3 MODELING APPROACH

3.1 FUEL CYCLES AND THEIR STAGES

For a given transportation fuel, a *fuel cycle* includes the following chain of processes: energy feedstock (or primary energy) production, feedstock transportation and storage (T&S); fuel (or energy source) production; fuel transportation, storage, and distribution (T&S&D); and fuel combustion. The *energy cycle* for a vehicle technology is supposed to include the cycle for producing the vehicle (vehicle production, operations, disposal and recycling) and the cycle for producing the fuel used in the vehicle. The current version of the GREET is a fuel-cycle model. The model may be developed as an energy-cycle model in the future. The current version includes the following 17 fuel cycles (Table 1): 11 primary energy sources (petroleum; NG; coal; uranium; corn; woody biomass; herbaceous biomass; landfill gases; and hydropower, solar energy, and wind) and nine fuels (conventional gasoline, RFG, clean diesel, LPG, CNG, methanol, ethanol, hydrogen, and electricity). Because electricity generated from hydropower, solar energy, and wind has virtually no emissions, these cycles are treated together as zero-emission cycles in the GREET. The 17 fuel cycles selected are included in the GREET essentially because of a general interest and the availability of data. Other cycles can be added to the GREET, as data on their emissions and energy use become available.

3.2 VEHICLE TYPES

The current version of the GREET model estimates the emissions and energy use of light-duty vehicles (i.e., passenger cars, vans, and light-duty trucks). Heavy-duty vehicles will be incorporated into a future version. For light-duty vehicles, the GREET includes the following technologies: EVs; HEVs; FCVs fueled with hydrogen or methanol; and ICEVs fueled with RFG, low-sulfur diesel (LSD), CNG, M85, M100, LPG, E85, or E100.

3.3 CALCULATION OF ENERGY USE DURING A FUEL-CYCLE STAGE

The GREET calculates fuel-cycle grams-per-mile (g/mi) emissions and Btu-per-mile (Btu/mi) energy use for each combination of vehicle technologies and fuels. The model also calculates changes in g/mi emissions and Btu/mi energy use by advanced or alternative vehicle technologies relative to conventional GVs (the benchmark vehicle). The fuel-cycle energy use for a given technology is calculated by taking into account the amount of energy consumed during each of the stages involved in a fuel cycle.

TABLE 1 Fuel Cycles Included in the GREET Model

Primary Energy Source	Fuel
Petroleum	Conventional gasoline
	RFG
	Clean diesel
	LPG
	Electricity via residual oil
Natural gas	CNG
	LPG
	Methanol
	Hydrogen
	Electricity
Coal	Electricity
Uranium	Electricity
Hydropower, solar energy, wind	Electricity
Corn	Ethanol
Woody biomass	Ethanol
Herbaceous biomass	Ethanol
Landfill gases	Methanol

Because fuel-cycle fossil fuel and petroleum consumption are of interest, the model is designed to calculate both of these values as well as fuel-cycle total energy consumption. Fossil fuels here include petroleum, natural gas, and coal. Thus, the GREET model can estimate fossil fuel and petroleum displacement by advanced vehicle technologies or alternative fuel technologies relative to conventional GVs.

For each fuel-cycle stage, the energy efficiency — defined as the energy throughput divided by energy input (including process energy as well as feedstock energy) — is assumed first. The energy efficiencies of each of fuel-cycle stage have been estimated in previous studies. For this study, we reviewed the previous research and assumed the set of default energy efficiencies that is presented in the GREET model.

By using the assumed energy efficiency for a given stage, we calculate energy use for the stage in Btu per million Btu (Btu/10^6 Btu) of energy throughput as 10^6 Btu × (1/efficiency - 1). The calculated total energy consumption for the particular stage is allocated into different process fuels burned during the stage. For example, if 10^3 Btu is consumed for 10^6 Btu of fuel throughput during a given stage, the GREET model allocates the 10^3 Btu into various process fuels such as diesel, residual oil, electricity, etc. The model includes the following process fuels: NG, residual oil, diesel, gasoline, crude oil, coal, electricity, and biomass. Allocation of the total energy consumption to the different process fuels is necessary to calculate the emissions for each stage because the level of emissions attributable to fuel combustion depends very much on the type of fuel burned; so

emissions must be calculated at each stage for each fuel burned. The allocation process is also necessary for calculating fossil fuel use and petroleum use for each stage. The shares of process fuels in total energy consumption for various fuel-cycle stages are taken primarily from Delucchi (1991 and 1993).

