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Development and Applications of GREET 2.7 — The Transportation Vehicle-Cycle Model

Energy Systems Division

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Development and Applications of GREET 2.7 — The Transportation Vehicle-Cycle Model

by
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NOTATION

The following is a list of the abbreviations, acronyms, and units of measure used in this document. (Some acronyms and abbreviations used only in tables may be defined only in those tables.)

GENERAL ACRONYMS AND ABBREVIATIONS

ABS	anti-lock braking system
ADR	assembly, disposal, and recycling
Al	aluminum
AlF_3	aluminum fluoride
$Al(OH)_3$	aluminum hydroxide
Al_2O_3	alumina
ASCM	Automotive System Cost Model
BFG	blast furnace gas
BIW	body-in-white
BOP	basic oxygen process
$CaCO_3$	limestone
CARB	California Air Resources Board
CFRP	carbon fiber-reinforced plastic
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
COG	coke oven gas
Cu	copper
CV	conventional vehicle
DOE	U.S. Department of Energy
EAF	electric arc furnace
EAP	electric arc process
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
EV	electric vehicle
EVTECA	Electric Vehicle Total Energy Cycle Assessment

FC	fuel cycle
FCV	fuel cell vehicle
FCVT	Fuel Cell and Vehicle Technologies Program
FRP	fiber-reinforced plastic
GI	grid-independent
GFRP	glass fiber-reinforced plastic
GHG	greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation model
H_2	hydrogen
HCl	hydrochloric acid
HDPE	high-density polyethylene
HEV	hybrid electric vehicle
HVAC	heating, ventilation, and air conditioning
ICE	internal combustion engine
ICEV	internal combustion engine vehicle
KOH	potassium hydroxide
LEM	Life-Cycle Emissions Model
Li-ion	lithium-ion
LW	lightweight
LW ICEV	lightweight internal combustion engine vehicle
LW FCV	lightweight gaseous hydrogen fuel cell vehicle
LW HEV	lightweight hybrid electric vehicle
MEA	membrane electrode assembly
Mg	magnesium
$MgCl_2$	magnesium chloride
MgO	magnesium oxide
MIT	Massachusetts Institute of Technology
MY	model year
NA	North America(n)
Na_2CO_3	soda ash
Na_3AlF_6	cryolite
$Ni(OH)_2$	nickel hydroxide
$Ni(CO)_4$	nickel carbonyl
NG	natural gas
Ni-MH	nickel metal hydride
N_2O	nitrous oxide
NO_x	nitrogen oxide

PAN	polyacrylonitrile
Pb-Ac	lead acid
PbS	lead sulfite
PEM	proton exchange membrane
PET	polyester (polyethylene terephthalate)
PFSA	perfluorosulfonic acid
PGM	platinum group metals
PM_{10}	particulate matter measuring between 2.5 and 10 micrometers in diameter
PP	polypropylene
PSAT	Powertrain System Analysis Toolkit
PTFE	polytetrafluoroethylene
PTW	pump-to-wheels
PVB	polyvinyl butyral
R&D	research and development
RFG	reformulated gasoline
SA	South Africa
SAE	Society of Automotive Engineers
SBR	styrene-butadiene rubber
SCS	Scientific Certification Systems
SI	spark ignition
SMMT	Society of Motor Manufacturers and Traders
SO_2	sulfur dioxide
SO_x	sulfur oxides
SUV	sport-utility vehicle
TEAM	Tool for Environmental Analysis and Management
UK	United Kingdom
USCAR	United States Council for Automotive Research
VC	vehicle cycle
VMT	vehicle miles traveled
VO	vehicle operations
VOC	volatile organic compound
VRP	Vehicle Recycling Partnership
WTW	well-to-wheels
ZEV	zero emission vehicle
Zn	zinc

UNITS OF MEASURE

Btu	British thermal unit(s)
cm^3	cubic centimeter(s)
g	gram(s)
gal	gallon(s)
GJ	gigaJoule(s)
Gpa	gigapascal(s)
kg	kilogram(s)
kW	kilowatt(s)
kWh	kilowatt-hour(s)
mi	mile(s)
MJ	megaJoule(s)
mm	millimeter(s)
mmBtu	million British thermal unit(s)
mph	mile(s) per hour
psi	pound(s) per square inch
TJ	teraJoule(s)
W	watt(s)
Wh	watt-hour(s)

DEVELOPMENT AND APPLICATIONS OF GREET 2.7 — THE TRANSPORTATION VEHICLE-CYCLE MODEL

by

Andrew Burnham, Michael Wang, and Ye Wu

ABSTRACT

Argonne National Laboratory has developed a *vehicle-cycle* module for the **G**reenhouse gases, **R**egulated **E**missions, and **E**nergy use in **T**ransportation (GREET) model. The *fuel-cycle* GREET model has been cited extensively and contains data on fuel cycles and vehicle operations. The *vehicle-cycle* model evaluates the energy and emission effects associated with vehicle material recovery and production, vehicle component fabrication, vehicle assembly, and vehicle disposal/recycling. With the addition of the vehicle-cycle module, the GREET model now provides a comprehensive, lifecycle-based approach to compare the energy use and emissions of conventional and advanced vehicle technologies (e.g., hybrid electric vehicles and fuel cell vehicles). This report details the development and application of the GREET 2.7 model. The current model includes six vehicles — a conventional material and a lightweight material version of a mid-size passenger car with the following powertrain systems: internal combustion engine, internal combustion engine with hybrid configuration, and fuel cell with hybrid configuration. The model calculates the energy use and emissions that are required for vehicle component production; battery production; fluid production and use; and vehicle assembly, disposal, and recycling. This report also presents vehicle-cycle modeling results. In order to put these results in a broad perspective, the fuel-cycle model (GREET 1.7) was used in conjunction with the vehicle-cycle model (GREET 2.7) to estimate total energy-cycle results.

1 INTRODUCTION

Alternative transportation fuels and advanced vehicle technologies are being promoted to help solve urban air pollution problems, reduce greenhouse gas (GHG) emissions, and reduce the United States' dependence on imported oil. To more accurately and completely evaluate the energy and emissions effects of alternative fuels and vehicle technologies, researchers should consider emissions and energy use from vehicle operations, fuel production processes, and vehicle production processes. This research area is especially important for technologies that employ fuels and materials with distinctly different primary energy sources and production processes, i.e., those for which upstream emissions and energy use can be significantly different.

The Center for Transportation Research at Argonne National Laboratory has been conducting fuel-cycle analyses for various transportation fuels and vehicle technologies for more than 20 years. In 1996, with funding from the U.S. Department of Energy's (DOE's) Office of Transportation Technologies, Argonne developed a fuel-cycle model called GREET (**G**reenhouse gases, **R**egulated **E**missions, and **E**nergy use in **T**ransportation) (Argonne National Laboratory 2006a). The goal was to provide a computer tool that would allow researchers to evaluate the fuel-cycle energy and emission impacts of various transportation technologies. Since the model's development, researchers at Argonne and other institutions have used it extensively to calculate the fuel-cycle energy requirements of and emissions from various alternative transportation fuels and advanced vehicle technologies. The GREET model has evolved significantly since its introduction.

In order to perform a more complete lifecycle-based analysis of automotive technologies, and with support from DOE's FreedomCAR and Vehicle Technologies (FCVT) Program, Argonne recently developed a vehicle-cycle model to examine the energy use and emissions associated with vehicle production and disposal processes. The variety of vehicle technologies being developed and evaluated to reduce vehicle fuel use and emissions resulted in a need to analyze the full vehicle cycle.

Hybrid electric vehicles (HEVs), in particular, are being introduced into the marketplace at a fast pace, and fuel cell vehicles (FCVs) are the subject of vigorous research and development (R&D) efforts. Primarily because of powertrain efficiency advantages, these advanced vehicle technologies achieve better fuel economy and lower in-use emissions than conventional vehicle technologies (DeCicco 2001). At the same time, these technologies employ new vehicle components — such as advanced batteries, electric motors, and fuel cell stacks — and new materials for producing these components, all of which might have significantly different energy and emission impacts. All of these factors point to the need for a vehicle-cycle comparison of internal combustion engine vehicles (ICEVs) with these advanced powertrain vehicles.

In addition, lightweight automotive material R&D is one of the major components of DOE's FCVT Program (FCVT 2004). One of the goals of FCVT's Automotive Lightweight Materials Program is to develop and validate materials and manufacturing technologies to reduce vehicle weight without affecting key vehicle attributes such as safety and performance. The development of advanced lightweight vehicles has generated a need to investigate the energy and emission effects of their production and disposal, because these vehicles contain components and materials not used in conventional vehicles.

This report describes the development and use of the GREET vehicle-cycle model, GREET 2.7, which calculates — for a given vehicle type and material composition combination — the vehicle-cycle emissions of five criteria pollutants: volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter with diameters of 10 micrometers or less (PM_{10}). The model also calculates the vehicle-cycle emissions of three GHGs — carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) — and the vehicle-cycle consumption of total energy, fossil fuel, and petroleum. It is important to note that although GREET 2.7, along with GREET 1.7, can help researchers understand the energy use and emission effects associated with various vehicle types, the models do not address all of the issues that should be examined when making policy decisions and selecting vehicle alternatives. Important issues that are not addressed include vehicle and fuel cost, material supply and resource depletion, industry and government commitment to new technologies, and customer acceptance of new technologies, among others. However, the model is designed to address the energy and emissions impacts of vehicle technologies as they are introduced into the marketplace. The model allows researchers to readily input their own assumptions and generate vehicle-cycle energy and emissions results for specific vehicle types and material composition combinations.

Section 2 presents a review of previous vehicle-cycle studies. Section 3 describes Argonne's modeling approach. Vehicle specifications used in the model, including total vehicle weight, vehicle component definitions, vehicle component material composition and weight, fuel cell and battery sizing, battery replacement, and tire and fluid replacement, are presented in Section 4. Section 5 describes the materials used to produce the vehicles and the production and recycling process for each material, including metals, glass, plastics, rubber, fluids, battery and fuel cell materials, and other materials. Section 6 presents a discussion of vehicle assembly, disposal, and recycling, and Section 7 provides a brief introduction to the structure of the GREET 2.7 model. Energy use and emissions results are presented in Section 8 and conclusions in Section 9. Section 10 lists the references used to prepare the report.

2 REVIEW OF PREVIOUS VEHICLE-CYCLE STUDIES

Previous studies conducted to analyze the vehicle-cycle energy and emission effects of various technologies are described briefly in the following sections.

2.1 ALUMINUM-INTENSIVE VEHICLE STUDY — 1995

In 1995, an Argonne study examined the life-cycle energy impacts of aluminum-intensive passenger cars. By simulating the market share of these vehicles, the researchers predicted a national net energy savings between 2005 and 2030 (Stodolsky et al. 1995). Their study revealed that the petroleum energy saved by reducing the vehicle weight — by means of aluminum substitution — and thus improving fuel efficiency offset the additional energy required to manufacture the aluminum, compared with steel. The researchers estimated that, eventually, 80% of the aluminum used in cars would be from scrap (all of that aluminum was assumed to be cast). They also calculated that cast aluminum parts have an embedded energy value of 38 million Btu/ton, while the gray iron castings that they would replace have an embedded energy value of about 32 million Btu/ton. Makers of the aluminum-intensive vehicle would substitute a large amount of sheet steel with wrought aluminum. The Argonne researchers estimated that producing automotive parts from virgin sheet steel requires about 56 million Btu of energy per ton; recycling sheet steel requires about 45 million Btu of energy per ton. Finally, the research team estimated that producing parts from virgin wrought aluminum requires about 183 million Btu of energy per ton and that recycling wrought aluminum requires about 45 million Btu of energy per ton. Therefore, if the original virgin wrought aluminum used in the first generation of vehicles were recycled back to wrought aluminum, the energy required to produce future generations of aluminum-intensive vehicles would be reduced significantly.

2.2 HYBRID ELECTRIC VEHICLE STUDY — 1997

In 1997, Wang and his colleagues compared the vehicle-cycle energy and emission effects of HEVs with those of conventional vehicles (Wang et al. 1997). By using an early version of GREET to model the fuel cycle and vehicle cycle, the researchers examined two series HEVs: a conventional vehicle (CV)-like HEV and an electric vehicle (EV)-like HEV. The CV-like HEV had an engine sized to provide enough power for 6.5% gradability at 55 miles per hour (mph) and a battery sized to make up the power needed to accelerate from 0 to 60 mph in 12 seconds. The EV-like HEV, on the other hand, had an engine sized to provide enough power for 6.5% gradability at 55 mph and a battery sized to provide enough power to accelerate from 0 to 60 mph in 16 seconds. These HEVs were compared with a steel-intensive and an aluminum-intensive conventional vehicle over the timeframe from 2003 to 2013. Looking at the total energy from the fuel cycle, vehicle operation, and vehicle cycle, they found that the HEVs reduced energy use and GHG emissions by around 40% compared with the steel-intensive conventional vehicle because of their improved fuel economy.

2.3 HEAVY-DUTY VEHICLE STUDY — 1998

In 1998, Gaines and her colleagues undertook a vehicle-cycle analysis of heavy-duty vehicles to evaluate potential reductions in life-cycle energy use and GHG emissions that could be achieved by various heavy-duty truck technologies (Gaines et al. 1998). Their study revealed that substituting aluminum for steel in a tractor-semitrailer would slightly increase total energy use; however, such a substitution could allow for increased hauling capacity if the truck was weight-limited. In this study, material recycling was only considered through scrap inputs; the use of recycled aluminum would have resulted in larger benefits with respect to total energy use. The study also revealed that the use of alternative fuels (such as natural gas [NG]) in trucks minimizes petroleum consumption, as expected, but it does not save fossil energy nor minimize GHG emissions. Reductions in GHG emissions for trucks using any fuel could be achieved most effectively by improving truck engine and drivetrain efficiency, as well as reducing the weight of the trucks.

2.4 ELECTRIC VEHICLE STUDY — 1998

Also in 1998, Argonne National Laboratory, National Renewable Energy Laboratory, and Pacific Northwest National Laboratory, in a joint effort, examined the total energy cycle of EVs powered by four types of batteries: advanced lead-acid (Pb-Ac), nickel cadmium, nickel metal hydride (Ni-MH), and sodium sulfur (Argonne National Laboratory et al. 1998). In this study, the researchers calculated the energy use and emissions resulting from (1) the generation of electricity to charge vehicle batteries, (2) the fuel extraction and transport to generate that electricity, and (2) battery and vehicle production. These EV energy use and emissions estimates were compared to those for a conventional vehicle running on reformulated gasoline (RFG). The researchers assumed that the EV and CV both had very similar material compositions: each vehicle containing 85% iron, steel, aluminum, plastic, and rubber. However, the production of EV batteries results in significant energy use and emissions when compared with production of the rest of the vehicle components because of the large weight of the batteries and the assumption that they would need to be replaced at least once during the lifetime of the vehicle. The research team found that the manufacture of EVs generally led to increased criteria air pollutant emissions compared with the production of CVs across the total energy cycle.

2.5 FUEL AND VEHICLE TECHNOLOGIES STUDY — 2000

In a 2000 Massachusetts Institute of Technology (MIT) study, researchers used a life-cycle approach to compare the costs, energy use, and GHG emissions of eleven combinations of fuels and vehicle technologies for a mid-size passenger car that could be made commercially available by 2020 (Weiss et al. 2000). That study examined the use of a lightweight, aluminum-intensive body and chassis to improve fuel economy and reduce GHG emissions. The results showed that a steel-intensive gasoline ICEV, aluminum-intensive gasoline ICEV, and aluminum-intensive gasoline HEV had nearly the same vehicle-cycle energy use and emissions when assuming a 95% recycling rate for all metals and a 50% recycling rate for all plastics. On the other hand, an aluminum-intensive hydrogen FCV had a 14% increase in vehicle-cycle energy use and a 19% increase in CO_2 emissions.

2.6 U.S. PASSENGER VEHICLE STUDY — 2001

In 2001, Hackney and de Neufville compared emissions, energy efficiency, and costs for different vehicle technologies on a fuel-cycle and vehicle-cycle basis for a passenger car platform in the United States (Hackney and de Neufville 2001). They concluded that, in the long term, FCVs powered by liquid hydrocarbon fuels with onboard reforming might offer large emission and energy savings at a competitive cost and that NG (and liquid NG derivatives) should be promoted as the primary alternative vehicle fuel source to reduce the nation's dependence on petroleum. However, their analysis also found that vehicles using petroleum fuels and some form of internal combustion engine (ICE) were likely to dominate the market for the conceivable future.

2.7 LIFE-CYCLE EMISSIONS MODEL STUDY — 2003

In 2003, Delucchi released a series of reports documenting the updated version of the Life-Cycle Emissions Model (LEM), which estimates the energy use, criteria pollutant emissions, and CO_2-equivalent GHG emissions from a variety of transportation and energy life cycles. For transport modes, the model includes life cycles of fuels, vehicles, materials, and infrastructure (Delucchi 2003a). The framework for the life cycle of vehicles includes the recovery and transport of crude ores; the manufacture of finished materials from raw materials; the transport of finished materials to end users; the assembly and transport of vehicles; the operation and maintenance of motor vehicle service stations and parts shops; and a secondary fuel cycle that includes building, servicing, and providing administrative support for transport and distribution modes. The specific results of the vehicle-cycle analysis are not presented in the main report; however, Appendix H details many of the key assumptions for the materials used (Delucchi 2003b). Appendix H examines the energy use and emissions from the production of the primary materials used in automobiles, in addition to other materials used in other life cycles, such as the fuel cycle and infrastructure cycle.

