31,264	31,330	31,335
Curb wt. of reference, and extra wt. relative to reference, with 300-lb payload & fuel, LDVs (lbs)	3,641	105	n.a.	n.a.	43	173	36	59	(8)	35	27
Curb wt. of reference, and extra wt. relative to reference, with payload & fuel, HDVs (lbs)	(69)	35,350	428	(223)	968	2,755	696	658	(228)	491	553

Notes: see next page.

MeOH = methanol, CNG = compressed natural gas, LNG = liquefied natural gas, CH2 = compressed hydrogen, LH2 = liquefied hydrogen, LPG = liquefied petroleum gases.

1) The gasoline LDV is the LDV reference. The diesel HDV is the HDV reference.

2) The fuel weight is calculated from the range, fuel economy, and fuel characteristics.

3) The weight of the fuel storage system is equal to lbs of fuel multiplied by lb-storage-system/lb-fuel.

4) The curb weight of the gasoline LDV is calculated automatically based on a statistical relationship between weight and combined city/highway mpg. The weight of the gasoline LDV without fuel, etc. is equal to the curb weight minus the assumed 300-lb payload minus the weight of fuel and fuel-storage.

5) The extra weight of an AFV is equal to the difference in fuel-system and powertrain weight, multiplied by a weight compounding factor.

6) All LDVs have a 300-lb payload. All HDVs have the same, unspecified payload.

TABLE Y-11. CALCULATED VEHICLE ENERGY USE (U. S. 2010)

	Relative mi/MMBTU		**MMBTU/mile**		**MPG equivalent**		**Efficiency**	**bhp-hr/mi**
	LDVs	*HDVs*	*LDVs*	*HDVs*	*LDVs*	*HDVs*	*HDVs*	*HDVs*
ICE Vehicles								
Conventional gasoline	1.0000	0.7557	0.00484	0.0558	25.8	2.5	0.274	6.018
Conventional diesel (including F-T diesel)	1.2881	1.0000	0.00376	0.0422	33.3	3.3	0.363	6.022
SD100	n.a.	0.9014	n.a.	0.0468	n.a.	3.0	0.327	6.010
Methanol active in model (M85)	1.0636	n.a.	0.00455	n.a.	27.5	n.a.	n.a.	n.a.
M100	1.0857	0.9652	0.00446	0.0437	28.0	3.2	0.354	6.072
NGV active in model (CNG)	1.0266	0.8305	0.00472	0.0508	26.5	2.7	0.309	6.166
CNG	1.0266	0.8305	0.00472	0.0508	26.5	2.7	0.309	6.166
LNG	1.0363	0.8454	0.00467	0.0499	26.8	2.8	0.309	6.058
Compressed hydrogen (CH2)	1.1472	1.0069	0.00422	0.0419	29.6	3.3	0.368	6.056
Liquified hydrogen (LH2)	1.1673	1.0361	0.00415	0.0407	30.2	3.4	0.376	6.010
Ethanol active in model (E90 (corn))	1.0741	n.a.	0.00451	n.a.	27.7	n.a.	n.a.	n.a.
E100	1.0863	0.9691	0.00446	0.0435	28.1	3.2	0.354	6.047
LPG	1.0370	0.8464	0.00467	0.0498	26.8	2.8	0.309	6.050
Electric vehicles								
Battery-powered EVs (from outlet)	3.3529	n.a.	0.00144	n.a.	86.6	n.a.	n.e.	n.e.
Gasoline fuel-cell vehicle	1.6875	1.3478	0.00287	0.03129	43.6	4.4	n.e.	n.e.
Methanol (M100) fuel-cell vehicle	1.7128	1.3613	0.00283	0.03098	44.3	4.5	n.e.	n.e.
Ethanol (E100) fuel-cell vehicle	1.6782	1.3359	0.00288	0.03157	43.4	4.4	n.e.	n.e.
Hydrogen (CH2) fuel-cell vehicle	2.3445	1.8499	0.00206	0.02280	60.6	6.1	n.e.	n.e.
Hydrogen (LH2) fuel-cell vehicle	2.3680	1.8730	0.00204	0.02251	61.2	6.2	n.e.	n.e.

Notes: see next page.

bhp-hr = is brake horsepower-hour. ICE = internal combustion engine, E100 = 100% ethanol, M100 = 100% ethanol, SD100 = 100% soy biodiesel.

1) "LDVs" refers to gasoline application, "HDVs" to diesel application

2) The relative thermal efficiency of alcohol/gasoline and soy/diesel mixtures is proportional to the alcohol or soy share of total energy.

3) The alcohol vehicle is designed to meet range requirement on the "active" alcohol/gasoline mix.

The vehicle so designed is used as the basis for calculating the M100 andE100 effciency, too.

4) MPG equivalent is with respect to diesel (for HDVs) and conventional gasoline (for LDVs).

5) "Efficiency" for HDVs is brake-kJ/fuel-kJ energy efficiency.

TABLE Y-12A. CALCULATED EMISSIONS FROM LIGHT-DUTY ICEVS (G/MI, EXCEPT AS NOTED) (BEST CEFS) (U. S. 2010)

Pollutant	CG	RFG	ULSD	M100	M85	CNG	CH2	E100	E90	LPG	Gas mix
Fuel evaporation or leakage	0.40	0.34	0.02	0.43	0.41	0.09	0.09	0.22	0.23	0.19	0.34
NMOC exhaust	0.56	0.39	0.28	0.51	0.48	0.12	0.01	0.51	0.49	0.28	0.39
Evaporation +NMOC exhaust	0.96	0.73	0.30	0.93	0.89	0.21	0.10	0.72	0.73	0.47	0.73
Carbon in evap. + NMOC exh.	0.82	0.61	0.26	0.36	0.42	0.16	0.01	0.39	0.42	0.38	0.61
Ozone-weighted total NMOC	0.86	0.63	0.17	0.28	0.36	0.07	0.00	0.45	0.48	0.19	0.63
CH4 exhaust	0.044	0.044	0.022	0.022	0.027	0.665	0.002	0.066	0.064	0.044	0.044
CO exhaust	7.3	5.9	1.5	4.4	4.7	4.4	0.2	4.4	4.6	4.4	5.9
N2O exhaust	0.060	0.060	0.015	0.060	0.060	0.045	0.000	0.060	0.060	0.060	0.060
NOx as NO2 exhaust	0.82	0.70	1.24	0.74	0.73	0.74	0.74	0.74	0.74	0.74	0.70
SOx as SO2 (incl. lube oil)	0.070	0.008	0.003	0.004	0.005	0.001	0.001	0.003	0.004	0.002	0.008
PM exhaust	0.023	0.023	0.046	0.009	0.012	0.005	0.005	0.009	0.011	0.006	0.023
Non-CO2 C in fuel and lube	4.01	3.18	0.94	2.27	2.48	2.55	0.08	2.33	2.44	2.30	3.18
Non-CO2 C in lube oil	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00
CO2 from fuel	328.1	328.9	268.5	276.3	288.6	242.4	5.14	292.4	297.0	285.1	328.9
CO2 biofuel credit	n.a.	n.a.	n.a.	(276.3)	(211.8)	(242.4)	n.a.	(292.4)	(255.1)	n.a.	n.a.
CO2 from fuel (g/10^6 BTU)	*67,777*	*67,928*	*71,444*	*61,956*	*63,396*	*51,409*	*1,218*	*65,600*	*65,898*	*61,065*	*67,928*
SO2 from fuel (g/10^6 BTU)	*14.51*	*1.60*	*0.85*	*0.90*	*1.07*	*0.28*	*0.26*	*0.74*	*0.86*	*0.47*	*1.60*
CO2 equivalents											
Non-CO2 gases	107.7	94.8	84.7	63.4	70.7	66.9	1.40	64.7	68.6	63.1	94.8
CO2 biofuel credit	n.a.	n.a.	n.a.	(8.3)	(6.4)	(9.3)	n.a.	(8.5)	(7.5)	n.a.	n.a.
Total CO2*+nonCO2	***435.8***	***423.7***	***353.2***	***339.6***	***359.2***	***309.3***	***6.5***	***357.1***	***365.6***	***348.2***	***423.7***

Table Y-12a continued.

Road dust, brakewear, tirewear

PM10 road dust	0.398	0.398	0.408	0.402	0.401	0.414	0.404	0.402	0.401	0.401	0.398
PM10 brake wear	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
PM10 tire wear	0.007	0.007	0.008	0.007	0.007	0.008	0.008	0.007	0.007	0.007	0.007
PM10 total	0.419	0.419	0.428	0.423	0.422	0.435	0.424	0.422	0.422	0.421	0.419
PM2.5 total	0.064	0.064	0.066	0.065	0.065	0.067	0.065	0.065	0.065	0.065	0.064
CO2 equivalent	(3.0)	(3.0)	(3.1)	(3.0)	(3.0)	(3.1)	(3.1)	(3.0)	(3.0)	(3.0)	(3.0)

Notes:

CG = conventional gasoline, RFG = reformulated gasoline, ULSD = ultra-low-sulfur diesel, gas mix = mix of gasolines used in off-road vehicles.

*Total CO2 excludes CO2 from lube-oil combustion, which is itemized separately. Non-CO2 total includes non-CO2 from lube-oil, however.

1) Assumes 100% methanol in HD application.

2) Emissions from gasoline vehicles, methanol FFVs, and ethanol FFVs automatically reflect whether conventional or reformulated

gasoline is used, and the amount of methanol or ethanol in mixture.

3) SOx emissions are calculated assuming that the sulfur in lube oil and fuel is oxidized to SO2. I assume that hydrogen has no sulfur.

4) CH4 emissions from methanol FFVs are assumed to be proportional to the gasoline content of the fuel.

5) "HD" and "diesel" should be interpreted as "compression-ignition".

6) Vehicular evaporative emissions include diurnal, hot-soak, resting-loss, running-loss, boil-off, and gas-leakage emissions.

Upstream evaporative emissions comprise evaporative emissions from storage, distribution, and dispensing.

7) The CO2 credit for biofuels accounts for biomass origin of carbon in organic emissions. Credit for ethanol if RFG is taken but not shown on separate line.

8) Any emissions from an EV heater are included under "CO2 from fuel".

9) Evaporative emissions of CNG, LNG, H2, and LPG are assumed to have the chemical composition of the fuel. LH2 is assumed to be pure H2. The CEF is calculated on the basis of this composition.

10) Methodological note regarding CEF of evaporative emissions/leaks from biofuels: for liquid fuels, which are all NMOCs, the CEF is just the ozone-formation/ methane-enhancement effect. For gaseous fuels, the CEF includes that, plus the effect of non-NMOC components (namely, methane and CO), net of carbon-fixation.

11) NMOC, CO, and PM emissions from hydrogen vehicles are from lubricating oil. Lubricating-oil values for ozone reactivity and PM composition are used.

TABLE Y-13A. ENERGY INTENSITY: BTUS OF PROCESS ENERGY CONSUMED PER NET BTU OF FUEL TO END USERS (U. S. 2010)

Fuel -->	Coal	CG	RFG	Diesel	FTD	Fuel oil	Stillgas	Coke	LPG	LPG	CNG	Nuclear
Feedstock ---->	*Coal*	*oil*	*oil*	*oil*	*NG*	*oil*	*oil*	*oil*	*NG*	*oil*	*NG*	*uranium*
Fuel dispensing	n.a.	0.0018	0.0018	0.0018	0.0018	0.0019	n.a.	n.a.	0.0018	0.0018	0.0221	n.a.
Fuel distribution	n.a.	0.0072	0.0073	0.0074	0.0128	0.0098	n.a.	n.a.	0.0073	0.0073	0.0463	n.a.
Fuel production	n.a.	0.1415	0.1520	0.0777	1.6464	0.0438	n.a.	n.a.	0.0265	0.0527	0.0177	0.0185
Feedstock transmission	0.0069	0.0122	0.0111	0.0125	0.0187	0.0130	0.0110	0.0164	feed rec.	0.0122	fuel dist.	0.0002
Feedstock recovery	0.0070	0.0533	0.0484	0.0549	0.0645	0.0570	0.0482	0.0719	0.0254	0.0533	0.0243	0.0060
Ag. chemicals	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Fuel -->	CH2	CH2	MeOH	MeOH	MeOH	SCG	Ethanol	Ethanol	Biodies.	Grass	Wood
Feedstock ---->	*water*	*NG*	*NG*	*coal*	*wood*	*wood*	*wood/gra.*	*corn*	*soy*	*grass*	*wood*
Fuel dispensing	0.0855	0.0855	0.0037	0.0037	0.0037	0.0221	0.0028	0.0028	0.0021	n.a.	n.a.
Fuel distribution	0.0599	0.0000	0.0267	0.0205	0.0176	0.0411	0.0150	0.0135	0.0100	n.a.	n.a.
Fuel production	power	1.2500	1.5222	1.5024	1.8395	1.3945	2.1231	0.5095	0.4057	n.a.	n.a.
Feedstock transmission	power	0.0552	0.0173	0.0115	0.0190	0.0147	0.0194	0.0285	0.0185	0.0092	0.0108
Feedstock recovery	power	0.0508	0.0597	0.0104	0.0331	0.0255	0.0402	0.0849	0.2032	0.0191	0.0188
Ag. chemicals	n.a.	n.a.	n.a.	n.a.	0.0168	0.0130	0.0789	0.1888	0.4150	0.0374	0.0095

Fuel -->	CH2	CH2
Feedstock ---->	*wood*	*coal*

Fuel dispensing	0.0855	0.0855
Fuel distribution	0.0399	0.0499
Fuel production	1.7085	1.5912
Feedstock transmission	0.0182	0.0120
Feedstock recovery	0.0317	0.0109
Ag. chemicals	0.0161	n.a.

Notes: see next page

CG = conventional gasoline; RFG = reformulated gasoline; Coke = petroleum coke; CNG = compressed natural gas; LNG = liquefied natural gas; CH2 = compressed hydrogen; LH2 = liquefied hydrogen; SCG = synthetic compressed gas; SLG = synthetic liquefied gas; LPG = liquefied petroleum gas; n.a = not applicable.

*For wood-to-plant cycle, the results are BTU process energy/BTU wood to plant.

1) For nuclear/uranium, "Fuel production" refers to conversion, enrichment, and fabrication.

2) Electricity use (e.g., for CNG compressors) is counted at 3412 Btu/kWh.

3) Pipeline distribtion factor is higher for bio-NG than for fossil NG, because batches and pipelines probably will be smaller.

4) CO2 emissions from methanol, H2, FTD, and syncrude plants are estimated on the basis of the difference between carbon in and carbon out.

5) The figure for fuel production for F-T diesel, methanol, and ethanol from wood or grass, includes includes the energy value of the feedstock.

6) Fuel loss and fuel own-use (shown below) are accounted for in the figures shown here.

7) No co-product emission-displacement credits taken here.

8) "Ag chemical manufacture" includes use of pesticides and herbicides and other chemicals. Note that ag. chem. results are used only in BTU/mi figures shown below.)

9) Assumes that fuel-delivery trucks fill up at bulk terminals, not fuel stations, so that they do not deliver their own fuel.

10) The transportation requirement for corn-ethanol includes any transport of residue.

11) Energy to make methanol, ethanol, or NGLs for MTBE, ETBE is not included here in figures for gasoline, but is accounted for elsewhere. However, the volumetric reduction due to addition of methanol, ethanol, MTBE, or ETBE, is accounted for here.

12) The figures here do not include energy used to make concrete to plug oil wells.

13) For CNG and LNG, all NG shipment is under "Fuel distribution"; for methanol and hydrogen, it is under "Feedstock transmission". Distribution of LNG, SLNG or LH2/water from a centralized site to a refueling station is *not* accounted for in this table, but is accounted for in the final results.

14) CH2 from NG and CNG from NG are assumed to be made at the site of refueling. H2 from water is made at centralized facility and piped as H2 to station. LNG and LH2 can be made at central site and piped to station as H2; or can be made at refueling station from piped in NG.

15) For NGTLs, feedstock recovery includes NGL removal plant. However, this is used only in BTU/mile table; in final g/BTU calculations, recovery and NGL plant are separate.

16) "Fuel production" stage here does not include energy required to make any chemicals (used, for example, in the wood-to-ethanol process).

17) "Dispensing" stage here includes compression and liquefaction of gases, even if that occurs at centralized facilities apart from refueling sites.

TABLE Y-13B. ENERGY CONSUPMTION OF FUELCYCLES: BTUS OF PROCESS ENERGY CONSUMED PER MILE OF TRAVEL BY VEHICLES (U. S. 2010)

Fuel --> Feedstock ---->	CG *oil*	ULSD *oil*	F-T Diesel *NG*	SD100 *soy*	LPG *NG*	LPG *oil*	CNG *NG*
End use	4,841	42,170	42,170	46,784	4,669	4,669	4,716
Fuel dispensing	9	77	74	96	9	9	104
Fuel distribution, storage	35	311	539	467	34	34	219
Fuel production	736	3,275	69,429	18,982	124	246	84
Feedstock transmission	54	529	789	865	0	57	0
Feedstock recovery	235	2,315	2,722	9,509	118	249	115
Ag. chemical manufacture	0	0	0	19,417	0	0	0
Total	*5,909*	*48,678*	*115,723*	*96,120*	*4,953*	*5,263*	*5,237*

Fuel --> Feedstock ---->	CH2 *NG*	CH2 *coal*	M100 *NG*	M100 *coal*	M100 *wood*	SCG *wood*	E100 *wood/grass*	E100 *corn*
End use	4,220	4,220	4,459	4,459	4,459	4,716	4,457	4,457
Fuel dispensing	361	361	16	16	16	104	12	12
Fuel distribution,	0	211	119	92	79	194	67	60

storage								
Fuel production	1,055	2,495	2,329	2,240	3,744	1,861	5,005	2,271
Feedstock transmission	233	51	77	51	85	69	87	127
Feedstock recovery	214	46	266	47	148	120	179	378
Ag. chemical manufacture	0	0	0	0	75	61	352	841
Total	*6,084*	*7,383*	*7,266*	*6,905*	*8,606*	*7,125*	*10,159*	*8,147*

Notes: See Table Y-13a. Diesel, F-T diesel, and SD100 are used in HDVs; all other fuels are used in LDVs.

TABLE Y-15A. LEM-CALCULATED EFFICIENCY OF ELECTRICITY GENERATION, BY FUEL TYPE

U. S. 2010

Coal	Oil	Gas boiler	Gas turbine	Nuclear	MeOH	H2	Biomass
0.326	*0.345*	*0.458*	*0.458*	*n.a.*	*0.458*	*0.458*	*0.247*

U. S. 2050

Coal	Oil	Gas boiler	Gas turbine	Nuclear	MeOH	H2	Biomass
0.359	*0.351*	*0.514*	*0.514*	*n.a.*	*0.514*	*0.514*	*0.378*

Japan 2010

Coal	Oil	Gas boiler	Gas turbine	Nuclear	MeOH	H2	Biomass

0.450	*0.441*	*0.392*	*0.505*	*n.a.*	*0.392*	*0.425*	*0.469*

Japan 2050

Coal	Oil	Gas boiler	Gas turbine	Nuclear	MeOH	H2	Biomass
0.488	*0.477*	*0.441*	*0.526*	*n.a.*	*0.441*	*0.539*	*0.596*

Note: In all cases, efficiency is defined to be BTUs of power out of the plant for sale to the grid divided by BTUs of fuel input to the plant (HHV).

China 2010

Coal	Oil	Gas boiler	Gas turbine	Nuclear	MeOH	H2	Biomass
0.329	*0.339*	*0.334*	*0.468*	*n.a.*	*0.331*	*0.425*	*0.205*

China 2050

Coal	Oil	Gas boiler	Gas turbine	Nuclear	MeOH	H2	Biomass
0.386	*0.397*	*0.392*	*0.549*	*n.a.*	*0.373*	*0.539*	*0.261*

Germany 2010

Coal	Oil	Gas boiler	Gas turbine	Nuclear	MeOH	H2	Biomass
0.377	*0.430*	*0.392*	*0.505*	*n.a.*	*0.392*	*0.425*	*0.355*

Germany 2050

Coal	Oil	Gas boiler	Gas turbine	Nuclear	MeOH	H2	Biomass
0.409	*0.466*	*0.441*	*0.526*	*n.a.*	*0.441*	*0.539*	*0.451*

Note: In all cases, efficiency is defined to be BTUs of power out of the plant for sale to the grid divided by BTUs of fuel input to the plant (HHV).

TABLE Y-15B. SOURCE OF ELECTRICITY, BY TYPE OF GENERATING PLANT, FOR GENERIC POWER

U. S. 2010

Coal	Oil	Gas boiler	Gas turbine	Nuclear	MeOH	H2	Biomass	Hydro	Other
0.504	0.008	0.149	0.103	0.135	0.000	0.000	0.016	0.078	0.007

U. S. 2050

Coal	Oil	Gas boiler	Gas turbine	Nuclear	MeOH	H2	Biomass	Hydro	Other
0.406	0.003	0.210	0.209	0.018	0.000	0.000	0.094	0.045	0.016

Japan 2010

Coal	Oil	Gas boiler	Gas turbine	Nuclear	MeOH	H2	Biomass	Hydro	Other
0.191	0.089	0.154	0.118	0.330	0.000	0.000	0.021	0.092	0.004

Japan 2050

Coal	Oil	Gas boiler	Gas turbine	Nuclear	MeOH	H2	Biomass	Hydro	Other
0.162	0.010	0.112	0.149	0.415	0.000	0.000	0.056	0.084	0.012

China 2010

Coal	Oil	Gas boiler	Gas turbine	Nuclear	MeOH	H2	Biomass	Hydro	Other
0.763	0.023	0.002	0.007	0.018	0.000	0.000	0.002	0.184	0.000

China 2050

Coal	Oil	Gas boiler	Gas turbine	Nuclear	MeOH	H2	Biomass	Hydro	Other
0.450	0.003	0.000	0.409	0.030	0.000	0.000	0.014	0.093	0.000

Germany 2010

Coal	Oil	Gas boiler	Gas turbine	Nuclear	MeOH	H2	Biomass	Hydro	Other
0.490	0.006	0.032	0.104	0.245	0.000	0.000	0.025	0.048	0.049

Germany 2050

Coal	Oil	Gas boiler	Gas turbine	Nuclear	MeOH	H2	Biomass	Hydro	Other
0.083	0.000	0.007	0.085	0.023	0.000	0.000	0.020	0.012	0.771

TABLE Y-16A. CO$_2$-EQUIVALENT EMISSIONS PER UNIT OF ENERGY DELIVERED TO END USERS, BY STAGE AND FEEDSTOCK/FUEL COMBINATION (G/10^6-BTU): U. S. 2010 AND 2050

A1. U. S. 2010

Fuel ------>	**Coal**	**CG**	**RFG**	**ULSD**	**FTD**	**Fuel oil**	**Still gas**	**Coke**	**LPG**	**LPG**	**LPG**	**CNG**
Feedstock ------>	*coal*	*oil*	*oil*	*oil*	*NG*	*oil*	*oil*	*oil*	*oil*	*NGL57*	*NG*	*NG*
Fuel dispensing	0	412	411	355	344	369	0	0	392	392	392	4,308
Fuel distribution, storage	0	1,085	1,081	924	1,381	1,143	0	0	1,123	1,123	1,123	3,460
Fuel production	0	12,133	13,125	6,631	19,004	3,552	0	0	4,074	2,764	1,759	1,178
Feedstock transmission	804	2,302	2,091	2,370	1,401	1,257	2,082	1,586	2,235	971	0	0
Feedstock recovery	1,371	5,334	4,843	5,490	4,443	5,697	4,824	7,185	5,334	3,324	1,780	1,705
Land-use, cultivation*	46	0	0	0	0	0	0	0	0	0	0	0
Fertilizer manufacture	0	0	0	0	0	0	0	0	0	0	0	0
Gas leaks and flares**	2,099	(691)	(627)	(711)	2,259	(761)	(645)	(960)	(691)	433	1,297	4,664
CO2, H2S from NG^	0	0	0	0	442	0	0	0	0	209	369	373
Emissions displaced	(384)	0	0	0	(1,789)	0	0	0	0	0	0	0
Total	*3,937*	*20,576*	*20,924*	*15,059*	*27,485*	*11,257*	*6,261*	*7,811*	*12,467*	*9,217*	*6,719*	*15,689*

Notes: see end of all Y-16 tables.