3.4 CALCULATION OF EMISSIONS FOR EACH FUEL-CYCLE STAGE

Emissions of VOCs, CO, NO_x, PM_{10}, SO_x, CH_4, N_2O, and CO_2 for a particular stage are calculated in grams per million Btu ($g/10^6$ Btu) of fuel throughput from the stage. Emissions during a stage include those from combustion of process fuels, fuel leakage and evaporation, and other emission sources. Emissions from combustion of process fuels for a particular stage are calculated by using the following formula:

$$\text{Emissions}_i = \Sigma_j \Sigma_k \, EF_{i,j,k} \times FC_{j,k} \div 1{,}000{,}000 \qquad (1)$$

where:

Emissions_i = Emissions of pollutant i in $g/10^6$ Btu of fuel throughput;

$EF_{i,j,k}$ = Emission factor of pollutant i for process fuel j with combustion technology k ($g/10^6$ Btu of fuel burned);

$FC_{j,k}$ = Consumption of process fuel j with combustion technology k ($Btu/10^6$ Btu of fuel throughput).

Emission factors for VOCs, CO, NO_x, PM_{10}, CH_4, and N_2O for different process fuels with different combustion technologies are derived from the fifth edition of EPA's AP-42 document (EPA 1995). The GREET model has an archive containing emission factors for 38 combustion technologies.

In the GREET model, the SO_x emission factors for the combustion technologies fueled with NG, LSD, gasoline, and LPG are calculated by assuming that all sulfur contained in these process fuels is converted into sulfer dioxide (SO_2). The following formula is used to calculate the SO_x emissions of these combustion technologies:

$$SO_x = \text{Density} \div \text{LHV} \times 1{,}000{,}000 \times \text{S\_ratio} \times 64 \div 32 \qquad (2)$$

where:

SO_x = SO_x emission factor for a particular combustion technology burning a particular fuel (in g/10^6 Btu of the fuel burned);

Density = Density of the fuel (in g/gal for LSD, gasoline, and LPG, or g/standard curb ft for NG);

LHV = Low heating value of the fuel (in Btu/gal for LSD, gasoline, and LPG, or Btu/standard curb ft for NG);

S_ratio = Sulfur ratio by weight for the fuel;

64 = Molecular weight of SO_2; and

32 = Molecular weight of elemental sulfur.

SO_x emission factors for combustion technologies fueled with residual oil, crude oil, and coal, where desulfurization measures are usually applied, are derived from the fifth edition of EPA's AP-42 document (EPA 1995).

In the GREET model, CO_2 emissions are calculated by using a carbon balance approach, in which the carbon contained in the fuel burned minus the carbon contained in combustion emissions of VOCs, CO, and CH_4 is assumed to convert to CO_2. The following formula is used to calculate CO_2 emissions:

$$CO_2 = [\text{Density} \div \text{LHV} \times 1{,}000{,}000 \times \text{C\_ratio} - (\text{VOC} \times 0.85 + \text{CO} \times 0.43 + CH_4 \times 0.75)] \times 44 \div 12 \quad (3)$$

where:

CO_2 = CO_2 emission factor for a particular combustion technology burning a particular fuel (in g/10^6 Btu of the fuel burned);

Density = Density of the fuel burned (in g/gal for liquid fuels, or g/standard curb ft for NG);

LHV = Low heating value of the fuel burned (in Btu/gal for liquid fuels, or Btu/standard curb ft for NG);

C_ratio = Carbon ratio by weight for the fuel burned;

VOC = VOC emission factor for the particular combustion technology burning the particular fuel (in g/10^6 Btu of the fuel burned);

0.85 = Estimated carbon ratio by weight for VOC emissions;

CO = CO emission factor for the particular combustion technology burning the particular fuel (in g/10^6 Btu of the fuel burned);

0.43 = Carbon ratio by weight for CO;

CH_4 = CH_4 emission factor for the particular combustion technology burning the particular fuel (in g/10^6 Btu of the fuel burned);

0.75 = Carbon ratio by weight for CH_4;

44 = Molecular weight of CO_2; and

12 = Molecular weight of elemental carbon.

Calculations involved in formulas (1), (2), and (3) require fuel specifications such as low heating value, fuel density, weight ratio of carbon, and weight ratio of sulfur. Fuel specifications for various fuels are presented in the GREET model. Throughout the model, low heating values are used for all the fuels involved.

The GREET model takes into account the following emissions caused by mechanisms other than combustion. (Details concerning calculation of noncombustion emissions are presented in the following sections.)