2.8 SUSTAINABLE AUTOMOTIVE INDUSTRY STUDY — 2000

In 2006, the Society of Motor Manufacturers and Traders released a report detailing the efforts of the automotive industry in the United Kingdom (UK) to make their industry more sustainable (SMMT 2006). The report examines several environmental indicators, including energy use; water use; air pollutant emissions; CO_2 emissions; and landfill waste resulting from vehicle production, use, and disposal. Although the report is unclear about what activities are covered in the vehicle production category, it does not seem to address any upstream energy use and emissions from materials production, and likely includes only vehicle assembly and distribution. SMMT reports that the energy required for UK vehicle production and distribution has decreased from about 14.7 million Btu/vehicle in 2001 to 7.8 million Btu/vehicle in 2005.

Emissions of CO_2 have likewise decreased from 1,300 kg/vehicle in 2001 to 600 kg/vehicle in 2005. These values are similar to those that we have estimated in our analysis of passenger car assembly, which are provided in Section 8.1.

3 MODELING APPROACH

Two different energy cycles, production and use of motor fuels (fuel cycle) and production and use of motor vehicles (vehicle cycle), should be considered when evaluating the energy use and emissions of various vehicle technologies. The GREET fuel-cycle model was developed at Argonne National Laboratory to calculate fuel-cycle energy use and emissions for various fuel-cycle paths (Wang et al. 2005). The fuel cycle for a given transportation fuel includes the following processes: primary energy production, transportation, and storage; fuel production, transportation, storage, and distribution; and vehicle operations that involve fuel combustion or other chemical conversions. The most recent version of the Series 1 GREET fuel-cycle model, GREET 1.7, was released in November 2005.

In GREET 1.7, for a given fuel-cycle stage, energy consumed is calculated in Btu per million Btu of energy throughput. The calculated total energy use for the particular stage is allocated to different process fuels (e.g., NG, residual oil, diesel, coal, electricity) burned during the stage. Fuel-specific energy use, together with fuel-specific emission factors for combustion technologies, is then used to calculate combustion-related emissions for the stage. GREET 1.7 includes a database of emission factors for various combustion technologies fueled with different fuels and equipped with different control technologies. Combustion emission factors for VOCs, CO, NO_x, PM_{10}, CH_4, and N_2O for different combustion technologies are derived primarily from the U.S. Environmental Protection Agency's (EPA's) AP-42 document (EPA 1995). SO_x emission factors for most fuels are calculated on the basis of the assumption that all sulfur contained in process fuels is converted into sulfur dioxide (SO_2). CO_2 emissions are calculated by using a carbon balance method, in which the carbon contained in the fuel burned minus that contained in combustion emissions of VOCs, CO, and CH_4 is assumed to be converted to CO_2. Emissions of CH_4 and N_2O are estimated on the basis of various data sources. Fuel-cycle (FC) energy use and emissions are calculated by using GREET 1.7. Emissions from vehicle operations (VO) include tailpipe exhaust emissions, evaporative VOC emissions, and tirewear PM_{10} emissions. These are from EPA's vehicle modeling efforts for MOBILE6.2 and the California Air Resources Board's (CARB's) efforts for EMFAC2002 (Wu et al. 2006).

The GREET vehicle-cycle model was developed at Argonne to calculate vehicle-cycle energy use and emissions for various vehicle types and material compositions. The vehicle cycle for each vehicle type and material composition includes the following processes: raw material recovery and extraction, material processing and fabrication, vehicle component production, vehicle assembly, and vehicle disposal and recycling. Currently, the model does not include energy use and emissions from transportation of raw and processed materials for each process step. However, future versions of the model will likely address this issue because the location of each process step is important in determining urban air pollution impacts. Material production can take place outside of the United States.

To estimate vehicle energy use and emissions by using the GREET vehicle-cycle model, we follow the simulation logic depicted in Figure 1. This illustration shows the input data required for each vehicle in order to estimate its energy use and emissions.

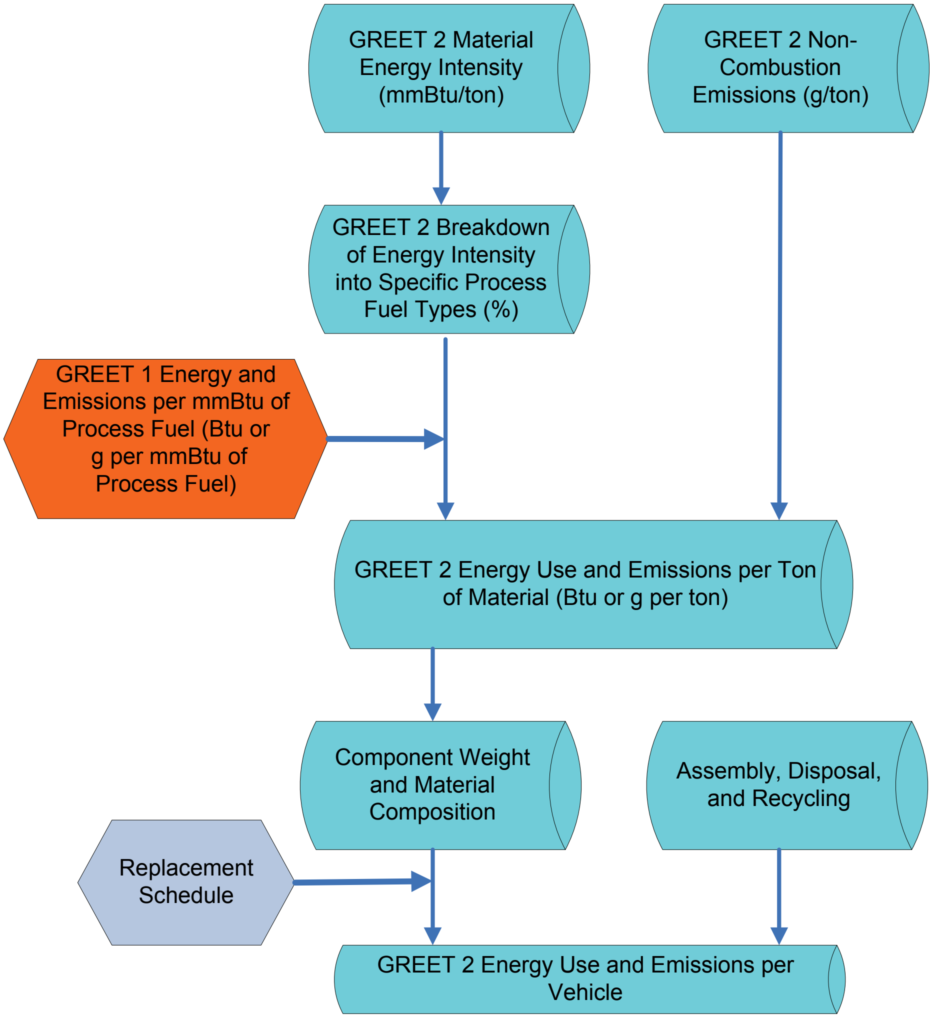

FIGURE 1 Simulation Logic for GREET Vehicle-Cycle Analysis

The first step of the vehicle-cycle analysis is to estimate vehicle component weight. This estimate takes into account the weight of the major components of a vehicle, such as the body (including body-in-white [BIW], body interior, body exterior, and glass), chassis, batteries, fluids, powertrain (either a spark-ignition [SI] engine or a fuel cell stack and auxiliaries), and transmission or gearbox. Depending on the vehicle type, the component weight could include the weight of a motor, controller, and generator. Second, for each major vehicle component, the vehicle-cycle model considers its material composition (i.e., breakdowns of total component weight into steel, aluminum, iron, plastic, rubber, and any other materials). For components that are subject to replacement during a vehicle's lifetime (e.g., batteries, tires, and various vehicle fluids), the model then develops replacement schedules. For disposal and recycling, the model takes into account the energy required and emissions generated during recycling of scrap materials back into original materials for reuse. Finally, the estimates of energy used during the processes from raw material recovery to vehicle assembly (e.g., mining taconite and processing it into sheet steel to be stamped) are used for vehicle-cycle simulations.

Figure 2 shows the model structure of GREET 2.7. As the figure shows, GREET 1.7 inputs data into the model, specifically for calculating the energy use and emissions that result from burning fuels during the processes included in GREET 2.7; its FC and VO results that can be used, along with the vehicle-cycle (VC) results, to examine the total energy cycle. Therefore, it is advisable for users to open GREET 1.7 in order to have the most recent assumptions available when using GREET 2.7.

Using such input data, the vehicle-cycle model calculates the energy use and emissions of four major groups: vehicle materials; batteries; fluids; and vehicle assembly, disposal, and recycling (ADR). The vehicle material group includes the raw material recovery; raw material transportation and processing; and material production, fabrication, and processing. The battery group includes material production and fabrication for the start-up and storage batteries. The fluids group includes production and disposal of coolants, engine oil, windshield fluid, steering fluid, brake fluid, and transmission fluid. The ADR group includes vehicle assembly, painting, disposal, and recycling. For each activity within these groups, the energy use and emissions (including emissions from both fuel combustion and specific processes) are estimated.

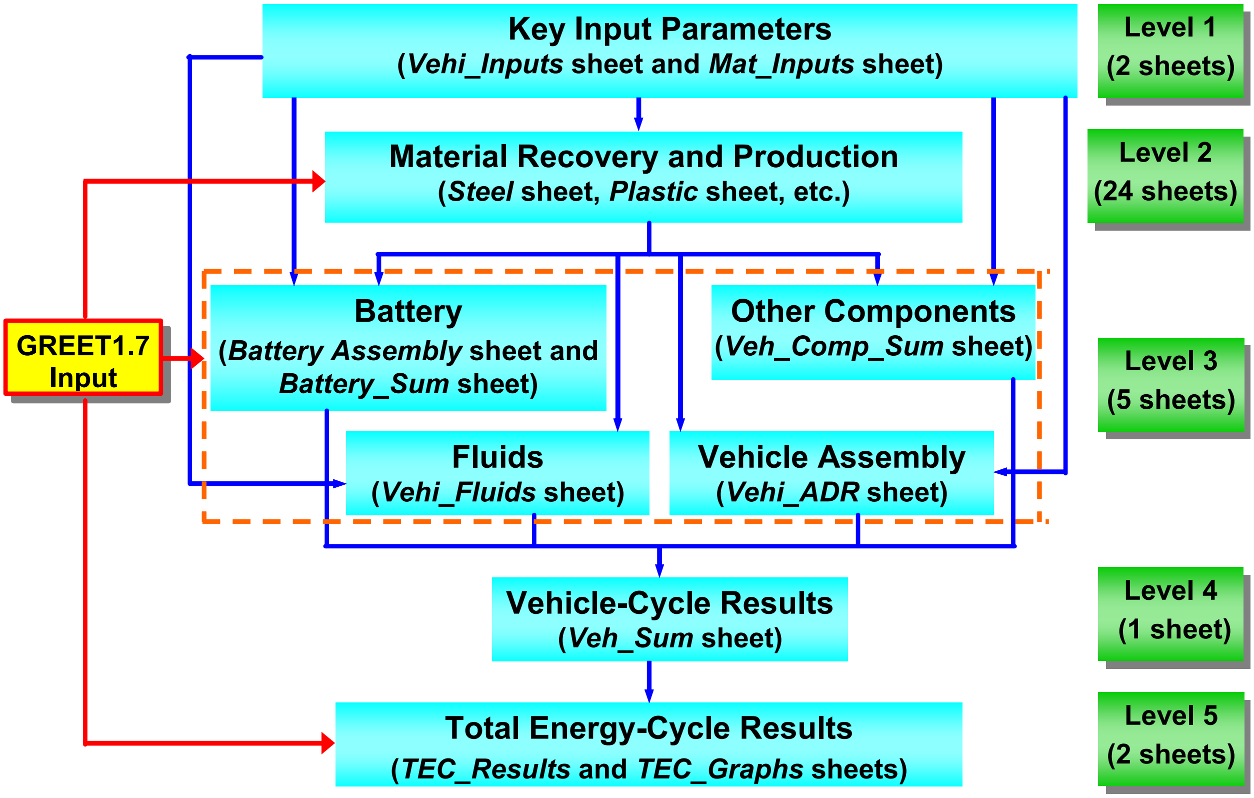

FIGURE 2 GREET 2.7 Model Structure (34 Sheets)

To evaluate various motor vehicle technologies, both the fuel cycle and the vehicle cycle should be considered in order to perform a comprehensive life-cycle based analysis; for transportation technologies, such an analysis is known as a total energy-cycle analysis. Figure 3 illustrates the total energy cycle.

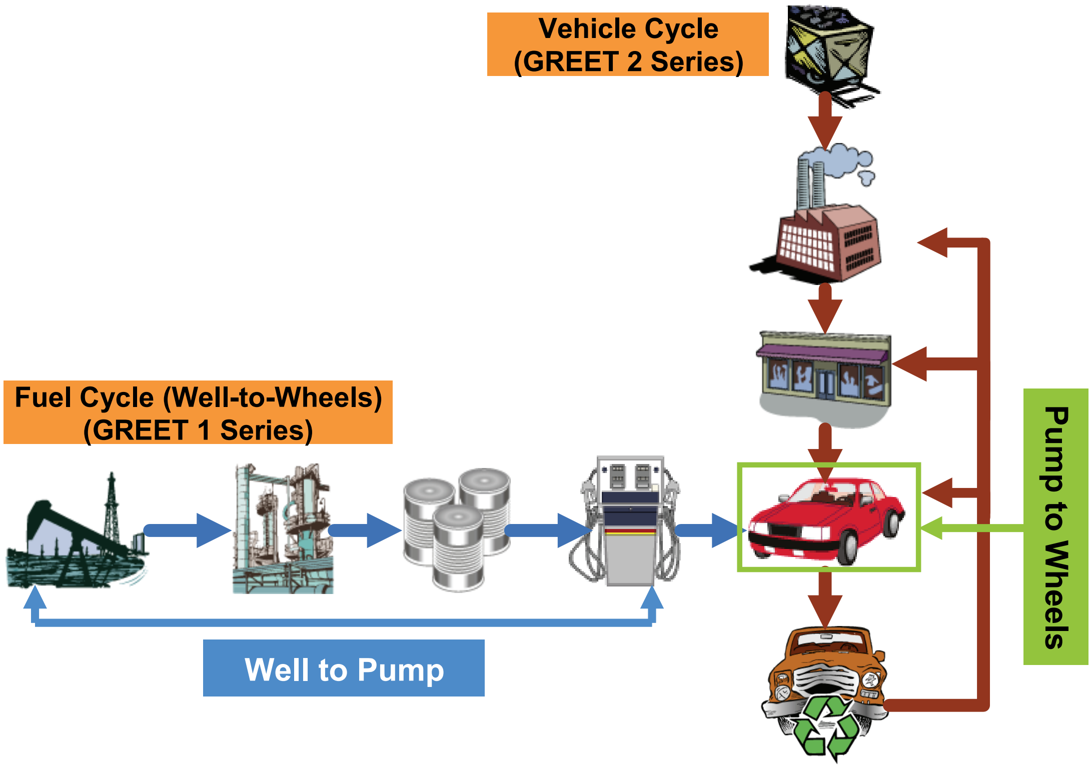

FIGURE 3 Total Energy Cycle for Transportation Technologies

4 VEHICLE SPECIFICATIONS

The latest version of the GREET model, GREET 2.7, is based on a mid-size passenger car platform. However, Argonne has completed preliminary work on other light-duty vehicles — such as sport-utility vehicles (SUVs), light trucks, and minivans — and on several heavy-duty trucks; these vehicles could potentially be added in the future. In the current version, the vehicle propulsion technologies examined are an ICEV with an SI engine, a grid-independent (GI) HEV with an SI engine, and an FCV with a hybrid configuration. A wide variety of data sources were used to characterize our mid-size passenger cars and the various propulsion systems. These sources include vehicle tear-down data, various automotive models, personal communications, and literature reviews.

4.1 TOTAL VEHICLE WEIGHT

The default total vehicle weights listed in Table 1 were estimated separately for conventional and lightweight (LW) vehicles. Selecting appropriate values is very important when comparing different vehicles in GREET 2.7 because these weights, along with assumptions about component material compositions, are used to determine how much of each material is in each vehicle. For consistency, the conventional vehicles were assumed to have the same total weight as the passenger vehicles in GREET 1.7. We chose to take this approach because we link the FC and VO results of GREET 1.7 to those in GREET 2.7 so that the models can be used in conjunction. To allow users to accurately conduct life-cycle analysis using GREET 1.7 and 2.7, it is important to keep the simulation vehicle consistent across both models.