A1. U. S. 2010 continued.

Fuel ------>	**Nuclear#**	**CH2**	**CH2**	**MeOH**	**MeOH**	**MeOH**	**Ethanol**	**Ethanol**	**SCG**	**Biodies.**	**Grass**	**Wood**
Feedstock ------>	*uranium*	*water*	*NG*	*NG*	*coal*	*wood*	*corn*	*Grass*	*wood*	*soy*	*grass*	*wood*
Fuel dispensing	0	16,691	16,691	744	744	551	556	424	3,268	402	0	0
Fuel distribution, storage	0	839	0	2,960	2,748	2,430	2,090	2,150	1,279	1,519	0	0
Fuel production	3,836	3,298	71,074	17,692	17,624	14,195	49,480	16,894	6,359	40,765	0	0
Feedstock transmission	30	0	4,176	1,293	1,378	3,162	3,739	3,225	2,437	2,979	1,528	1,791
Feedstock recovery	912	0	3,480	4,100	2,032	8,633	17,768	10,453	6,654	50,147	4,953	4,889
Land-use, cultivation*	0	0	0	0	68	(5,154)	50,568	14,102	(3,972)	166,253	6,682	(2,919)
Fertilizer manufacture	0	0	0	0	0	3,134	17,011	8,434	2,415	34,191	3,996	1,775
Gas leaks and flares**	0	6,189	7,467	2,085	3,111	0	0	0	3,754	0	0	0
CO2, H2S from NG	0	0	451	408	0	0	0	0	0	0	0	0
Emissions displaced	0	0	0	0	0	0	(28,142)	(8,375)	0	(84,278)	0	0
Total	*4,778*	*27,017*	*103,339*	*29,282*	*27,705*	*26,952*	*113,069*	*47,307*	*22,194*	*211,978*	*17,160*	*5,536*

Notes: see end of all Y-16 tables.

A1. U. S. 2010 continued.

Fuel ------> *Feedstock ------>*	**CH2** *wood*	**CH2** *coal*
Fuel dispensing	16,691	16,691
Fuel distribution, storage	560	699
Fuel production	4,143	32,668
Feedstock transmission	3,027	1,441
Feedstock recovery	8,265	2,125
Land-use, cultivation*	(4,934)	72
Fertilizer manufacture	3,000	0
Gas leaks and flares**	5,716	9,256
CO2, H2S from NG	0	0
Emissions displaced	0	0
Total	*36,468*	*62,951*

Notes: see end of all Y-16 tables.

A2. U. S. 2050

Fuel ------>	**Coal**	**CG**	**RFG**	**ULSD**	**FTD**	**Fuel oil**	**Still gas**	**Coke**	**LPG**	**LPG**	**LPG**	**CNG**
Feedstock ------>	*coal*	*oil*	*oil*	*oil*	*NG*	*oil*	*oil*	*oil*	*oil*	*NGL57*	*NG*	*NG*
Fuel dispensing	0	341	344	319	309	331	0	0	337	337	337	3,864
Fuel distribution, storage	0	1,130	1,139	1,059	1,120	1,233	0	0	817	817	817	3,598
Fuel production	0	11,264	12,043	6,131	9,591	3,193	0	0	3,733	2,505	1,561	1,041
Feedstock transmission	747	2,035	1,848	2,097	1,200	1,156	1,842	1,458	1,978	859	0	0
Feedstock recovery	1,264	5,288	4,802	5,448	4,045	5,653	4,786	7,131	5,289	3,403	1,954	1,865
Land-use, cultivation*	56	0	0	0	0	0	0	0	0	0	0	0
Fertilizer manufacture	0	0	0	0	0	0	0	0	0	0	0	0
Gas leaks and flares**	989	(2,456)	(2,230)	(2,530)	1,196	(2,617)	(2,216)	(3,302)	(2,456)	(633)	768	2,647
CO2, H2S from NG^	0	0	0	0	443	0	0	0	0	234	414	417
Emissions displaced	(276)	0	0	0	(2,375)	0	0	0	0	0	0	0
Total	*2,780*	*17,603*	*17,946*	*12,525*	*15,528*	*8,949*	*4,413*	*5,288*	*9,698*	*7,522*	*5,851*	*13,434*

Notes: see end of all Y-16 tables.

A2. U. S. 2050 continued.

Fuel ------>	**Nuclear#**	**CH2**	**CH2**	**MeOH**	**MeOH**	**MeOH**	**Ethanol**	**Ethanol**	**SCG**	**Biodies.**	**Grass**	**Wood**
Feedstock ------>	*uranium*	*water*	*NG*	*NG*	*coal*	*wood*	*corn*	*Grass*	*wood*	*soy*	*grass*	*wood*
Fuel dispensing	0	14,942	14,942	656	656	487	494	373	2,904	361	0	0
Fuel distribution, storage	0	728	0	2,379	2,053	1,693	1,433	1,471	750	1,046	0	0
Fuel production	3,035	2,857	65,585	10,361	11,181	12,283	43,068	11,380	4,339	32,427	0	0
Feedstock transmission	21	0	4,082	1,128	918	1,619	2,352	1,458	1,361	1,727	948	1,110
Feedstock recovery	718	0	3,297	3,803	1,509	4,053	10,715	4,363	3,407	29,208	2,835	2,779
Land-use, cultivation*	0	0	0	0	67	(9,983)	38,068	8,330	(8,392)	131,356	5,412	(6,845)
Fertilizer manufacture	0	0	0	0	0	1,991	12,401	4,704	1,674	28,934	3,056	1,365
Gas leaks and flares**	0	3,846	4,317	1,124	1,181	0	0	0	2,277	0	0	0
CO2, H2S from NG	0	0	474	417	0	0	0	0	0	0	0	0
Emissions displaced	0	0	0	0	0	0	(17,169)	(23,780)	0	(84,278)	0	0
Total	*3,775*	*22,373*	*92,697*	*19,868*	*17,566*	*12,142*	*91,362*	*8,299*	*8,320*	*140,780*	*12,251*	*(1,591)*

Notes: see end of all Y-16 tables.

A2. U. S. 2050 continued.

Fuel ------> *Feedstock ------>*	**CH2** *wood*	**CH2** *coal*
Fuel dispensing	14,942	14,942
Fuel distribution, storage	485	607
Fuel production	3,262	26,252
Feedstock transmission	1,728	954
Feedstock recovery	4,325	1,569
Land-use, cultivation*	(10,654)	69
Fertilizer manufacture	2,125	0
Gas leaks and flares**	3,539	4,950
CO2, H2S from NG	0	0
Emissions displaced	0	0
Total	*19,752*	*49,343*

Notes: see end of all Y-16 tables.

TABLE Y-16B. CO_2-EQUIVALENT EMISSIONS PER UNIT OF ENERGY DELIVERED TO END USERS, BY STAGE AND FEEDSTOCK/FUEL COMBINATION (G/10^6-BTU): JAPAN 2010 AND 2050

B1. Japan 2010

Fuel ------>	**Coal**	**CG**	**RFG**	**ULSD**	**FTD**	**Fuel oil**	**Still gas**	**Coke**	**LPG**	**LPG**	**LPG**	**CNG**
Feedstock ------>	*coal*	*oil*	*oil*	*oil*	*NG*	*oil*	*oil*	*oil*	*oil*	*NGL57*	*NG*	*NG*
Fuel dispensing	0	276	272	215	208	223	0	0	252	252	252	2,603
Fuel distribution, storage	0	996	990	832	2,628	897	0	0	1,122	1,122	1,122	13,194
Fuel production	0	11,240	12,249	6,144	19,722	3,139	0	0	3,747	2,621	1,757	1,173
Feedstock transmission	7,269	3,363	3,054	3,461	1,172	2,390	3,041	3,015	3,295	1,432	0	0
Feedstock recovery	1,268	3,416	3,102	3,516	4,463	3,648	3,089	4,601	3,416	2,492	1,781	1,702
Land-use, cultivation*	38	0	0	0	0	0	0	0	0	0	0	0
Fertilizer manufacture	0	0	0	0	0	0	0	0	0	0	0	0
Gas leaks and flares**	2,051	(1,004)	(912)	(1,034)	2,545	(1,061)	(898)	(1,338)	(1,004)	421	1,516	3,923
CO2, H2S from NG^	0	0	0	0	(7)	0	0	0	0	3	6	6
Emissions displaced	(392)	0	0	0	(1,081)	0	0	0	0	0	0	0
Total	*10,233*	*18,286*	*18,754*	*13,134*	*29,650*	*9,236*	*5,232*	*6,277*	*10,827*	*8,342*	*6,433*	*22,601*

Notes: see end of all Y-16 tables.

B1. Japan 2010 continued.

Fuel ------>	**Nuclear#**	**CH2**	**CH2**	**MeOH**	**MeOH**	**MeOH**	**Ethanol**	**Ethanol**	**SCG**	**Biodies.**	**Grass**	**Wood**
Feedstock ------>	*uranium*	*water*	*NG*	*NG*	*coal*	*wood*	*corn*	*Grass*	*wood*	*soy*	*grass*	*wood*
Fuel dispensing	0	10,086	10,086	461	461	347	340	269	2,038	243	0	0
Fuel distribution, storage	0	340	0	5,564	2,790	2,641	2,233	2,363	1,226	1,625	0	0
Fuel production	710	4,474	69,170	18,165	15,539	12,005	51,339	17,654	5,024	38,114	0	0
Feedstock transmission	36	0	15,925	1,082	11,629	3,754	4,145	3,830	2,884	3,501	1,815	2,126
Feedstock recovery	751	0	3,470	4,119	1,879	8,623	17,412	10,428	6,624	50,464	4,942	4,883
Land-use, cultivation*	0	0	0	0	56	(5,561)	56,904	20,184	(4,272)	184,068	9,564	(3,149)
Fertilizer manufacture	0	0	0	0	0	3,242	18,043	8,995	2,490	35,143	4,262	1,836
Gas leaks and flares**	0	5,354	6,573	2,349	3,039	0	0	0	2,707	0	0	0
CO2, H2S from NG	0	0	7	(7)	0	0	0	0	0	0	0	0
Emissions displaced	0	0	0	0	0	0	(30,475)	(5,224)	0	(84,278)	0	0
Total	*1,497*	*20,255*	*105,230*	*31,733*	*35,393*	*25,052*	*119,941*	*58,499*	*18,722*	*228,880*	*20,583*	*5,696*

Notes: see end of all Y-16 tables.

B1. Japan 2010 continued.

Fuel ------> *Feedstock ------>*	**CH2** *wood*	**CH2** *coal*
Fuel dispensing	10,086	10,086
Fuel distribution, storage	227	283
Fuel production	4,343	26,057
Feedstock transmission	3,589	12,137
Feedstock recovery	8,243	1,961
Land-use, cultivation*	(5,316)	59
Fertilizer manufacture	3,099	0
Gas leaks and flares**	5,215	8,499
CO2, H2S from NG	0	0
Emissions displaced	0	0
Total	*29,486*	*59,082*

Notes: see end of all Y-16 tables.

B2. Japan 2050

Fuel ------>	**Coal**	**CG**	**RFG**	**ULSD**	**FTD**	**Fuel oil**	**Still gas**	**Coke**	**LPG**	**LPG**	**LPG**	**CNG**
Feedstock ------>	*coal*	*oil*	*oil*	*oil*	*NG*	*oil*	*oil*	*oil*	*oil*	*NGL57*	*NG*	*NG*
Fuel dispensing	0	174	173	147	142	152	0	0	164	164	164	1,776
Fuel distribution, storage	0	599	597	513	2,053	560	0	0	694	694	694	12,067
Fuel production	0	9,888	10,593	5,377	10,295	2,663	0	0	3,226	2,278	1,549	1,031
Feedstock transmission	5,990	2,553	2,319	2,631	984	1,710	2,311	2,157	2,496	1,085	0	0
Feedstock recovery	1,057	3,391	3,079	3,493	4,035	3,625	3,069	4,572	3,391	2,572	1,943	1,850
Land-use, cultivation*	46	0	0	0	0	0	0	0	0	0	0	0
Fertilizer manufacture	0	0	0	0	0	0	0	0	0	0	0	0
Gas leaks and flares**	1,464	(2,374)	(2,155)	(2,445)	1,347	(2,533)	(2,144)	(3,195)	(2,374)	(523)	899	2,216
CO2, H2S from NG^	0	0	0	0	18	0	0	0	0	13	23	23
Emissions displaced	(273)	0	0	0	(1,092)	0	0	0	0	0	0	0
Total	*8,284*	*14,232*	*14,606*	*9,715*	*17,783*	*6,178*	*3,236*	*3,534*	*7,597*	*6,281*	*5,270*	*18,963*

Notes: see end of all Y-16 tables.

B2. Japan 2050 continued.

Fuel ------>	**Nuclear#**	**CH2**	**CH2**	**MeOH**	**MeOH**	**MeOH**	**Ethanol**	**Ethanol**	**SCG**	**Biodies.**	**Grass**	**Wood**
Feedstock ------>	*uranium*	*water*	*NG*	*NG*	*coal*	*wood*	*corn*	*Grass*	*wood*	*soy*	*grass*	*wood*
Fuel dispensing	0	6,868	6,868	309	309	239	230	184	1,414	166	0	0
Fuel distribution, storage	0	258	0	4,326	1,822	1,573	1,254	1,361	602	913	0	0
Fuel production	571	3,200	62,985	10,806	9,316	8,433	42,881	11,495	3,037	28,564	0	0
Feedstock transmission	20	0	13,689	925	7,601	1,551	2,302	1,397	1,301	1,657	908	1,063
Feedstock recovery	539	0	3,268	3,793	1,262	3,817	9,857	4,102	3,201	28,022	2,665	2,617
Land-use, cultivation*	0	0	0	0	55	(10,878)	42,147	11,718	(9,125)	144,425	7,614	(7,459)
Fertilizer manufacture	0	0	0	0	0	2,049	12,926	4,975	1,719	28,801	3,232	1,405
Gas leaks and flares**	0	3,297	3,828	1,266	1,748	0	0	0	1,622	0	0	0
CO2, H2S from NG	0	0	26	17	0	0	0	0	0	0	0	0
Emissions displaced	0	0	0	0	0	0	(18,186)	(11,581)	0	(84,278)	0	0
Total	*1,130*	*13,624*	*90,665*	*21,442*	*22,113*	*6,783*	*93,410*	*23,651*	*3,770*	*148,269*	*14,418*	*(2,374)*

Notes: see end of all Y-16 tables.

B2. Japan 2050 continued.

Fuel -------> *Feedstock ------->*	**CH2** *wood*	**CH2** *coal*
Fuel dispensing	6,868	6,868
Fuel distribution, storage	172	215
Fuel production	2,818	18,822
Feedstock transmission	1,653	7,889
Feedstock recovery	4,069	1,310
Land-use, cultivation*	(11,597)	57
Fertilizer manufacture	2,184	0
Gas leaks and flares**	3,202	5,090
CO2, H2S from NG	0	0
Emissions displaced	0	0
Total	*9,370*	*40,251*

Notes: see end of all Y-16 tables.

TABLE Y-16C. CO$_2$-EQUIVALENT EMISSIONS PER UNIT OF ENERGY DELIVERED TO END USERS, BY STAGE AND FEEDSTOCK/FUEL COMBINATION (G/10^6-BTU): CHINA 2010 AND 2050

C1. China 2010

Fuel ------>	**Coal**	**CG**	**RFG**	**ULSD**	**FTD**	**Fuel oil**	**Still gas**	**Coke**	**LPG**	**LPG**	**LPG**	**CNG**
Feedstock ------>	*coal*	*oil*	*oil*	*oil*	*NG*	*oil*	*oil*	*oil*	*oil*	*NGL57*	*NG*	*NG*
Fuel dispensing	0	475	469	373	361	387	0	0	435	435	435	4,527
Fuel distribution, storage	0	1,157	1,125	786	852	992	0	0	1,225	1,225	1,225	3,147
Fuel production	0	12,438	13,489	6,673	20,389	3,920	0	0	4,181	2,832	1,795	1,207
Feedstock transmission	896	1,781	1,616	1,829	1,175	696	1,607	878	1,712	744	0	0
Feedstock recovery	1,513	4,338	3,938	4,456	4,564	4,624	3,915	5,831	4,337	2,902	1,800	1,732
Land-use, cultivation*	49	0	0	0	0	0	0	0	0	0	0	0
Fertilizer manufacture	0	0	0	0	0	0	0	0	0	0	0	0
Gas leaks and flares**	2,666	96	87	99	2,603	(5)	(4)	(6)	96	1,027	1,742	6,562
CO2, H2S from NG^	0	0	0	0	(7)	0	0	0	0	(2)	(4)	(4)
Emissions displaced	(407)	0	0	0	(1,880)	0	0	0	0	0	0	0
Total	*4,716*	*20,284*	*20,725*	*14,216*	*28,056*	*10,614*	*5,518*	*6,704*	*11,987*	*9,163*	*6,992*	*17,170*

Notes: see end of all Y-16 tables.

C1. China 2010 continued.

Fuel ------>	**Nuclear#**	**CH2**	**CH2**	**MeOH**	**MeOH**	**MeOH**	**Ethanol**	**Ethanol**	**SCG**	**Biodies.**	**Grass**	**Wood**
Feedstock ------>	*uranium*	*water*	*NG*	*NG*	*coal*	*wood*	*corn*	*Grass*	*wood*	*soy*	*grass*	*wood*
Fuel dispensing	0	17,540	17,540	799	799	550	591	426	3,226	423	0	0
Fuel distribution, storage	0	1,246	0	1,940	2,759	2,465	2,175	2,200	1,763	1,557	0	0
Fuel production	5,426	10,441	71,435	19,027	17,931	14,129	56,939	18,497	6,342	41,912	0	0
Feedstock transmission	31	0	3,798	1,086	1,530	3,259	3,640	3,323	2,520	3,053	1,574	1,844
Feedstock recovery	981	0	3,547	4,216	2,244	8,638	17,695	10,456	6,679	50,156	4,951	4,886
Land-use, cultivation*	0	0	0	0	72	7,765	90,104	34,522	6,003	296,309	16,346	4,393
Fertilizer manufacture	0	0	0	0	0	3,429	19,833	9,772	2,651	40,883	4,627	1,940
Gas leaks and flares**	0	8,790	9,758	2,405	3,955	0	0	0	5,126	0	0	0
CO2, H2S from NG	0	0	(5)	(7)	0	0	0	0	0	0	0	0
Emissions displaced	0	0	0	0	0	0	(41,678)	(8,272)	0	(84,278)	0	0
Total	*6,438*	*38,017*	*106,072*	*29,466*	*29,291*	*40,234*	*149,297*	*70,923*	*34,309*	*350,014*	*27,497*	*13,062*

Notes: see end of all Y-16 tables.

C1. China 2010 continued.

Fuel ------>	**CH2**	**CH2**
Feedstock ------>	*wood*	*coal*
Fuel dispensing	17,540	17,540
Fuel distribution, storage	831	1,038
Fuel production	4,315	33,874
Feedstock transmission	3,141	1,611
Feedstock recovery	8,327	2,364
Land-use, cultivation*	7,485	76
Fertilizer manufacture	3,305	0
Gas leaks and flares**	8,316	12,788
CO2, H2S from NG	0	0
Emissions displaced	0	0
Total	*53,261*	*69,291*

Notes: see end of all Y-16 tables.

C2. China 2050

Fuel ------>	**Coal**	**CG**	**RFG**	**ULSD**	**FTD**	**Fuel oil**	**Still gas**	**Coke**	**LPG**	**LPG**	**LPG**	**CNG**
Feedstock ------>	*coal*	*oil*	*oil*	*oil*	*NG*	*oil*	*oil*	*oil*	*oil*	*NGL57*	*NG*	*NG*
Fuel dispensing	0	360	362	329	318	341	0	0	352	352	352	3,980
Fuel distribution, storage	0	723	721	615	637	750	0	0	809	809	809	5,126
Fuel production	0	10,769	11,530	5,844	10,962	3,254	0	0	3,547	2,439	1,587	1,063
Feedstock transmission	969	1,625	1,476	1,674	1,007	718	1,471	905	1,568	681	0	0
Feedstock recovery	1,385	4,440	4,032	4,573	4,137	4,745	4,018	5,985	4,440	3,041	1,965	1,882
Land-use, cultivation*	59	0	0	0	0	0	0	0	0	0	0	0
Fertilizer manufacture	0	0	0	0	0	0	0	0	0	0	0	0
Gas leaks and flares**	2,214	(2,086)	(1,894)	(2,149)	1,377	(2,319)	(1,963)	(2,925)	(2,086)	(302)	1,069	3,805
CO2, H2S from NG^	0	0	0	0	18	0	0	0	0	7	12	12
Emissions displaced	(293)	0	0	0	(2,446)	0	0	0	0	0	0	0
Total	*4,334*	*15,832*	*16,226*	*10,886*	*16,010*	*7,489*	*3,525*	*3,966*	*8,630*	*7,027*	*5,795*	*15,868*

Notes: see end of all Y-16 tables.

C2. China 2050 continued.

Fuel ------> *Feedstock ------>*	**Nuclear#** *uranium*	**CH2** *water*	**CH2** *NG*	**MeOH** *NG*	**MeOH** *coal*	**MeOH** *wood*	**Ethanol** *corn*	**Ethanol** *Grass*	**SCG** *wood*	**Biodies.** *soy*	**Grass** *grass*	**Wood** *wood*
Fuel dispensing	0	15,389	15,389	680	680	512	511	393	3,047	372	0	0
Fuel distribution, storage	0	1,134	0	1,379	1,972	1,691	1,451	1,475	947	1,056	0	0
Fuel production	3,063	6,228	65,755	11,658	11,285	12,633	50,749	12,459	4,474	33,359	0	0
Feedstock transmission	22	0	5,815	947	1,203	1,640	2,258	1,477	1,383	1,741	960	1,124
Feedstock recovery	770	0	3,341	3,890	1,654	4,055	10,551	4,366	3,419	29,105	2,837	2,780
Land-use, cultivation*	0	0	0	0	70	(5,746)	62,870	18,688	(4,845)	215,123	12,140	(3,939)
Fertilizer manufacture	0	0	0	0	0	2,178	14,843	5,383	1,837	34,814	3,497	1,493
Gas leaks and flares**	0	5,200	5,631	1,295	2,645	0	0	0	3,233	0	0	0
CO2, H2S from NG	0	0	14	17	0	0	0	0	0	0	0	0
Emissions displaced	0	0	0	0	0	0	(24,566)	(24,957)	0	(84,278)	0	0
Total	*3,854*	*27,950*	*95,945*	*19,866*	*19,508*	*16,964*	*118,667*	*19,284*	*13,495*	*231,292*	*19,434*	*1,459*

Notes: see end of all Y-16 tables.

C2. China 2050 continued.

Fuel ------> *Feedstock ------>*	**CH2** *wood*	**CH2** *coal*
Fuel dispensing	15,389	15,389
Fuel distribution, storage	756	945
Fuel production	3,335	26,795
Feedstock transmission	1,757	1,256
Feedstock recovery	4,343	1,725
Land-use, cultivation*	(6,155)	73
Fertilizer manufacture	2,333	0
Gas leaks and flares**	4,746	7,773
CO2, H2S from NG	0	0
Emissions displaced	0	0
Total	*26,505*	*53,956*

Notes: see end of all Y-16 tables.