- For liquid fuels, VOC evaporative emissions and emissions from fuel spillage for feedstock T&S and fuel T&S&D;
- For gaseous fuels, emissions from gas leakage;
- For petroleum-based fuels, emissions from NG flaring in oil fields and noncombustion emissions in petroleum refineries;
- For NG-based fuels, CH_4 emissions caused by gas leakage and noncombustion emissions during NG processing and during fuel production;

- For the coal-to-electricity cycle, CH_4 emissions during coal mining and noncombustion emissions during coal processing.

Emissions from ICEVs powered by conventional fuels (i.e., conventional gasoline, RFG, and clean diesel) are included in the GREET model for two reasons. First, heavy-duty trucks fueled with diesel or gasoline are used for fuel transportation and distribution (T&D), so their emissions need to be taken into account in calculating emissions during this process. Second, emissions of benchmark light-duty GVs are needed for calculating vehicular emissions for both benchmark GVs and AFVs. In the GREET model, vehicular emissions from AFVs are calculated by using benchmark GV emissions and emission reductions by AFVs relative to benchmark GVs. Emissions of VOCs, CO, and NO_x for benchmark GVs, light-duty vehicles fueled by RFG and LSD, and heavy-duty trucks fueled by LSD are calculated with EPA's Mobile5a outside of the GREET model; PM_{10} emissions are calculated with EPA's PART5 outside of the GREET model; SO_x emissions from these vehicles are calculated inside of the GREET model with the assumption that all sulfur contained in RFG or LSD is converted into SO_2; emissions of CH_4 and N_2O are estimated from existing data sources; and CO_2 emissions from these vehicles are calculated by using a carbon balance approach (carbon contained in RFG or diesel minus carbon contained in emissions of VOCs, CO, and CH_4 is assumed to convert to CO_2). Emissions of VOCs, CO, NO_x, PM, CH_4, and N_2O for AFVs are estimated from benchmark GV emissions and AFV emission reduction potentials. Emissions of SO_x and CO_2 for AFVs are calculated by using the same process used for benchmark GVs.

Besides providing separate emission estimates for each of the three GHGs (CO_2, CH_4, and N_2O), the GREET model combines these three GHGs with their GWPs to estimate CO_2-equivalent GHG emissions. Based on documents prepared by the Intergovernmental Panel on Climatic Change (IPCC 1995), the GREET model uses a set of default GWPs for the three GHGs: 1 for CO_2, 21 for CH_4, and 310 for N_2O.

In estimating upstream emissions, the GREET model takes into account, in most cases, the first-order emissions only. That is, for a given stage, emissions occurring directly during the stage are considered; emissions beyond that stage — such as those occurring during production of the fuels that are, in turn, burned during the stage — are not considered. Second-order emissions are taken into account in only two cases. The first is for electricity generation, where emissions of electricity generated at power plants are considered for the stages in which electricity is used as a process fuel. The other exception is emissions of fertilizer products, which are considered for production of corn and biomass where fertilizer is applied.

For the five criteria pollutants (VOCs, CO, NO_x, PM_{10}, and SO_x), the model calculates both all-location and in-basin emissions. In-basin emissions are important because they pose a significant human exposure risk. Users need to provide information on the share of in-basin and out-of-basin facilities for each upstream fuel stage. Using the shares, the GREET calculates in-basin emissions from all-location emissions.

4 CALCULATION OF FUEL-CYCLE EMISSIONS AND ENERGY USE

Default values for technology shares, emissions, and energy efficiencies are provided for each of the 17 fuel cycles in the GREET model. This section presents detailed assumptions and data sources for these default values. The default values provided in the GREET are for the year 2005. By modifying these default values, one can simulate any other target years in the GREET.

4.1 PETROLEUM-BASED FUEL CYCLES

The GREET model includes four petroleum-based fuel cycles: petroleum to RFG, petroleum to LSD, petroleum to electricity via residual oil, and petroleum to LPG. Detailed assumptions on energy efficiencies and emissions for these four cycles are presented in the following sections.

4.1.1 Energy Efficiencies

Table 2 lists data sources and assumed energy efficiency values for the petroleum-based energy stages.

4.1.2 VOC Evaporation and Fuel Spillage

Delucchi, Greene, and Wang (1992) estimated VOC evaporative emissions of 0.009 g/10^6 Btu of crude produced during oil drilling, 0.197 g/10^6 Btu produced during treatment in the oil fields, and 0.496 g/10^6 Btu generated during storage in the oil fields. On the basis of their estimates, the GREET model assumes a VOC evaporative emission rate of 0.702 g/10^6 Btu of crude produced for crude recovery.

Delucchi, Greene, and Wang (1992) estimated VOC evaporative emissions of 0.162 g/10^6 Btu of crude handled during loading to vessels and for vessels in transit, and 1.372 g/10^6 Btu of crude during storage at refineries. On the basis of these estimates, the GREET model assumes a VOC evaporative emission rate of 1.534 g/10^6 Btu for crude transportation and storage.