The weights are not specified explicitly in GREET 1.7; rather, simulations using the Powertrain Systems Analysis Toolkit (PSAT), which was developed at Argonne (Argonne National Laboratory 2006b), were conducted to calculate the fuel economy of the vehicles included in the model (Wu et al. 2006). For those simulations, the test vehicle weights are specified because they are crucial to a vehicle's fuel economy. The test vehicle weight is the curb weight plus 300 lb (which represents passengers and cargo). For GREET 2.7 simulations, vehicle fuel, which is accounted for in the curb weight, is not included in our total vehicle weight, nor is the 300 lb for passengers and cargo. For GREET 1.7 vehicle fuel economy simulations, on the other hand, we assume that about 80 lb of gasoline are used in the conventional ICEV and HEV, and 10 lb of hydrogen are used in the conventional FCV. GREET 1.7 does not include lightweight vehicles, so we used a bottom-up approach to calculate the total vehicle weights for these vehicles. As described in the following paragraph, we aggregated the weights of all vehicle

TABLE 1 Total Vehicle Weight Excluding Fuel (lb)

	ICEV	HEV	FCV	LW ICEV	LW HEV	LW FCV
Total weight	3,330	2,810	3,020	1,970	2,000	2,280

parts to get a total weight, relying on data from several sources, including the Automotive System Cost Model (ASCM) developed by IBIS Associates and Oak Ridge National Laboratory.

The total weight of each vehicle is broken down into three major categories: vehicle components, battery, and fluids. The vehicle components category includes eight major systems: body, powertrain, transmission, chassis, electric traction motor, generator, electronic controller, and fuel cell auxiliaries. Each vehicle does not necessarily have all eight systems; an ICEV, for example, only has a body, powertrain, transmission, and chassis. The HEV in our simulation was modeled after the Toyota Prius combined series and parallel hybrid system, so it has both a motor and a generator. The FCV was modeled as a hybrid, so it has a battery in conjunction with the fuel cell stack. The battery category includes a Pb-Ac battery to handle the startup and accessory load for each vehicle and, for the HEVs and FCVs, the option to use either an Ni-MH or lithium-ion (Li-ion) battery in the electric-drive system. The fluid category includes engine oil, power steering fluid, brake fluid, transmission fluid, powertrain coolant, windshield fluid, and adhesives.

Depending on how one classifies the pieces of a vehicle, it can have thousands of parts; however, for this analysis, we studied the vehicle at an aggregate level, specifically looking at major systems and components. In order to examine the differences among ICEVs, HEVs, and FCVs, we broke the vehicle down into 10 major systems (Table 2) and calculated the weight and material composition of each system.

4.2 DEFINITIONS OF VEHICLE COMPONENTS

As stated previously, each vehicle does not necessarily have every system. When collecting data for various vehicles, the specific weights and material compositions often did not correspond perfectly to our definitions. Therefore, we needed a more detailed breakdown of each system in order to place part and subsystem data into the right component category; parts are aggregated into subsystems, and subsystems are aggregated into systems. In GREET 2.7, users

TABLE 2 Vehicle Systems Included in GREET 2.7

	ICEV	HEV	FCV
Body system	✓	✓	✓
Powertrain system	✓	✓	✓
Transmission system	✓	✓	✓
Chassis system	✓	✓	✓
Traction motor		✓	✓
Generator		✓	
Electronic controller		✓	✓
Fuel cell auxiliary system			✓
Batteries	✓	✓	✓
Fluids (excluding fuel)	✓	✓	✓

do not see parts or subsystems — only systems. Tables 3 through 9 provide definitions for the major parts and subsystems in each component category (i.e., body, powertrain, transmission, chassis, electric-drive, battery, and fluid).

TABLE 3 Body System

Body-in-white	Primary vehicle structure, usually a single-body assembly to which other major components are attached
Body panels	Closure panels and hang-on panels, such as the hood, roof, decklid, doors, quarter panels, and fenders
Front/rear bumpers	Impact bars, energy absorbers, and mounting hardware
Body hardware	Miscellaneous body components
Glass	Front windshield, rear windshield, and door windows
Paint	E-coat, priming, base coats, and clear coats
Exterior trim	Molding, ornaments, bumper cover, air deflectors, ground effects, side trim, mirror assemblies, and nameplates
Body sealers/deadeners	All rubber trim
Exterior lighting	Head lamps, fog lamps, turn signals, side markers, and tail light assemblies
Instrument panel module	Panel structure, knee bolsters and brackets, instrument cluster, exterior surface, console storage, glove box panels, glove box assembly and exterior, and top cover
Trim and insulation	Emergency brake cover, switch panels, ash trays, arm rests, cup holders, headliner assemblies, overhead console assemblies, assist handles, coat hooks, small item overhead storage, pillar trim, sun visors, carpet, padding, insulation, and accessory mats
Door module	Door insulation, trim assemblies, speaker grills, switch panels and handles (door panels are considered as part of the body panels category)
Seating and restraint system	Seat tracks, seat frames, foam, trim, restraints, anchors, head restraints, arm rests, seat belts, tensioners, clips, air bags, and sensor assemblies
Heating, ventilation, air conditioning (HVAC) module	Air flow system, heating system, and air conditioning system (which includes a condenser, fan, heater, ducting, and controls)
Interior electronics	Wiring and controls for interior lighting, instrumentation, and power accessories

TABLE 4 Powertrain System

Engine unit	Engine block, cylinder heads, fuel injection, engine air system, ignition system, alternator, and containers and pumps for the lubrication system
Fuel cell stack	Membrane electrode assembly, bipolar plates, gaskets, current collector, insulator, outer wrap, and tie bolts
Engine fuel storage system	Fuel tank, tank mounting straps, tank shield, insulation, filling piping, and supply piping
Powertrain thermal system	Water pump, radiator, and fan
Exhaust system	Catalytic converter, muffler, heat shields, and exhaust piping
Powertrain electrical system	Control wiring, sensors, switches, and processors
Emission control electronics	Sensors, processors, and engine emission feedback equipment

TABLE 5 Transmission System

Transmission unit	Gearbox, torque converter, and controls
ICEV	Uses an automatic transmission and therefore a torque converter
HEV	Uses a type of continuously variable transmission with a planetary gear set and therefore does not have a torque converter
FCV	Weighs approximately one-third less than the HEV transmission and consists of a single-ratio gearbox and no torque converter (Bohn 2005)

4.3 VEHICLE COMPONENT MATERIAL COMPOSITION AND WEIGHT

Our goal was to try to make a fair comparison among the vehicles without compromising the simulated performance of any vehicle. Component sizing calculations completed by Argonne for the ASCM were used to keep the vehicles' simulated performance consistent. ASCM allows users to select various options at a system level, and at a more detailed component level, to build a vehicle. The purpose of the model is to compare the cost of vehicles at the system level. For example, users can determine the cost of replacing a conventional engine system with a fuel cell system in an otherwise identical vehicle or the cost of using lightweight components versus conventional components throughout an ICEV. The interest in the ASCM model for our research was not the cost analysis, but rather the component weights and materials, which were needed to calculate the system costs.

For each component, the ASCM model offers various options; for example, users can select bumpers made of sheet steel, roll formed steel, sheet aluminum, extruded aluminum, glass fiber composite, or carbon fiber composite. A weight is associated with each of these

TABLE 6 Chassis System

Cradle	Frame assembly, front rails, and underbody extensions, cab and body brackets (the cradle bolts to the BIW and supports the mounting of the engine/fuel cell)
Driveshaft/axle	A propeller shaft, halfshaft, front axle and rear axle (the propeller shaft connects the gearbox to a differential, while the halfshaft connects the wheels to a differential)
Differential	A gear set that transmits energy from the driveshaft to the axles and allows for each of the driving wheels to rotate at different speeds, while supplying them with an equal amount of torque
Corner suspension	Upper and lower control arms, ball joints, springs, shock absorbers, steering knuckle, and stabilizer shaft
Braking system	Hub, disc, bearings, splash shield, and calipers
Wheels	Four main wheels and one spare
Tires	Four main tires and one spare
Steering system	Steering wheel, column, joints, linkages, bushes, housings, and hydraulic-assist equipment
Chassis electrical system	Signals; switches; horn wiring; and the anti-lock braking system (ABS) wiring, sensors, and processors

TABLE 7 Electric-Drive Systems

Generator	Power converter that takes mechanical energy from the engine and produces electrical energy to recharge the batteries and power the electric motor for HEVs
Motor	Electric motor used to drive the wheels
Electronic controller (controller/converter)	Power controller/phase inverter system that converts power between the batteries and motor/generators for electric-drive vehicles
Fuel cell auxiliaries	Compressed hydrogen tank system, water supply system, air supply system, cooling system, and piping system

TABLE 8 Battery System

ICEV	Pb-Ac battery to handle the startup and accessory load
HEV/FCV	Pb-Ac battery to handle the startup and accessory load and either an Ni-MH or Li-ion battery for use in the electric-drive system

TABLE 9 Fluid System

ICEV/HEV	Engine oil, power steering fluid, brake fluid, transmission fluid, powertrain coolant, windshield fluid, and adhesives
FCV	Power steering fluid, brake fluid, transmission fluid, powertrain coolant, windshield fluid, and adhesives

components, and the material composition is generally obvious from the name. However, for some components that contain more than one material (e.g., engine, transmission, and motor), the description was not useful in determining the material composition. Therefore, the material compositions of these components were estimated on the basis of (1) personal communications with Roy Muir (U.S Council for Automotive Research/Vehicle Recycling Partnership [USCAR/VRP]), Roy Cuenca (Argonne), and Eric Carlson (TIAX) (Muir 2005; Cuenca 2005; Carlson 2004); (2) vehicle dismantling reports; (3) literature review; and (4) our assumptions. Table 10 lists the material compositions for the vehicle components. The information on material composition of the battery (Table 11) was collected from three sources: Pb-Ac from a literature review; Ni-MH from vehicle dismantling reports; and Li-ion from Paul Nelson, one of Argonne's experts on the technology (Nelson 2005).

For the conventional material ICEV, HEV, and FCV, the weight of components such as the engine, fuel cell system, and transmission were scaled so that all would meet the same performance requirements. For the lightweight material vehicles, additional components (such as the BIW and various chassis components) were also scaled. In addition, chassis components for the lightweight vehicles were assigned a 25% mass savings for reductions in the weight of other, non-chassis components. For example, a reduction of 100 lb in BIW mass would result in 25 lb of chassis mass reduction; we made this adjustment to compensate for the fact that the chassis needs less mass to support the other components if their mass is reduced. However, because the fuel storage systems are the same in both the conventional and lightweight models, the lightweight models will have a larger driving range; this is also true for the HEVs compared with the ICEVs. Table 12 lists the weights for the vehicle components; rows that contain values that differ significantly are in bold.

The weight of each component was aggregated with the weights of those in its corresponding system (e.g., body, powertrain, and chassis); this number was then divided by the total weight of all the systems to obtain the percentage weight associated with each system. Those results are listed in Table 13. In the GREET model, when a user changes the total vehicle weight, these percentages are used (along with material composition percentages) to determine the weight of each material in the vehicle components category.

After calculating the weight of each component, the data on the material composition of each component can be used to examine aggregate material composition (Table 14). This table shows that the conventional vehicles all contain about 56% to 65% steel, while the lightweight vehicles contain significantly less, 21% to 31%. The conventional HEV and FCV both have

TABLE 10 Material Composition of Components

Component	Conventional	Lightweight	Source(s)
Body			
Body-in-white	100% steel	100% carbon fiber composite	ASCM
Body panels	100% steel	100% carbon fiber composite	ASCM
Front/rear bumpers	100% steel	100% carbon fiber composite	ASCM
Body hardware	89.8% plastic 5.3% steel 2.3% rubber 2% copper 0.6% glass	89.8% plastic 5.3% steel 2.3% rubber 2% copper 0.6% glass	Dismantling reports
Weld blanks and fasteners (electronics to body)	50% steel 50% plastic	50% wrought Al 50% plastic	Dismantling reports and our assumptions
Weld blanks and fasteners (other systems to body)	50% steel 50% plastic	50% wrought Al 50% plastic	Dismantling reports and our assumptions
Glass	100% glass	100% glass	ASCM
Exterior			
Paint	100% paint	100% paint	ASCM
Exterior trim	93.6% plastic 4.3% steel 1.5% rubber 0.6% organic	93.6% plastic 4.3% steel 1.5% rubber 0.6% organic	Dismantling reports
Sealers/deadeners	100% rubber	100% rubber	ASCM
Exterior electrical	59% plastic 41% copper	59% plastic 41% copper	Dismantling reports
Interior			
Instrument panel	46% steel 47% plastic 4% organic 1% wrought Al 1% rubber 1% magnesium	47% plastic 29% steel 19% magnesium 4% organic 1% wrought Al	Dismantling reports
Trim & insulation	67.2% plastic 29.5% steel 3.2% organic 0.1% wrought Al	67.2% plastic 29.6% wrought Al 3.2% organic	Dismantling reports

TABLE 10 (Cont.)

Component	Conventional	Lightweight	Source(s)
Interiors (Cont.)			
Door modules	65.3% plastic 32.6% organic 1.8% steel 0.3% glass	65.3% plastic 32.6% organic 1.8% steel 0.3% glass	Dismantling reports
Seating & restraint	58% steel 39% plastic 3% organic	42% steel 39% plastic 16% wrought Al 3% organic	Dismantling reports
HVAC	56.2% steel 21.5% wrought Al 16.7% copper 2.4% plastic 2% rubber 0.5% zinc 0.7% other	56.2% steel 21.5% wrought Al 16.7% copper 2.4% plastic 2% rubber 0.5% zinc 0.7% other	Dismantling reports
Interior electrical	59% plastic 41% copper	59% plastic 41% copper	Dismantling reports
Weld blanks and fasteners (interior to body)	50% steel 50% plastic	50% wrought Al 50% Plastic	Dismantling reports and our assumptions
Powertrain			
Engine	50% cast iron 30% wrought Al 10% steel 4.5% plastic 4.5% rubber 1% copper	42% wrought Al 27.3% steel 12.6% cast iron 8.4% stainless steel 4.2% rubber 4.2% plastic 1.3% copper	Conventional: Muir 2005 and our assumptions Lightweight: Cuenca 2005 and our assumptions
Fuel cell stack	62.8% carbon fiber composite 23.2% wrought Al 5.4% PFSA[a] 5.0% carbon paper 1.5% steel 1.4% PTFE[a] 0.6% carbon/PFSA[a] suspension 0.1% platinum	62.8% carbon fiber composite 23.2% wrought Al 5.4% PFSA[a] 5.0% carbon paper 1.5% steel 1.4% PTFE[a] 0.6% carbon/PFSA[a] suspension 0.1% platinum	Cooper 2004
Engine fuel storage system	100% steel	100% steel	Cuenca 2005
Powertrain thermal	50% steel 50% plastic	50% steel 50% plastic	Dismantling reports and our assumptions

TABLE 10 (Cont.)

Component	Conventional	Lightweight	Source(s)
Powertrain (Cont.)			
Exhaust	99.985% steel 0.015% platinum	99.985% steel 0.015% platinum	Cuenca 2005 and our assumptions
Powertrain electrical	59% plastic 41% copper	59% plastic 41% copper	Dismantling reports
Emission control electronics	59% plastic 41% copper	59% plastic 41% copper	Dismantling reports
Weld blanks and fasteners (powertrain to body)	100% steel	100% wrought Al	Dismantling reports and our assumptions
Transmission (ICEV)	30% steel 30% wrought Al 30% cast iron 5% plastic 5% rubber	30% steel 30% wrought Al 30% cast Al 5% plastic 5% rubber	Muir 2005 and our assumptions
Transmission (HEV/FCV)	60.5% steel 20% wrought Al 19% copper 0.3% organic 0.2% plastic	60.5% steel 20% wrought Al 19% copper 0.3% organic 0.2% plastic	Dismantling reports
Chassis			
Cradle	100% steel	100% glass fiber composite	ASCM
Driveshaft/axle	100% steel	100% cast Al	ASCM
Differential	100% steel	100% steel	ASCM
Corner suspension	100% steel	100% cast Al	ASCM
Braking system	60% iron 35% steel 5% friction material	60% iron 35% steel 5% friction material	Cuenca 2005
Wheels	100% steel	100% cast Al	ASCM
Tires	67% steel 33% rubber	67% steel 33% rubber	Muir 2005 and our assumptions
Steering system	80% steel 15% wrought Al 5% rubber	80% steel 15% wrought Al 5% rubber	Cuenca 2005
Chassis electrical	59% plastic 41% copper	59% plastic 41% copper	Dismantling reports
Weld blanks and fasteners (chassis to body)	100% steel	100% wrought Al	Dismantling reports and our assumptions

TABLE 10 (Cont.)

Component	Conventional	Lightweight	Source(s)
Chassis (Cont.)			
Generator	36.1% steel 36.1% cast Al 27.3% copper	36.1% steel 36.1% cast Al 27.3% copper	Dismantling reports
Motor	36.1% steel 36.1% cast Al 27.3% copper	36.1% steel 36.1% cast Al 27.3% copper	Dismantling reports
Controller/inverter	5.0% steel 47.0% cast Al 8.2% copper 3.7% rubber 23.8% plastic 12.3% organic	5.0% steel 47.0% cast Al 8.2% copper 3.7% rubber 23.8% plastic 12.3% organic	Dismantling reports
Fuel cell auxiliaries (includes H_2 fuel storage)	36.8% steel 25.7% carbon fiber composite 16.7% wrought Al 9.6% copper 8.7% plastic 1.5% rubber 0.5% nickel 0.5% other	36.8% steel 25.7% carbon fiber composite 16.7% wrought Al 9.6% copper 8.7% plastic 1.5% rubber 0.5% nickel 0.5% other	Cooper 2004 and Carlson 2004

[a] PFSA = perfluorosulfonic acid; PTFE = polytetrafluoroethylene.