TABLE Y-16D. CO_2-EQUIVALENT EMISSIONS PER UNIT OF ENERGY DELIVERED TO END USERS, BY STAGE AND FEEDSTOCK/FUEL COMBINATION (G/10^6-BTU): GERMANY 2010 AND 2050

D1. Germany 2010

Fuel ------>	**Coal**	**CG**	**RFG**	**ULSD**	**FTD**	**Fuel oil**	**Still gas**	**Coke**	**LPG**	**LPG**	**LPG**	**CNG**
Feedstock ------>	*coal*	*oil*	*oil*	*oil*	*NG*	*oil*	*oil*	*oil*	*oil*	*NGL57*	*NG*	*NG*
Fuel dispensing	0	353	350	294	285	305	0	0	331	331	331	3,568
Fuel distribution, storage	0	884	876	717	2,055	819	0	0	980	980	980	3,907
Fuel production	0	10,980	11,924	6,003	20,088	3,337	0	0	3,644	2,590	1,779	1,198
Feedstock transmission	1,262	2,021	1,835	2,080	1,123	957	1,828	1,207	1,954	849	0	0
Feedstock recovery	1,299	6,437	5,844	6,625	4,668	6,874	5,820	8,671	6,437	4,027	2,176	2,096
Land-use, cultivation*	40	0	0	0	0	0	0	0	0	0	0	0
Fertilizer manufacture	0	0	0	0	0	0	0	0	0	0	0	0
Gas leaks and flares**	2,022	(954)	(867)	(982)	2,331	(903)	(765)	(1,140)	(954)	483	1,588	6,224
CO2, H2S from NG^	0	0	0	0	(7)	0	0	0	0	(2)	(4)	(4)
Emissions displaced	(376)	0	0	0	(1,482)	0	0	0	0	0	0	0
Total	*4,247*	*19,720*	*19,963*	*14,736*	*29,061*	*11,389*	*6,883*	*8,738*	*12,391*	*9,258*	*6,850*	*16,988*

Notes: see end of all Y-16 tables.

D1. Germany 2010 continued.

Fuel ------>	**Nuclear#**	**CH2**	**CH2**	**MeOH**	**MeOH**	**MeOH**	**Ethanol**	**Ethanol**	**SCG**	**Biodies.**	**Grass**	**Wood**
Feedstock ------>	*uranium*	*water*	*NG*	*NG*	*coal*	*wood*	*corn*	*Grass*	*wood*	*soy*	*grass*	*wood*
Fuel dispensing	0	13,823	13,823	621	621	460	462	354	2,716	333	0	0
Fuel distribution, storage	0	2,572	0	4,367	2,430	2,158	1,807	1,883	1,292	1,311	0	0
Fuel production	11,807	25,802	69,800	18,609	16,601	13,022	49,881	16,829	5,738	39,057	0	0
Feedstock transmission	25	0	4,715	1,037	2,080	2,655	3,359	2,708	2,055	2,530	1,283	1,503
Feedstock recovery	7,482	0	3,975	4,308	1,925	8,424	17,132	10,195	6,521	48,995	4,831	4,771
Land-use, cultivation*	0	0	0	0	60	(2,495)	58,855	21,760	(1,932)	186,327	10,311	(1,413)
Fertilizer manufacture	0	0	0	0	0	3,056	16,907	8,411	2,366	33,108	3,986	1,731
Gas leaks and flares**	0	7,567	9,350	2,151	2,997	0	0	0	5,169	0	0	0
CO2, H2S from NG	0	0	(5)	(7)	0	0	0	0	0	0	0	0
Emissions displaced	0	0	0	0	0	0	(30,483)	(6,961)	0	(84,278)	0	0
Total	*19,313*	*49,765*	*101,658*	*31,086*	*26,714*	*27,279*	*117,920*	*55,179*	*23,926*	*227,382*	*20,411*	*6,592*

Notes: see end of all Y-16 tables.

D1. Germany 2010 continued.

Fuel ------>	**CH2**	**CH2**
Feedstock ------>	*wood*	*coal*
Fuel dispensing	13,823	13,823
Fuel distribution, storage	1,715	2,143
Fuel production	3,599	29,629
Feedstock transmission	2,549	2,183
Feedstock recovery	8,090	2,021
Land-use, cultivation*	(2,396)	63
Fertilizer manufacture	2,935	0
Gas leaks and flares**	6,714	10,347
CO2, H2S from NG	0	0
Emissions displaced	0	0
Total	*37,029*	*60,209*

Notes: see end of all Y-16 tables.

D2. Germany 2050

Fuel ------>	**Coal**	**CG**	**RFG**	**ULSD**	**FTD**	**Fuel oil**	**Still gas**	**Coke**	**LPG**	**LPG**	**LPG**	**CNG**
Feedstock ------>	*coal*	*oil*	*oil*	*oil*	*NG*	*oil*	*oil*	*oil*	*oil*	*NGL57*	*NG*	*NG*
Fuel dispensing	0	96	94	67	65	69	0	0	84	84	84	807
Fuel distribution, storage	0	568	565	480	1,647	563	0	0	588	588	588	3,665
Fuel production	0	9,725	10,359	5,288	10,659	2,827	0	0	3,164	2,264	1,572	1,053
Feedstock transmission	1,100	1,539	1,397	1,585	935	625	1,393	789	1,481	644	0	0
Feedstock recovery	927	5,223	4,743	5,381	4,240	5,584	4,728	7,044	5,224	3,616	2,380	2,279
Land-use, cultivation*	49	0	0	0	0	0	0	0	0	0	0	0
Fertilizer manufacture	0	0	0	0	0	0	0	0	0	0	0	0
Gas leaks and flares**	1,328	(2,697)	(2,449)	(2,779)	1,234	(2,846)	(2,409)	(3,590)	(2,697)	(639)	942	3,583
CO2, H2S from NG^	0	0	0	0	18	0	0	0	0	7	12	12
Emissions displaced	(263)	0	0	0	(496)	0	0	0	0	0	0	0
Total	*3,140*	*14,454*	*14,709*	*10,023*	*18,302*	*6,824*	*3,711*	*4,242*	*7,844*	*6,562*	*5,578*	*11,400*

Notes: see end of all Y-16 tables.

D2. Germany 2050 continued.

Fuel ------>	**Nuclear#**	**CH2**	**CH2**	**MeOH**	**MeOH**	**MeOH**	**Ethanol**	**Ethanol**	**SCG**	**Biodies.**	**Grass**	**Wood**
Feedstock ------>	*uranium*	*water*	*NG*	*NG*	*coal*	*wood*	*corn*	*Grass*	*wood*	*soy*	*grass*	*wood*
Fuel dispensing	0	3,122	3,122	147	147	110	107	86	637	76	0	0
Fuel distribution, storage	0	1,687	0	3,479	1,566	1,464	1,143	1,265	617	832	0	0
Fuel production	8,755	16,145	61,773	11,034	8,438	6,414	38,648	10,819	2,372	23,983	0	0
Feedstock transmission	20	0	4,158	879	1,366	1,505	2,162	1,355	1,269	1,605	881	1,032
Feedstock recovery	4,188	0	3,780	3,986	1,107	3,681	9,430	3,952	3,103	27,281	2,567	2,524
Land-use, cultivation*	0	0	0	0	58	(8,839)	43,274	12,606	(7,453)	144,443	8,190	(6,061)
Fertilizer manufacture	0	0	0	0	0	1,930	11,784	4,588	1,628	25,619	2,981	1,324
Gas leaks and flares**	0	4,745	5,379	1,160	1,586	0	0	0	3,191	0	0	0
CO2, H2S from NG	0	0	14	17	0	0	0	0	0	0	0	0
Emissions displaced	0	0	0	0	0	0	(18,040)	(5,216)	0	(84,278)	0	0
Total	*12,962*	*25,700*	*78,227*	*20,703*	*14,268*	*6,264*	*88,509*	*29,454*	*5,364*	*139,561*	*14,619*	*(1,182)*

Notes: see end of all Y-16 tables.

D2. Germany 2050 continued.

Fuel ------> *Feedstock ------>*	**CH2** *wood*	**CH2** *coal*
Fuel dispensing	3,122	3,122
Fuel distribution, storage	1,125	1,406
Fuel production	2,614	15,447
Feedstock transmission	1,609	1,423
Feedstock recovery	3,936	1,153
Land-use, cultivation*	(9,452)	60
Fertilizer manufacture	2,064	0
Gas leaks and flares**	4,183	6,153
CO2, H2S from NG	0	0
Emissions displaced	0	0
Total	*9,201*	*28,766*

Notes: see end of all Y-16 tables.

Notes to all Tables Y-16.

#Units are grams per million BTU of power generated.

*Includes emissions of N2O, NOx, and CH4 associated with cultivation and the use of fertilizer.

**Includes emissions of H2S from crude oil tanks. Assumes that flared gas is burned completely to CO2 and H2O, with no residual CH4, NMOC, CO, NOx, N2O.

^SO2 emissions from the incineration of H2S. Very little H2S is incinerated; most is recovered as a source of sulfur or sulfuric acid.

"Best CEFs" are my best estimates of CO2-equivalency factors, as distinguished from the IPCC GWPs.

NGLxx = % of LPG from natural-gas liquids plants; RFxx = % of LPG from refineries; Cxx = percent of methanol from coal;

NGxx = percent of methanol from natural gas; Wxx = % of ethanol from wood; Gxx = % of ethanol from grass.

1) Diesel use for uranium and coal mining is assigned 1/2 to scrapers, 1/2 to wheeled loader; for biomass recovery, to tractors.

2) Use of NG, coal in fuel recovery or production stage excludes emissions from fuel transmission.

3) Diesel use in oil recovery is assigned to well equipment.

4) For uranium, fuel transmission includes all truck movements in the fuelcycle, including disposal by truck.

5) Hydrogen distribution assumes hydrogen pipelines use hydrogen-fired compressors.

6) Fertilizer manufacture includes manufacture of pesticides, herbicides, and seeds.

7) In NG/methanol fuelcycle, feed recovery includes NGL-plant emissions; feed transmission is NG shipment.

8) If corn residue is used as boiler fuel, emissions attributable to loss of residue as fertilizer are counted.

9) Gasoline production emissions include emissions from manufacture of methanol, ethanol MTBE, and ETBE.

10) Volumetric reduction due to addition of methanol, ethanol, MTBE, and ETBE, is accounted for.

11) "Fuel dispensing" is compression or liquefaction of gaseous fuels, and pumping of liquid fuels, including fuel oil. Liquefaction at large central facilities is included here.

12) For hydrogen from electrolysis, "fuel production" is entire cycle for electricity source; "feedstock" stages refer to water.

13) For CNG and LNG, all NG shipment is under "Fuel distribution"; for methanol, it is under "Feedstock transmission".

14) Gas leaks and flares includes leakage from all stages, including losses at dispensing stations and from pipelines. However, leaks from compressor engines are included with total emission factor for those engines, which is part of transmission stage.

15) Hydrogen from coal, methanol from coal, and syncrude from coal assume sequestration of 90% of CO_2 from fuel production.

TABLE Y-18. TOTAL EMISSIONS OVER THE WHOLE UPSTREAM FUELCYCLE, PER UNIT OF ENERGY DELIVERED TO END USERS, BY POLLUTANT AND FEEDSTOCK/FUEL COMBINATION (G/10^6-BTU) (BEST CEFS) (U. S. 2010)

Fuel ------>	**Coal**	**CG**	**RFG**	**ULSD**	**FTD**	**Fuel oil**	**Still gas**	**Coke**	**LPG**	**LPG**	**LPG**	**CNG**
Feedstock ------>	*coal*	*oil*	*oil*	*oil*	*NG*	*oil*	*oil*	*oil*	*oil*	*57NGL*	*NG*	*NG*
Carbon dioxide (CO2)	1,479	18,482	18,665	13,357	24,232	10,701	4,872	7,246	11,023	7,640	5,040	10,587
Nonmethane organic compounds	1.0	50.2	42.1	13.9	9.0	11.8	8.0	10.1	22.5	15.2	9.6	6.9
Methane (CH4)	141.1	223.8	221.2	215.2	208.8	134.2	169.9	152.6	199.5	149.7	111.4	357.7
Carbon monoxide (CO)	9.9	67.4	59.2	61.7	55.6	57.8	41.3	61.6	54.0	38.5	26.5	36.3
Nitrous oxide (N2O)	0.1	1.2	0.6	0.9	1.0	0.6	0.2	0.3	0.5	0.3	0.2	0.3
Nitrogen oxides (NO2)	12.6	81.2	80.3	73.9	88.6	73.1	49.0	73.0	68.7	50.9	37.3	64.6
Sulfur oxides (SOx)	3.1	62.4	52.9	58.7	11.0	52.8	36.2	54.0	54.7	28.1	7.7	15.6
Particulate matter (BC+OM)	0.3	2.3	2.3	1.9	1.6	1.7	1.1	1.7	1.7	1.2	0.9	1.5
Particulate matter (dust)	(0.0)	0.0	0.0	0.0	(0.0)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hydrogen (H2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sodium hexafluoride (SF6) (mg)	0.1	0.9	1.0	0.8	(0.2)	0.8	0.4	0.7	0.8	0.5	0.2	1.0
HFC-134a (mg)	0.1	0.4	0.4	0.4	0.4	0.4	0.1	0.1	0.4	0.3	0.3	0.1
CO2-equivalent GHG emissions	3,939	20,581	20,929	15,064	27,489	11,262	6,262	7,813	12,471	9,221	6,723	15,690

Table Y-18 continued.

Fuel ------>	**Nuclear**	**CH2**	**CH2**	**MeOH**	**MeOH**	**MeOH**	**Ethanol**	**Ethanol**	**SCG**	**biodiesel**	**Grass**	**Wood**
Feedstock ------>	*uranium*	*water*	*NG*	*NG*	*coal*	*wood*	*corn*	*Grass*	*wood*	*soy*	*grass*	*wood*
Carbon dioxide (CO2)	4,796	19,565	95,087	26,625	22,410	14,873	78,697	25,401	9,393	108,822	9,179	1,503
Nonmethane organic compounds	0.6	1.0	8.8	17.2	100.4	26.7	239.1	31.3	11.8	115.6	5.7	5.7
Methane (CH4)	9.9	145.0	413.6	198.9	248.8	70.0	221.7	109.8	125.6	373.8	31.9	16.9
Carbon monoxide (CO)	11.3	9.3	69.2	54.0	52.2	183.5	339.0	207.4	493.5	1,017.8	61.8	62.6
Nitrous oxide (N2O)	0.1	0.7	1.7	1.1	2.6	8.0	91.6	39.6	6.4	297.4	18.0	3.7
Nitrogen oxides (NO2)	12.0	40.6	133.7	121.1	114.5	187.6	949.1	445.9	142.0	4,125.6	180.7	59.8
Sulfur oxides (SOx)	11.6	39.0	59.6	22.0	71.5	32.5	94.8	17.1	25.7	104.2	5.4	5.1
Particulate matter (BC+OM)	0.2	0.6	2.7	1.5	4.5	8.4	10.6	12.4	6.4	22.1	2.0	1.9
Particulate matter (dust)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hydrogen (H2)	0.0	147.2	67.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sodium hexafluoride (SF6) (mg)	0.8	3.7	5.0	0.5	1.7	2.4	2.8	(1.6)	2.3	5.6	0.2	0.1
HFC-134a (mg)	0.0	0.2	1.3	0.7	1.3	3.8	2.9	4.1	2.2	6.3	1.2	1.4
CO2-equivalent GHG emissions	4,778	27,021	103,353	29,290	27,719	27,014	113,194	47,376	22,235	212,209	17,185	5,562

Table Y-18 continued.

Fuel ------> *Feedstock ------>*	**CH2** *wood*	**CH2** *coal*
Carbon dioxide (CO2)	22,062	53,815
Nonmethane organic compounds	55.5	5.5
Methane (CH4)	74.1	297.9
Carbon monoxide (CO)	178.3	62.7
Nitrous oxide (N2O)	8.0	3.6
Nitrogen oxides (NO2)	166.1	142.0
Sulfur oxides (SOx)	52.4	130.2
Particulate matter (BC+OM)	6.9	4.5
Particulate matter (dust)	0.0	0.0
Hydrogen (H2)	133.2	151.4
Sodium hexafluoride (SF6) (mg)	4.2	7.7
HFC-134a (mg)	4.1	1.3
CO2-equivalent GHG emissions	36,531	62,967

Notes.

See Notes to Table Y-16.

TABLE Y-19A. GRAM-PER-MILE EMISSIONS BY VEHICLE/FUEL/FEEDSTOCK COMBINATION, AND STAGE OF THE FUELCYCLE (BEST CEFS): U. S. 2010 AND 2050

A1. U. S. 2010: ICEVs using fossil fuels.

General fuel -->	**Gasoline**	**Gasoline**	**Diesel**	**Methanol**	**NG**	**Hydrogen**	**Blank**	**LPG**
Fuel specification -->	CG	RFG-Ox10	0.001% S	M85	CNG	CH2	Blank	P95/BU5
Feedstock -->	*crude oil*	*crude oil*	*crude oil*	*NG100/C0*	*NG100*	*NG100*	*Blank*	*NGL57*
Vehicle operation: fuel	435.8	423.7	353.2	359.2	309.3	6.5		348.2
Fuel dispensing	2.0	2.0	1.3	3.0	20.3	70.4		1.8
Fuel storage and distribution	5.3	5.2	3.5	11.3	16.3	0.0		5.2
Fuel production	58.7	63.5	24.9	75.4	5.6	299.9		12.9
Feedstock transport	11.1	10.1	8.9	6.8	0.0	17.6		4.5
Feedstock, fertilizer production	25.8	23.4	20.6	19.5	8.0	14.7		15.5
CH4, CO2 gas leaks and flares	-3.3	-3.0	-2.7	7.8	23.8	33.4		3.0
Emissions displaced	0.0	0.0	0.0	0.0	0.0	0.0		0.0
Sub total (fuelcycle)	***535.4***	***525.0***	***409.8***	***483.1***	***383.3***	***442.7***	***0.0***	***391.3***
% changes (fuelcycle)	***--***	***-1.9%***	***-23.5%***	***-9.8%***	***-28.4%***	***-17.3%***	***-100.0%***	***-26.9%***
Vehicle assembly and transport	25.6	25.6	22.0	25.6	27.2	26.6		26.0
Materials in vehicles	59.6	59.6	51.3	59.8	63.1	67.1		60.1
Road dust, tire wear, brake wear	-3.0	-3.0	-3.1	-3.0	-3.1	-3.1		-3.0
Lube oil production and use	4.6	4.6	4.6	4.6	2.3	4.3		3.4
Refrigerant (HFC-134a)	10.6	10.6	10.6	10.6	10.6	10.6		10.6
Grand total	***632.7***	***622.3***	***495.2***	***580.6***	***483.4***	***548.2***	***0.0***	***488.3***
% changes (grand total)	***--***	***-1.6%***	***-21.7%***	***-8.2%***	***-23.6%***	***-13.3%***	***-100.0%***	***-22.8%***

A1. U. S. 2010: ICEVs using biomass fuels

General fuel -->	**Ethanol**	**Ethanol**	**Methanol**	**NG**
Fuel specification -->	E90 (corn)	E90	M85	CNG
Feedstock -->	*Coal/NG*	*Grass*	*Wood*	*Wood*
Vehicle operation: fuel	365.6	365.6	359.2	309.3
Fuel dispensing	2.4	1.9	2.4	15.4
Fuel storage and distribution	8.8	9.0	9.5	6.0
Fuel production	200.6	73.8	63.4	30.0
Feedstock transport	15.8	13.8	13.2	11.5
Feedstock, fertilizer production	138.3	76.5	45.7	42.8
Land use changes, cultivation	196.7	54.9	(17.6)	(18.7)
CH4, CO2 gas leaks and flares	(0.4)	(0.4)	(0.7)	17.7
C in end-use fuel from air CO2	(262.6)	(262.6)	(218.2)	(251.8)
Emissions displaced	(109.5)	(32.6)	0.0	0.0
Sub total (fuelcycle)	***555.8***	***300.0***	***256.9***	***162.2***
% changes (fuelcycle)	***3.8%***	***-44.0%***	***-52.0%***	***-69.7%***
Vehicle assembly and transport	25.6	25.6	25.6	27.2
Materials in vehicles	59.7	59.7	59.8	63.1
Road dust, tire wear, brake wear	-3.0	-3.0	-3.0	-3.1
Lube oil production and use	4.6	4.6	4.6	2.3
Refrigerant (HFC-134a)	10.6	10.6	10.6	10.6
Grand total	***653.2***	***397.4***	***354.5***	***262.3***
% changes (grand total)	***3.3%***	***-37.2%***	***-44.0%***	***-58.5%***

A1. U. S. 2010: Battery EVs, by type of power plant fuel.

	Coal	**Fuel oil**	**NG/ boiler**	**NG/ turbine**	**Nuclear***	**Biomass**	**Hydro***	**Other**
Fuelcycle (g/mi)	428.3	373.5	227.5	231.3	23.5	38.9	16.7	12.4
Fuelcycle (% changes)	***-20.0%***	***-30.2%***	***-57.5%***	***-56.8%***	***-95.6%***	***-92.7%***	***-96.9%***	***-97.7%***
Fuel and materials (g/mi)	589.2	534.3	388.4	392.1	184.4	199.7	177.6	173.3
Fuel and materials (% changes)	***-6.9%***	***-15.5%***	***-38.6%***	***-38.0%***	***-70.9%***	***-68.4%***	***-71.9%***	***-72.6%***

A1. U. S. 2010: Fuel cell EVs.

General fuel -->	**Gasoline**	**Methanol**	**Methanol**	**Ethanol**	**Hydrogen**	**Hydrogen**	**Hydrogen**	**Hydrogen**
Fuel specification -->	RFG-Ox10	M100	M100	E100	CH2	CH2 (NG)	CH2	CH2
Feedstock -->	*Crude oil*	*NG*	*Wood*	*Grass*	*Water*	*NG*	*Wood*	*Coal*
Vehicle operation: fuel	204.0	181.4	181.4	195.9	1.7	4.2	4.8	4.8
Fuel dispensing	1.2	2.1	1.6	1.2	34.5	34.5	34.5	34.5
Fuel storage and distribution	3.1	8.4	6.9	6.2	1.7	0.0	1.2	1.4
Fuel production	37.7	50.0	40.1	48.7	6.8	146.8	8.6	67.5
Feedstock transport	6.0	3.7	8.9	9.3	0.0	8.6	6.3	3.0
Feedstock, fertilizer production	13.9	11.6	33.3	54.5	0.0	7.2	23.3	4.4
Land use changes, cultivation	0.0	0.0	(14.6)	40.7	0.0	0.0	(10.2)	0.1
CH4, CO2 gas leaks and flares	(1.8)	7.0	0.0	0.0	12.8	16.3	11.8	19.1
C in end-use fuel from air CO2	0.0	0.0	(180.4)	(194.8)	0.0	0.0	(3.0)	0.0
Emissions displace	0.0	0.0	0.0	(24.2)	0.0	0.0	0.0	0.0
Sub total (fuelcycle)	***264.0***	***264.2***	***77.2***	***137.6***	***57.5***	***217.6***	***77.0***	***134.7***
% changes (fuelcycle)	***-50.7%***	***-50.7%***	***-85.6%***	***-74.3%***	***-89.3%***	***-59.4%***	***-85.6%***	***-74.8%***
Vehicle assembly and transport	24.2	24.4	24.4	24.4	24.0	24.0	24.0	24.0
Materials in vehicles	64.2	64.7	64.7	64.5	66.5	66.5	66.5	66.5
Road dust, tire wear, brake wear	-3.1	-3.1	-3.1	-3.1	-3.0	-3.0	-3.0	-3.0
Lube oil production and use	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Refrigerant (HFC-134a)	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6
Grand total	***360.0***	***360.8***	***173.8***	***233.9***	***155.6***	***315.7***	***175.1***	***232.8***
% changes (grand total)	***-43.1%***	***-43.0%***	***-72.5%***	***-63.0%***	***-75.4%***	***-50.1%***	***-72.3%***	***-63.2%***

A2. U. S. 2050: ICEVs using fossil fuels.