NREL et al. (1991) estimated VOC evaporative emissions of 7.92 g/10^6 Btu of RFG and VOC spillage emissions of 3.34 g/10^6 Btu during T&S&D of RFG. These emission rates are used in the GREET model. For diesel and LPG, no evaporative emissions are assumed. Emissions from spillage (in gal/gal of fuel handled) are assumed to be constant among RFG, diesel, and LPG. On

TABLE 2 Energy Efficiencies of Petroleum-Based Fuel-Cycle Stages

Petroleum-Based Fuel-Cycle Stage	Energy Efficiency (%)					
	GREET	NREL et al. (1991)	Delucchi (1991)	Ecotraffic, AB (1992)	Bentley et al. (1992)	Acurex (1995)
Crude recovery	98.0	99.2	97.5	97.0	NE	NE
Crude T&S	99.5	96.2	99.8	99.3	96.0	NE
RFG refining	82.5	90.0	81.7	84.5	90.0	82.8
RFG T&S&D	98.5	97.7	99.2	98.6	98.0	NE
LPG refining	93.5[a]	NE[b]	94.6	90.0	NE	93.2
LPG T&S&D	98.0[c]	NE	99.0	97.5	NE	NE
Residual refining	95.0[a]	NE	94.9	97.0	NE	NE
Residual T&S&D	99.0[c]	NE	99.0	NE	NE	NE
LSD refining	93.0[a]	NE	93.0	NE	NE	NE
LSD T&S&D	98.7[c]	NE	99.1	NE	NE	NE

[a] On the basis of the refining intensity involved in generating each product, the GREET model assumes that the order of refinery efficiency (from low to high) is RFG, LSD, LPG, and residual oil.

[b] NE = not estimated.

[c] Primarily on the basis of the energy content per gallon of each fuel, the GREET model assumes that the order of T&S&D efficiency (from low to high) is LPG, RFG, LSD, and residual oil. Besides the energy content of each fuel, transportation distance and length of storage time affect the T&S&D efficiency of each product. While efficiencies for RFG and residual oil are simply assumed, the efficiency values for LPG and LSD are calculated by using the efficiency of RFG and the energy content of RFG, LPG, and LSD.

the basis of this assumption, the RFG spillage emission rate (in g/10^6 Btu) is adjusted to the spillage emissions rates for diesel and LPG, considering their mass density and energy content. For residual oil, the model assumes that evaporative emissions are 50% of those for RFG because of the low volatility of residual oil. Spillage emissions (in gal/gal of residual oil handled) are assumed to be 80% of those for RFG because of the short distance of transportation and infrequent loading involved in residual oil T&S&D.

4.1.3 Noncombustion Emissions at Refineries

Besides those generated during fuel combustion, emissions are produced by noncombustion sources such as catalyst regeneration, thermal cracking, and blowdown systems at refineries. Fugitive emissions are also produced in various refining processes. Because of a lack of

data, emissions from sulfur recovery plants and water treatment plants are ignored here. On the basis of EPA's AP-42 document (EPA 1995), we estimated in this study that noncombustion emissions at refineries are 0.998 g/10^6 Btu of RFG produced for VOCs, 0.358 g/10^6 Btu for CO, 4.260 g/10^6 Btu for NO_x, 1.429 g/10^6 Btu for PM_{10}, 6.481 g/10^6 Btu for SO_x, and 1,172 g/10^6 Btu for CO_2. For diesel, LPG, and residual oil, we assumed that noncombustion emissions are proportional to the intensity of the refining process involved in producing each fuel. Thus, the noncombustion emission rates for RFG are adjusted by the difference in energy intensity between RFG and each of these three other fuels to generate noncombustion emission rates for each.

4.2 NATURAL-GAS-BASED FUEL CYCLES

Five NG-based fuel cycles are included in the GREET model: NG to CNG, NG to methanol, NG to LPG, NG to hydrogen, and NG to electricity. Assumptions concerning energy efficiencies and emissions for these NG cycles are presented in the following sections.

4.2.1 Energy Efficiencies

Table 3 lists the data sources and values for energy efficiencies of NG-based fuel-cycle stages used in the GREET model.

4.2.2 CH_4 Leakage and Fuel Spillage

Delucchi (1993) estimated that 0.2% of the gas produced in NG fields leaks into the atmosphere. Using Delucchi's estimate, we calculated that leakage in NG fields is 44.181 g/10^6 Btu of NG produced; we also assumed that all NG leaked is CH_4.