TABLE 11 Material Composition of Battery

	Pb-Ac	Ni-MH	Li-Ion	Sources
Battery	69% lead 14.1% water 7.9% sulfuric acid 6.1% plastic 2.1% fiberglass 0.8% other	28.2% nickel 23.7% steel 22.5% plastic 12% iron 6.3% rare earth metals 3.9% copper 1.8% cobalt 1% magnesium 0.5% wrought Al 0.1% rubber	24.5% copper 18.6% wrought Al 10.9% plastics 10.6% graphite/carbon 10.6% cast Al 8.7% electrolyte 5.3% lithium oxide 2.7% cobalt 2.6% nickel 2.5% manganese 2.1% binder 0.5% thermal insulation 0.3% electronic parts 0.2% steel	Argonne National Laboratory et al. 1998, dismantling reports, Nelson 2005, and our assumptions

TABLE 12 Vehicle Component Weights (lb)

	ICEV	HEV	FCV	LW ICEV	LW HEV	LW FCV	Source(s)
Body							
BIW	**551**[a]	**551**	**551**	**185**	**205**	**238**	ASCM
Body panels	176	176	176	88	88	88	ASCM
Front/rear bumpers	22	22	22	5	5	5	ASCM
Body hardware	22	22	22	22	22	22	ASCM
Weld blanks and fasteners (electronics to body)	22	22	22	10	10	10	ASCM
Weld blanks and fasteners (other systems to body)	22	22	22	10	10	10	ASCM
Glass	88	88	88	56	56	56	ASCM
Exterior							
Paint	26	26	26	13	13	13	ASCM
Exterior trim	22	22	22	9	9	9	ASCM
Sealers/deadeners	4	4	4	4	4	4	ASCM
Exterior electrical	22	22	22	22	22	22	ASCM
Interior							
Instrument panel	53	53	53	35	35	35	ASCM
Trim & insulation	49	49	49	36	36	36	ASCM
Door modules	55	55	55	55	55	55	ASCM
Seating & restraint	132	132	132	103	103	103	ASCM
HVAC	44	44	44	44	44	44	ASCM
Interior electrical	22	22	22	22	22	22	ASCM
Weld blanks and fasteners (interior to body)	22	22	22	10	10	10	ASCM
Powertrain							
Engine	**450**	**243**		**240**	**151**		ASCM
Fuel cell stack			**214**			**166**	ASCM and Cooper 2004
Engine fuel storage System	119	119		119	119		ASCM
Powertrain thermal	53	32		53	32		ASCM
Exhaust	99	64		99	64		ASCM
Powertrain electrical	22	22		22	22		ASCM
Emission control Electronics	22	4		22	4		ASCM
Weld blanks and fasteners (powertrain to body)	22	22		10	10		ASCM
Transmission	**193**	**214**	**83**	**123**	**146**	**59**	ASCM

TABLE 12 (Cont.)

	ICEV	HEV	FCV	LW ICEV	LW HEV	LW FCV	Source(s)
Chassis							
Cradle	**66**	**66**	**66**	**33**	**36**	**41**	ASCM
Driveshaft/axle	**163**	**163**	**163**	**49**	**65**	**78**	ASCM
Differential	**55**	**55**	**55**	**54**	**55**	**55**	ASCM
Corner suspension	**90**	**90**	**90**	**41**	**44**	**50**	ASCM
Braking system	**84**	**84**	**84**	**61**	**66**	**75**	ASCM
Wheels (4.5); spare = 0.5	91	91	91	38	38	38	ASCM
Tires (4.5); spare = 0.5	90	90	90	90	90	90	ASCM
Steering system	**49**	**49**	**49**	**25**	**29**	**36**	ASCM
Chassis electrical	22	22	22	22	22	22	ASCM
Weld blanks and fasteners (chassis to body)	22	22	22	10	10	10	ASCM
Generator		**61**			**37**		ASCM and dismantling reports
Motor		**61**	**122**		**37**	**81**	ASCM and dismantling reports
Controller/inverter		**54**	**107**		**33**	**71**	ASCM and dismantling reports
Fuel cell auxiliaries			**571**			**462**	ASCM, Carlson 2004, and Cooper 2004

[a] Bold indicates rows containing values that differ significantly.

TABLE 13 Component Weight Breakdown (%)

	ICEV	HEV	FCV	LW ICEV	LW HEV	LW FCV
Body	44.1	45.3	39.9	39.6	40.3	38.5
Powertrain	25.7	17.0	8.0	30.7	21.6	8.1
Transmission	6.3	7.2	2.6	6.7	7.8	2.8
Chassis	23.9	24.5	23.0	23.0	24.5	23.8
Generator	0.0	2.1	0.0	0.0	2.0	0.0
Motor	0.0	2.1	3.8	0.0	2.0	3.8
Controller/inverter	0.0	1.8	3.4	0.0	1.8	3.3
Fuel cell auxiliaries	0.0	0.0	19.3	0.0	0.0	19.7

TABLE 14 Material Composition Aggregated by Component (% by weight)[a]

	ICEV	HEV	FCV	LW ICEV	LW HEV	LW FCV
Steel	61.7	30.5	65.2	30.9	56.4	21.4
Stainless steel	0.0	1.1	0.0	0.7	0.0	0.0
Cast iron	11.1	4.2	6.0	3.7	1.8	2.6
Wrought aluminum	2.2	6.9	1.8	6.3	5.9	10.3
Cast aluminum	4.7	14.7	5.1	14.1	3.2	11.2
Copper/brass	1.9	3.2	4.3	5.4	4.8	5.5
Magnesium	0.02	0.4	0.02	0.4	0.02	0.3
Glass	2.9	3.0	2.9	3.0	2.6	2.8
Average plastic	11.2	14.0	10.6	12.6	10.2	11.7
Rubber	2.4	2.6	1.9	2.0	1.8	1.8
CFRP[b]	0.0	15.1	0.0	16.0	10.0	26.4
GFRP[b]	0.0	2.3	0.0	2.4	0.0	2.3
Nickel	0.0	0.0	0.0	0.0	0.1	0.1
PFSA[b]	0.0	0.0	0.0	0.0	0.4	0.4
Carbon paper	0.0	0.0	0.0	0.0	0.4	0.4
PTFE[b]	0.0	0.0	0.0	0.0	0.1	0.1
Carbon and PFSA suspension	0.0	0.0	0.0	0.0	0.05	0.05
Platinum	0.0005	0.0009	0.0003	0.0004	0.007	0.007
Others	1.9	2.2	2.2	2.5	2.2	2.5

[a] Batteries excluded.

[b] CFRP = carbon fiber-reinforced plastic; GFRP = glass fiber-reinforced plastic; PFSA = perfluorosulfonic acid; PTFE = polytetrafluoroethylene.

slightly more total aluminum and plastic than the ICEV because they have additional components that contain these materials; automakers use these materials primarily to reduce the total weight of the vehicle. The lightweight vehicles contain a higher percentage of both aluminum and plastic compared with their counterparts. The conventional FCV contains advanced composites, which are used in the bipolar plates of the fuel cell stack, while the other conventional vehicles do not. Each lightweight vehicle has an advanced composite body made up of 70% polyester and 30% carbon fiber, while the FCV again contains additional composites in its fuel cell stack.

4.4 FUEL CELL AND BATTERY SIZING

On the basis of Argonne component sizing calculations, the power delivered via fuel cell stack in the conventional FCV was calculated to be 70 kW; the lightweight FCV has a stack power of 54 kW, or 77% of the power of the conventional FCV stack. However, GREET 2.7 allows users to select their own stack power by using equations to calculate the resulting fuel cell stack and auxiliary weights. These equations, which use weights of 3.23 lb/kW for the stack and 7.8 lb/kW for the auxiliaries, are from a fuel cell component breakdown presented in a Society of Automotive Engineers (SAE) paper (Cooper 2004). If users want to change the stack power, they will likely also want to change the battery power, which can be input manually by the user. According to PSAT simulations, the total system power for a conventional FCV hybrid should be 100 kW. With a stack power of 70 kW, the default battery power is 30 kW. For lightweight FCVs, the Argonne component sizing equations were used to calculate a battery power of 19 kW, which is 63% of the power of the conventional FCV battery.

The default battery power (23 kW) for a full HEV was calculated, based on PSAT simulations, to be similar to battery power in the conventional ICEV. For lightweight HEVs, the Argonne component sizing equations were used to calculate a battery power of 14 kW, which is 61% of the battery power of a conventional HEV. The power of a startup Pb-Ac battery is about 6 kW for the conventional ICEV and about 4 kW for the conventional HEV and FCV (Argonne National Laboratory et al. 1998 and ASCM). The startup Pb-Ac batteries for the lightweight vehicles were scaled down according to the Argonne component sizing calculations; the lightweight ICEV battery power is about 4 kW, while the battery power for both the lightweight HEV and the lightweight FCV is about 2.5 kW. We assumed a specific power of 600 W/kg for the Ni-MH and 1,500 W/kg for the Li-ion battery on the basis of discussions about current battery technology (Duvall 2005; Bohn 2005). We assumed a specific power of approximately 390 W/kg for the Pb-Ac battery on the basis of information in ASCM. Table 15 lists battery weights.

4.5 BATTERY REPLACEMENT

Another important factor when considering batteries is the number of times they will need to be replaced during the vehicle's lifetime. A key assumption used in determining the battery replacement interval is the distance traveled by the vehicles during their lifetimes. The VISION model developed at Argonne shows an average lifetime distance of 160,000 miles by a passenger car; this value is used for our analysis (Argonne National Laboratory 2006c). There is some uncertainty regarding the life of advanced batteries, such as Ni-MH and Li-ion, during actual use in electric-drive vehicles. This is a concern for potential buyers because of the cost of replacement.

TABLE 15 Battery Weights (lb)

	ICEV	HEV	FCV	LW ICEV	LW HEV	LW FCV
Pb-Ac	36.0	22.1	22.1	23.4	14.4	14.4
Ni-MH		84.3	110.0		51.3	69.7
Li-ion		33.7	44.0		20.5	27.9

Currently, the manufacturer's warranty for a new 2006 Toyota Prius and 2006 Ford Escape Hybrid covers the Ni-MH battery and other hybrid-related components for 8 years or 100,000 miles, whichever comes first (Toyota Motor Corporation 2006; Ford Motor Company 2006). For Honda's 2006 Civic, Accord, and Insight hybrids, the warranty is for 8 years or 80,000 miles (Honda Motor Company 2006). However, in states that have adopted California's zero emission vehicle (ZEV) program, the warranty for these electric-drive vehicles is 10 years or 150,000 miles (Ford Motor Company 2006). Warranty information provides some indication of battery life, but there is still some uncertainty. A recent study examines the use of Ni-MH batteries in various electric-drive vehicles, including an HEV, a plug-in hybrid electric vehicle, and a battery-electric vehicle; the study states that it is highly probable that Ni-MH batteries can achieve 130,000 to 150,000 lifetime mileage (Duvall 2003).

Currently, the United States Advanced Battery Consortium goal for high-power Li-ion batteries is a 15-year calendar life, but significant work remains to be done before this goal can be accomplished cost effectively (Wall and Duong 2005). Li-ion batteries have yet to be used in a mass-produced vehicle, so in-use data are not available; however, laboratory tests from Saft America Inc. have shown that Li-ion batteries have met a life goal of 300,000 cycles, which the company estimates to be 15 years of calendar life (Wall and Duong 2005).

Because of the lack of in-use data, we decided to assume that both the Ni-MH and Li-ion batteries would be replaced once in the lifetime of the HEV or FCV; however, there could be some useful life in them when the rest of the vehicle is scrapped, and these batteries could potentially be reused. In order to accurately determine replacement intervals for Li-ion and Ni-MH batteries, further research and real-world data are needed.

Pb-Ac battery life, on the other hand, can be determined with more certainty because the technology is fairly mature. On the basis of data collected from a life-cycle inventory performed by USCAR, we assume that the Pb-Ac battery will require two replacements in the lifetime of the ICEV, HEV, and FCV (Sullivan et al. 1998). In addition, Pb-Ac batteries are the top recycled consumer product, at more than 97%; new batteries contain 60% to 80% recycled lead and plastic (Battery Council International 2006).

The recycling of Ni-MH and Li-ion batteries used in automotive applications is an important issue that has been getting more attention as the fleet of HEVs grows (DOE 2002). The United States already has a network to collect rechargeable consumer batteries, which are consolidated into 10,000- to 40,000-lb shipments and sent to a central processing plant run by INMETCO. INMETCO, North America's leading recycler of metal wastes, has a proprietary high-temperature method of recycling Ni-MH batteries to recover nickel, iron, manganese, and zinc to be used as alloying materials in the production of stainless steel. In addition to the type of pyrometallurgical processing used by INMETCO, mechanical processing and hydrometallurgical treatment are also being considered for recycling Ni-MH batteries. Toxco Inc. has the only lithium battery recycling process in North America. The process involves cryogenically freezing the batteries in liquid nitrogen to render them non-reactive, then shearing the batteries and separating the materials. The metals are collected and sold, while the lithium components are separated and converted to lithium carbonate for resale. Plastic casings and other miscellaneous components are separated for recycling or scrapping.

There are still many challenges involved in the recycling of these advanced batteries. One is the lack of information regarding the exact material composition of each battery, which raises the question of whether it is worthwhile to reclaim the unknown materials left in the slag after pyrometallurgical processing. In addition, there is an apparent reluctance by battery manufacturers to reuse components after they have been separated and cleaned. The level of impurities that can be tolerated in reclaimed battery materials has not been disclosed by manufacturers, which leaves a lot of questions about the development of potential recycling processes (DOE 2002). As these batteries reach their end-of-life stage, these issues need to be addressed in order to make advanced battery recycling as successful as Pb-Ac battery recycling.

4.6 TIRE AND FLUID REPLACEMENT

Additional components also require replacement during a vehicle's lifetime. In GREET 2.7, we include tire and fluid replacement. Replacement of parts such as air filters, brake pads, spark plugs, and windshield wiper blades was not included because of the small weight of these parts and because the model aggregates these parts into larger components that are not completely replaced. Tires, which are composed of approximately two-thirds rubber and one-third steel (by weight) are replaced regularly; however, their life span varies depending on tire specifications (Muir 2005). In this analysis, we assume that the tires are replaced every 40,000 miles, so about three replacements are needed over the vehicle's lifetime. The last set of tires is at the end of its useful life when the rest of the vehicle is scrapped (Sullivan et al. 1998). Potentially, the tires could last slightly longer on average, but because of safety concerns, used tires are not reused on vehicles. In 2003, approximately 290 million scrap tires were generated; about 80% of those were consumed in a scrap market such as tire-derived fuel, ground rubber, and civil engineering applications (Rubber Manufacturers Association 2004).

The fluids in a vehicle are replaced during routine maintenance (e.g., oil changes and other maintenance intervals). We assumed that the engine oil is replaced, on average, every 4,000 mi, requiring 40 lifetime replacements; most vehicle manufacturers recommend oil changes every 5,000 mi, while maintenance shops recommend changes every 3,000 miles. In addition, we assumed that the windshield wiper fluid, which is a 50%/50% mix of methanol and water, is completely consumed every 8,000 mi, requiring 20 lifetime refills. This fluid is often filled during oil changes, when incremental amounts are added to fill the wiper fluid reservoir.

Power steering fluid, which is mineral based, is not replaced. In addition, makers of most new ICEVs and all HEVs (and FCVs in the future) are transitioning to a fluidless electric power assist steering system because it requires fewer parts and no maintenance and weighs less (Bohn 2005). Most HEVs combine their anti-lock braking system (ABS) with the hybrid control system; regenerative brakes and conventional brakes are used together to slow the vehicle down, and the amount of braking from each is controlled electronically. However, because this is a controls modification, the amount of brake fluid used does not significantly change from one vehicle to another (Bohn 2005). We assumed that both the brake fluid and powertrain coolant, which is a 50%/50% mix of ethylene glycol and water, are replaced every 40,000 mi, requiring three lifetime replacements each (Sullivan et al. 1998).

Transmission fluid, a mineral-based lubricant, is used significantly less in HEVs and FCVs compared with ICEVs because of the differences in the gearboxes in these vehicles compared with the automatic transmission in ICEVs (which we assume to be used in our analysis) (Bohn 2005). We assume that each vehicle has one lifetime replacement and that, at a density of about 7 lb/gal, the ICEV requires about 24 lb of transmission fluid, while the HEV and FCV each needs about 2 lb (Royal Purple 2006). Finally each type of vehicle uses about 30 lb of adhesives, which are not replaced (Argonne National Laboratory et al. 1998). We assume that two-thirds of each fluid, except for the windshield wiper fluid, is combusted when it is replaced, while the remaining one-third is lost during operation; all of the wiper fluid is released to the atmosphere. The weights of the fluids were determined by using dismantling reports to calculate the volume required and density formulas to calculate the weights; the results are shown in Table 16.