General fuel -->	**Gasoline**	**Gasoline**	**Diesel**	**Methanol**	**NG**	**Hydrogen**	**Blank**	**LPG**
Fuel specification -->	CG	RFG-Ox10	0.001% S	M85	CNG	CH2	Blank	P95/BU5
Feedstock -->	*crude oil*	*crude oil*	*crude oil*	*NG100/C0*	*NG100*	*NG100*	*Blank*	*NGL57*
Vehicle operation: fuel	365.6	363.5	308.9	297.5	248.5	8.3		286.1
Fuel dispensing	1.7	1.7	1.2	2.5	16.9	57.8		1.5
Fuel storage and distribution	5.5	5.5	4.0	8.9	15.8	0.0		3.5
Fuel production	54.5	58.3	23.0	46.5	4.6	253.7		10.9
Feedstock transport	9.9	8.9	7.9	5.6	0.0	15.8		3.7
Feedstock, fertilizer production	25.6	23.2	20.5	17.5	8.2	12.8		14.8
CH4, CO2 gas leaks and flares	-11.9	-10.8	-9.5	2.6	13.4	18.5		-1.7
Emissions displaced	0.0	0.0	0.0	0.0	0.0	0.0		0.0
Sub total (fuelcycle)	***450.9***	***450.3***	***356.0***	***381.2***	***307.3***	***366.8***	***0.0***	***318.8***
% changes (fuelcycle)	--	*-0.1%*	*-21.0%*	*-15.5%*	*-31.8%*	*-18.6%*	*-100.0%*	*-29.3%*
Vehicle assembly and transport	14.5	14.5	12.5	14.5	15.4	15.0		14.7
Materials in vehicles	39.8	39.8	34.3	39.9	47.4	44.4		40.1
Road dust, tire wear, brake wear	-2.8	-2.8	-2.8	-2.8	-2.9	-2.8		-2.8
Lube oil production and use	4.0	4.0	4.0	4.0	2.0	3.7		3.0
Refrigerant (HFC-134a)	3.3	3.3	3.3	3.3	3.3	3.3		3.3
Grand total	***509.7***	***509.2***	***407.3***	***440.1***	***372.6***	***430.5***	***0.0***	***377.1***
% changes (grand total)	--	*-0.1%*	*-20.1%*	*-13.7%*	*-26.9%*	*-15.5%*	*-100.0%*	*-26.0%*

A2. U. S. 2050: ICEVs using biomass fuels

General fuel -->	**Ethanol**	**Ethanol**	**Methanol**	**NG**
Fuel specification -->	E90 (corn)	E90	M85	CNG
Feedstock -->	*Coal/NG*	*Grass*	*Wood*	*Wood*
Vehicle operation: fuel	302.7	302.7	297.5	248.5
Fuel dispensing	2.0	1.6	1.9	12.7
Fuel storage and distribution	5.9	6.0	6.7	3.3
Fuel production	164.6	48.6	52.7	19.0
Feedstock transport	9.7	6.4	7.2	6.0
Feedstock, fertilizer production	87.4	36.0	24.7	22.3
Land use changes, cultivation	139.3	30.5	(32.4)	(36.8)
CH4, CO2 gas leaks and flares	(1.3)	(1.3)	(2.4)	10.0
C in end-use fuel from air CO2	(247.0)	(247.0)	(206.8)	(233.9)
Emissions displaced	(62.8)	(87.0)	0.0	0.0
Sub total (fuelcycle)	***400.4***	***96.5***	***149.4***	***51.0***
% changes (fuelcycle)	***-11.2%***	***-78.6%***	***-66.9%***	***-88.7%***
Vehicle assembly and transport	14.5	14.5	14.5	15.4
Materials in vehicles	39.9	39.9	39.9	47.4
Road dust, tire wear, brake wear	-2.8	-2.8	-2.8	-2.9
Lube oil production and use	4.0	4.0	4.0	2.0
Refrigerant (HFC-134a)	3.3	3.3	3.3	3.3

Grand total	*459.4*	*155.4*	*208.3*	*116.2*
% changes (grand total)	*-9.9%*	*-69.5%*	*-59.1%*	*-77.2%*

A2. U. S. 2050: Battery EVs, by type of power plant fuel.

	Coal	Fuel oil	NG/ boiler	NG/ turbine	Nuclear*	Biomass	Hydro*	Other
Fuelcycle (g/mi)	366.3	317.6	170.6	173.6	12.6	(5.1)	8.4	4.8
Fuelcycle (% changes)	*-18.7%*	*-29.6%*	*-62.2%*	*-61.5%*	*-97.2%*	*-101.1%*	*-98.1%*	*-98.9%*
Fuel and materials (g/mi)	422.5	373.8	226.8	229.8	68.8	51.1	64.6	61.0
Fuel and materials (% changes)	*-17.1%*	*-26.7%*	*-55.5%*	*-54.9%*	*-86.5%*	*-90.0%*	*-87.3%*	*-88.0%*

A2. U. S. 2050: Fuel cell EVs.

General fuel -->	**Gasoline**	**Methanol**	**Methanol**	**Ethanol**	**Hydrogen**	**Hydrogen**	**Hydrogen**	**Hydrogen**
Fuel specification -->	RFG-Ox10	M100	M100	E100	CH2	CH2 (NG)	CH2	CH2
Feedstock -->	*Crude oil*	*NG*	*Wood*	*Grass*	*Water*	*NG*	*Wood*	*Coal*
Vehicle operation: fuel	172.2	150.8	150.8	165.9	1.0	3.4	3.9	3.9
Fuel dispensing	0.8	1.5	1.1	0.9	28.9	28.9	28.9	28.9
Fuel storage and distribution	2.8	5.6	4.0	3.6	1.4	0.0	0.9	1.2
Fuel production	29.3	24.3	28.9	27.8	5.5	126.7	6.3	50.7
Feedstock transport	4.5	2.7	3.8	3.6	0.0	7.9	3.3	1.8
Feedstock, fertilizer production	11.7	8.9	14.2	22.2	0.0	6.4	12.5	3.0
Land use changes, cultivation	0.0	0.0	(23.5)	20.4	0.0	0.0	(20.6)	0.1
CH4, CO2 gas leaks and flares	(5.4)	3.6	0.0	0.0	7.4	9.3	6.8	9.6
C in end-use fuel from air CO2	0.0	0.0	(149.9)	(165.0)	0.0	0.0	(2.8)	0.0
Emissions displace	0.0	0.0	0.0	(58.1)	0.0	0.0	0.0	0.0
Sub total (fuelcycle)	***215.8***	***197.5***	***29.4***	***21.2***	***44.3***	***182.4***	***39.2***	***99.2***
% changes (fuelcycle)	***-52.1%***	***-56.2%***	***-93.5%***	***-95.3%***	***-90.2%***	***-59.5%***	***-91.3%***	***-78.0%***
Vehicle assembly and transport	11.9	12.0	12.0	12.0	12.3	12.3	12.3	12.3
Materials in vehicles	35.1	35.4	35.4	35.3	39.0	39.0	39.0	39.0
Road dust, tire wear, brake wear	-2.5	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6	-2.6
Lube oil production and use	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Refrigerant (HFC-134a)	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3

Grand total	263.6	245.6	77.5	69.2	96.2	234.4	91.2	151.2
% changes (grand total)	-48.3%	-51.8%	-84.8%	-86.4%	-81.1%	-54.0%	-82.1%	-70.3%

TABLE Y-19B. GRAM-PER-MILE EMISSIONS BY VEHICLE/FUEL/FEEDSTOCK COMBINATION, AND STAGE OF THE FUELCYCLE (BEST CEFS): JAPAN 2010 AND 2050

B1. Japan 2010: ICEVs using fossil fuels.

General fuel -->	**Gasoline**	**Gasoline**	**Diesel**	**Methanol**	**NG**	**Hydrogen**	**Blank**	**LPG**
Fuel specification -->	CG	RFG-Ox10	0.001% S	M85	CNG	CH2	Blank	P95/BU5
Feedstock -->	*crude oil*	*crude oil*	*crude oil*	*NG100/C0*	*NG100*	*NG100*	*Blank*	*NGL57*
Vehicle operation: fuel	441.4	426.7	355.6	361.8	311.4	6.9		350.7
Fuel dispensing	1.3	1.3	0.8	1.9	12.4	42.9		1.2
Fuel storage and distribution	4.9	4.8	3.1	20.3	62.7	0.0		5.3
Fuel production	54.8	59.7	23.3	76.5	5.6	294.0		12.3
Feedstock transport	16.4	14.9	13.1	7.2	0.0	67.7		6.7
Feedstock, fertilizer production	16.7	15.1	13.3	17.7	8.1	14.7		11.7
CH4, CO2 gas leaks and flares	-4.9	-4.4	-3.9	7.0	18.7	28.0		2.0
Emissions displaced	0.0	0.0	0.0	0.0	0.0	0.0		0.0
Sub total (fuelcycle)	***530.5***	***518.2***	***405.3***	***492.5***	***418.7***	***454.2***	***0.0***	***389.9***
% changes (fuelcycle)	--	*-2.3%*	*-23.6%*	*-7.2%*	*-21.1%*	*-14.4%*	*-100.0%*	*-26.5%*
Vehicle assembly and transport	24.7	24.7	21.3	24.8	26.3	25.8		25.1
Materials in vehicles	60.0	60.0	51.7	60.2	63.6	68.0		60.6
Road dust, tire wear, brake wear	-2.9	-2.9	-3.0	-2.9	-3.0	-2.9		-2.9
Lube oil production and use	4.7	4.7	4.7	4.7	2.3	4.4		3.5
Refrigerant (HFC-134a)	10.6	10.6	10.6	10.6	10.6	10.6		10.6

Grand total	627.7	615.3	490.7	589.8	518.6	560.1	0.0	486.8
% changes (grand total)	--	-2.0%	-21.8%	-6.0%	-17.4%	-10.8%	-100.0%	-22.4%

B1. Japan 2010: ICEVs using biomass fuels

General fuel -->	**Ethanol**	**Ethanol**	**Methanol**	**NG**
Fuel specification -->	E90 (corn)	E90	M85	CNG
Feedstock -->	*Coal/NG*	*Grass*	*Wood*	*Wood*
Vehicle operation: fuel	368.1	368.1	361.8	311.4
Fuel dispensing	1.5	1.2	1.5	9.7
Fuel storage and distribution	9.4	9.9	10.2	5.8
Fuel production	208.8	76.8	55.3	23.9
Feedstock transport	18.1	16.9	16.4	13.7
Feedstock, fertilizer production	140.9	78.0	44.4	43.3
Land use changes, cultivation	223.0	79.1	(19.2)	(20.3)
CH4, CO2 gas leaks and flares	(0.6)	(0.6)	(1.0)	12.9
C in end-use fuel from air CO2	(264.5)	(264.5)	(219.8)	(253.6)
Emissions displaced	(119.4)	(20.5)	0.0	0.0
Sub total (fuelcycle)	***585.3***	***344.5***	***249.7***	***146.7***
% changes (fuelcycle)	***10.3%***	***-35.1%***	***-52.9%***	***-72.3%***
Vehicle assembly and transport	24.8	24.8	24.8	26.3
Materials in vehicles	60.1	60.1	60.2	63.6
Road dust, tire wear, brake wear	-2.9	-2.9	-2.9	-3.0
Lube oil production and use	4.7	4.7	4.7	2.3
Refrigerant (HFC-134a)	10.6	10.6	10.6	10.6

Grand total	*682.6*	*441.9*	*347.1*	*246.6*
% changes (grand total)	*8.8%*	*-29.6%*	*-44.7%*	*-60.7%*

B1. Japan 2010: Battery EVs, by type of power plant fuel.

	Coal	Fuel oil	NG/ boiler	NG/ turbine	Nuclear*	Biomass	Hydro*	Other
Fuelcycle (g/mi)	346.5	297.9	283.1	225.5	18.1	28.5	16.6	12.5
Fuelcycle (% changes)	*-34.7%*	*-43.8%*	*-46.6%*	*-57.5%*	*-96.6%*	*-94.6%*	*-96.9%*	*-97.7%*
Fuel and materials (g/mi)	492.1	443.5	428.7	371.1	163.7	174.0	162.2	158.1
Fuel and materials (% changes)	*-21.6%*	*-29.3%*	*-31.7%*	*-40.9%*	*-73.9%*	*-72.3%*	*-74.2%*	*-74.8%*

B1. Japan 2010: Fuel cell EVs.

General fuel -->	**Gasoline**	**Methanol**	**Methanol**	**Ethanol**	**Hydrogen**	**Hydrogen**	**Hydrogen**	**Hydrogen**
Fuel specification -->	RFG-Ox10	M100	M100	E100	CH2	CH2 (NG)	CH2	CH2
Feedstock -->	*Crude oil*	*NG*	*Wood*	*Grass*	*Water*	*NG*	*Wood*	*Coal*
Vehicle operation: fuel	206.0	183.1	183.1	197.7	1.7	4.3	4.8	4.8
Fuel dispensing	0.8	1.3	1.0	0.8	21.0	21.0	21.0	21.0
Fuel storage and distribution	2.9	15.9	7.5	6.9	0.7	0.0	0.5	0.6
Fuel production	35.5	51.8	34.2	51.4	9.3	144.1	9.0	54.3
Feedstock transport	8.8	3.1	10.7	11.2	0.0	33.2	7.5	25.3
Feedstock, fertilizer production	9.0	11.8	33.8	56.6	0.0	7.2	23.6	4.1
Land use changes, cultivation	0.0	0.0	(15.9)	58.8	0.0	0.0	(11.1)	0.1
CH4, CO2 gas leaks and flares	(2.6)	6.7	0.0	0.0	11.2	13.7	10.9	17.7
C in end-use fuel from air CO2	0.0	0.0	(182.1)	(196.6)	0.0	0.0	(3.1)	0.0
Emissions displace	0.0	0.0	0.0	(15.2)	0.0	0.0	0.0	0.0
Sub total (fuelcycle)	*260.3*	*273.6*	*72.5*	*171.4*	*43.9*	*223.5*	*63.2*	*127.9*
% changes (fuelcycle)	*-50.9%*	*-48.4%*	*-86.3%*	*-67.7%*	*-91.7%*	*-57.9%*	*-88.1%*	*-75.9%*
Vehicle assembly and transport	23.6	23.8	23.8	23.7	23.3	23.3	23.3	23.3
Materials in vehicles	64.2	64.7	64.7	64.5	66.7	66.7	66.7	66.7
Road dust, tire wear, brake wear	-3.0	-3.0	-3.0	-3.0	-2.9	-2.9	-2.9	-2.9
Lube oil production and use	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Refrigerant (HFC-134a)	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6

Grand total	355.8	369.6	168.5	267.2	141.6	321.2	160.9	225.6
% changes (grand total)	-43.3%	-41.1%	-73.2%	-57.4%	-77.4%	-48.8%	-74.4%	-64.1%

B2. Japan 2050: ICEVs using fossil fuels.

General fuel -->	**Gasoline**	**Gasoline**	**Diesel**	**Methanol**	**NG**	**Hydrogen**	**Blank**	**LPG**
Fuel specification -->	CG	RFG-Ox10	0.001% S	M85	CNG	CH2	Blank	P95/BU5
Feedstock -->	*crude oil*	*crude oil*	*crude oil*	*NG100/C0*	*NG100*	*NG100*	*Blank*	*NGL57*
Vehicle operation: fuel	370.7	366.2	311.0	299.7	250.2	8.4		288.2
Fuel dispensing	0.8	0.8	0.6	1.2	7.8	26.8		0.7
Fuel storage and distribution	2.9	2.9	1.9	14.8	53.2	0.0		3.0
Fuel production	48.2	51.7	20.4	46.7	4.6	245.4		10.0
Feedstock transport	12.5	11.3	10.0	5.5	0.0	53.3		4.7
Feedstock, fertilizer production	16.5	15.0	13.2	15.7	8.2	12.7		11.2
CH4, CO2 gas leaks and flares	-11.6	-10.5	-9.3	1.9	9.9	15.0		-2.2
Emissions displaced	0.0	0.0	0.0	0.0	0.0	0.0		0.0
Sub total (fuelcycle)	***440.1***	***437.4***	***347.7***	***385.5***	***333.9***	***361.7***	***0.0***	***315.6***
% changes (fuelcycle)	--	*-0.6%*	*-21.0%*	*-12.4%*	*-24.1%*	*-17.8%*	*-100.0%*	*-28.3%*
Vehicle assembly and transport	12.3	12.3	10.6	12.3	13.0	12.7		12.5
Materials in vehicles	38.7	38.7	33.3	38.8	46.5	43.4		39.0
Road dust, tire wear, brake wear	-2.7	-2.7	-2.7	-2.7	-2.7	-2.7		-2.7
Lube oil production and use	3.8	3.8	3.8	3.8	1.9	3.6		2.9
Refrigerant (HFC-134a)	3.3	3.3	3.3	3.3	3.3	3.3		3.3
Grand total	***495.6***	***492.9***	***396.1***	***441.0***	***395.9***	***422.0***	***0.0***	***370.6***
% changes (grand total)	--	*-0.5%*	*-20.1%*	*-11.0%*	*-20.1%*	*-14.8%*	*-100.0%*	*-25.2%*

B2. Japan 2050: ICEVs using biomass fuels

General fuel -->	**Ethanol**	**Ethanol**	**Methanol**	**NG**
Fuel specification -->	E90 (corn)	E90	M85	CNG
Feedstock -->	*Coal/NG*	*Grass*	*Wood*	*Wood*
Vehicle operation: fuel	304.9	304.9	299.7	250.2
Fuel dispensing	0.9	0.8	1.0	6.2
Fuel storage and distribution	5.0	5.4	5.8	2.7
Fuel production	164.3	48.6	39.0	13.4
Feedstock transport	9.8	6.5	7.6	5.7
Feedstock, fertilizer production	85.8	35.3	22.5	21.7
Land use changes, cultivation	155.4	43.2	(35.5)	(40.3)
CH4, CO2 gas leaks and flares	(1.3)	(1.3)	(2.3)	7.2
C in end-use fuel from air CO2	(248.8)	(248.8)	(208.3)	(235.6)
Emissions displaced	(67.0)	(42.7)	0.0	0.0
Sub total (fuelcycle)	***408.9***	***151.8***	***129.3***	***31.2***
% changes (fuelcycle)	***-7.1%***	***-65.5%***	***-70.6%***	***-92.9%***
Vehicle assembly and transport	12.3	12.3	12.3	13.0
Materials in vehicles	38.7	38.7	38.8	46.5
Road dust, tire wear, brake wear	-2.7	-2.7	-2.7	-2.7
Lube oil production and use	3.8	3.8	3.8	1.9
Refrigerant (HFC-134a)	3.3	3.3	3.3	3.3

Grand total	*464.5*	*207.3*	*184.9*	*93.3*
% changes (grand total)	*-6.3%*	*-58.2%*	*-62.7%*	*-81.2%*

B2. Japan. 2050: Battery EVs, by type of power plant fuel.

	Coal	Fuel oil	NG/ boiler	NG/ turbine	Nuclear*	Biomass	Hydro*	Other
Fuelcycle (g/mi)	282.5	228.6	210.2	180.0	8.7	(1.6)	8.3	4.8
Fuelcycle (% changes)	*-35.8%*	*-48.1%*	*-52.2%*	*-59.1%*	*-98.0%*	*-100.4%*	*-98.1%*	*-98.9%*
Fuel and materials (g/mi)	333.8	279.9	261.5	231.4	60.1	49.7	59.7	56.2
Fuel and materials (% changes)	*-32.6%*	*-43.5%*	*-47.2%*	*-53.3%*	*-87.9%*	*-90.0%*	*-88.0%*	*-88.7%*

B2. Japan 2050: Fuel cell EVs.

General fuel -->	**Gasoline**	**Methanol**	**Methanol**	**Ethanol**	**Hydrogen**	**Hydrogen**	**Hydrogen**	**Hydrogen**
Fuel specification -->	RFG-Ox10	M100	M100	E100	CH2	CH2 (NG)	CH2	CH2
Feedstock -->	*Crude oil*	*NG*	*Wood*	*Grass*	*Water*	*NG*	*Wood*	*Coal*
Vehicle operation: fuel	174.0	152.3	152.3	167.5	1.1	3.4	3.9	3.9
Fuel dispensing	0.4	0.7	0.6	0.5	13.4	13.4	13.4	13.4
Fuel storage and distribution	1.5	10.3	3.7	3.4	0.5	0.0	0.3	0.4
Fuel production	26.0	25.6	20.0	28.4	6.2	122.8	5.5	36.7
Feedstock transport	5.7	2.2	3.7	3.4	0.0	26.7	3.2	15.4
Feedstock, fertilizer production	7.6	9.0	13.9	22.4	0.0	6.4	12.2	2.6
Land use changes, cultivation	0.0	0.0	(25.8)	28.9	0.0	0.0	(22.6)	0.1
CH4, CO2 gas leaks and flares	(5.3)	3.0	0.0	0.0	6.4	7.5	6.2	9.9
C in end-use fuel from air CO2	0.0	0.0	(151.4)	(166.6)	0.0	0.0	(2.9)	0.0
Emissions displace	0.0	0.0	0.0	(28.6)	0.0	0.0	0.0	0.0
Sub total (fuelcycle)	***209.8***	***203.1***	***17.0***	***59.3***	***27.6***	***180.2***	***19.3***	***82.4***
% changes (fuelcycle)	***-52.3%***	***-53.8%***	***-96.1%***	***-86.5%***	***-93.7%***	***-59.1%***	***-95.6%***	***-81.3%***
Vehicle assembly and transport	10.1	10.2	10.2	10.2	10.4	10.4	10.4	10.4
Materials in vehicles	33.9	34.2	34.2	34.1	37.9	37.9	37.9	37.9
Road dust, tire wear, brake wear	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5
Lube oil production and use	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Refrigerant (HFC-134a)	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3

Grand total	*254.7*	*248.3*	*62.2*	*104.4*	*76.8*	*229.4*	*68.5*	*131.6*
% changes (grand total)	*-48.6%*	*-49.9%*	*-87.5%*	*-78.9%*	*-84.5%*	*-53.7%*	*-86.2%*	*-73.5%*

TABLE Y-19C. GRAM-PER-MILE EMISSIONS BY VEHICLE/FUEL/FEEDSTOCK COMBINATION, AND STAGE OF THE FUELCYCLE (BEST CEFS): CHINA 2010 AND 2050

C1. China 2010: ICEVs using fossil fuels.