Delucchi (1993) estimated that 0.4% of NG leakage occurs during T&D; this translates into a CH_4 emission rate of 88.362 g/10^6 Btu of NG transported and distributed.

Spillage of VOCs during methanol T&S&D is calculated by assuming that the spillage rate (in gal/gal of methanol handled) is the same as the rate for RFG. The gal/gal spillage rate is then converted into g/10^6 Btu of methanol handled using the mass density and energy content values for RFG methanol.

TABLE 3 Energy Efficiencies of Natural-Gas-Based Fuel-Cycle Stages

NG-Based Fuel-Cycle Stage	Energy Efficiency (%)								
	GREET	Delucchi (1991)	Bentley (1992)	Ecotraffic, AB (1992)	NREL (1992)	Smith (1993)	Acurex (1995)	Darrow (1994a)	Darrow (1994b)
NG recovery	97.0	97.2	94.0	97.0	NE[a]	NE	96.2	NE	NE
NG processing	97.5	97.5	97.0	98.0	NE	NE	96.2	NE	NE
NG T&D	97.0	96.4	97.0	98.0	NE	NE	NE	NE	NE
NG compression	95.0	95.0	87.0	93.0	NE	NE	NE	97.9	98.0
Methanol production	65.0	45.9	70.0	60.0	NE	NE	68.3	66.4	NE
Methanol T&S&D	97.0	96.2	90.2	97.8	NE	NE	NE	97.7	NE
LPG production[b]	96.5	96.7	NE	NE	NE	NE	NE	NE	NE
Hydrogen production	68.0	NE	NE	NE	68.0	68.0	61.1	NE	NE
Hydrogen liquefaction	70.0	70-74	NE	NE	NE	68.0	NE	NE	NE
Hydrogen T&S&D	95.0[c]	NE	NE	NE	NE	NE	NE	NE	NE

[a] NE = not estimated.

[b] The energy efficiency for the T&S&D of LPG is presented in Table 2.

[c] An efficiency for T&S&D of liquid hydrogen lower than the efficiencies for T&S&D of other liquid fuels is assumed here primarily because the energy content of liquid hydrogen is lower than those for other liquid fuels.

4.2.3 Noncombustion Emissions during Natural Gas Processing and Fuel Production

SO_x emissions are generated during the sweetening of NG (removal of H_2S contained in NG). Using a formula contained in EPA's AP-42 document (EPA 1995), and assuming an H_2S mole content for NG of 0.3% and 99% SO_x control efficiency in NG processing plants, we calculated that the SO_x emission rate from NG sweetening is 2.226 g/10^6 Btu of NG processed.

Because the carbon ratio of methanol is higher than that of NG (primarily CH_4), the process of converting 10^6 Btu of NG to 10^6 Btu of methanol results in a net carbon absorption. We assumed here that the additional carbon in the 10^6 Btu of methanol comes from NG burned during the conversion process. The carbon absorption rate of the methanol conversion process is estimated here as 12,495 g/10^6 Btu methanol produced. This CO_2 emissions value is subtracted from the CO_2 emissions value calculated for NG combustion in methanol plants.

Emissions of SO_x are generated during LPG production because NG contains about 0.0007% sulfur but LPG contains no sulfur. The model assumes that all sulfur contained in NG is converted into SO_2 (which accounts for most SO_x emissions) and that SO_x emissions produced this way make up 0.155 g/10^6 Btu of LPG produced. SO_x emissions are also generated during hydrogen production; the GREET model assumes an SO_x emission rate of 0.155 g/10^6 Btu of hydrogen produced.

Because of the elimination of carbon in hydrogen, the conversion of NG to hydrogen produces excess CO_2 emissions. We estimated that the conversion process produces CO_2 at 59,777 g/10^6 Btu of hydrogen produced. This CO_2 emissions value is added to the CO_2 emissions value for fuel combustion in hydrogen production plants.

4.3 ETHANOL PRODUCTION CYCLES

The GREET model includes three ethanol-producing fuel cycles: corn to ethanol, woody biomass to ethanol, and herbaceous biomass to ethanol. While the technology involved in converting corn to ethanol is mature, the technology for converting biomass (both woody and herbaceous) to ethanol has not been demonstrated commercially. The large-scale production of biomass to obtain ethanol also has yet to be demonstrated. So, while the corn-to-ethanol cycle can be treated as a near-term option, the other cycles (herbaceous and woody biomass to ethanol) should be treated as long-term options.

In the GREET model, the emissions and energy use involved in the production of corn, woody biomass, and herbaceous biomass are calculated on the basis of the amount of fuel and fertilizer used, rather than the energy efficiencies of the production process. So, by inputting the