TABLE 16 Fluid Weight (lb)

	Engine Oil	Power Steering Fluid	Brake Fluid	Transmission Fluid	Powertrain Coolant	Windshield Wiper Fluid	Adhesives
ICEV	8.5	0.0	2.0	24.0	23.0	6.0	30.0
HEV	8.5	0.0	2.0	1.8	23.0	6.0	30.0
FCV	0.0	0.0	2.0	1.8	15.8	6.0	30.0

5 MATERIALS

In order to estimate the amount of energy used during vehicle production, we first had to identify the materials used in the vehicles and then characterize the production processes and, if possible, the recycling processes for each material. Energy use for material production can be estimated on the basis of information in the open literature or obtained from producers, but recycling data — especially for newer and less-common materials — may be available only from experimental results or theoretical calculations. Emissions data are available for many materials, but only the air emissions data for common materials have been summarized in an accessible format. Our limited resources did not allow us to collect additional data that could not be readily obtained.

For each material, we characterized raw material sources, production and fabrication processes, and recycling processes. We estimated energy use by type at each step and calculated emissions from fuel combustion by using the estimated energy use (by type) and the emission factors for various combustion technologies contained in GREET 1.7. Some steps also generate process-related emissions as a result of chemical reactions or physical processes; we included these emissions. We present some material-specific assumptions used for vehicle-cycle energy and emissions calculations; we used current industry data whenever possible. Because of a lack of available data, we were not able to model the effect of plant age on energy use and emissions. We suspect that future material production may be more heavily weighted to modern, efficient production technologies, rather than current averages.

5.1 METALS

Production of metals is very energy intensive because the ore must be mined, concentrated, and subjected to endothermic chemical reactions to yield the metal product. Recycling is generally less polluting and less energy intensive because the basic material only needs to be remelted. However, in either case, the basic metal product requires fabrication to yield a final product.

5.1.1 Steel

The first step in steelmaking is extracting iron ore (usually taconite in the United States), which involves mining the ore by blasting and further processing it to concentrate the ore to a purity of at least 66% before it can be used in steelmaking. First the ore is crushed into a fine powder, then the metal is separated from the waste rock by means of magnetism. The powder is wet down and then rolled with clay inside a large rotating cylinder; it is then heated and cooled to form iron ore pellets. Uncontrolled emissions from the pelletizing process are 18 g VOCs/ton, 45 g CO/ton, 682 g NO_x/ton, 286 g PM_{10}/ton, and 132 g SO_x/ton of finished pellet; control efficiencies range from 86% for CO, to 80% for PM_{10}, to 67% for SO_x (EPA 1995). Sinter, which is an intermediate product in steelmaking, is produced from a mixture of fine iron ore powder, coke, limestone ($CaCO_3$), dolomite, and flue dust that is ignited by a gas-fired furnace and fused into a porous cake-like substance. This process can release a significant amount of CO: 20,000 g/ton of finished sinter (EPA 1995). In addition, uncontrolled PM_{10} emissions are 774 g/ton; however the control efficiency is around 98% (EPA 1995). Both the iron ore pellets and the sinter are inputs to blast furnaces that produce pig iron, which is a crude, high-carbon form of iron that is brittle and requires further processing.

Coking involves heating metallurgical coal in the absence of oxygen to drive off 25% to 30% of its mass as volatiles, producing a carbonaceous product called coke, which is used both as a fuel and a reducing agent in blast furnaces. The process also produces coke oven gas (COG), which is a high-quality fuel that is also used in the blast furnace. Two major by-products, coal tar and chemicals extracted from the gas, also result from this process. Coal tar can be used as pitch, road tar, and several basic chemicals, while condensed coal gas provides light oil, anhydrous ammonia, and sulfur from gas desulfurization (Scientific Certification Systems, Inc. [SCS] 2000).

The coking process is a major source of both gaseous emissions and particulates. Gaseous emissions include CH_4, CO, hydrogen, and other hydrocarbons, which are the major constituents of COG. Emissions of SO_2 depend on the sulfur content of the coal feed and the underfire gas, which can potentially be NG, COG, or blast furnace gas (BFG). Benzene and other toxic VOC emissions from the by-product chemical plant have been a particular concern. Coal dust may be released during oven charging. Particulates that result from the steelmaking process can be captured in hoods or other systems and sent to a baghouse (Argonne National Laboratory et al. 1998). Significant uncontrolled emissions from the coking process include 706 g VOCs, 214 g CO, 6.7 g NO_x, 933 g PM_{10}, and 857 g SO_x for every ton of coke produced. However, various controls can vastly reduce emissions; for example, control efficiencies are 95% for VOCs, 94% for CO, 81% for PM_{10}, and 82% for SO_x (EPA 1995).

In a blast furnace, the iron ore pellets, sinter, and coke are poured into the top of a tall chimney-like furnace, while pre-heated air is blown into the middle of the furnace, the “blast.” The furnace temperature ranges from 1,200°C to 1,500°C, reducing the iron ore into molten pig iron. Limestone that absorbs the iron impurities, called “slag,” floats on top of the molten iron. First, the slag is removed from the furnace, then the pig iron is drained from the bottom. The process also produces BFG, a fuel that can be used for coke production or electricity generation. In GREET 2.7, we estimate an export credit for the BFG of 1.0 million Btu of electricity per ton of pig iron produced in the blast furnace (SCS 2000). Direct iron reduction is a possible future substitute technology to produce pig iron that does not require coke, and therefore reduces the total energy requirements and emissions associated with steelmaking. However, there are significant cost and technology hurdles that need to be overcome before direct iron reduction can be widely used (SCS 2000).

In the next step in the steelmaking process, the basic oxygen process (BOP) is used to convert the molten iron to steel. First, the molten iron is poured into a large ladle, where magnesium is added to reduce sulfur impurities. Next, it is poured into a vessel where 99% pure oxygen is blown onto the iron, raising the temperature to about 1,700°C. Then, burnt limestone is fed into the vessel to form slag and absorb additional impurities. Next, the iron is poured into a furnace where various alloying materials are added, depending on the end use. The remaining slag is poured off and, finally, the resulting steel is poured into an ingot mold and allowed to cool.

The ingots are then sent to a hot-rolling mill, where the steel is reheated in a furnace to around 1,200°C. The steel then undergoes hot rolling to reduce its thickness from the initial 100–250 mm to a final 2–3 mm. Because of the high temperature involved in hot rolling, a thin layer of iron oxide, called "scale," forms on the surface of the steel. To remove the scale, the steel goes through a pickling process, in which it is run through tanks of hydrochloric acid (HCl). Then, the thinner slab is coiled and transported to a cold-rolling mill for further processing, depending on the desired application. For automotive products, sheet steel, measuring approximately 0.5 mm thick, is produced. The cold-rolling process hardens the steel, making it more brittle and difficult to form. To restore the steel's formability, it undergoes a heat-treating process called annealing. Finally, the steel sheet is stamped by using multiple dies to shape the sheet into automotive parts, such as body panels and BIW structures.

Secondary steel and stainless steel are produced from steel scrap via the electric arc process (EAP). In this process, steel scrap is fed into an electric arc furnace (EAF) by an overhead crane. An electric current, in the form of an arc, is passed through graphite electrodes that are lowered into the EAF, which melts the scrap. Limestone is added to form a slag that removes impurities. Once the steel reaches the correct temperature and chemistry, it is poured into a preheated ladle. Various alloying materials are added, depending on the end use. The remaining slag is poured off and, finally, the resulting steel is poured into an ingot mold and allowed to cool. Figure 4 presents a steel production flowchart. Table 17 lists the energy use and fuel shares associated with steel production, and Table 18 lists the tons of intermediate material per ton of final product.

5.1.2 Cast Iron

Cast iron parts for automobiles, such as a cast iron engine block, can be produced by automakers in their own foundries, using scrap iron and steel as the raw materials. Scrap is reduced in size by shredding, shearing, cutting, or crushing, depending on the source, and charged to a cupola furnace, which resembles a small blast furnace. Foundry coke, similar to metallurgical coke but slightly more energy intensive, supplies the heat to melt the metal, which is then poured into molds.

5.1.3 Aluminum

The first step in the virgin aluminum-making process is extracting bauxite ore, which involves mining the ore by using blasting, basic processing steps to facilitate handling and refining, and transportation of the ore to the refining plant. The next step, the Bayer process, involves washing the bauxite with lime and a heated (250°C) solution of lye in a digester. When the solution of lye is cooled, aluminum hydroxide [$Al(OH)_3$] crystals precipitate out. In the final

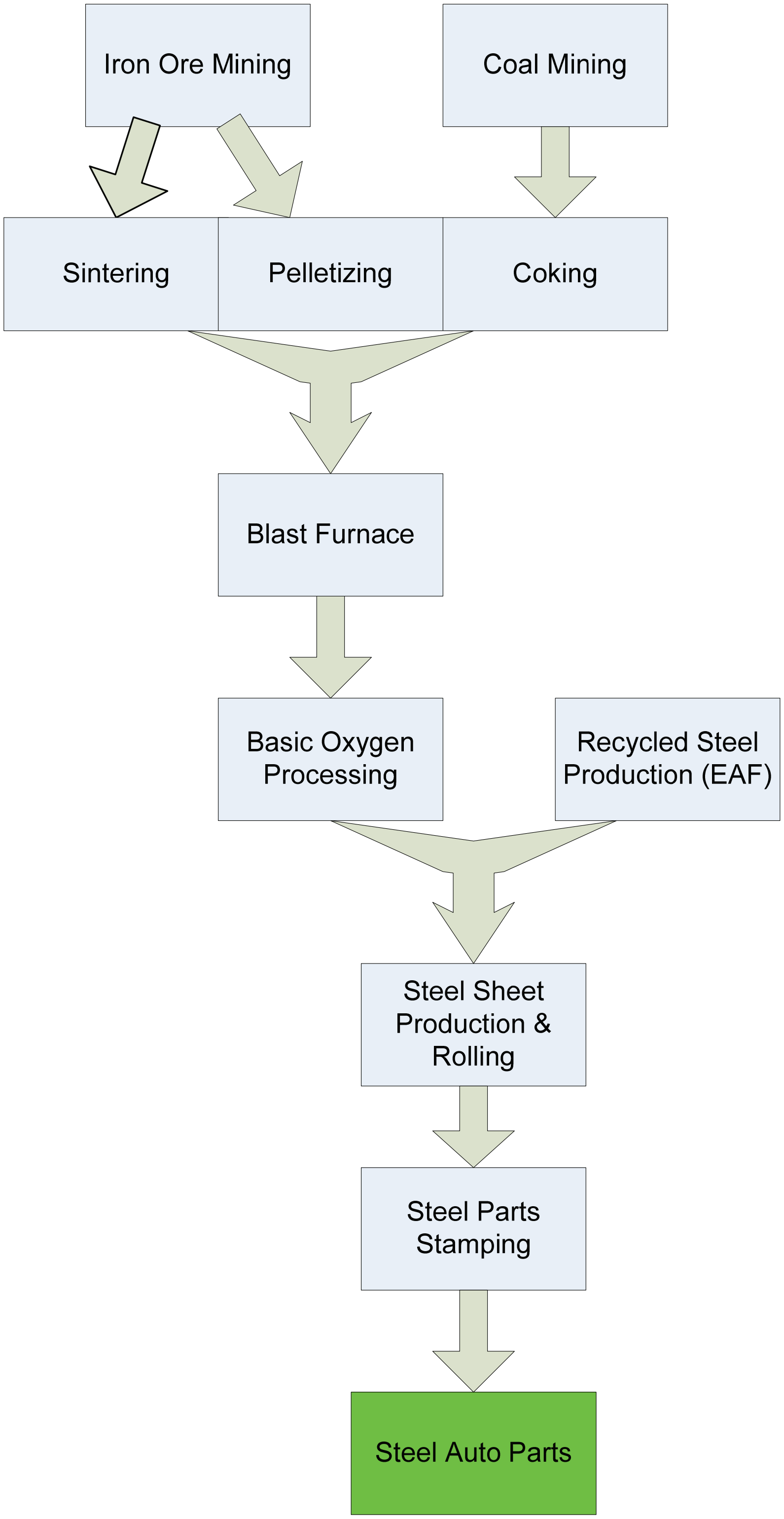

FIGURE 4 Steel Production Flowchart

TABLE 17 Energy Use and Fuel Shares for Steel Component Manufacture

Process	Taconite Mining	Ore Pelletizing and Sintering	Coke Production	Blast Furnace	BOP	EAF (virgin and recycled steel)	EAF (stainless steel)	Sheet Production and Rolling	Stamping
Energy use (mmBtu/ton of material product)	0.054	1.391	5.580	15.886	1.627	4.240	4.819	6.108	5.453
Fuel share (%)									
Diesel	100								
BFG									
COG									
Coke									
NG		82.5		100		5.4	5.4	84.4	79
Coal									
Electricity		17.5	100		100	94.6	94.6	15.6	21

TABLE 18 Tons of Intermediate Material Needed per Ton of Final Steel Product

Type	Taconite Mining	Ore Pelletizing and Sintering	Coke Production	Blast Furnace	BOP	EAF	Sheet Production and Rolling	Stamping
Virgin steel	5.200	1.860	0.531	1.180	1.420	0.220	1.340	1.000
Recycled steel					0.090	1.530	1.340	1.000
Stainless steel						1.610	1.340	1.000

step, the aluminum hydroxide is heated to 1,050°C, leaving alumina (Al_2O_3). Large quantities of particulates are generated during bauxite grinding, calcining, and handling; these are generally recovered because of their high economic value, leaving small residual emissions.

The Hall-Heroult process entails dissolving the alumina in a carbon-lined steel vat filled with molten (960°C) cryolite (Na_3AlF_6) and aluminum fluoride (AlF_3) to form an electrolyte solution that conducts electricity from carbon rods placed in it to the carbon-lined bed of the vat. A direct current is passed through the solution, breaking the aluminum and oxygen bonds, which results in dense liquid aluminum sinking to the bottom of the vat to be collected by a crucible. The liquid aluminum is often then placed in a holding furnace at 700–800°C to allow addition of alloying materials, or it can be poured directly into molds and allowed to cool to form ingots; however, unalloyed aluminum is not used for vehicle applications (The Aluminum Association 1998). Emissions from this aluminum reduction process include gaseous hydrogen fluoride, alumina, CO, VOCs, and SO_2. Particulates include alumina, carbon, and aluminum and calcium fluorides; additional VOCs are emitted from the anode baking process. Wet scrubbers and electrostatic precipitators may be used to control fluoride emissions, but fluoride adsorption systems that control 99% of gaseous and particulate fluorides are becoming prevalent.

Ingots, which can weigh more than several thousand pounds each, can then be shipped for casting, which involves melting the ingot and pouring the aluminum into molds to produce automotive parts, such as wheels, pistons, and cylinder blocks and heads. Alternatively, the ingot can be shipped to a mill to first undergo hot rolling at 500°C to reduce the thickness of the metal from 600 mm to 6 mm. This thinner ingot is then coiled and transported to a cold-rolling mill for further processing, depending on the desired application. For automotive products, sheet aluminum measuring between 0.2 mm and 6 mm thick is produced. Finally, the aluminum sheet is stamped by using multiple dies to shape the sheet into an automotive part, such as body panels and BIW structures.

Secondary (i.e., recycled) cast aluminum production involves scrap preparation, melting, ingot casting, and parts casting. Aluminum scrap is melted in large, NG-fired reverberatory furnaces. Chlorine is added to remove magnesium, which leads to chlorine emissions that require controls. The molten aluminum is poured into ingot molds, where it can be shipped for casting into automotive parts. Secondary wrought aluminum production also involves scrap preparation, melting, and ingot casting; however, after the ingot is produced, it is sent to a mill for the rolling and parts stamping described above. Alloy compatibility is a major concern for producing quality parts from recycled materials. Thus, for large-scale recycling of aluminum automotive parts, the cast and wrought materials should be separated so that the chemistry of the recycled parts is predictable and desirable. Figures 5 and 6 provide flowcharts for wrought and cast aluminum production, respectively. Table 19 lists the energy use and fuel shares of wrought aluminum production, while Table 20 lists the tons of intermediate material per ton of final product. The energy use and fuel shares of cast aluminum production are listed in Table 21, while the tons of intermediate material per ton of final product are listed in Table 22.

5.1.4 Copper

Copper (Cu) is smelted or recovered by leaching from dilute sulfide ores found in the southwestern United States. The smelting process leads to significant emissions of SO_x, which are captured and converted to sulfuric acid for sale. Because the ores are dilute, the energy use required for mining and beneficiation (crushing and separating the ore) is significant. In this analysis, we combined all copper production processes (i.e., mining, concentrating, pyrometallurgical processing, and wire production) into one characterization; the combined energy required for these processes is 66 million Btu/ton of copper wire (Argonne National Laboratory et al. 1998). Pure copper's outstanding electrical conductivity makes it the material of choice for automotive wiring, including electric motors. The other major automotive use of copper is in the form of brass alloys (Cu-Zn) that can be used in radiators. Radiators are among the components that are generally stripped from scrapped vehicles prior to shredding because of their value for possible reuse or recycling. The recycling process is considerably less energy intensive and causes no sulfur emissions; energy requirements depend on scrap grade and vary from 6 to 42 million Btu/ton (Kusik and Kenahan 1978). In the current version of the model, we examine only primary copper production.