General fuel -->	**Gasoline**	**Gasoline**	**Diesel**	**Methanol**	**NG**	**Hydrogen**	**Blank**	**LPG**
Fuel specification -->	CG	RFG-Ox10	0.001% S	M85	CNG	CH2	Blank	P95/BU5
Feedstock -->	*crude oil*	*crude oil*	*crude oil*	*NG100/C0*	*NG100*	*NG100*	*Blank*	*NGL57*
Vehicle operation: fuel	454.1	443.3	380.7	368.5	319.8	4.3		354.3
Fuel dispensing	2.3	2.3	1.4	3.3	21.7	75.3		2.1
Fuel storage and distribution	5.7	5.5	2.9	8.0	15.1	0.0		5.8
Fuel production	61.3	66.5	24.7	81.8	5.8	306.8		13.5
Feedstock transport	8.8	8.0	6.8	5.6	0.0	16.3		3.5
Feedstock, fertilizer production	21.4	19.4	16.5	19.2	8.3	15.2		13.8
CH4, CO2 gas leaks and flares	0.5	0.4	0.4	8.4	31.5	41.9		4.9
Emissions displaced	0.0	0.0	0.0	0.0	0.0	0.0		0.0
Sub total (fuelcycle)	***554.0***	***545.4***	***433.4***	***495.0***	***402.2***	***459.9***	***0.0***	***397.8***
% changes (fuelcycle)	*--*	*-1.6%*	*-21.8%*	*-10.7%*	*-27.4%*	*-17.0%*	*-100.0%*	*-28.2%*
Vehicle assembly and transport	29.8	29.8	25.6	29.9	31.8	31.1		30.3
Materials in vehicles	61.8	61.8	53.2	62.0	65.4	70.0		62.3
Road dust, tire wear, brake wear	-3.1	-3.1	-3.2	-3.1	-3.2	-3.1		-3.1
Lube oil production and use	4.8	4.8	4.8	4.8	2.4	4.6		3.6
Refrigerant (HFC-134a)	10.6	10.6	10.6	10.6	10.6	10.6		10.6

Grand total	*657.9*	*649.3*	*524.5*	*599.1*	*509.2*	*573.0*	*0.0*	*501.5*
% changes (grand total)	*--*	*-1.3%*	*-20.3%*	*-8.9%*	*-22.6%*	*-12.9%*	*-100.0%*	*-23.8%*

C1. China 2010: ICEVs using biomass fuels

General fuel -->	**Ethanol**	**Ethanol**	**Methanol**	**NG**
Fuel specification -->	E90 (corn)	E90	M85	CNG
Feedstock -->	*Coal/NG*	*Grass*	*Wood*	*Wood*
Vehicle operation: fuel	374.0	374.0	368.5	319.8
Fuel dispensing	2.6	2.0	2.5	15.5
Fuel storage and distribution	9.3	9.4	9.9	8.5
Fuel production	233.9	81.7	64.7	30.4
Feedstock transport	15.4	14.2	13.2	12.1
Feedstock, fertilizer production	151.1	82.6	46.5	44.8
Land use changes, cultivation	356.8	136.7	27.0	28.8
CH4, CO2 gas leaks and flares	0.1	0.1	0.1	24.6
C in end-use fuel from air CO2	(267.3)	(267.3)	(222.1)	(256.2)
Emissions displaced	(165.0)	(32.8)	0.0	0.0
Sub total (fuelcycle)	***710.9***	***400.6***	***310.4***	***228.3***
% changes (fuelcycle)	***28.3%***	***-27.7%***	***-44.0%***	***-58.8%***
Vehicle assembly and transport	29.9	29.9	29.9	31.8
Materials in vehicles	61.9	61.9	62.0	65.4
Road dust, tire wear, brake wear	-3.1	-3.1	-3.1	-3.2
Lube oil production and use	4.8	4.8	4.8	2.4
Refrigerant (HFC-134a)	10.6	10.6	10.6	10.6

Grand total	*815.0*	*504.7*	*414.5*	*335.3*
% changes (grand total)	*23.9%*	*-23.3%*	*-37.0%*	*-49.0%*

C1. China 2010: Battery EVs, by type of power plant fuel.

	Coal	Fuel oil	NG/ boiler	NG/ turbine	Nuclear*	Biomass	Hydro*	Other
Fuelcycle (g/mi)	348.1	350.2	294.7	214.9	24.7	89.3	15.8	11.7
Fuelcycle (% changes)	*-37.2%*	*-36.8%*	*-46.8%*	*-61.2%*	*-95.5%*	*-83.9%*	*-97.1%*	*-97.9%*
Fuel and materials (g/mi)	517.3	519.4	463.9	384.1	193.8	258.4	185.0	180.8
Fuel and materials (% changes)	*-21.4%*	*-21.1%*	*-29.5%*	*-41.6%*	*-70.5%*	*-60.7%*	*-71.9%*	*-72.5%*

C1. China 2010: Fuel cell EVs.

General fuel -->	Gasoline	Methanol	Methanol	Ethanol	Hydrogen	Hydrogen	Hydrogen	Hydrogen
Fuel specification -->	RFG-Ox10	M100	M100	E100	CH2	CH2 (NG)	CH2	CH2
Feedstock -->	*Crude oil*	*NG*	*Wood*	*Grass*	*Water*	*NG*	*Wood*	*Coal*
Vehicle operation: fuel	188.9	167.4	167.4	180.7	1.5	3.8	4.3	4.3
Fuel dispensing	1.2	2.1	1.4	1.1	32.4	32.4	32.4	32.4
Fuel storage and distribution	3.0	5.1	6.4	5.8	2.3	0.0	1.5	1.9
Fuel production	35.7	49.6	36.8	49.2	19.3	132.0	8.0	62.6
Feedstock transport	4.3	2.8	8.5	8.8	0.0	7.0	5.8	3.0
Feedstock, fertilizer production	10.4	11.0	31.4	53.8	0.0	6.6	21.5	4.4
Land use changes, cultivation	0.0	0.0	20.2	91.8	0.0	0.0	13.8	0.1
CH4, CO2 gas leaks and flares	0.2	6.2	0.0	0.0	16.2	18.0	15.4	23.6
C in end-use fuel from air CO2	0.0	0.0	(166.3)	(179.5)	0.0	0.0	(2.7)	0.0
Emissions displace	0.0	0.0	0.0	(22.0)	0.0	0.0	0.0	0.0
Sub total (fuelcycle)	***243.7***	***244.2***	***106.0***	***189.8***	***71.8***	***199.8***	***99.9***	***132.3***
% changes (fuelcycle)	***-56.0%***	***-55.9%***	***-80.9%***	***-65.7%***	***-87.0%***	***-63.9%***	***-82.0%***	***-76.1%***
Vehicle assembly and transport	28.4	28.6	28.6	28.5	28.0	28.0	28.0	28.0
Materials in vehicles	67.9	68.4	68.4	68.1	69.7	69.7	69.7	69.7
Road dust, tire wear, brake wear	-3.2	-3.2	-3.2	-3.2	-3.1	-3.1	-3.1	-3.1
Lube oil production and use	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Refrigerant (HFC-134a)	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6

Grand total	*347.4*	*348.6*	*210.3*	*293.9*	*176.9*	*305.0*	*205.1*	*237.5*
% changes (grand total)	*-47.2%*	*-47.0%*	*-68.0%*	*-55.3%*	*-73.1%*	*-53.6%*	*-68.8%*	*-63.9%*

C2. China 2050: ICEVs using fossil fuels.

General fuel -->	**Gasoline**	**Gasoline**	**Diesel**	**Methanol**	**NG**	**Hydrogen**	**Blank**	**LPG**
Fuel specification -->	CG	RFG-Ox10	0.001% S	M85	CNG	CH2	Blank	P95/BU5
Feedstock -->	*crude oil*	*crude oil*	*crude oil*	*NG100/C0*	*NG100*	*NG100*	*Blank*	*NGL57*
Vehicle operation: fuel	374.5	377.1	322.8	306.8	256.4	8.2		294.1
Fuel dispensing	1.8	1.8	1.2	2.6	17.7	60.6		1.6
Fuel storage and distribution	3.6	3.6	2.3	5.3	22.9	0.0		3.6
Fuel production	53.1	56.8	21.7	51.0	4.7	258.9		10.8
Feedstock transport	8.0	7.3	6.2	4.7	0.0	22.9		3.0
Feedstock, fertilizer production	21.9	19.9	17.0	17.2	8.4	13.2		13.4
CH4, CO2 gas leaks and flares	-10.3	-9.3	-8.0	2.3	17.0	22.2		-1.3
Emissions displaced	0.0	0.0	0.0	0.0	0.0	0.0		0.0
Sub total (fuelcycle)	***452.5***	***457.1***	***363.2***	***390.0***	***327.1***	***385.9***	***0.0***	***325.2***
% changes (fuelcycle)	*--*	*1.0%*	*-19.7%*	*-13.8%*	*-27.7%*	*-14.7%*	*-100.0%*	*-28.1%*
Vehicle assembly and transport	18.8	18.8	16.2	18.8	19.9	19.5		19.0
Materials in vehicles	42.0	42.0	36.2	42.1	50.4	47.1		42.3
Road dust, tire wear, brake wear	-2.8	-2.8	-2.9	-2.9	-2.9	-2.9		-2.9
Lube oil production and use	4.0	4.0	4.0	4.0	2.0	3.7		3.0
Refrigerant (HFC-134a)	3.3	3.3	3.3	3.3	3.3	3.3		3.3
Grand total	***517.7***	***522.3***	***419.9***	***455.4***	***399.8***	***456.7***	***0.0***	***390.0***
% changes (grand total)	*--*	*0.9%*	*-18.9%*	*-12.0%*	*-22.8%*	*-11.8%*	*-100.0%*	*-24.7%*

C2. China 2050: ICEVs using biomass fuels

General fuel -->	**Ethanol**	**Ethanol**	**Methanol**	**NG**
Fuel specification -->	E90 (corn)	E90	M85	CNG
Feedstock -->	*Coal/NG*	*Grass*	*Wood*	*Wood*
Vehicle operation: fuel	311.8	311.8	306.8	256.4
Fuel dispensing	2.1	1.7	2.1	13.6
Fuel storage and distribution	5.8	5.9	6.4	4.2
Fuel production	195.8	53.2	54.3	20.0
Feedstock transport	9.3	6.4	7.0	6.2
Feedstock, fertilizer production	97.0	38.7	25.0	23.4
Land use changes, cultivation	234.2	69.6	(19.0)	(21.6)
CH4, CO2 gas leaks and flares	(1.1)	(1.1)	(2.1)	14.4
C in end-use fuel from air CO2	(251.4)	(251.4)	(210.4)	(238.1)
Emissions displaced	(91.5)	(93.0)	0.0	0.0
Sub total (fuelcycle)	***512.0***	***141.8***	***170.0***	***78.5***
% changes (fuelcycle)	***13.1%***	***-68.7%***	***-62.4%***	***-82.7%***
Vehicle assembly and transport	18.8	18.8	18.8	19.9
Materials in vehicles	42.1	42.1	42.1	50.4
Road dust, tire wear, brake wear	-2.9	-2.9	-2.9	-2.9
Lube oil production and use	4.0	4.0	4.0	2.0
Refrigerant (HFC-134a)	3.3	3.3	3.3	3.3

Grand total	*577.3*	*207.1*	*235.4*	*151.2*
% changes (grand total)	*11.5%*	*-60.0%*	*-54.5%*	*-70.8%*

C2. China 2050: Battery EVs, by type of power plant fuel.

	Coal	Fuel oil	NG/ boiler	NG/ turbine	Nuclear*	Biomass	Hydro*	Other
Fuelcycle (g/mi)	325.2	250.2	214.0	156.5	11.8	6.2	7.9	4.5
Fuelcycle (% changes)	*-28.1%*	*-44.7%*	*-52.7%*	*-65.4%*	*-97.4%*	*-98.6%*	*-98.3%*	*-99.0%*
Fuel and materials (g/mi)	387.5	312.5	276.3	218.7	74.1	68.5	70.1	66.7
Fuel and materials (% changes)	*-25.2%*	*-39.6%*	*-46.6%*	*-57.7%*	*-85.7%*	*-86.8%*	*-86.5%*	*-87.1%*

C2. China 2050: Fuel cell EVs.

General fuel -->	**Gasoline**	**Methanol**	**Methanol**	**Ethanol**	**Hydrogen**	**Hydrogen**	**Hydrogen**	**Hydrogen**
Fuel specification -->	RFG-Ox10	M100	M100	E100	CH2	CH2 (NG)	CH2	CH2
Feedstock -->	*Crude oil*	*NG*	*Wood*	*Grass*	*Water*	*NG*	*Wood*	*Coal*
Vehicle operation: fuel	159.9	140.3	140.3	153.9	0.9	3.1	3.5	3.5
Fuel dispensing	0.8	1.5	1.1	0.9	26.9	26.9	26.9	26.9
Fuel storage and distribution	1.6	3.0	3.7	3.3	2.0	0.0	1.3	1.7
Fuel production	26.0	25.5	27.6	28.2	10.9	115.1	5.8	46.9
Feedstock transport	3.3	2.1	3.6	3.3	0.0	10.2	3.1	2.2
Feedstock, fertilizer production	9.1	8.5	13.6	22.1	0.0	5.8	11.7	3.0
Land use changes, cultivation	0.0	0.0	(12.6)	42.3	0.0	0.0	(10.8)	0.1
CH4, CO2 gas leaks and flares	(4.3)	2.9	0.0	0.0	9.1	9.9	8.3	13.6
C in end-use fuel from air CO2	0.0	0.0	(139.4)	(152.9)	0.0	0.0	(2.6)	0.0
Emissions displace	0.0	0.0	0.0	(56.5)	0.0	0.0	0.0	0.0
Sub total (fuelcycle)	***196.4***	***183.7***	***38.0***	***44.7***	***49.9***	***171.0***	***47.4***	***98.0***
% changes (fuelcycle)	***-56.6%***	***-59.4%***	***-91.6%***	***-90.1%***	***-89.0%***	***-62.2%***	***-89.5%***	***-78.3%***
Vehicle assembly and transport	15.4	15.5	15.5	15.5	15.8	15.8	15.8	15.8
Materials in vehicles	37.4	37.7	37.7	37.6	41.1	41.1	41.1	41.1
Road dust, tire wear, brake wear	-2.6	-2.7	-2.7	-2.7	-2.7	-2.7	-2.7	-2.7
Lube oil production and use	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Refrigerant (HFC-134a)	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3

Grand total	*249.9*	*237.6*	*91.9*	*98.4*	*107.5*	*228.6*	*104.9*	*155.6*
% changes (grand total)	*-51.7%*	*-54.1%*	*-82.3%*	*-81.0%*	*-79.2%*	*-55.8%*	*-79.7%*	*-69.9%*

TABLE Y-19D. GRAM-PER-MILE EMISSIONS BY VEHICLE/FUEL/FEEDSTOCK COMBINATION, AND STAGE OF THE FUELCYCLE (BEST CEFS): GERMANY 2010 AND 2050

D1. Germany 2010: ICEVs using fossil fuels.

General fuel -->	**Gasoline**	**Gasoline**	**Diesel**	**Methanol**	**NG**	**Hydrogen**	**Blank**	**LPG**
Fuel specification -->	CG	RFG-Ox10	0.001% S	M85	CNG	CH2	Blank	P95/BU5
Feedstock -->	*crude oil*	*crude oil*	*crude oil*	*NG100/C0*	*NG100*	*NG100*	*Blank*	*NGL57*
Vehicle operation: fuel	440.2	426.5	355.4	361.6	311.2	6.7		350.5
Fuel dispensing	1.7	1.7	1.1	2.5	16.9	58.8		1.6
Fuel storage and distribution	4.3	4.3	2.7	16.0	18.6	0.0		4.6
Fuel production	53.5	58.2	22.7	77.7	5.7	296.7		12.2
Feedstock transport	9.9	9.0	7.9	5.7	0.0	20.0		4.0
Feedstock, fertilizer production	31.4	28.5	25.1	21.5	10.0	16.9		18.9
CH4, CO2 gas leaks and flares	-4.7	-4.2	-3.7	6.4	29.5	39.7		2.3
Emissions displaced	0.0	0.0	0.0	0.0	0.0	0.0		0.0
Sub total (fuelcycle)	***536.3***	***523.9***	***411.2***	***491.5***	***391.9***	***438.9***	***0.0***	***394.1***
% changes (fuelcycle)	--	*-2.3%*	*-23.3%*	*-8.4%*	*-26.9%*	*-18.2%*	*-100.0%*	*-26.5%*
Vehicle assembly and transport	24.7	24.7	21.3	24.8	26.3	25.7		25.1
Materials in vehicles	58.3	58.3	50.2	58.4	61.7	65.8		58.8
Road dust, tire wear, brake wear	-2.9	-2.9	-3.0	-2.9	-3.0	-2.9		-2.9
Lube oil production and use	4.8	4.8	4.8	4.8	2.4	4.6		3.6
Refrigerant (HFC-134a)	10.6	10.6	10.6	10.6	10.6	10.6		10.6

Grand total	631.8	619.4	495.1	587.2	490.0	542.7	0.0	489.3
% changes (grand total)	--	-2.0%	-21.6%	-7.1%	-22.5%	-14.1%	-100.0%	-22.6%

D1. Germany 2010: ICEVs using biomass fuels

General fuel -->	**Ethanol**	**Ethanol**	**Methanol**	**NG**
Fuel specification -->	E90 (corn)	E90	M85	CNG
Feedstock -->	*Coal/NG*	*Grass*	*Wood*	*Wood*
Vehicle operation: fuel	368.0	368.0	361.6	311.2
Fuel dispensing	2.0	1.6	2.0	12.9
Fuel storage and distribution	7.6	7.9	8.4	6.1
Fuel production	202.9	73.4	58.5	27.3
Feedstock transport	14.3	11.8	11.2	9.8
Feedstock, fertilizer production	137.0	76.5	46.2	42.2
Land use changes, cultivation	230.6	85.3	(8.6)	(9.2)
CH4, CO2 gas leaks and flares	(0.5)	(0.5)	(1.0)	24.5
C in end-use fuel from air CO2	(264.5)	(264.5)	(219.8)	(253.6)
Emissions displaced	(119.4)	(27.3)	0.0	0.0
Sub total (fuelcycle)	***578.0***	***332.1***	***258.6***	***171.3***
% changes (fuelcycle)	***7.8%***	***-38.1%***	***-51.8%***	***-68.1%***
Vehicle assembly and transport	24.8	24.8	24.8	26.3
Materials in vehicles	58.4	58.4	58.4	61.7
Road dust, tire wear, brake wear	-2.9	-2.9	-2.9	-3.0
Lube oil production and use	4.8	4.8	4.8	2.4
Refrigerant (HFC-134a)	10.6	10.6	10.6	10.6

Grand total	*673.7*	*427.8*	*354.3*	*269.3*
% changes (grand total)	*6.6%*	*-32.3%*	*-43.9%*	*-57.4%*

D1. Germany 2010: Battery EVs, by type of power plant fuel.

	Coal	Fuel oil	NG/ boiler	NG/ turbine	Nuclear*	Biomass	Hydro*	Other
Fuelcycle (g/mi)	385.7	302.8	264.6	211.1	45.5	37.5	16.7	12.5
Fuelcycle (% changes)	*-28.1%*	*-43.5%*	*-50.7%*	*-60.6%*	*-91.5%*	*-93.0%*	*-96.9%*	*-97.7%*
Fuel and materials (g/mi)	537.6	454.7	416.5	363.0	197.4	189.4	168.6	164.3
Fuel and materials (% changes)	*-14.9%*	*-28.0%*	*-34.1%*	*-42.6%*	*-68.8%*	*-70.0%*	*-73.3%*	*-74.0%*

D1. Germany 2010: Fuel cell EVs.

General fuel -->	**Gasoline**	**Methanol**	**Methanol**	**Ethanol**	**Hydrogen**	**Hydrogen**	**Hydrogen**	**Hydrogen**
Fuel specification -->	RFG-Ox10	M100	M100	E100	CH2	CH2 (NG)	CH2	CH2
Feedstock -->	*Crude oil*	*NG*	*Wood*	*Grass*	*Water*	*NG*	*Wood*	*Coal*
Vehicle operation: fuel	206.0	183.1	183.1	197.7	1.7	4.3	4.8	4.8
Fuel dispensing	1.0	1.8	1.3	1.0	28.8	28.8	28.8	28.8
Fuel storage and distribution	2.5	12.5	6.2	5.5	5.4	0.0	3.6	4.5
Fuel production	34.5	53.1	37.1	49.0	53.8	145.4	7.5	61.7
Feedstock transport	5.3	3.0	7.6	7.9	0.0	9.8	5.3	4.5
Feedstock, fertilizer production	16.9	12.3	32.7	54.2	0.0	8.3	23.0	4.2
Land use changes, cultivation	0.0	0.0	(7.1)	63.4	0.0	0.0	(5.0)	0.1
CH4, CO2 gas leaks and flares	(2.5)	6.1	0.0	0.0	15.8	19.5	14.0	21.6
C in end-use fuel from air CO2	0.0	0.0	(182.1)	(196.6)	0.0	0.0	(3.1)	0.0
Emissions displace	0.0	0.0	0.0	(20.3)	0.0	0.0	0.0	0.0
Sub total (fuelcycle)	***263.8***	***271.7***	***78.8***	***161.8***	***105.4***	***216.1***	***78.9***	***130.3***
% changes (fuelcycle)	***-50.8%***	***-49.3%***	***-85.3%***	***-69.8%***	***-80.3%***	***-59.7%***	***-85.3%***	***-75.7%***
Vehicle assembly and transport	23.6	23.7	23.7	23.7	23.3	23.3	23.3	23.3
Materials in vehicles	62.9	63.3	63.3	63.1	65.2	65.2	65.2	65.2
Road dust, tire wear, brake wear	-3.0	-3.0	-3.0	-3.0	-2.9	-2.9	-2.9	-2.9
Lube oil production and use	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Refrigerant (HFC-134a)	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6

Grand total	357.8	366.4	173.5	256.2	201.5	312.2	175.0	226.4
% changes (grand total)	-43.4%	-42.0%	-72.5%	-59.5%	-68.1%	-50.6%	-72.3%	-64.2%

D2. Germany 2050: ICEVs using fossil fuels.

General fuel -->	**Gasoline**	**Gasoline**	**Diesel**	**Methanol**	**NG**	**Hydrogen**	**Blank**	**LPG**
Fuel specification -->	CG	RFG-Ox10	0.001% S	M85	CNG	CH2	Blank	P95/BU5
Feedstock -->	*crude oil*	*crude oil*	*crude oil*	*NG100/C0*	*NG100*	*NG100*	*Blank*	*NGL57*
Vehicle operation: fuel	369.8	366.2	311.0	299.7	250.2	8.4		288.2
Fuel dispensing	0.5	0.5	0.3	0.6	3.6	12.2		0.4
Fuel storage and distribution	2.8	2.8	1.8	12.0	16.2	0.0		2.6
Fuel production	47.4	50.5	20.0	47.2	4.6	240.7		9.9
Feedstock transport	7.5	6.8	6.0	4.4	0.0	16.2		2.8
Feedstock, fertilizer production	25.5	23.1	20.4	18.1	10.1	14.7		15.8
CH4, CO2 gas leaks and flares	-13.2	-11.9	-10.5	1.2	15.9	21.0		-2.8
Emissions displaced	0.0	0.0	0.0	0.0	0.0	0.0		0.0
Sub total (fuelcycle)	***440.3***	***437.9***	***348.9***	***383.2***	***300.5***	***313.2***	***0.0***	***316.9***
% changes (fuelcycle)	--	*-0.5%*	*-20.7%*	*-13.0%*	*-31.7%*	*-28.9%*	*-100.0%*	*-28.0%*
Vehicle assembly and transport	12.6	12.6	10.8	12.6	13.3	13.0		12.7
Materials in vehicles	36.8	36.8	31.7	36.8	44.2	41.2		37.0
Road dust, tire wear, brake wear	-2.7	-2.7	-2.7	-2.7	-2.7	-2.7		-2.7
Lube oil production and use	3.9	3.9	3.9	3.9	1.9	3.6		2.9
Refrigerant (HFC-134a)	3.3	3.3	3.3	3.3	3.3	3.3		3.3
Grand total	***494.2***	***491.8***	***395.9***	***437.1***	***360.5***	***371.7***	***0.0***	***370.2***
% changes (grand total)	--	*-0.5%*	*-19.9%*	*-11.5%*	*-27.0%*	*-24.8%*	*-100.0%*	*-25.1%*

D2. Germany 2050: ICEVs using biomass fuels

General fuel -->	**Ethanol**	**Ethanol**	**Methanol**	**NG**
Fuel specification -->	E90 (corn)	E90	M85	CNG
Feedstock -->	*Coal/NG*	*Grass*	*Wood*	*Wood*
Vehicle operation: fuel	304.9	304.9	299.7	250.2
Fuel dispensing	0.5	0.4	0.5	2.8
Fuel storage and distribution	4.5	5.0	5.4	2.7
Fuel production	148.5	45.9	32.1	10.5
Feedstock transport	8.8	5.8	6.4	5.6
Feedstock, fertilizer production	81.0	34.3	23.4	20.9
Land use changes, cultivation	159.5	46.5	(28.9)	(32.9)
CH4, CO2 gas leaks and flares	(1.4)	(1.4)	(2.6)	14.1
C in end-use fuel from air CO2	(248.8)	(248.8)	(208.3)	(235.6)
Emissions displaced	(66.5)	(19.2)	0.0	0.0
Sub total (fuelcycle)	***390.9***	***173.2***	***127.7***	***38.3***
% changes (fuelcycle)	***-11.2%***	***-60.7%***	***-71.0%***	***-91.3%***
Vehicle assembly and transport	12.6	12.6	12.6	13.3
Materials in vehicles	36.8	36.8	36.8	44.2
Road dust, tire wear, brake wear	-2.7	-2.7	-2.7	-2.7
Lube oil production and use	3.9	3.9	3.9	1.9
Refrigerant (HFC-134a)	3.3	3.3	3.3	3.3

Grand total	*444.9*	*227.2*	*181.7*	*98.3*
% changes (grand total)	*-10.0%*	*-54.0%*	*-63.2%*	*-80.1%*

D2. Germany. 2050: Battery EVs, by type of power plant fuel.