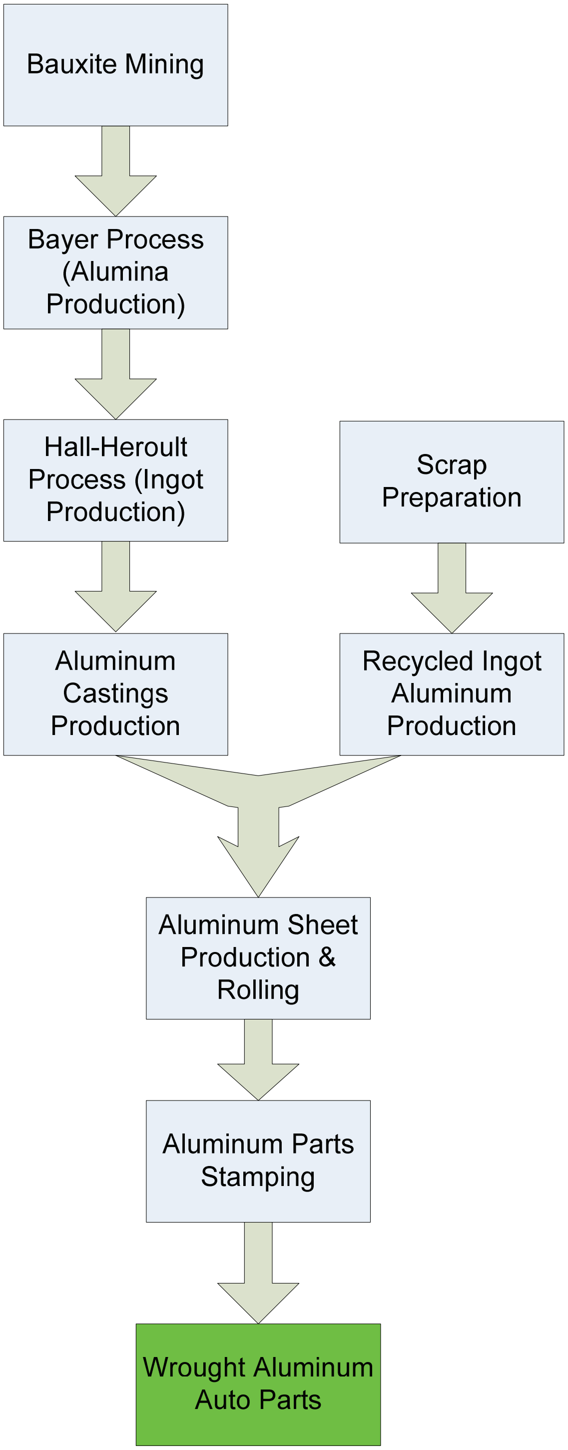

FIGURE 5 **Wrought Aluminum Production Flowchart**

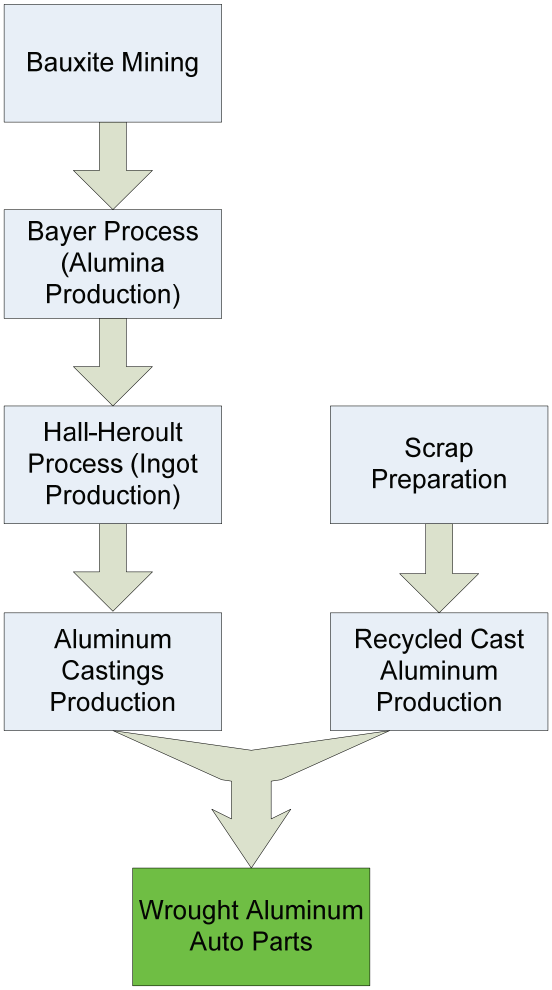

FIGURE 6 **Cast Aluminum Production Flowchart**

TABLE 19 Energy Use and Fuel Shares for Wrought Aluminum Manufacture

Process	Bauxite Mining	Bauxite Refining (Bayer process)	Alumina Reduction (Hall-Heroult process)	Scrap Preparation (recycled wrought Al)	Reverb Melting and Ingot Casting (recycled wrought Al)	Al Melting and Casting	Sheet Production and Rolling	Stamping
Energy use (mmBtu/ton of material product)	0.563	9.527	65.843	0.623	9.500	4.146	8.344	5.453
Fuel share (%)								
Residual oil		0.3	17.2		2.9	2.8	5.4	
Diesel	100			62.1				
NG		89.4	4.6		95.6	91.7	67.2	79
Coal		3.7	5.9					
Electricity		6.6	72.3	37.9	1.5	5.5	27.4	21

TABLE 20 Tons of Intermediate Material Needed per Ton of Final Wrought Aluminum Product

Type	Bauxite Mining	Bauxite Refining (Bayer process)	Alumina Reduction (Hall-Heroult Process)	Scrap Preparation (recycled wrought Al)	Reverb Melting and Ingot Casting (recycled wrought Al)	Al Melting and Casting	Sheet Production and Rolling	Stamping
Virgin wrought Al	4.800	1.900	1.000			1.000	1.380	1.000
Recycled wrought Al				1.060	1.000	1.000	1.380	1.000

TABLE 21 Energy Use and Fuel Shares for Cast Aluminum Manufacture

Process	Bauxite Mining	Bauxite Refining (Bayer process)	Alumina Reduction (Hall-Heroult process)	Al Melting and Casting	Al Recycling (recycled cast Al)	Al Casting (recycled cast Al)
Energy use (mmBtu/ton of material product)	0.563	9.527	65.843	4.146	1.450	34.650
Fuel share (%)						
Residual oil		0.3	17.2	2.8		
Diesel	100				93	
NG		89.4	4.6	91.7		100
Coal		3.7	5.9			
Electricity		6.6	72.3	5.5	7	

TABLE 22 Tons of Intermediate Material Needed per Ton of Final Cast Aluminum Product

Type	Bauxite Mining	Bauxite Refining (Bayer process)	Alumina Reduction (Hall-Heroult process)	Al Melting & Casting	Al Recycling (recycled cast Al)	Al Casting (recycled cast Al)
Virgin cast Al	4.800	1.900	1.000	1.000		
Recycled cast Al					1.000	1.000

5.1.5 Zinc

Zinc, like copper, is smelted from sulfide ores with a mining energy requirement of 3.7 million Btu/ton of zinc (Ruth 1998); the production energy requirement is about 86 million Btu/ton (Argonne National Laboratory et al. 1998). The quantity of zinc per automobile has been decreasing steadily since the late 1970s; automobiles currently contain less than 10 lb of zinc die castings per vehicle, down from 31 lb in 1978 (Wrigley 2003). Much of the zinc in automobiles is used for galvanization of steel parts and is extremely difficult to recycle.

5.1.6 Magnesium

Magnesium (Mg) compounds are found both in solid deposits and in aqueous solutions, but never in elemental form. Seawater is the main source of magnesium, providing a nearly unlimited supply and a consistent concentration that allows for standard extraction procedures. The primary production process, which is used by both major producers (Dow Chemical Company and Norsk Hydro) with varying degrees of magnesium dichloride ($MgCl_2$) hydration, involves the electrolytic reduction of $MgCl_2$. Dow has the world's largest magnesium plant in Freeport, Texas. The electrolytic processes, which use electricity and NG as feedstocks, are extremely energy intensive, consuming 167 million Btu/ton — significantly higher than the energy required to produce aluminum (Gaines et al. 1996). However, research is underway to reduce the energy use and cost of production through the use of magnesium oxide (MgO) as a feedstock for an electrolytic process. Although magnesium can be recycled, it seldom is. Therefore, the data on secondary production are very scarce. Emissions include hydrochloric acid, particulate MgO, NO_x, and CO; particulates are typically controlled, reducing emissions from 4 lb/ton to 0.4 lb/ton.

Although only 10 lb of magnesium are currently used per vehicle, the amount has been increasing steadily from 1 lb per vehicle in 1978 (Wrigley 2003). The reason is that magnesium is an extremely lightweight metal, with a density of 1.74 g/cm^3 — 36% lighter per unit volume than aluminum and 78% lighter than iron (Argonne National Laboratory et al. 1998). In addition, magnesium (when alloyed) has the highest strength-to-weight ratio of all structural metals. Most of the current use of magnesium is for die-castings, in components such as steering column brackets, instrument panel support beams, and seat frames; however, future structural uses of wrought magnesium in components such as roof panels, hoods, and rear deck lids are possible with a reduction in material costs (Gaines et al. 1996).

5.2 GLASS

Glass is produced by bringing raw materials to the plant, preparing them, melting them at a high temperature (1,300–1,600°C), and finally forming them into products. Glass is made from sand (silica), limestone, soda ash (Na_2CO_3), feldspar (aluminum silicates with potassium, sodium, calcium, or barium), and small quantities of other additives. The main automotive uses for glass are windows and mirrors; glass fiber is also used as the reinforcing material in reinforced plastic auto parts. The glass for automotive uses is generally produced by means of a float process, in which a thin sheet of glass is formed by flotation on a molten tin bath under a nitrogen atmosphere. Windshields are generally made from two sheets, laminated with a polyvinyl butyral (PVB) plastic layer between them to prevent shattering in a crash. Glass fiber is produced by using a similar float process, except the molten glass is forced through small openings to form fibers, which can be wound onto spools or cut into desired lengths, depending on the thickness and intended use.

The major energy inputs for virgin glass production are NG and electricity at the glass plant (gas for melting and annealing, electricity for forming) and NG for raw material mining and processing. The total energy consumed in flat glass processing is approximately 14.8 million Btu/ton of final flat product and 14.0 million Btu/ton for fibers (based on Babcock et al. 1988). Automotive glass is not currently recycled, but it ends up in the auto shredder fluff fraction. This could change as technologies are developed to recover some of the materials in that stream. Clean material would be difficult to recover from composites.

Fugitive dust and raw material particles from raw material handling are controlled by moist handling or by fabric filters on enclosed transfer points. Emissions from melting and refining may include volatile organics, raw material particles, and combustion gases; these are controlled by fabric filters. Particulate emissions are common to all glass manufacture; boron and fluoride emissions may result from the special chemical composition of fiberglass.

5.3 PLASTICS

Plastics are made from petroleum derivatives or NG liquids via a series of chemical reactions that produce a building block or monomer, which is then reacted with itself or other monomers — often at elevated temperatures or pressures — to form a polymer or plastic. In a vehicle, different uses require different types of plastics. For example, many dismantling reports that address the recyclability of a vehicle contain breakdowns of nearly 30 thermoplastics and thermosets. Thermoplastics account for 70% of the plastics produced and are characterized as having high molecular weights resulting from a high degree of polymerization. The long molecular chain of thermoplastics has side chains that are not attached to other polymer molecules and therefore can be repeatedly softened by heating, which allows for recycling. However, there is often a degree of chemical change that takes place during the recycling process, so the recycled polymer may not be the same as the virgin polymer.

Thermosets differ from thermoplastics in that the chemical bonds between molecular chains, which are known as cross-linking, form an interconnected network of polymer chains. Thermosets have greater mechanical strength and stability, but they cannot be softened and recycled. Very little of the plastic recycled in the United States comes from vehicles, because the variety of plastics used and the number of small parts make the economics poor. However, numerous research projects are underway to improve the economics and technical feasibility of separating, recovering, and recycling automotive plastics (Jody 2006). One case in which recycled plastic from vehicles is used is in bumpers made for several vehicle models by Visteon that have a 15% recycled content (Vasilash undated).

For this analysis, we examined the energy use and emissions associated with three important automotive plastics: polypropylene (PP), polyester (polyethylene terephthalate [PET]), and high-density polyethylene (HDPE), which frequently account for about half of the plastics used in an automobile. We used the assumption that, of the total weight of plastics in a vehicle, 24% would be PP, 14% would be PET, and 10% would be HDPE (Argonne National Laboratory et al. 1998). Our cross check of vehicle dismantling reports confirmed that these shares are reasonable. We then used these three plastics percentages to calculate an average plastic energy intensity by weight-averaging their energy inputs and fuel shares. This average plastic energy intensity was applied to all thermoplastics and thermosets in each vehicle. The energy inputs and fuel shares for the production of these three plastics are described in the following sections.

5.3.1 Polypropylene

Polypropylene has good surface hardness; good chemical and heat resistance (up to 120°C); and high compression, flexural, and tensile strength. These properties are the reason why PP is used for many automobile parts, including battery trays, clips, covers, and cases; fender liners; fuel tank shields; engine splash shields; fan shrouds; and carpet. PP now represents the largest share of automotive plastics use. The energy required to produce PP is approximately 28.4 million Btu/ton, mostly in the form of oil and gas (Gaines and Shen 1980). Recycling simply requires remelting at low temperatures and consumes about one-fourth of the energy of virgin PP production. Cases for Pb-Ac automotive batteries are generally recycled back to the same use, while PP from other parts can be recycled to automotive parts, carpets, and industrial fibers.

Emissions from propylene polymerization are in the form of particulates (polymer resin) and gases (mostly the propylene monomer). Pollution control is via the systems used for recovery of reactants or products (EPA 1995). Emissions from the entire PP production chain occur at petroleum refineries, NG processing plants, and large chemical complexes. These facilities are located outside of major population centers and are concentrated on the Texas Gulf Coast, with a few scattered elsewhere in the United States.

5.3.2 Polyester

PET, a polymer resin of the polyester family, is a tough, clear, high-melting-point plastic with good barrier properties that is available in both thermoplastic and thermoset types. It is often the resin base for fiber-reinforced plastics (FRPs) used in automotive applications. PET is produced from para-xylene, a petroleum refinery product, and ethylene, a hydrocarbon made primarily from cracking of NG liquids. The total energy required to make PET is approximately 61.2 million Btu/ton; this estimate includes the energy needed to refine the hydrocarbon feedstocks, which accounts for 51% of the input energy (Gaines and Shen 1980). This value was derived from the Electric Vehicle Total Energy Cycle Assessment (EVTECA) report data (Argonne National Laboratory et al. 1998), plus assumed improvements in the process that would yield about a 20% reduction in energy intensity. Recycling PET by means of chemical methods consumes about one-third of the energy of virgin PET production (Chem Systems 1980); recycling by means of mechanical methods requires potentially less than that (Wang et al. 1997).

Emissions from PET manufacture are primarily VOCs and particulates, which are generally controlled in order to recover the valuable material constituents, primarily ethylene glycol and methanol. Emission factors reported by EPA range from 0.36–0.73 g of non-methane VOCs/kg of product if spray condensers are used to 3.6–3.9 g/kg of product if they are not. Particulate emission factors are reported as 0.0003–0.17 g/kg with controls on product storage and 0.4 g/kg without such controls (EPA 1995).

5.3.3 High-Density Polyethylene

Polyethylene is an inexpensive plastic that has good moisture barrier properties. Automotive uses include windshield washer fluid containers and other reservoirs and shields. Polyethylene is made from ethylene in a single-step polymerization process in which the pressure, catalyst, and other conditions determine the physical properties of the product. Production of virgin HDPE requires 33.0 million Btu of energy per ton of product, with over 80% of the input energy in the form of oil and gas (Gaines and Shen 1980). The energy needed to recycle HDPE is low (around one-fourth of that needed for virgin production) because the plastic can simply be cleaned, dried, ground, and remelted (Wang et al. 1997).

5.3.4 Fiber-Reinforced Plastics

Fiber-reinforced plastics are composite materials that are engineered by using two or more constituent materials that remain separate on a macroscopic level but form a single element. The two necessary constituent materials are a matrix and a reinforcement. The matrix is the material that surrounds and supports the reinforcement material, while the reinforcement's physical properties enhance the matrix properties (e.g., by improving strength, stiffness, or conductivity). The matrix material for FRPs is a plastic that is called a resin base and is often polyester or vinyl ester. The reinforcement material is most often a fiber but can also be pulverized minerals.

Carbon fiber-reinforced plastics (CFRPs) have been used in aerospace, bicycle, and other applications because of their high strength and light weight; however, the high cost of carbon fiber has limited its use in automotive applications. A few major automakers have begun to use CFRPs in publicly available models. BMW produces CFRPs in its plant in Landshut, Germany, and uses them in the roof, interior trim, and dashboard for its limited-edition 2003 M3 CSL sports car. BMW's newly released 2007 M6 is one of the first mass-produced vehicles with CRFP components, such as the bumpers and roof, which BMW says are 55% lighter than their conventional steel counterparts and allow the center of gravity to be lowered by nearly half an inch. Chevrolet's 2004 Corvette LeMans Commemorative Edition was the first attempt by a U.S. automaker to produce a CFRP exterior body panel; the hood weighed 50% less than a steel and 33% less than a comparable fiberglass hood. With the weight and performance benefits proved, the development of lower-cost carbon fiber for use in automotive applications has been a research focus.