	Coal	Fuel oil	NG/ boiler	NG/ turbine	Nuclear*	Biomass	Hydro*	Other
Fuelcycle (g/mi)	322.8	233.0	195.6	167.8	24.6	(0.5)	8.4	4.8
Fuelcycle (% changes)	*-26.7%*	*-47.1%*	*-55.6%*	*-61.9%*	*-94.4%*	*-100.1%*	*-98.1%*	*-98.9%*
Fuel and materials (g/mi)	371.5	281.7	244.3	216.5	73.3	48.2	57.1	53.5
Fuel and materials (% changes)	*-24.8%*	*-43.0%*	*-50.6%*	*-56.2%*	*-85.2%*	*-90.3%*	*-88.5%*	*-89.2%*

D2. Germany 2050: Fuel cell EVs.

General fuel -->	**Gasoline**	**Methanol**	**Methanol**	**Ethanol**	**Hydrogen**	**Hydrogen**	**Hydrogen**	**Hydrogen**
Fuel specification -->	RFG-Ox10	M100	M100	E100	CH2	CH2 (NG)	CH2	CH2
Feedstock -->	*Crude oil*	*NG*	*Wood*	*Grass*	*Water*	*NG*	*Wood*	*Coal*
Vehicle operation: fuel	173.9	152.3	152.3	167.5	1.1	3.4	3.9	3.9
Fuel dispensing	0.2	0.3	0.3	0.2	6.1	6.1	6.1	6.1
Fuel storage and distribution	1.4	8.3	3.5	3.1	3.3	0.0	2.2	2.7
Fuel production	25.4	26.2	15.2	26.7	31.5	120.4	5.1	30.1
Feedstock transport	3.4	2.1	3.6	3.3	0.0	8.1	3.1	2.8
Feedstock, fertilizer production	11.6	9.5	13.3	21.1	0.0	7.4	11.7	2.2
Land use changes, cultivation	0.0	0.0	(21.0)	31.1	0.0	0.0	(18.4)	0.1
CH4, CO2 gas leaks and flares	(6.0)	2.8	0.0	0.0	9.3	10.5	8.2	12.0
C in end-use fuel from air CO2	0.0	0.0	(151.4)	(166.6)	0.0	0.0	(2.9)	0.0
Emissions displace	0.0	0.0	0.0	(12.9)	0.0	0.0	0.0	0.0
Sub total (fuelcycle)	***210.0***	***201.4***	***15.7***	***73.6***	***51.2***	***156.0***	***19.0***	***60.0***
% changes (fuelcycle)	***-52.3%***	***-54.3%***	***-96.4%***	***-83.3%***	***-88.4%***	***-64.6%***	***-95.7%***	***-86.4%***
Vehicle assembly and transport	10.3	10.4	10.4	10.4	10.7	10.7	10.7	10.7
Materials in vehicles	31.9	32.2	32.2	32.1	35.7	35.7	35.7	35.7
Road dust, tire wear, brake wear	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5	-2.5
Lube oil production and use	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Refrigerant (HFC-134a)	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3

Grand total	253.2	244.8	59.2	116.9	98.3	203.1	66.2	107.2
% changes (grand total)	-48.8%	-50.5%	-88.0%	-76.3%	-80.1%	-58.9%	-86.6%	-78.3%

Notes to all Tables Y-19.

"Best CEFs" are my best estimates of CO2-equivalency factors, as distinguished from the IPCC GWPs.

In the case of regional results for EVs: trade data are NOT region specific; national values apply to all regions.

LDGV = light-duty gasoline vehicle

HDDV = heavy-duty diesel vehicle

CG = conventional gasoline

RFG = reformulated gasoline

Ox = oxygenate (ETBE, MTBE, ethanol, methanol) (volume % in active gasoline)

M = methanol (volume % in fuel for methanol vehicle; remainder is gasoline)

CNG = compressed natural gas

LNG = liquefied natural gas

CH2 = compressed hydrogen

LH2 = liquefied hydrogen

E = ethanol (volume % in fuel for ethanol vehicle; remainder is gasoline)

P = propane (volume % in LPG)

BU = butane (volume % in LPG)

FTD = Fischer-Tropsch dieses (volume % in fuel; remainder is soy diesel or conventional diesel)

SD = soydiesel (volume % in fuel; remainder is petroleum diesel)

NG = natural gas (% as feedstock [methanol, hydrogen, NGVs], or % of electricity generation [EVs], or % of energy input to fuel production)

RG = refinery gas (% of energy input to fuel production)

EL = electricity, % of energy input to fuel production processes

C = coal (% as feedstock [methanol], or % of electricity generation [EVs], or % of energy input to fuel production process)

F = fuel oil (% of electricity generation, % of energy input to fuel production process)

N = nuclear power (% of electricity generation [EVs, hydrogen vehicles])

B = biomass power (% of electricity generation [EVs], or % of energy input to fuel production process)
So = solar power (% of electricity generation [EVs, hydrogen vehicles])
H = Hydro power (% of electricity generation [EVs, hydrogen vehicles])
NGL = natural gas liquids (volume % as source of LPG)
LRG = liquid refinery gases (volume % as source of LPG)
S = sulfur
W = wood (trees) (% as feedstock [ethanol])
G = perennial grasses (% as feedstock [ethanol])

1) Emissions of CFC-12 or HFC-134a from HDVs used in the fuel and feestock distribution.

2) In the biomass and hydrogen fuelcycles, the electricity generation mix is relatively high in renewables.

3) For EVs, "Fuel production" includes emissions from power plants, and emissions from making the fuel used by power plants. The "Fuel distribution, storage" stage includes shipment of fuel oil, and distribution of natural gas.

4) For hydrogen, "Fuel production" is uranium conversion and enrichment. Feedstock stages are uranium recovery and transport.

5) Bio-methanol assumes that any methanol used in fuel delivery trucks is derived from biomass.

6) "Land use changes and cultivation" includes emissions of CO_2, N_2O, NO_x, and CH_4 associated with cultivation and the use of fertilizer.

7) Gasoline production emissions include emissions from the production of ethanol or methanol to make ETBE or MTBE.

8) In the case of EVs using biomass-power, all emissions from the biomass fuelcycle are counted under "Fuel production".

9) The "Fuel distribution, storage" stage includes evaporative NMOC emissions

10) For CNG and LNG, NG transmission and distribution is under "Fuel distribution"; for methanol, it is under "Feedstock transmission".

11) "Fuel dispensing" is compression or liquefaction of gaseous fuels, and pumping of liquid fuels.

12) "C in end use fuel from CO_2 in air" pertains only to the end-use fuel; it does not include the C in any biomass-derived process fuel. The photosynthesis/CO_2 "credit" for the use of biomass process fuels is included in the calculation of the net emissions from that stage.

13) Non-CO_2 emissions from lube-oil combustion are included under "vehicle operation;" all others under "lube oil."

TABLE Y-25. UPSTREAM FUELCYCLE EMISSIONS AS A PERCENTAGE OFF END-USE EMISSIONS, BY POLLUTANT AND FEEDSTOCK/FUEL COMBINATION (BEST CEFS) (U. S. 2010)

Fuel ------>	**Coal**	**CG**	**RFG**	**ULSD**	**FTD**	**Fuel oil**	**Still gas**	**Coke**	**LPG**	**LPG**	**LPG**	**CNG**
Feedstock ------>	*coal*	*oil*	*oil*	*oil*	*NG*	*oil*	*oil*	*oil*	*oil*	*57NGL*	*NG*	*NG*
Carbon dioxide (CO2)	n.a.	27%	27%	19%	36%	n.a.	n.a.	n.a.	18%	13%	8%	21%
Nonmethane organic compounds	n.a.	28%	33%	32%	26%	n.a.	n.a.	n.a.	56%	38%	24%	49%
Methane (CH4)	n.a.	2446%	2417%	5543%	5977%	n.a.	n.a.	n.a.	2103%	1577%	1174%	254%
Carbon monoxide (CO)	n.a.	4.5%	4.9%	5.7%	7.9%	n.a.	n.a.	n.a.	5.7%	4.1%	2.8%	3.9%
Nitrous oxide (N2O)	n.a.	9.4%	4.8%	7.5%	9.1%	n.a.	n.a.	n.a.	4.1%	2.6%	1.4%	3.7%
Nitrogen oxides (NO2)	n.a.	48%	55%	25%	32%	n.a.	n.a.	n.a.	43%	32%	23%	41%
Sulfur oxides (SOx)	n.a.	430%	3312%	7528%	1633%	n.a.	n.a.	n.a.	11618%	5970%	1631%	5673%
Particulate matter (BC+OM)	n.a.	47%	48%	12%	14%	n.a.	n.a.	n.a.	137%	100%	71%	156%
HFC-134a (mg)	n.a.	n.e.	n.e.	n.e.	n.e.	n.a.	n.a.	n.a.	n.e.	n.e.	n.e.	n.e.
CO2-equivalent GHG emissions	n.a.	23%	24%	14%	29%	n.a.	n.a.	n.a.	17%	12%	9%	24%

Table Y-25 continued.

Fuel ------> *Feedstock ------>*	**Nuclear** *uranium*	**CH2** *water*	**CH2** *NG*	**MeOH** *NG*	**MeOH** *coal*	**MeOH** *wood*	**Ethanol** *corn*	**Ethanol** *Grass*	**SCG** *wood*	**biodiesel** *soy*	**Grass** *grass*	**Wood** *wood*
Carbon dioxide (CO2)	n.a.	1606%	77470%	43%	36%	24%	120%	39%	18%	148%	n.a.	n.a.
Nonmethane organic compounds	n.a.	90%	823%	28%	162%	43%	234%	31%	84%	1103%	n.a.	n.a.
Methane (CH4)	n.a.	30600%	87279%	4004%	5009%	1408%	1487%	736%	89%	35672%	n.a.	n.a.
Carbon monoxide (CO)	n.a.	26.1%	194.8%	5.5%	5.3%	18.6%	34%	21%	53%	209%	n.a.	n.a.
Nitrous oxide (N2O)	n.a.	n.a.	n.a.	8.2%	19.4%	60.0%	684%	296%	68%	2905%	n.a.	n.a.
Nitrogen oxides (NO2)	n.a.	23%	76%	73%	69%	113%	570%	268%	90%	1426%	n.a.	n.a.
Sulfur oxides (SOx)	n.a.	14920%	22777%	2448%	7965%	3617%	12768%	2311%	9326%	3393%	n.a.	n.a.
Particulate matter (BC+OM)	n.a.	51%	228%	75%	215%	404%	510%	600%	655%	322%	n.a.	n.a.
HFC-134a (mg)	n.a.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.e.	n.a.	n.a.
CO2-equivalent GHG emissions	n.a.	1743%	6666%	38%	36%	35%	141%	59%	34%	235%	n.a.	n.a.

Table Y-25 continued.

Fuel ------> *Feedstock ------>*	**CH2** **wood**	**CH2** **coal**
Carbon dioxide (CO2)	1502%	3664%
Nonmethane organic compounds	n.a.	n.a.
Methane (CH4)	n.a.	n.a.
Carbon monoxide (CO)	n.a.	n.a.
Nitrous oxide (N2O)	n.a.	n.a.
Nitrogen oxides (NO2)	n.a.	n.a.
Sulfur oxides (SOx)	n.a.	n.a.
Particulate matter (BC+OM)	n.a.	n.a.
HFC-134a (mg)	n.e.	n.e.
CO2-equivalent GHG emissions	1587%	2736%

Notes:

"Best CEFs" are my best estimates of CO2-equivalency factors, as distinguished from the IPCC GWPs (see Appendix D of Delucchi [2003]).

1) g/million-BTU emissions from Table Y-18 are multiplied by end-use million-BTU/mi energy use, and then divided by vehicular emissions, for each pollutant.

2) PM brakewear, tirewear, and road-dust are excluded in these comparisons.

3) All fuels are compared against ICEV end use except H2 from coal or wood, which are compared with FCV end use.

4) All fuels except highway diesel (oil), F-T diesel (NG), and biodiesel (soy) are compared with LDV emissions. Assumes M100, E100, and SD100.

TABLE Y-27. CO_2-EQUIVALENT EMISSIONS FROM THE LIFEYCLE OF VEHICLE MATERIALS AND VEHICLE ASSEMBLY (G/LB) (BEST CEFS) (U. S. 2010)

	Total g/lb[a]		**Total g/mi**[b]		**Relative to end-use**[c]	
Pollutant	*LD ICEVs*	*HD ICEVs*	*LDGVs*	*HDDVs*	*LDGVs*	*HDDVs*
CO2	2,782	2,378	79.8	205.6	24%	7%
NMOCs	2.23	2.19	0.06	0.19	7%	10%
CH4	6.61	5.27	0.19	0.46	428%	278%
CO	8.09	5.44	0.23	0.47	3%	1%
N2O	0.09	0.10	0.00	0.01	4%	2%
NO2	6.01	4.91	0.17	0.42	21%	3%
SO2	6.04	4.61	0.17	0.40	247%	1211%
PM (BC+OM)	0.32	0.28	0.01	0.02	40%	4%
HFC-134a	0.00	0.00	0.00	0.00	n.e.	n.e.
CO2-equivalents	2,976	2,611	85.1	225.7	20%	5%

Notes:

LD ICEVs = light-duty internal-combustion engine vehicles; HD ICEVs = heavy-duty internal-combustion engine vehicles; LDGVs = light-duty gasoline vehicles; HDDVs = heavy-duty diesel vehicles. "Best CEFs" are my best-estimates of CO_2-equivalency factors, as distinguished from the IPCC's GWPs.

[a] Grams of CO_2-equivalent emissions from the lifecycle of materials used in motor vehicles, plus emissions from vehicle assembly, per lb of vehicle. Does not include the fuel-storage system, except in the case of CO_2-equivalents.

[b] Equal to g/lb emissions multiplied by the weight of the vehicle (in this case including the fuel-storage system) divided by the life of the vehicle in miles. See the Main Report and Appendix H for assumptions.

[c] Equal to g/mi emissions from the materials and assembly lifecycle divided by g/mi emissions from end use.

Table Y-28. Comparison of lifecycle emissions with LEM CEFs vs. IPCC GWPs

A. United States, year 2010.

	LEM CEFs		**IPCC GWPs**		**Difference between IPCC GWPs and LEM CEFs**[a]		
	fuelcycle g/mi	*% ch. vs. gasoline*	*fuelcycle g/mi*	*% ch. vs. gasoline*	*% ch. g/mi*	*% ch. relative*	*% ch. absolute*
Baseline gasoline	535	n.a.	492	n.a.	8.9%	n.a.	n.a.
ICEV, diesel	410	-23%	357	-27%	15%	-14%	4%
ICEV, CNG	383	-28%	370	-25%	4%	14%	-4%
ICEV, LPG	391	-27%	370	-25%	6%	9%	-2%
ICEV, corn ethanol	556	4%	466	-5%	19%	-172%	9%
ICEV, cell. ethanol	300	-44%	212	-57%	41%	-23%	13%
Battery EV, coal	428	-20%	484	-2%	-12%	1205%	-18%
Battery EV, NG	227	-58%	224	-55%	2%	5%	-3%
FCEV, MeOH/NG	264	-51%	271	-45%	-2%	13%	-6%
FCEV, H_2/water	57	-89%	48	-90%	20%	-1%	1%
FCEV, H_2/ NG	135	-75%	131	-73%	3%	2%	-2%

ICEV = internal-combustion-engine vehicle; FCEV = fuel-cell electric vehicles; CNG = compressed natural gas; LPG = liquefied petroleum gases; cell. = cellulosic; EV = electric vehicle; MeOH = methanol; NG = natural gas; H_2 = hydrogen; g/mi = grams per mile; % ch. = percentage change; % ch. relative = relative % percentage change; % ch. absolute = absolute percentage change.

[a] The percentage change in g/mi emissions (% ch. g/mi) is the percentage change in g/mi emissions going from the g/mi results with the IPCC GWPs to the g/mi results with LEM CEFs:

$$\text{\% ch. g/mi} = \left(\frac{GMDEL}{GMIPCC} - 1\right) \cdot 100$$

where:

GMDEL = g/mi emissions calculated with LEM CEFs (shown in the main text)
GMDEL = g/mi emissions calculated with IPCC GWPs (shown in the main text)

The relative percentage change (% ch. relative) is the percentage change in the quantity "% ch. vs. gasoline" going from the results with the IPCC GWPs to the results with LEM CEFs:

$$\text{\% ch. relative} = \left(\frac{\%CHDEL}{\%CHIPCC} - 1 \right) \cdot 100$$

where:

%CHDEL = the % change in g/mi emissions versus gasoline given LEM CEFs (shown in the main text)
%CHIPCC = the % change in g/mi emissions versus gasoline given the IPCC GWPs (shown in the main text)

The absolute percentage change (% ch. absolute) is the absolute difference between the percentage change versus gasoline (% ch. vs. gasoline) given LEM CEFs and the percentage versus gasoline given the IPCC GWPs:

$$\text{\% ch. absolute} = \%\text{CHDEL} - \%\text{CHIPCC}$$

B. JAPAN, YEAR 2010.

	LEM CEFs		IPCC GWPs		Difference between IPCC GWPs and LEM CEFs[a]		
	fuelcycle g/mi	*% ch. vs. gasoline*	*fuelcycle g/mi*	*% ch. vs. gasoline*	*% ch. g/mi*	*% ch. relative*	*% ch. absolute*
Baseline gasoline	531	n.a.	481	n.a.	10.4%	n.a.	n.a.
ICEV, diesel	405	-24%	350	-27%	16%	-13%	4%
ICEV, CNG	419	-21%	398	-17%	5%	23%	-4%
ICEV, LPG	390	-27%	367	-24%	6%	12%	-3%
ICEV, corn ethanol	585	10%	467	-3%	25%	-455%	13%
ICEV, cell. ethanol	345	-35%	227	-53%	52%	-33%	18%
Battery EV, coal	347	-35%	360	-25%	-4%	38%	-10%
Battery EV, NG	283	-47%	276	-43%	3%	10%	-4%
FCEV, MeOH/NG	274	-48%	279	-42%	-2%	16%	-7%
FCEV, H_2/water	44	-92%	29	-94%	50%	-2%	2%
FCEV, H_2/ NG	128	-76%	120	-75%	7%	1%	-1%

Notes: see Table part A.

C. CHINA, YEAR 2010.

	LEM CEFs		**IPCC GWPs**		**Difference betweenIPCC GWPs and LEM CEFs**[a]		
	fuelcycle g/mi	*% ch. vs. gasoline*	*fuelcycle g/mi*	*% ch. vs. gasoline*	*% ch. g/mi*	*% ch. relative*	*% ch. absolute*
Baseline gasoline	554	n.a.	500	n.a.	10.9%	n.a.	n.a.
ICEV, diesel	433	-22%	354	-29%	22%	-25%	7%
ICEV, CNG	402	-27%	388	-22%	4%	22%	-5%
ICEV, LPG	398	-28%	369	-26%	8%	8%	-2%
ICEV, corn ethanol	711	28%	534	7%	33%	310%	21%
ICEV, cell. ethanol	401	-28%	218	-56%	84%	-51%	29%
Battery EV, coal	348	-37%	461	-8%	-25%	382%	-29%
Battery EV, NG	295	-47%	291	-42%	1%	12%	-5%
FCEV, MeOH/NG	244	-56%	251	-50%	-3%	12%	-6%
FCEV, H_2/water	72	-87%	67	-87%	7%	1%	-0%
FCEV, H_2/ NG	132	-76%	141	-72%	-6%	6%	-4%

Notes: see Table part A.

D. GERMANY, YEAR 2010.

	LEM CEFs		IPCC GWPs		Difference between IPCC GWPs and LEM CEFs[a]		
	fuelcycle g/mi	*% ch. vs. gasoline*	*fuelcycle g/mi*	*% ch. vs. gasoline*	*% ch. g/mi*	*% ch. relative*	*% ch. absolute*
Baseline gasoline	536	n.a.	492	n.a.	9.0%	n.a.	n.a.
ICEV, diesel	411	-23%	359	-27%	15%	-14%	4%
ICEV, CNG	392	-27%	381	-23%	3%	20%	-4%
ICEV, LPG	394	-27%	373	-24%	6%	10%	-2%
ICEV, corn ethanol	578	8%	467	-5%	24%	-254%	13%
ICEV, cell. ethanol	332	-38%	222	-55%	50%	-31%	17%
Battery EV, coal	386	-28%	410	-17%	-6%	68%	-11%
Battery EV, NG	265	-51%	264	-46%	0%	9%	-4%
FCEV, MeOH/NG	272	-49%	282	-43%	-4%	16%	-7%
FCEV, H_2/water	105	-80%	86	-83%	23%	-3%	2%
FCEV, H_2/ NG	130	-76%	121	-75%	8%	0%	-0%

Notes: see Table part A.

APPENDIX A: PATHWAY DIAGRAMS

Guihua Wang
Mark Delucchi
madelucchi@ucdavis.edu

available on the internet at: www.its.ucdavis.edu/publications.html (by year)
or by contacting itspublications@ucdavis.edu

Institute of Transportation Studies
One Shields Avenue
University of California
Davis, CA 95616

May 30, 2005

AVAILABLE IN A SEPARATE FILE

APPENDIX B: DATA FOR JAPAN, CHINA, AND GERMANY

Mark Delucchi
madelucchi@ucdavis.edu

available on the internet at www.its.ucdavis.edu/publications.html.
or by contacting itspublications@ucdavis.edu.

Institute of Transportation Studies
One Shields Avenue
University of California
Davis, CA 95616

May 30, 2005

PARAMETER VALUES

General

As discussed above, the LEM has country-specific data sets for a number of parameters in the model. This appendix documents the values used for all of the country-specific parameters in the LEM.

The LEM presently has at least some data sets for the following countries, which I have classified as "developed" or less-developed countries ("LDC") for the purpose of estimating emission factors:

U. S.	developed
Canada	developed
Italy	developed
China	LDC
India	LDC
South Africa	LDC
Chile	LDC
Mexico	LDC
Australia	developed
Brazil	LDC
Egypt	LDC
Germany	developed
Japan	developed
Korea	developed
Poland	LDC
Russia	LDC
Thailand	LDC
Turkey	LDC
United Kingdom	developed

This documentation appendix is first organized by model parameter rather than by country. Major data sources used in this analysis include reports by the International Energy Agency (IEA), the U. S. Energy Information Administration (EIA), and the Intergovernmental Panel on Climate Change (IPCC), and country communications to the *United Nations Framework Convention on Climate Change.*

Motor vehicle fuel use

General. The LEM requires as an input the fuel economy of gasoline passenger cars, full-size diesel buses, diesel minibuses, and gasoline motor scooters. For alternative-fuel vehicles, it requires inputs that describe thermal efficiency and weight relative to conventional petroleum-fuel counterparts. Given these and other inputs, the LEM calculates the fuel economy of alternative-fuel vehicles, including diesel-fueled passenger cars and gasoline buses. (See the main documentation report for more details.)

In the LEM, fuelcycle emissions from minibuses are calculated with respect to fuelcycle emissions from full-size buses, by scaling emissions according to the fuel economy of minibuses relative to that of full-size buses. Material and vehicle lifecycle emissions from minibuses also are calculated with respect to emissions from full-size buses, by scaling according to the weight of minibuses relative to the weight of full-size buses.

Parameter values. For all countries except China, I assumed 25 mpg city driving, 36 mpg highway driving, and 55% of VMT in city for LDVs, and 3.0 mpg city, 4.8 mpg highway, and 75% of VMT in city for buses. (Note that the fuel economy is not important, and in fact should be kept the same in all countries, if one wishes to compare "inherent" between fuels and production processes.)

• China. Dengqing et al. (1996) report that gasoline-powered passenger vehicles in China achieve 26.7 mpg. (Qunren and Yushi [2001] report that gasoline passenger vehicles get about 10 mpg, but this seems far too low.) I assume figures that result in 25.4 mpg. Dengqing et al. (1996) also estimate that in China, diesel vehicles are 18-33% more efficient than there gasoline counterparts. I assume that in all countries (including China) diesel vehicles are 25% more efficient.

Jinxia et al. (1996) report a national average fuel consumption of 26-29 l/100km for standard buses, 32-36 for l/100km articulated buses, and 65-85 kWh/100km for trolley bus. I assume 8 mpg for buses (29 l/100 km). Their figure for trolley buses appears to be imply about 100 BTUs/passenger-capacity mile, which I assume here, and which is consistent with data for U. S. light-rail systems (Delucchi, 1996).

Sperling (2000) reports a communication from Prof. Zhou indicating that 2-wheel scooters in China get 81 mpg. I therefore assume that scooters in China are bigger and less efficient than those in India, which apparently achieve well over 100 mpg (Bose and Nesamani, 2000). However, an informal reviewer claims that a manufacturer in China produces a direct-injection 2-stroke scooters that consume only 1.3 l/100 km (180 mpg) and are cleaner than most 4-strokes. I was not able to verify the claim.

Daxiong et al. (1996) report that freight trucks consume up to 2400 BTU/ton-mile. They do not say what the average is, or to what size truck the figure applies. I assume 2000 BTU/ton-mile for large trucks, and 4000 BTU/ton-mile for medium trucks.

Motor vehicle exhaust emissions: light-duty gasoline vehicles

In the LEM, exhaust emissions from light-duty gasoline vehicles (LDGVs) in countries other than the U. S. are estimated relative to emissions from vehicles in the U.

S. The LEM calculates U. S. LDGV emission factors on the basis of model year, target year, deterioration rates, mileage accumulation rates, and other factors. It then looks up the pertinent country-specific relative emission factor for each pollutant, and multiplies this with the calculated U. S. emission factor.

Emissions of course depend greatly on emission -control technology, which in turn are driven in large part by emissions standards. Hence, my estimates of emission factors in other countries relative to those in the U. S. are informed in part by emission standards in other countries relative to those in the U. S. With this in mind, I show below Walsh's (2002) compilation of NOx and PM emission standards for LDGVs ("gas") internationally.

Country	Level	Year	NOx gas (g/mi)	NOx diesel (g/mi)	PM diesel (g/mi)	useful life (mi)
US National	Tier 1	1994	0.60	1.25	0.10	99,441
	NLEV	2001	0.30	0.30	0.08	99,441
	Tier 2	2004	0.07	0.07	0.01	120,000
California	TLEV	1994	0.60	0.60	0.08	99,441
	LEV	1994	0.30	0.30	0.08	99,441
	ULEV	1994	0.30	0.30	0.04	99,441
	LEV2	2004	0.07	0.07	0.01	120,000
	ULEV2	2004	0.07	0.07	0.01	120,000
	SULEV	2004	0.02	0.02	0.01	120,000
Japan	Japan 2000*	2000*	0.13	0.45	0.08	49,720
EU	Euro 3	2000	0.24	0.80	0.08	49,720
	Euro 4	2005	0.13	0.40	0.04	62,150

* Year 2002 for diesel PM.

A data spreadsheet, available on request, presents other information on emission standards used to estimate relative emissions. Generally, I assume that emissions in developed countries are the same as those in the United States. Also, more detailed analysis was done for China.

Motor vehicle exhaust emissions: heavy-duty diesel vehicles

In the LEM, exhaust emissions from heavy-duty diesel vehicles (HDDVs) are estimated on the basis of *sets* of zero-mile emission factors and deterioration rates for each pollutant. There are a number of such sets, representing the range of emission factors that one might expect to see around the world from the period 1970 to 2050 (the period covered by the LEM). For example, there are emission-factor sets for 1979 in the U. S., 1997 in Europe, and 2007 in the U. S. The LEM adopts the emission-factor set that corresponds with the user-specified target country and the calculated model year of the analysis. See Appendix J of the documentation for the LEM for full details.

Exhaust missions from alternative-fuel vehicles

In the LEM, exhaust emissions from alternative-fuel vehicles (CNG, LPG, methanol, ethanol, etc.) are estimated relative to emissions from baseline gasoline or diesel vehicles. I assume that these relative emission factors depend on inherent technological differences between alternative and conventional fuels that do *not* vary from country to country. Hence, there is one set of relative emission factors for all countries. These relative emission factors are estimated on the basis of a literature review, presented in the LEM main documentation report.

Emissions related to the use of lubricating oil by motor vehicles

The LEM estimates emissions from the lifecycle of lubricating oil, as a function of the total supply of lubricating oil, the carbon (C) and sulfur (S) content of lube oil, emissions of non-CO_2 C-containing compounds due to lube-oil combustion, and other factors. I assume that the C and S content of lubricating oil are the same in all countries, and equal to the values assumed for the U. S. (see the main report). However, I assume that the "use" of lubricating oil by vehicles, as represented by the total supply in grams of oil per mile of travel, does vary from country to country and model year to model year. In the LEM this is represented by relating the use of lubricating oil to the global emission-factor "sets" that are used to estimate emissions as a function of model year and country (see Appendix J).

Emissions of non-CO_2 C-containing compounds from the combustion of lubricating oil are assumed to vary with tailpipe emissions of NMOCs, which in turn vary from country to country and model year to model year. See the main LEM documentation report and Appendix J for details.

Emissions of particulate matter from road dust, brake wear, and tire wear

The use of motor vehicles results directly in three kinds of PM emissions other than exhaust PM from fuel combustion: road dust kicked up into the air by moving vehicles, particles from brake wear, and particles from tire wear. These emissions can constitute a significant fraction of a country's total inventory of emissions of fine PM, and hence can be important in comparisons of emissions from different transportation modes.

In the LEM, all three kinds of emissions (road dust, brake wear, and tire wear) are estimated as a function of vehicle weight. The main report presents the methods and data used to estimate emissions for the U. S. reference case. Emissions in countries other than the U. S. are estimated relative to U. S. reference emissions as a function of two country-specific parameters: vehicle weight, and a general parameter that specifies emissions in country *C* relative to emissions in the U. S. *apart* from the effect of vehicle weight. Vehicle weight in target country *C* is calculated in the LEM as a function of user-specified fuel economy. The general relative emissions parameter is meant to account for factors that affect emissions and might vary from country to country, such as (in the case of road dust) the amount of dust on roads, the amount of rainfall, or the frequency of street cleaning.

I assume that the general relative emissions parameter is 1.0 for brake wear and tirewear in all countries, because I have no basis for assuming any pertinent differences in brakewear or tirewear across countries apart from those related to vehicle weight. In the case of road dust, I assume that countries that have significantly more precipitation than does the U. S. (e.g., India and Brazil) have slightly lower emissions. I estimate relative precipitation on the basis of mean annual precipitation contours in the *Encyclopedia Britannica Atlas.*

Note that the methods and data used to estimate road dust, brakewear, and tirewear apply to conventional LDVs and HDVs (including buses and minibuses), and even to mini-cars, but not to off-road vehicles (including forklifts), motor-scooters, or non-motorized modes (such as bicycles). Also, the LEM does not estimate what might be called "track-dust" emissions attributable to passenger or freight trains.

Motor vehicles (lifetime to scrappage)

The lifetime VMT is a parameter in the calculation of the lifetime average emissions per mile due to the use of materials in motor vehicles: total emission related to making materials for motor vehicles are divided by *discounted* lifetime mileage to produce a gram/mile emission factor which can be added to gram/mile emissions from the use of fuel (Appendix H). (Note that lifetime mileage is discounted to its present value in year zero so that it is on the same temporal basis as the material-related emissions with which it is being compared.)

On the basis of some data from China, I assume that trucks and buses in LDCs have 80% (trucks) and 60% (buses) of the lifetime VMT of trucks and buses in the U. S. (except that in China specifically, I assume that buses have 40% of the life of buses in the U. S.) For all other cases, I assume the same lifetime as in the U. S.

Upstream liquid-fuel evaporative emissions

In the LEM, upstream liquid-fuel evaporative emissions are estimated as a function of emissions in a base year, the difference between the base year and the target year, and a rate of change exponent. The actual base-year emission rate is the same for all countries, and is the rate in the U. S. in 2000 in the case of refueling and 1988 in the case of fuel marketing. What varies from country to country is the base year in which these emission rates are assumed to be realized, and the annual rate of change parameters. In developed countries, the base years are assumed to be the actual base years of the data in the U. S. In LDCs, the base years are assumed to occur much later than they actually occurred in the U. S.

Electricity generation and distribution efficiency

The LEM estimates the efficiency of electricity generation by type of fuel and country. Actual generation efficiency values are calculated for the year 2000 using data on fuel inputs and electricity outputs reported in the IEA's *Energy Balances of OECD Countries* (2002) and *Energy Balances of Non-OECD Countries* (2002).

I estimate the efficiency of electricity distribution for every country on the basis of data on electricity losses in transmission and distribution and total electricity consumption, reported in the IEA's *Energy Statistics of OECD Countries* (2002) and *Energy Statistics of Non-OECD Countries* (2002). It is important to have an accurate estimate of these losses because in some countries (e.g., Brazil, India, Mexico, Russia, and Turkey) they can be quite high.

A data spreadsheet, available on request, and the LEM model itself show the estimated and assumed values.

Generation efficiency is assumed to improve in relative terms at a rate of 0.1% to 0.6% per year, depending on the country and generation fuel. The efficiency of biomass generation is assumed to improve the most (0.6%/year), on the assumption that current inefficient combustors will be replaced by integrated gasification-combined-cycle systems.

Distribution efficiency is assumed to improve 0.2% to 0.4% per year (relative terms) in countries where the efficiency currently is less than 90%. In countries where the efficiency is above 90%, the distribution efficiency is assumed to remain the same.

The following information also was relevant to my estimates of parameter values:

- China: Shuoyi (1996) reports on the use of coal in China. He states that although coal-fired power plants in China are becoming cleaner and more efficient, they still are dirtier and less efficient than coal plants in developed countries. Daxiong et al. (1996) report that coal plants were about 29% efficient in 1994, and that the electricity distribution system was 91.3% efficient. Similarly, Farinelli et al. (2001) report that coal plants in China are 30% efficient, compared with an "advanced international level" of 38%. (The IEA values used here show a similar efficiency for electricity distribution and a higher efficiency for generation in the year 2000.)

However, henceforth new gas and coal-fired plants in China may have efficiencies comparable to those of plants in the industrialized west. For example, in its detailed analyses of the cost and performance of power plants in China, APERC (2004) assumes that new coal plants have an efficiency of 36%, and that new combined-cycle gas-turbine plants have an efficiency of 50%.

- Japan: General information from IEA's *Energy Policies of IEA Countries Japan 1999 Review* (1999): Japan has very few indigenous energy resources, and as a result must import most of its primary energy. The islands of Japan are densely populated, making exposure to air pollution a serious problem which the government has addressed by adopting strict environmental regulations. The added costs of importing and of environmental controls make energy prices in Japan relatively high. As a result, Japanese energy policy is concerned with finding secure, clean, efficient sources of energy at reasonable costs. I consider this when projecting efficiency and emission factors in Japan.

Electricity generation fuel mix

National average generation mixes. The LEM calculates each country's national average electricity generation mix in the target year on the basis of two sets of data:

1) **Actual electricity generation by type of fuel, in gWh, for each country, in the year 2000.** These data are taken from IEA's *Energy Statistics of OECD Countries* (2002) and *Energy Balances of Non-OECD (*2002).

2) **Projections of the annual rate of increase or decrease in generation by fuel type.** The LEM actually allows for the specification of three rates of change in generation by fuel type: the actual historical rate of change from the year 1970 to the year 2000; the projected rate of change from the year 2000 to a break year Y*, and the rate of change from the break year Y* to the year 2050. The year Y*, as well as the rates of change in generation, vary by fuel type and country. (*Note that in the present version of the LEM, the actual historical rates of change from 1970 to 2000 have not been estimated*.) Generally, the break year Y* is 2025. The projected rates of change in generation are estimated on the basis of four sets of data:

    a. the historical rate of change in generation by fuel type from 1990 to 2000, for all countries, as reported in the IEA's *Energy Statistics of OECD Countries* (2002) and *Energy Balances of Non-OECD Countries* (2002);
    b. the IEA's projections of changes in generating capacity from 2000 to 2020, for all countries (IEA, *Electricity Information 2002*, 2002);
    c. the Asia Pacific Energy Research Centre's (APERC, 2002) projections of changes in generation by fuel type from 2000 to 2020, for countries bordering the Pacific Ocean; and
    d. projections of changes in generation by specific fuels in particular countries (discussed below).

Unfortunately, in many cases the IEA (2002) projections (item *b*) and the APERC (2002) projections (item *c*) differ considerably. Moreover, in some cases the projections (items *b* and *c*) the imply future trends that differ from the actual historical trends from 1990 to 2000 (item *a*). My assumptions are based on my assessment of all the available data, including the country-specific data discussed next.

• China: APERC (2004) reports several studies that project electricity demand in China. These studies, like the IEA (2002) and APERC (2002) studies referred to above, make quite different projections of the electricity generation fuel mix:

	ERI Scenario A year 2020	ERI Scenario C year 2020	Tsinghua U. year 2020	Tsinghua U. year 2030	IEA year 2030
Coal	72.4%	57.1%	55.2%	47.1%	72.8%

Natural gas	2.2%	6.0%	20.8%	27.7%	7.3%
Oil	0.3%	0.3%	0.1%	n.e.	n.e.
Hydro	18.6%	26.6%	21.8%	18.7%	12.9%
Other renewable	0.8%	2.4%	0.1%	n.e.	n.e.
Nuclear	5.6%	7.6%	1.9%	1.6%	5.0%
Other	n.a.	n.a.	n.a.	4.9%	2.0%

APERC (2004) notes that the Tsinghua University study makes comparatively aggressive assumptions about the share of natural-gas power.

• Germany: The EIA's *Country Analysis Briefs, Germany* (2001) states that German imports of hard coal are expected to double over the next 20 years as nuclear power is phased out and domestic production declines

The EIA's *Renewables, Wind Energy Developments: Incentives in Selected Countries* (2002) notes that there has been major growth in wind power in Germany and Denmark, due to a variety of factors.

Generation mixes for specific activities. The LEM allows country-specific generation mixes for EV recharging, ethanol production from crops, ethanol production from biomass, the operation of rail transit systems, and water electrolysis. In the absence of information on how the generation mix varies country by country and activity by activity, I assume that for all these activities, the generation mix is the national average mix for the target country and year.

Electricity trade

The LEM has a simple representation of electricity imports, solely for the purpose of allocating emissions between the domestic sector and the rest of the world. For each country there is a parameter for net electricity imports as a fraction of total national electricity consumption. This fraction is assigned to the emissions sector "rest of the world" in the geographical allocation macro. When the geographic allocation macro is run, emissions from the generation of imported electricity are deducted from the national total and assigned to the "rest of the world" sector.

Only Italy (14%), Brazil (11%), and Germany (7%) have significant net electricity imports. Thailand does trade electricity with Malaysia, but according to APERC (*APEC Energy Demand and Supply Outlook 2002*, 2002) the trade is for mutual backup, so that "absolute electricity trade is almost nil" (p. 92).

Electricity generation emissions

In the LEM, emission factors for all fossil-fuel electricity generation in non-U. S. countries are estimated as a multiple or fraction of emission factors for all fossil-fuel generation in the U. S. Data were available to perform somewhat detailed analyses for a few countries, as indicated below. I used these estimates, along with information on emissions standards for new coal-fired power plants (IEA, *Coal Information* 2002, 2002; see the IEA/WBCSD data spreadsheet for details) and my judgment to estimate relative emissions in all countries.

China: The EIA *International Energy Outlook 1999* (1999) discusses PM and SOx emissions in China. Their data imply that coal-fired power plants emit at least 3 times as much SO_X per kWh as do coal-fired plants in the U. S. Similarly, Shuoyi (1996) states that although coal-fired power plants in China are becoming cleaner and more efficient, they still are dirtier and less efficient than coal plants in developed countries. However, the IEA's *Energy Policies of IEA Countries 2001 Review* (2001) reports that new Chinese energy policy calls for the development of clean-coal technologies (p. 84).

APERC (2004) uses emissions factors from a Korean study to estimate SO_x and NO_x emissions from electricity generation in China. The emission factors (g/kWh) are as follows:

	Coal	Oil	LNG
SO_x	2.9	2.5	0.4
NO_x	1.3	1.5	0.01

These factors are roughly comparable to LEM-estimated average emission factors for the U. S. in 2020. Elsewhere, APERC (2004) cites different emissions factors for new power plants, from a different study:

	Coal	NG
SO_x (90% control)	1.7	n.e.
NO_x	0.3	0.05
PM (dust)	0.2	0.05

These factors are relatively low, and imply a high degree of emission control.

Given these data and projections, and considering the emissions standards for new power plants reported in the IEA's *Coal Information 2002* (2002), I assume the following ratios of pollutant emissions in China to pollutant emissions in the U. S., from Chinese power generation:

Period	NOx	SOx	PM	Underlying assumption
pre 1980	1.15 times higher in China	1.4 times higher in China	3 times higher in China	Generation in U. S. relatively uncontrolled; generation in China entirely uncontrolled

1980-1998	1.15 in 1980; ratio then increases by 1.5%/year	1.4 in 1980; ratio then increases by 4.0%/year	4.0 in 1980; ratio then increases by 6.0%/year	New generation in U. S. subject to stringent controls; generation in China still uncontrolled
after 1998	ratio decreases by 2.0% per year from 1998 value	ratio decreases by 3.0% per year from 1998 value	ratio decreases by 3.5% per year from 1998 value	New generation in China begins to be subject to controls

• All countries: A summary of emission standards for new large coal-fired power plants (IEA, *Coal Information 2002*, 2002; see IEA/WBCSD data spreadsheet) indicates that in most countries PM standards are much higher (less strict) than in the U. S., but that SOx standards actually are lower (more strict), and NOx standards about the same.

I assume that in all countries gas turbines are relatively modern combined-cycle power plants with modern emission controls.

Diesel fuel sulfur content

The sulfur content of diesel fuel is a parameter in the calculation of emissions of SO_2 from motor vehicles *and* from petroleum refineries (see the main documentation report). SO_2 is an urban air pollutant and, as a component of particulate matter, a GHG

The LEM has a table of values of the sulfur content of diesel fuel, by year, for vehicles, off-road use, and heating use, for each country. The information used to estimate these sulfur values is presented in the IEA/WBCSD data spreadsheet. Two major general data sources are Walsh's *Car Lines* (December, 2002) and the website www.dieselnet.com.

Other petroleum fuel sulfur content

In the LEM, the sulfur content of coal and petroleum products other than diesel fuel is estimated relative to the sulfur content in the U. S. The estimation of the sulfur content in the U. S. is discussed in the main documentation report. I assume that conventional gasoline in the U. S. has a sulfur content of 320 ppm, and that reformulated gasoline has a sulfur content of 236 ppm in 2000, declining to a minimum level of 30 ppm.

The following information was used to estimate relative sulfur contents:

• All OECD countries: The IEA (*Oil Information*, 2002) reports consumption of heavy fuel oil according to sulfur content in OECD countries. It distinguishes low-sulfur (less than 1% S) from high-sulfur (1% or higher S) heavy fuel oil. I use these data to specify the sulfur content of heavy fuel oil in OECD countries relative to that in the U. S. I assume that the relative sulfur content of crude oil is the same as the relative sulfur content of fuel oil.

• European Union: Walsh (*Car Lines*, 2002) reports the following caps on sulfur in gasoline in the EU (ppm):

Current	150
Year 2005	50
Year 2009	10

• <u>China</u>: Walsh (2002) reports the following limits on the sulfur content of gasoline in China:

Year 1993	1500
Year 1999	800

• <u>Japan</u>: Japan traditionally had very low levels of sulfur in gasoline, usually below 30-PPM sulfur.

Coal sulfur content

In the LEM, the sulfur content of coal is estimated relative to the sulfur content in the U. S. The estimation of the sulfur content of coal in the U. S. (generally about 1% by weight) is discussed in the main documentation report. The following information was used to estimate the sulfur content in other countries relative to that in the U. S.:

• <u>China</u>: In its *Country Analysis Brief* for China, the EIA (2000) notes that Chinese coal has a high sulfur content. I assume that the sulfur content is 40% higher than in the U. S.

• <u>Japan</u>: I assume a 25% lower sulfur content of coal, because of strict environmental regulations that force Japanese utilities to use coal with a relatively low sulfur content (IEA, *Energy Policies of IEA Countries, Japan 1999 Review*, 1999).

Flows of materials: general

The LEM represents international trade in steel, aluminum, plastics, and other materials. For each consuming country trade is represented as the fraction of the country's total material consumption that comes from each world producing region. For each country/producer pair, the LEM also represents the fraction of transport that occurs by ship, and the shipping distance.

Data on flows of materials are from the United Nations Statistics Division, Comtrade Database (2003), and are shown in the IEA/WBCSD data spreadsheet. Comtrade reports total imports and exports, and imports by country, for every country in the world, for iron and steel (Standard Industrial Trade Classification [SITC] Revision 3 code 67), aluminum (SITC Revision 3 code 684), plastics in primary form (SITC Revision 3 code 57), and more specific materials categories (not used in this analysis). With these data, and estimates of total material consumption in each target country, one can estimate the fraction of each country's total material consumption that comes from each world producing region. Details are given in Appendix B to the LEM documentation.

Sources of materials embedded in motor vehicles

The preceding section discusses direct flows of basic materials from producers of materials to consumers of materials. However, in many cases, such as with motor vehicles, there is an intermediate "assembly" step between production of the basic materials and consumption of a finished product. The assembly step may occur in a country different from the country of material production or the country of final consumption. Thus, steel may be produced in country X, assembled into motor vehicles in country Y, and used in motor vehicles in country Z.

The LEM properly traces the source of materials embedded in vehicles back through assembly to production of basic materials. More formally, the contribution of any material-producing country X to the total final consumption of the material M in motor vehicles in country Z is calculated as the contribution of country X to total use of M for vehicle assembly in country Y multiplied by the contribution of vehicle-assembly country Y to final consumption of vehicles in Z, summed over all assembly countries that contribute to Z. Flows of materials from producing countries to assembling countries are based on the data on material flows discussed above, and flows of materials in vehicles from assemblers to final consumers are based on the data on motor-vehicle flows, discussed below. Because some of the motor-vehicle assembly countries are not explicitly represented as material-using countries, I must make assumptions about sources of materials in these countries:

Vehicle assembler in the LEM:	Assumed to have same material sources as:
France	United Kingdom
Other Europe	Italy
Other	Thailand
General developed country	Germany
General developing country	China

It is important to assign embedded materials to their ultimate country of production because the energy intensity of material production varies from country to country, and because the LEM has a macro that apportions total emissions to major producing regions of the world.

Petroleum production and trade

The LEM represents trade between the major petroleum producing regions and countries of the world and the target consuming countries designated for analysis. Crude oil, light products (gas and diesel), and heavy products (residual fuel) are treated separately. For each consuming country trade is represented as the fraction of the country's total petroleum consumption that comes from each world producing region. For each country/producer pair, the LEM also represents the fraction of transport that occurs by ship, and the shipping distance.