Carbon fiber is made out of long, thin sheets of a type of carbon similar to graphite. The most common means of production is the oxidation and thermal pyrolysis of polyacrylonitrile (PAN). When PAN, a polymer, is heated, the molecular chains bond together — forming planar sheets of carbon atoms called grapheme, which merge to form a tubular filament or "fiber." The fibers are then enhanced to make high-strength carbon through heat treatment; for example, carbon heated in the range of 1,500–2,000°C possesses its highest tensile strength, while carbon heated in the range of 2,500–3,000°C possesses a high modulus of elasticity. Carbon fibers have a tensile strength of about 3–4 GPa, a modulus of elasticity of about 210–410 GPa, and a density of 1.8 g/cm^3 (O'Brien 2001). The high cost of carbon fiber is attributable primarily to the complexity of the production process, which requires careful heating to correctly orient the molecules to produce the fibers, and the subsequent heat treatment. In addition to its high cost, carbon fiber production is very energy intensive, requiring 160.2 million Btu of energy per ton of product (Argonne National Laboratory et al. 1998). For comparison, the production of manufactured graphite requires about 137.6 million Btu/ton, with most of the energy coming from electricity (Pehnt 2001).

As mentioned previously, glass fiber is produced by using a float process in which molten glass is forced through small openings to form fibers. Compared with carbon fiber production, the energy requirement for glass fiber production is significantly less: 14.0 million Btu/ton. However, both the tensile strength (1.7–2.7 Gpa) and elasticity modulus (69–72 Gpa) of glass fiber are also considerably less, and its density is considerable higher (2.6 g/cm^3) (O'Brien 2001).

The process for creating FRP varies, depending on product type and the amount required. If only a few parts a day are produced, vacuum forming can be used. A fiberglass or aluminum mold is coated with a release agent before the fiber and resin are applied, then the vacuum is pulled and set aside to allow the part to cure. The two methods of application are wet layup and resin induction system, both of which require hand work to spread the resin evenly for a clean finish. Another method of FRP production is dry layup, which involves application of the reinforcement material, already impregnated with resin (pre-preg), to the mold in a similar fashion to adhesive film, and placement of the filled mold in a vacuum to cure. This method produces less resin waste and potentially lighter components than wet layup. For mass-produced vehicle components, a process called compression molding is used to manufacture FRP faster. In this process, a two-piece mold (usually made of fiberglass or aluminum) is bolted together with the fiber and resin between each piece. The advantage of this method is that it is relatively clean, and the mold can be stored without a vacuum until after curing.

The energy use and fuel shares associated with various plastic production processes are listed in Table 23. Table 24 lists tons of intermediate material per ton of final FRP product.

TABLE 23 Energy Use and Fuel Shares for Plastic Manufacture

Process	PP Production	PET Production	HDPE Production	Inert Filler Production	Carbon Fiber Production	Reinforced Plastic Fabrication
Energy use (mmBtu/ton of material product)	28.400	61.161	33.000	0.641	160.2	7.886
Fuel share (%)						
Residual oil	37	75	40	85	50	44
NG	37	18	40		50	39
Electricity	26	7	20	15		17

5.4 RUBBER

Styrene-butadiene rubber (SBR), made from 75% butadiene and 25% styrene (by weight), is used for production of tires and other auto parts, such as gaskets and fan belts. SBR is produced from a cold emulsion process in which the butadiene, styrene, soap, water, a potassium persulfate catalyst, and a mercaptan regulator are heated in large jacketed reactors to about 50°C. The contents are stirred numerous times, leading to formation of SBR by means of a polymerization process. What results from this reactor is a latex that contains the rubber; the rubber is separated by treating the latex with a solution of aluminum sulfate or an acidic sodium chloride solution that causes the rubber to come out in the form of a fine crumb. The crumb is washed, dried in an oven, and then pressed into bales. The energy requirement for this production process, almost all of it from oil and gas, totals 34 million Btu/ton (based on Argonne National Laboratory et al. 1998). Several processes are available for recycling discarded tires, but tire manufacturers are very reluctant to risk potential decreases in product quality; therefore, the incorporation of rubber into paving asphalt offers the greatest potential for energy recovery.

TABLE 24 Tons of Intermediate Material Needed per Ton of Final Fiber-Reinforced Plastic Product

Carbon fiber-reinforced plastic	1.14
Glass fiber-reinforced plastic	1.14

5.5 FLUIDS

Various types of fluids are used in vehicles. Table 16 presents per-vehicle weight by fluid type. Note that in the GREET 2.7 model, we do not calculate fuel weight; all fuel-cycle calculations take place in GREET 1.7. We estimate energy and emissions for petroleum products, engine oil, power steering fluid, brake fluid, and transmission fluid by using those already in GREET 1.7 for gasoline manufacture.

Powertrain coolant or antifreeze is assumed to be a 50%/50% mix of ethylene glycol and water, while windshield wiper fluid is assumed to be a 50%/50% mix of methanol and water. The energy use required and the emissions generated from the production of these two fluids are calculated by using the values for ethylene glycol and methanol already in GREET 1.7. The energy use and emissions for windshield wiper fluid are calculated by using the methanol value in GREET 1.7. In addition, because windshield wiper fluid is dispersed, the methanol it contains is added to the VOC emissions.

5.6 BATTERY MATERIALS

Our analysis includes three battery types — Pb-Ac, Ni-MH, and Li-ion — each of which is discussed in the following sections.

5.6.1 Lead

Lead is extracted from several minerals, but the main ore is lead sulfite (PbS). In 2004, almost 95% of lead mining took place in Alaska and Missouri, and all the lead concentrates produced from that ore were processed at a smelter-refinery in Missouri (Gabby 2005). Froth flotation is used to separate the lead and other minerals from the waste rock to form a concentrate, which contains between 50% and 60% lead. The concentrate is then sintered before being smelted to produce a 97% lead concentrate, which is then refined by additional smelting to remove further impurities, which produces 99.99% pure lead. The energy required to produce primary lead was estimated to be roughly 21.1 million Btu/ton, with mining contributing 2.6 million Btu/ton (Hudson 1981). The primary effluent from smelting is SO_2, which is recovered and converted to sulfuric acid. Solid wastes generated from mining operations remain in the somewhat remote mining locations, and slag produced during smelting can be disposed of because it is a relatively inert solid.

Secondary lead production accounted for 88% of the lead domestically produced, with Pb-Ac batteries accounting for 92% of the lead produced from scrap sources (Gabby 2005). Secondary smelting and battery recycling are more geographically spread out than mining operations and may occur near population centers. Hudson estimated that secondary lead production required 9.5 million Btu of energy for each ton of lead produced, compared to a more recent estimate of 4.1 million Btu/ton for the smelting step alone at a modern smelter (Hudson 1981; Leiby 1993). Primary production energy also has also likely been reduced. Lead oxides and other compounds are released as particulates during both primary and secondary smelting operations and during battery manufacture and recycling. U.S. regulations have generally resulted in a significant reduction of these emissions to the environment; these are usually controlled by means of a baghouse, with control efficiencies exceeding 99% (Argonne National Laboratory et al. 1998).

5.6.2 Nickel

Production of primary nickel ore is found in countries outside of the United States, such as Canada, Wales, Australia, and Russia. Most of the nickel used for batteries comes from Canada and Wales (Gaines et al. 2002). However, byproduct nickel is recovered at some copper and precious metal refineries in the United States (Kuck 2005). Froth flotation is used to separate the nickel-bearing minerals from the waste rock to form a 12% concentrate. The concentrate is then smelted to produce a 70% nickel metal stage called matte, which can be easily transported over long distances. Various processes are used to further refine the granulated matte. Fluid bed roasting with chlorine-hydrogen reduction produces high-grade nickel oxides that contain greater than 95% nickel.

The positive electrode of a Ni-MH battery uses thin plates of nickel foam with nickel hydroxide [$Ni(OH)_2$] on the surface. Vapor processes, such as the carbonyl process, produce a highly pure powder, which contains greater than 99% nickel (Wang et al. 1997). During this process, CO is reacted with nickel at 50°C to form nickel carbonyl [$Ni(CO)_4$], leaving behind cobalt, copper, and iron impurities. Next, the nickel carbonyl is decomposed to nickel through moderate heating at 230°C. Nickel carbonyl is highly toxic and may be fatal if absorbed through the skin or inhaled, so its production requires careful process controls to limit health hazards. Nickel recovered from Ni-MH batteries at the end of their life could likely be recycled to battery-grade material by using this same process (Argonne National Laboratory et al. 1998).

Another common refinement technique is electrowinning, also known as electrorefining. In this process, the matte is first dissolved in a solution, commonly of sulfuric acid. The solution is electrolyzed, which results in the nickel being deposited on the cathode and oxygen produced at the anode. The oxygen forms bubbles at the anode and, when they reach the surface, they can form an aerosol of sulfuric acid, which requires controls to reduce environmental and health effects. The production energy required to make virgin nickel from sulfide ores by using the electrowinning process was estimated to be about 64 million Btu/ton (Gaines et al. 2002). At this time, data on the energy required for the carbonyl process are unavailable.

5.6.3 Metal Hydride Electrode

The negative electrode of a Ni-MH battery is made from one of several specially engineered metal hydrides that are intermetallic compounds made from rare earths or vanadium, nickel, titanium, zirconium, chromium, and manganese (Wang et al. 1997). Many different compounds have been developed for this application, but those in use today fall into two types. The most common is the so-called AB_5 type; A refers to a rare-earth Misch metal that contains a naturally occurring mixture of lanthanides (the elements from atomic number 57 to 71), and B is nickel, cobalt, manganese, or aluminum. There is a lack of significant published data on the energy use and emissions associated with Misch metal production, but Ishihara et al. estimated that the energy required for rare earth mining is 4.3 million Btu/ton; production requires 108 million Btu/ton (Ishihara et al. 1999). However, some researchers have called into question these values (Gaines et al. 2002).

The other metal hydride is the so-called AB_2 type; A refers to titanium or vanadium, and B is normally zirconium or nickel modified with chromium, cobalt, iron, or manganese. The negative electrode powder from scrap AB_2 consumer cells was typically found to contain 33% rare earths, 60% transition metals, and 7% other metals (Mn, Al) by weight (Lyman and Palmer 1994). The flat plate hydride electrode of the AB_2 battery uses an alloy produced by vacuum induction melting, which is relatively energy intensive because of the high temperatures required to melt vanadium and zirconium. The material is very hard and is only partially broken before hydriding. After the hydride is produced, the material can be ground more easily to a powder for pressing onto the electrode. Zirconium mining was estimated to require energy use of approximately 34 million Btu/ton and zirconium production about 100 million Btu/ton (Argonne National Laboratory et al. 1998). These values are quite high and, if contrary data become available, they should be replaced. No energy or emissions estimates are available for these other processes.

5.7 FUEL CELL MATERIALS

In this analysis, we examined the use of a direct-hydrogen polymer electrolyte membrane (PEM) fuel cell system for use in the fuel cell vehicle. As described on the Hydrogen, Fuel Cells & Infrastructure Technologies Program web page, there are three key elements to a PEM fuel cell: the membrane electrode assembly (MEA), hardware, and catalyst (DOE 2006). However, there are other components that are designed to draw hydrogen, air, heat, and water through the fuel cell — such as the compressed hydrogen tank system, air supply system, cooling system, and water supply system. These parts are classified as the Fuel Cell Accessory System in GREET 2.7. The compressed hydrogen tank system contains a tank with carbon fiber winding and an aluminum liner and accessories such as piping, regulator, fill port, and valves. The air supply system, cooling system, and water supply system consist of components such as piping, valves, and pumps (TIAX 2003).

5.7.1 Membrane Materials

The MEA consists of an anode, a cathode, a catalyst, platinum group metal (PGM) catalysts, and a perfluorinated PEM. The anode has channels etched into it to disperse hydrogen equally over the surface of the catalyst, while the cathode contains channels to distribute oxygen to the surface of the catalyst. The PEM can be made of a perfluorosulfonic acid (PFSA) polymer, typically Nafion® (which is trademarked by DuPont), because of its ability to permit hydrogen ion transport while preventing electron conduction. The reported energy required for production of the Nafion® PFSA sheet is 12.3 million Btu/ton, while the Nafion® dry polymer, which is carbon and PFSA in suspension, requires 12.0 million Btu/ton (Karakoussis et al. 2000).

Some researchers are skeptical of these values for Nafion®, maintaining that this membrane's production is a much more energy-intensive process than previously reported (Gaines 2006; Papasavva 2006). Unfortunately, publicly available data are lacking; these figures should be updated if contrary data become available. Moreover, some companies are researching hydrocarbon membranes, which may have a very significant impact on reducing process steps, energy use, and emissions (Hart 2006). PolyFuel is developing a hydrocarbon membrane for use in automotive applications, with the potential to provide lower costs, greater durability, and better performance. In addition, these membranes do not contain fluorine, which will make them easier to manufacture and recycle (Peck 2006).

5.7.2 Hardware Materials

The fuel cell hardware consists of backing layers, flow fields, and current collectors that are designed to maximize the current from an MEA. The backing layers are placed next to both the anode and cathode and are typically made of a porous carbon paper or carbon cloth so that they can conduct the electrons that leave the anode and enter the cathode. The energy required to produce carbon paper was calculated by using values from Karakoussis et al. (2000), which estimated that carbon paper production was 3.5 times as energy intensive as carbon fiber production. By using the Argonne value of 160.2 million Btu/ton for carbon fiber, the resulting energy use value is 560.7 million Btu/ton. This value is extremely high and, if any contrary data become publicly available, it should be replaced. The correct backing material allows the right amount of water vapor to reach the MEA and keep the PEM humidified. The backing layers are often coated with polytetrafluoroethylene (PTFE) better known as Teflon® (which is trademarked by DuPont) to ensure that most of the pores in the carbon paper do not become clogged with water, which would slow the rate of reaction at the electrodes. The energy required for PTFE production is 81.7 million Btu/ton (Karakoussis et al. 2000).

Bipolar plates that serve as both a flow field and current collector are pressed against the outer surface of each backing layer. The plates should be made of a lightweight, strong, gas-impermeable, electron-conducting material; graphite and aluminum can be used, but composite plates can offer significant weight reductions and therefore are used in this study. However, some companies are trying to use very thinly stamped stainless steel (Hart 2006), which, if successful, would reduce the production energy needed for these plates. The plates provide a gas flow field by means of channels etched into the side that is adjacent to the backing layer. The channels carry the reactant gas from the place where it enters the fuel cell to the place where it exits. In addition, each plate acts as a current collector in the electrochemical processes that take place in the fuel cell stack.

5.7.3 Catalyst: Platinum Group Metals

In a fuel cell, an oxidation half reaction takes place at the anode, while a reduction half reaction takes place at the cathode. However, a catalyst is needed so that the fuel cell can run at a low operating temperature. Therefore, both the anode and cathode are coated on one side with a catalyst layer that is usually made up of a platinum powder thinly coated onto carbon paper or cloth. Platinum-group metals are critical to these reactions but are extremely expensive. With the 2005 average platinum London fixed price at nearly $32/g, there has been a concerted effort by DOE to reduce the loading of these platinum group metals in order to reduce the cost of fuel cell stacks (London Platinum and Palladium Market 2006). In addition, catalytic converters in ICEVs use 1 to 3 g of PGMs to reduce the exhaust emissions of VOCs, CO, and NO_x, but when recycled, more than 95% of the PGMs in catalytic converters can be collected for secondary refining (USGS 2004). With FCVs requiring between 0.4 and 4.2 g of PGMs per kW, it is quite important to develop cost-effective methods of PGM recovery from the fuel cell stack (Cooper 2004). In 2004, the production of PGMs from catalytic converters was about 13,600 kg (George 2005). The recovery and recycling of PGMs from automotive catalysts has increased significantly in Western Europe because of high prices and legislation to increase the recycling of materials in vehicles. The European Union End-of-Life Vehicles Directive aims to increase reuse and recovery of vehicle materials to at least 85% by 2006 and 95% by 2015. Specific data were not available to calculate the energy use required for secondary production; therefore, we assumed that all PGMs are virgin PGMs. However, Pehnt states that the recycling of automotive catalysts can reduce the primary energy demand by a factor of 20 (Pehnt 2001).

We collected energy use data from PGM mining companies in North America (NA) and South Africa (SA) for their mining, smelting, refining, and other support processes. The North American mining company data detail the production of a 50% platinum concentrate. This concentrate is shipped and then further processed to produce the PGM; we do not have data on this further processing. The analysis of the North American PGMs requires allocation of energy use and emissions of mining operations among different mined products because, according to the North American data, for every 1 kg of PGMs mined, there is a yield of 0.02 kg of gold, 29 kg of copper, and 43 kg of nickel (Cluett 2005). In South Africa, for every 1 kg of platinum mined, there is a yield of 0.5 kg of palladium, 0.1 kg of rhodium, 300 kg of nickel, and 200 kg of copper (Pehnt 2001). Recovering and processing these other products contribute to the total mining energy use and emissions, so two methods — market value and weight — were examined for allocation.