My estimates of flows of petroleum are based on IEA's *Oil Information 2002* (2002) and *Energy Statistics of Non-OECD Countries* (2002), and on country-specific information cited below. The IEA report shows imports by country and total consumption, for the year 2001 (see the IEA/WBCSD data spreadsheet).

All international trade except for between the U. S. and Canada and between some countries in Europe is assumed to go by water. Distances between ports were read off an atlas. Where such an identification was possible, the actual major shipping port(s) of a country were used.

The parameter values for oil recovery (energy intensity, venting and flaring of associated gas, and more) and oil refining in the U. S. and elsewhere are based on data discussed in the main documentation report.

Import fractions by country are assumed to remain constant over the entire projection period, except as noted below.

• China: The IEA's *Energy Statistics of Non-OECD Countries* (2002) does not differentiate petroleum product imports by exporting country. However, APERC (2004) does. The APERC (2004) data indicate that about 70% of petroleum-product imports to China come from the Asian-Pacific region. I assign this mainly to the "Asian exporters" source category. (I do not assign it to Indonesia because APERC [2004] data indicate that Indonesia has relatively little spare refinery capacity.)

APERC (2004) presents several detailed scenarios of oil demand and oil imports in China in the year 2020. In these scenarios, imports of crude oil are about 45% to 60% of total crude-oil requirements, and imports of refined petroleum products are about 10% to 40% of total petroleum demand.

APERC (2004) does not specify where projected crude-oil and petroleum-product imports in 2020 will come from. However, the EIA's *International Energy Outlook 1999* (1999) projects that oil imports to China from the Persian Gulf will grow from almost 20% of total oil consumption in 1990 to over 50% in 2020. In another document, the EIA (*China*, 2000) notes that oil imports can vary dramatically from year to year, as a result of changes in government policy or the world oil market.

Considering these data and projections, I assume that 15% of total crude-oil consumption in China comes from the Persian Gulf in 1990, and that the share increases by 2% per year (relative terms, not absolute percentage points) up to a maximum of 70%. I also assume that 25% of total light-product consumption comes from "Asian exporters" in 2020, and that the share increases by 5% per year (relative terms) up to a maximum of 65%.

Coal production and trade

The LEM represents trade between the major coal producing regions and countries of the world and the target consuming countries designated for analysis. For each consuming country trade is represented as the fraction of the country's total coal consumption that comes from each world producing region. For each country/producer pair, the LEM also represents the fraction of transport that occurs by ship, and the shipping distance.

Data on flows of coal are from IEA's *Coal Information 2002* (2002) and are shown in the IEA/WBCSD data spreadsheet. The IEA reports imports by country and total consumption.

IEA data (*Coal Information*, 2002, Table 4.1) indicate that 92% of the international trade in coal goes by sea. The small amount of overland trade occurs between the countries of continental Europe and between the U. S. and Canada and Mexico. Therefore, in the LEM the fraction of international coal shipment that goes by sea is 1.0 for all import/export country and region pairs except those that represent intra-European or intra-North-American trade.

Import fractions by country are assumed to remain constant at year 2001 values over the entire projection period, except as follows:

- China: APERC (2004) cites a study that indicates that China could become a major importer of coal as early as 2005. I assume modest imports of coal from Australia after the year 2010.

Natural gas production and trade

Sources of natural gas. The LEM represents trade between the major natural-gas producing regions and countries of the world and the target consuming countries designated for analysis. For each consuming country trade is represented as the fraction of the country's total natural gas consumption that comes from each world producing region. For each country/producer pair, the LEM also represents the fraction of transport that occurs by ship, and the shipping distance.

Data on flows of natural gas are from IEA's *Natural Gas Information 2002* (2002) and are shown in the IEA/WBCSD data spreadsheet. The IEA reports imports by country and total consumption. In the LEM imports by pipeline are distinguished from imports as LNG.

Import fractions by country are assumed to remain constant at year 2001 values over the entire projection period, except as noted below.

The parameter values for natural gas production and processing (energy intensity, methane emissions from production and processing, and more) in the U. S. and elsewhere are based on data discussed in the main documentation report. Parameters for leaks from distribution systems are discussed in the next section.

Relative shipping distances. For the purpose of assigning emissions from pipeline compressors to in-country or out-of-country sources, the LEM distinguishes domestic from foreign pipeline mileage for every country. Specifically, for each target country C, the LEM estimates the average length of gas transmission pipelines inside of C and the average length of foreign pipelines shipping gas to C (up to the border of C) *relative* to the average length of domestic pipeline transmission in the U. S. I estimate these relative lengths on the basis of my inspections of maps of pipeline systems, and assuming that the average length in the U. S. is 1000 to 1500 miles. Country-specific information used to estimate shipping distances is discussed below.

- China: APERC (2004) cites studies indicating that by 2020, China will have to import between 9% and 43% of its gas demand. Data on committed and planned LNG and pipeline projects indicate the following sources of natural gas in China in 2020 (APERC, 2004):

Source	**10^9 m^3**	**share**
Domestic natural gas	107	75%
Pipeline from Russia	20	14%
LNG from Australia	8.2	6%
LNG from Indonesia	7.0	5%
Total	*142.2*	*100%*

(See also Brennand [2001].) On the basis of these data, I assume that China starts importing significant amounts of natural gas in the year 2015.

¨•Germany: The IEA's *Energy Policies of IEA Countries Germany 1998 Review* (1998) shows a map of existing and planned natural gas transmission lines in Germany; this map indicates relatively short transmission distances of about 250 miles.

- A note on LNG: The EIA's *Energy in the Americas* (2002) notes that Trinidad and Tobago, currently a major supplier of LNG to the U. S., has just increased its estimates of gas reserves, and is planning to build more LNG capacity.

Natural gas losses in distribution

The LEM has leakage rates for natural gas distribution systems in every country. (Note that leakage rates from *distribution* systems are entered for each consuming country, whereas leakage rates from production and processing are entered for producing countries.) As documented in the main report, detailed studies of leakage have been done for the U. S. Generally, where country-specific data were not available, I have assumed that leakage rates from developed countries are similar to those in the U. S., but that leakage rates from developing countries are higher. For countries with high current leakage rates, I assume a gradual reduction over time. Actual assumptions are shown in the LEM.

Note that the methods of Intergovernmental Panel on Climate Change (IPCC, 1997) result in a leakage rate of about 1%.

The following information on leakage rates was found in the literature:

Flows of motor vehicles

Background. The LEM represents international trade in light-duty and heavy-duty vehicles. For each consuming country trade is represented as the fraction of the country's total vehicle demand that comes from each world producing region. For each country/producer pair, the LEM also represents the fraction of transport that occurs by ship, and the shipping distance.

Data on flows of vehicles are from a variety of sources, and are shown in the IEA/WBCSD data spreadsheet. The general method is as follows. Recall that the objective is to represent, for each consuming country, the fraction of the country's total vehicle demand that comes from each world producing region. To do this, we need two kinds of data, for each consuming country: the quantity of imports that comes from each world producing region, and the total national demand for vehicles.

Quantity of imports from each producing region. The United Nations Comtrade database (2003) shows imports of passenger cars and imports of commercial vehicles, by country of origin, for every country in the world, for the year 2000. Imports are shown as the weight, number, or value of the vehicle imports, from each exporting country. I use these figures to apportion total imports across individual producing countries or regions (exporters). For example, if Egypt imported a total of $132 million in passenger vehicles in 2000, of which $36.5 million worth came from Korea (United Nations Statistics Division, Comtrade database, 2003), then I assume that 28% (36.5/132) of total imports of passenger vehicles to Egypt came from Korea.

Import fractions by country are assumed to remain constant at year 2001 values over the entire projection period, except as noted below.

Total national demand for vehicles. Given the information presented above, if we also know the ratio total imports : total demand (estimated to be 0.33 in the case of Korea), then we can calculate the figure of interest, which is the fraction of the country's total vehicle demand that comes from each producing region (in the case of Egypt, 0.28 x 0.33 = 9% of total demand is met by imports from Korea). Unfortunately, the calculation of this ratio is not straightforward.

First, I could not find a source that gave an estimate of demand for light-duty and heavy-duty vehicles, by country, as I have defined demand. Thus, domestic demand had to be estimated, as domestic production plus imports less exports. The difficulty with doing this is that no one readily available source provides production, import, and export data, and different sources use different definitions of vehicles and different units of measurement.

The International Organization of Motor Vehicle Manufacturers (2003) provides data on production of passenger cars (used to carry persons, up to 8 seats), light commercial vehicles (used to carry goods, up to 3.5 to 7.0 tons, depending on the country), minibuses, heavy trucks (over 3.5 to 7.0 tons, depending on the country), and buses, by country, in 2000. I combine the "light commercial vehicle" and the "heavy truck" categories into a "commercial vehicle" (or heavy-duty vehicle) domestic production category.

As mentioned above, the United Nations Statistics Division's Comtrade database (2003) provides data on total imports and exports of passenger cars and commercial vehicles, by country, in 2000. Unfortunately, for most countries the Comtrade data base reports imports and exports in units of weight (kg) or value ($). These weight or value units have to be converted to numbers of vehicles, by dividing by an estimate of the average weight or the average value per vehicle. These averages are difficult to estimate.

A final complication is that the Comtrade definitions of passenger cars and commercial vehicles is not identical to the definitions of the International Organization of Motor Vehicle Manufacturers.

Because of these problems of units and definitions, the calculation of total imports, total exports, and total national demand yielded is in some cases very uncertain.

Other. All international trade except for between the U. S. and Canada and between some countries in Europe is assumed to go by water. Distances between ports were read off an atlas. Where such an identification was possible, the actual major shipping port(s) of a country were used.

Appendix H and the main documentation report discusses parameter values associated with energy use for and emissions from the production of motor vehicles in the U. S. and other producing regions.

- China: Most analysts expect that the demand for private passenger vehicles in China will increase dramatically over the next few decades. Although this might be expected to result in increasing imports of motor vehicles, China's domestic motor-vehicle industry also has been expanding rapidly. APERC (2004) reports that the output of the industry grew six-fold from 1990 to 2002, and that this growth is expected to continue for some time. In 2002, China produced more trucks and freight vehicles than passenger cars, but the growth in the output of passenger cars has been greater, and as a result production of passenger cars may soon exceed production of trucks and freight vehicles. It therefore appears that domestic demand for motor vehicles in China will be satisfied almost entirely by domestic production. Consequently, I assume no change in the motor-vehicle import share over the projection period.

The nuclear fuelcycle

The LEM represents the production and enrichment of uranium in some detail. The main report presents the methods and data used to represent the nuclear fuelcycle in the U. S. For other countries, the LEM represents the nuclear fuelcycle as follows:

Stage	Representation in LEM, for non-U. S. countries
Uranium production	Source of uranium by producing country or method; energy requirements of production relative to that in U. S.
Conversion to UF_6	combined conversion, fabrication, disposal stage: use U. S. (global) values for all
Enrichment	detailed representation of energy requirements, by enriching technology and enriching country (see below)
Fabrication	see "conversion"
Disposal	see "conversion"
Transportation	use U. S. values (transportation-related emissions are negligible)

Uranium production. In the LEM the international parameters for the uranium-production phase of the nuclear fuelcycle are uranium requirements (tons U_3O_8/gWh), sources of uranium, and the energy intensity of uranium production.

Uranium requirements. The EIA (internet projections, 2003) and the World Nuclear Association (December 2002) project the uranium requirements (tons U_3O_8/gWh) of nuclear reactors worldwide. The two sources agree roughly on the requirements for the United States and Western Europe, but do not agree on the requirements for Korea and Japan. However, data analysis and discussion presented in the main documentation report suggest that the value is likely to be similar for all countries – about 0.033 to 0.035 tons/gWh in the year 2000.

The World Nuclear Association (October 2002) states that from 1970 to 1990 the ton/gWh uranium requirement of nuclear reactors in Europe declined by 25% due to the use of more highly enriched fuel and longer burn up of the fuel (to lower levels of U-235 in the depleted fuel). It also shows a graph that projects that this trend will continue worldwide through 2010. The EIA projections of ton/gWh uranium requirements for nuclear reactors worldwide through the year 2025 do show a decrease in uranium requirements in Western Europe (EIA, internet projections, 2003). More detailed projections for the U. S. also indicate a slight decrease (EIA, internet projections, 2003).

Given these data and projections, I assume that uranium requirements decrease by 0.25%/year for countries in Europe, and 0.2%/year for other countries.

Sources of uranium. The EIA's *Uranium Industry Annual 2001* (2002) reports sources of uranium required by U. S. nuclear utilities. The World Nuclear Association (October 2002) projects sources of uranium supply for the world through 2010, and other World Nuclear Association papers (July 2002 and August 2002) show uranium production from world mines. The World Nuclear Association (October 2002) projects that in 2010 mine production will satisfy 75% of world uranium demand, military uranium will satisfy 20%, and reprocessed fuel and re-enriched tails about 5%. It also shows that in 2001 Canada produced 35% of total world mine production of uranium, Australia produced 22%, the FSU produced19%, Niger 9%, the USA and South Africa 3% each, and the rest of the world 10% (World Nuclear Association, July 2002 and August 2002). Finally, the World Nuclear Association (December 2002) shows uranium requirements for nuclear power plants by country in 2002.

With these data, and by comparing each country's uranium requirements with its annual production, I estimate the sources of uranium for nuclear-power countries worldwide.

Energy intensity of uranium production. The LEM requires as an input the energy intensity of uranium production (BTUs/ton-uranium) for each production source *relative* to the energy intensity of production from uranium mines in the U. S. I assume that this relative intensity is 1.0 for all mine production worldwide, 0.50 for reprocessed tails and spent fuel, and 0.30 for military high-enriched uranium.

Uranium enrichment. Because there is international trade in uranium enrichment services (measured in separative work units, or SWUs), the LEM now represents, for each country that provides enrichment services: i) the contribution to the SWU requirement of any one of the consuming countries that can be targeted for analysis; ii) the fraction of SWUs provided by different enrichment technologies (gaseous diffusion, centrifuge, laser isotope separation [AVLIS]); and iii) the MWh of electrical energy required per SWU. The U. S. A., France, Germany, the Netherlands, the U. K., and Russia provide the bulk of the world's uranium enrichment services. With these data, and an estimate of the SWUs required per ton of natural uranium to be enriched, the model calculates the figure of interest: the energy efficiency of uranium enrichment, in MWh-enrichment-energy/MW-power-generated.

Note that the mix of fuels used to generate electricity in the uranium-enriching countries is discussed in the main report.

Sources of SWUs provided to nuclear utilities. The main report documents the methods of analysis and the parameter values pertinent to items ii) and iii) in the paragraph immediately above. It also documents the sources of SWUs provided to U. S. nuclear utilities. To estimate the sources of SWUs provided to nuclear utilities in other countries, I first compare the SWU production capacity of each country in 1999 (IEA, *World Energy Outlook*, 2001) with the SWUs required for the amount of nuclear power that the LEM estimates the country will generate in 2010. On the basis of the discussion in DeLuchi (1993) and the main documentation report there, I estimate approximately 0.0145 SWUs/MWh-nuclear power. I multiply this by the LEM projections of nuclear generation in 2010, and compare the result with the annual SWU production capacity:

Country	China	India	S. Africa	Mexico	Brazil	Germany	Japan	Korea	Russia	U. K.
SWUs needed	358	326	208	120	157	2,109	5,458	2,118	2,194	1,182
SWU capacity	300	0	200	0	0	1,100	950	0	19,000	1,800

I use these estimates to make assumptions regarding the total fraction of SWUs imported. I use my judgment to apportion total SWUs to individual producing countries.

SWUs required per ton of uranium enriched. The LEM also requires an estimate of SWUs required per ton of uranium enriched for the nuclear utilities of each consuming country. The EIA (internet projections, 2003) projects SWU and uranium requirements for nuclear utilities worldwide. These projections indicate that SWU/ton requirements in other countries are similar to those in the U. S. This seems plausible, because the degree of enrichment is the main factor determining SWU/ton requirements, and the degree of enrichment appears to be similar in most countries. Therefore, I assume a base value of 480 SWUs/ton-U_3O_8 in the year 2000, increasing at 0.25%/year as uranium is more highly enriched.

Note that the heavy-water moderated "CANDU" reactors in Canada use natural uranium, and hence do not require enrichment services.

Crop production and fertilizer use

Harvest yield. The LEM has parameters for harvest yield for corn, soy, grass, and wood production, by country. Generally, I assume that harvest yields, in bushels or tons/acre, are lower in developing countries, in the base year. However, I also assume that harvest yields improve at a slightly faster rate in developing countries, the difference in the improvement (developing countries vs. developed) being inversely related to the difference in base-year yields.

Nitrogen losses. The LEM performs a complete N input/output balancing, in which synthetic N fertilizer requirements are calculated as the amount needed to supply the N in the plant given all other N inputs and all N outputs and losses. Estimated N losses thus are an important part of the calculation of synthetic N input, which in turn affects several kinds of GHG emissions.

The major N losses are via leaching, erosion, and gaseous emission. The LEM has parameters for N loss rates in a base year in the U. S., the annual change in the loss rate in the U. S., and loss rates in other countries relative to those in the U. S. The U. S. parameter values are discussed in the Main Report. Generally, I assume that the base-year N loss rates are 5-10% higher in developing countries, on the assumption that N fertilizer is applied less efficiently in developing countries, but also that the annual change in the loss rate is 10-20% higher.

Energy intensity of N-fertilizer production. The LEM specifies the BTU/lb-N energy intensity of nitrogen fertilizer production relative to that estimated for the U. S. (The estimation of lifecycle CO_2-equivalent emissions for fertilizers in the U. S. is documented in Appendix H.) Generally, I assume that the energy intensity in the least developed countries or the most notoriously energy-profligate countries is 20% higher than it is in the U. S. In countries at an intermediate level of development I assume that the intensity is 10% higher.

Residue burning. The LEM also has country-specific parameters for the fraction of crop residue that is burned in the field rather than marketed or plowed under. This fraction turns out to be important, because CO_2-equivalent emissions of non-CO_2 GHGs from residue burning can be significant. (The method for estimating emissions from residue burning is presented in the Main Report.) The IPCC (1997) suggests that this fraction is 25% for developing countries, and 10% or less for developed countries. Generally, I assume 25% for agricultural crops in developing countries in Asia, less than 5% for agricultural crops in Europe and North America, 10% or less for wood and grass energy crops (because these are non-traditional crops that will be grown specifically for energy production), and intermediate values for other situations.

A few data relevant to the estimation of these parameters are presented below.

• China: Jingjing et al. (2001) report that in China a large amount of crop residue is burned in the field at harvest time because it decays too slowly to be allowed to just stand. Although the government banned residue burning in 1999 because of the resultant smoke pollution, Jingjing et al. (2001) believe that the ban will be difficult to enforce.

Farinelli et al. (2001) report that the BTU/lb energy intensity of synthetic ammonia production in China is about 35% higher than the "international advanced level" of energy intensity. (This figure is relevant to our estimation of the energy intensity of N-fertilizer production relative to that in the U. S.)

The LEM also specifies the types of land uses displaced by crop production. These parameters are pertinent to the calculation of changes in the amount of carbon (and hence effectively CO_2) sequestered in soils and plant material. For example, if a forest is cleared to plant a biofuel crop, the amount of carbon stored in the soil and the biomass will decrease. The main report documents the methods used to calculate the CO_2-equivalent of the changes in stored carbon.

There are nine land uses in the LEM, ranging from tropical forests to tundra. The main report presents assumptions on the extent to which each of these land uses is displaced, by crop, in the U. S. Presently, my assumptions for other countries are based on my judgment, without reference to any underlying studies. However, because these assumptions can significantly affect lifecycle CO_2-equivalent emissions in some cases, it is important that country-specific parameters based on actual data or models be developed.

Corn-ethanol production

The LEM has energy requirements (fuel use and electricity use) for corn ethanol production. Generally, I assume slightly higher energy requirements in developing countries, partly on account of less efficient technology, which in turn is due in part to the lower cost of fuels and electricity.

Nitrogen deposition

Fate of N. The LEM also has parameters that describe the fate of nitrogen deposited from the atmosphere onto different ecosystems, as part of the calculation of a CO_2-equivalency factor for NO_X emissions (Appendix D). Nitrogen deposition has a variety of environmental effects that affect climate, including fertilization and stimulation of plant growth and carbon sequestration, stimulation of emissions of N_2O, and more. Some of these effects depend on the type of ecosystem receiving the nitrogen deposition: tropical forest, temperate forest, grassland, agricultural land, and so on (Appendix D). The distribution of ecosystem types, and hence the fate of nitrogen by type of ecosystems, will vary from country to country.

General data pertinent to the fate of nitrogen are discussed in Appendices C and D of the LEM documentation. With those data I calculate a global average fate for nitrogen deposition (shown below). Given that global average and then using my judgment, I then estimate the fate of nitrogen deposition country by country:

	trop. forest	temp. forest	grass	agric.	arid	urban	lakes	rivers/ coasts	marine
global ave:	*0.06*	*0.12*	*0.12*	*0.18*	*0.06*	*0.06*	*0.03*	*0.15*	*0.22*
U. S.	0.02	0.12	0.14	0.18	0.07	0.08	0.04	0.15	0.20
Canada	0.01	0.20	0.20	0.05	0.12	0.04	0.05	0.12	0.21
Italy	0.01	0.08	0.08	0.20	0.08	0.08	0.03	0.17	0.27
China	0.06	0.12	0.13	0.21	0.06	0.05	0.03	0.15	0.19
India	0.10	0.10	0.11	0.22	0.02	0.05	0.03	0.15	0.22
South Africa	0.05	0.12	0.14	0.18	0.10	0.05	0.03	0.12	0.21
Chile	0.01	0.11	0.17	0.15	0.12	0.05	0.02	0.12	0.25
Mexico	0.08	0.12	0.12	0.15	0.10	0.06	0.03	0.10	0.24
Australia	0.04	0.07	0.13	0.10	0.18	0.05	0.02	0.13	0.28
Brazil	0.18	0.07	0.12	0.15	0.01	0.06	0.03	0.18	0.20
Egypt	0.00	0.03	0.10	0.18	0.25	0.04	0.03	0.15	0.22
Germany	0.01	0.16	0.13	0.20	0.01	0.08	0.06	0.18	0.18
Japan	0.04	0.10	0.10	0.20	0.01	0.08	0.03	0.17	0.27
Korea	0.08	0.11	0.12	0.15	0.01	0.06	0.03	0.17	0.27
Poland	0.01	0.20	0.15	0.20	0.01	0.06	0.04	0.15	0.18
Russia	0.01	0.15	0.15	0.15	0.12	0.06	0.03	0.15	0.18
Thailand	0.11	0.12	0.12	0.18	0.01	0.06	0.03	0.15	0.22
Turkey	0.01	0.12	0.15	0.12	0.11	0.05	0.04	0.16	0.24
U. K.	0.01	0.12	0.12	0.20	0.01	0.08	0.04	0.15	0.27

Note that each country is the source of nitrogen *emissions*, not necessarily the location of nitrogen deposition. Generally, emissions from country Y will be deposited partly in country Y and partly elsewhere. For our purposes we need identify only the ecosystem types that receive the deposition; we do not need to identify the countries that receive the deposition.

Absolute amount of N deposition. The absolute amount of N deposition (in kg/ac) is a parameter in the calculation of N inputs and outputs in agriculture. Data pertinent to the estimation of this parameter are discussed in the main report. I estimate a baseline value for the year 1990, and then an exponential rate of change assuming an s-shaped logistic function that has a lower bound of zero kg-N/ac and an upper bound of 20 kg-N/ac.

The data summarized in the main report indicate that deposition generally is highest in the industrialized temperate zones of the northern hemisphere (e.g., northern Europe and the United States), and lowest in the non-industrialized temperate zones of the southern hemisphere (e.g., some parts of South America and Africa). I assume base-year values of 3 to 5 kg-N/ac for most industrialized areas in the northern hemisphere, values of 1 to 3 kg-N/ac for other industrialized areas and for tropical areas, and 1-2 kg-N/ac for most other areas.

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