Little has been published on PGM energy and emissions allocation, but a few analyses have favored the market value method (Pehnt 2001; Karakoussis et al. 2000; Oko Institute 1997). This approach involves multiplying the market value of each of the products by the amount produced to generate total monetary revenue for each product. The revenue shares by product are then used to allocate the total energy use and emissions associated with mining and processing operations. The weight-based approach uses the ratio of each product's weight to the total weight of all products to calculate the allocation percentages. Although the weight-based allocation method reflects mining operations in practice, it has been argued that the method does not reflect the motivation of the mining operation.

The two methods have dramatically different results. The market-based approach results in the allocation of total energy and emission burdens of 93% to PGMs, 2% to gold, 1% to copper, and 4% to nickel and cobalt. The weight-based approach, on the other hand, results in allocations of 1.4% to PGMs, 0.03% to gold, 39.5% to copper, and 59.0% to nickel and cobalt. In our analysis, we examine both methods to determine their effects on energy use and emissions calculations for FCVs. The energy use for mining and production of PGMs using the North

American mining energy intensity with the market value-based allocation method resulted in a value of 56,879 million Btu/ton produced, while the weight-based allocation method resulted in a value of 11.7 million Btu/ton.

An English study using the Tool for Environmental Analysis and Management (TEAM) software (developed by Ecobilan) estimates that platinum production requires 196,897 MJ/kg or 169,301 million Btu/ton (Karakoussis et al. 2000). A German study estimates that the mining and processing of 1 g of platinum requires 23.76 KWh of electricity (or 73,550 million Btu/ton) and 10.45 MJ of NG (or 8,985 million Btu/ton) — for a total energy use value of about 82,535 million Btu/ton (Oko Institute 1997). In 2005, Lonmin Plc produced about 1.7 million ounces or 53 tons of PGMs from its South African operations, with a total energy use for their mining, smelting, and refining operations of 5,813 TJ or 5,510,000 million Btu (Lonmin plc 2005). The energy shares from these operations are 87% electricity, 6% coal, 5% fuels (primarily diesel), 1% industrial burning oil, and 1% NG. Lonmin estimates the 2005 energy efficiency at 3.46 GJ/ounce or 105,000 million Btu/ton of PGMs. The previous results all seem to apply all the energy use of mining and processing to PGMs and disregard any byproduct metals.

The only estimates that seemed to fit with a weight-based allocation method were the electricity consumption efficiency rates estimated by Lonmin for 2000 through 2002, with an average value of 21.69 KWh/kg or 67.1 million Btu/ton of noble metal (Lonmin 2002). Electricity accounted for about 85% of the total energy use, with fossil fuels accounting for the rest. Therefore, fossil fuels accounted for about 10.1 million Btu/ton of noble metal. These values for noble metals likely include gold in addition to PGMs; however, by weight, gold accounts for a very small portion of the metal produced. In 2002, Lonmin estimates that, of its total production of PGMs and gold, platinum accounted for 52%, palladium for 24%, ruthenium for 13%, rhodium for 8%, iridium for 2%, and gold for 1%; the reports do not provide details about any other metal production.

The energy use estimate for the market-value-based case is two orders of magnitude larger than the energy use estimates for any other material for which we have collected data; therefore, we use 77.2 million Btu/ton, derived from the South African electricity consumption efficiency rates, as our default value in GREET 2.7. Alternatively, we allow the user to select either the North American market or weight-based cases. While the co-production of metals such as copper and nickel makes the energy calculations difficult, they do fit well with the potential growth of FCVs, because the demand for these materials would likely increase as the demand for FCVs increases. Nickel could be used in Ni-MH batteries, while copper could be used in the various additional components needed for electric-drive technology. Nevertheless, an economic analysis should be conducted to determine how the price and demand of the co-products would be affected with the growth in PGM mining.

The effect of the production country, in terms of mining and production energy intensity, is another important issue. In South Africa, nearly all the electricity comes from coal and, because PGM production is very electricity-intensive, the emissions from production in South Africa are quite different from those in North America (Energy Information Administration [EIA] 2005). PGM loading was another issue we examined; for our base case, we chose to use DOE's 2004 estimate of current PGM loadings, 1.3 g/kW, for a direct-hydrogen PEM fuel cell stack (Kumar 2005). Using this range of values, we found that market-value-based allocation would need to be used for PGM loading to have a significant effect on energy use and emissions.

5.8 OTHER MATERIALS

A few materials — including cobalt, manganese, and lithium oxide — were not characterized in this analysis because of a lack of data. In each case, a placeholder value was used to approximate the energy use and emissions until better data are obtained. For both cobalt and lithium oxide, we use nickel data as a placeholder, while for manganese, we use zinc data.

6 VEHICLE ASSEMBLY, DISPOSAL, AND RECYCLING

The energy use and emissions associated with vehicle assembly were calculated by using data from research on the energy efficiency of assembly plants and life-cycle analyses of paint manufacturing and the painting process. Data from a survey of automotive assembly plants conducted by Argonne (those that included body welding, assembling, and painting) were used to estimate how the energy efficiency of these plants varied across the industry (Boyd 2005). We chose to use the mean energy use per vehicle assembled, which was calculated from a modeling effort of the survey results. We estimated that the energy required to assemble a mid-size passenger car is about 3.9 million Btu/vehicle. In addition, we collected life-cycle energy use and emissions data from research on paint production and vehicle painting (Papasavva et al. 2001; Papasavva et al. 2002). We calibrated the data in the reports regarding SUV painting operations to fit our mid-sized passenger car. We found that the painting process accounts for the vast majority of the process emissions from a vehicle assembly plant. Specifically, the energy use from the painting process accounts for about 20% of the plant's total energy use; VOC emissions from this process are also quite significant and, consequently, are a research focus. On the basis of these data, we calculated that the energy required to produce the paint is 0.23 million Btu/vehicle, and the energy required to actually paint the vehicle is 0.96 million Btu/vehicle.

Battery assembly and testing were examined because of the complexities of battery manufacturing. Information about the energy required for Pb-Ac battery assembly and testing was not found; however, we used as a starting point the ratio of battery production energy of Pb-Ac to Li-ion, 80%, from a Japanese report (Ishihara et al. 1999). We assumed that the energy requirement for assembly of Pb-Ac batteries would be 80% of the average of the energy required for assembly of Ni-MH (60 Wh/kg) and Li-ion (109 Wh/kg) batteries (Duvall 2005; Bohn 2005). Thus, the energy required for assembly of a Li-ion battery was estimated to be about 30.7 million Btu/ton of battery material, all from electricity (Ishihara et al. 1999). However, by using data from the same report, we estimated the energy required for assembly of a Ni-MH battery to be about 2.25 million Btu/ton of battery material, all from electricity (Ishihara et al. 1999). The order-of-magnitude difference between the batteries seems too large and is possibly an error. Thus, we did not use the energy intensity data for Ni-MH batteries.

We collected data from another source and calculated the energy required for assembly and testing of an Ni-MH battery to be approximately 35.2 million Btu/ton of battery material; the data revealed that battery testing requires significant amounts of electricity (Gaines 2006). The large discrepancy between the values for Ni-MH batteries is troubling, and even the other values have been questioned because the energy required for vehicle assembly is much lower. We decided to use the Li-ion value from Ishihara et al. (1999) and the Ni-MH value from Gaines (2006) as default values for GREET 2.7, but we hope to find publicly available data that could replace these sources. By using our default values, the resulting energy requirement for Pb-Ac assembly is 27.5 million Btu/ton of battery material.

While Pb-Ac vehicle batteries have been manufactured in mass quantities for decades, only recently have Ni-MH vehicle batteries been widely produced. In 2005, news reports revealed that the Ni-MH battery supplier, Sanyo, was not able to keep up with the demand and would need to either expand its plant or build another one. Li-ion vehicle batteries are not currently mass produced; manufacturers will likely face similar requirements to quickly expand their facilities to keep up with ever-increasing demand. Although as manufacturing moves away from handmade laboratory prototypes to full-scale automated production, the energy use required to build these batteries will decrease as the economies of scale increase.

The energy required for dismantling vehicles for disposal or recycling was estimated to be approximately 1.4 million Btu/vehicle for a vehicle weighing 3,000 lb (Stodolsky et al. 1995). This value does not include material recovery processes or combustion for energy recovery. The energy use of materials that are recycled and later used in a vehicle is taken into account in GREET 2.7 for each specific material.

7 GREET 2.7 MODEL STRUCTURE

The following sections briefly introduce the 35 individual working sheets in GREET 2.7.

7.1 OVERVIEW SHEET

This sheet contains the GREET copyright statement and a brief summary of the functions of each worksheet in GREET. We highly recommend that first-time GREET users read the Overview sheet before proceeding with any GREET calculations.

7.2 VEHI_INPUTS SHEET

This sheet is separated into eight sections:

1. Specification of total vehicle weight
2. Vehicle battery and fluids weight
3. Key input parameters for vehicle components: body, powertrain, transmission, chassis, traction motor, generator, electronic controller, and fuel cell auxiliary system
4. Key input parameters for batteries
5. Key input parameters for fluids
6. GREET default key assumptions for vehicle and vehicle component production
7. Lifetime vehicle miles traveled (VMT) of a vehicle
8. Ratios of fuel economy of lightweight-material vehicles relative to their conventional-material counterparts

This sheet presents key variables for vehicle-cycle scenarios and specifies key parametric assumptions for a vehicle and its components for use in GREET simulations. In this sheet, the user can specify the total weight of each vehicle to be simulated; input the weight of the Pb-Ac battery (the weights of the Ni-MH and Li-ion battery are calculated according to the power specified in Section 4 of this sheet); and enter the weight of each fluid for the vehicles.

In Section 3, the weight of the vehicle components (excluding the battery, fluids, and fuel) is listed for each vehicle, and the weight of each component is calculated by choosing a percentage of the total weight. The exceptions are for the powertrain and fuel cell auxiliary systems of the FCVs, which are specified by choosing a fuel cell stack size, and using embedded formulas to automatically calculate the component percentage. In addition, the body component is automatically calculated by subtracting the rest of the components from 100% in order to make sure all the weight is allocated.

In Section 4, either an Ni-MH or Li-ion battery for the HEV and FCV can be chosen for simulation, with an option to change battery power requirements and the specific power density assumption, which will affect battery weight. Next, various assumptions for fluids, battery and vehicle assembly, and vehicle lifetime are listed. Vehicle lifetime is in miles, not years, which allows GREET 2.7 vehicle-cycle results to be used with the per-mile fuel-cycle and vehicle-operation results in GREET 1.7. Finally, formulas for calculating the fuel economy of the lightweight vehicles show the relative change, compared with their conventional-material counterparts.

As explained in the Overview sheet, the cells that are colored yellow are input cells and represent the key options and parameters for simulating different vehicle cycles in GREET. Users can edit the yellow cells to change the default simulation options or assumptions in these cells. The cells without background color primarily contain formulas that are linked to other cells in the GREET model and can contain secondary assumptions.

Users are cautioned against making any changes to cells without background colors; such changes can result in broken formula links and failed GREET simulations.

7.3 MAT_INPUTS SHEET

This sheet is separated into five sections:

1. Material composition for vehicle components
2. Battery material composition
3. Share of key material composition in specific fluids
4. Key input parameters for material use
5. GREET default key assumptions for material production

This sheet presents key variables for vehicle-cycle scenarios and specifies key parametric assumptions for vehicle materials used for GREET simulations. In this sheet, the user can specify the material composition of each vehicle component: body, powertrain, transmission, chassis, traction motor, generator, electronic controller, and fuel cell auxiliaries; users can also input each battery's material composition.

In Section 4, users can specify the share of virgin and recycled steel, wrought aluminum, cast aluminum, lead, and nickel used in the vehicles. Next, they can enter the tons of intermediate material needed per ton of final product for steel, wrought aluminum, cast aluminum, nickel hydroxide, and fiber-reinforced plastics; these values are linked to each material's individual page. In order to estimate platinum's energy use and emissions, the user should select either the North American mine weight-based, the South African mine, or the North American mine market-based calculation method.

In Section 5, the user can specify the input energy use for each material included in GREET 2.7. This value is linked to each material's individual page.

7.4 STEEL SHEET

This worksheet consists of the following four sections:

1. **Key input parameters.** The values in this section derive from the Mat_Inputs sheet. Thus, this section is the interactive link between the Mat_Inputs sheet and this sheet.
2. **Shares of combustion processes for each stage.** These are used for emissions calculations.
3. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
4. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of virgin, recycled, and stainless steel. The tons of intermediate material needed per ton of final steel product and the energy inputs for each step are defined in the Mat_Inputs sheet and should not be changed in this sheet. However, the user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.5 C.IRON SHEET

This worksheet consists of the following three sections:

1. **Shares of combustion processes for each stage.** These are used for emissions calculations.
2. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
3. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of cast iron. The user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.6 W.AL SHEET

This worksheet consists of the following four sections:

1. **Key input parameters.** The values in this section derive from the Mat_Inputs sheet. Thus, this section is the interactive link between the Mat_Inputs sheet and this sheet.
2. **Shares of combustion processes for each stage.** These are used for emissions calculations.
3. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
4. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of virgin and wrought aluminum. The tons of intermediate material needed per ton of final wrought aluminum product and the energy inputs for each step are defined in the Mat_Inputs sheet and should not be changed in this sheet. However, the user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emission calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.7 C.AL SHEET

This worksheet consists of the following four sections:

1. **Key input parameters.** The values in this section derive from the Mat_Inputs sheet. Thus, this section is the interactive link between the Mat_Inputs sheet and this sheet.
2. **Shares of combustion processes for each stage.** These are used for emissions calculations.
3. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
4. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of virgin and recycled cast aluminum. The tons of intermediate material needed per ton of final cast aluminum product and the energy inputs for each step are defined in the Mat_Inputs sheet and should not be changed in this sheet. However, the user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.8 LEAD SHEET

This worksheet consists of the following three sections:

1. **Shares of combustion processes for each stage**. These are used for emissions calculations.
2. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
3. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of virgin and recycled lead. The user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.9 NICKEL SHEET

This worksheet consists of the following four sections:

1. **Key input parameters.** The values in this section derive from the Mat_Inputs sheet. Thus, this section is the interactive link between the Mat_Inputs sheet and this sheet.
2. **Shares of combustion processes for each stage.** These are used for emission calculations.
3. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
4. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of virgin and recycled nickel and virgin and recycled nickel hydroxide. The tons of intermediate material needed per ton of final nickel hydroxide product and the energy inputs for each step are defined in the Mat_Inputs sheet and should not be changed in this sheet. However, the user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.10 KOH SHEET

This worksheet consists of the following three sections:

1. **Shares of combustion processes for each stage**. These are used for emissions calculations.
2. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
3. **Summary of energy consumption and emissions**. Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of potassium hydroxide (KOH). The user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.11 COBALT SHEET

This worksheet consists of the following three sections:

1. **Shares of combustion processes for each stage.** These are used for emissions calculations.
2. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
3. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of virgin and recycled cobalt oxide. The user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.12 COPPER SHEET

This worksheet consists of the following three sections:

1. **Shares of combustion processes for each stage**. These are used for emissions calculations.
2. **Calculation of energy consumption and emissions for individual stages**. In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
3. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of virgin copper. The user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.13 ZINC SHEET

This worksheet consists of the following three sections:

1. **Shares of combustion processes for each stage.** These are used for emissions calculations.
2. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
3. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of virgin zinc. The user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.14 MAGNESIUM SHEET

This worksheet consists of the following three sections:

1. **Shares of combustion processes for each stage.** These are used for emissions calculations.

2. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
3. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of virgin magnesium. The user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.15 S.ACID SHEET

This worksheet consists of the following three sections:

1. **Shares of combustion processes for each stage.** These are used for emissions calculations.
2. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
3. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of sulfuric acid. The user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.16 GLASS SHEET

This worksheet consists of the following four sections:

1. **Key input parameters.** The values in this section derive from the Mat_Inputs sheet. Thus, this section is the interactive link between the Mat_Inputs sheet and this sheet.
2. **Shares of combustion processes for each stage.** These are used for emissions calculations.
3. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for

each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
4. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of glass and fiberglass. The composition of the fiberglass and the energy inputs for each step are defined in the Mat_Inputs sheet and should not be changed in this sheet. However, the user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.17 PLASTIC SHEET

This worksheet consists of the following four sections:

1. **Key input parameters.** The values in this section derive from the Mat_Inputs sheet. Thus, this section is the interactive link between the Mat_Inputs sheet and this sheet.
2. **Shares of combustion processes for each stage.** These are used for emissions calculations.
3. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
4. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of polypropylene, polyester, high-density polyethylene, inert filler, carbon fiber, carbon fiber-reinforced plastic and glass fiber-reinforced plastic. The share of PP, PET, and HDPE for average plastic calculation, the composition of GFRP and CFRP, the tons of intermediate material needed per ton of final fiber-reinforced plastic product, and the energy inputs for each step are defined in the Mat_Inputs sheet and should not be changed in this sheet. However, the user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.18 RUBBER SHEET

This worksheet consists of the following three sections:

1. **Shares of combustion processes for each stage.** These are used for emissions calculations.

2. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
3. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of rubber. The user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.19 PLATINUM SHEET

This worksheet consists of the following four sections:

1. **Key input parameters.** The values in this section derive from the Mat_Inputs sheet. Thus, this section is the interactive link between the Mat_Inputs sheet and this sheet.
2. **Shares of combustion processes for each stage.** These are used for emissions calculations.
3. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
4. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of platinum. The method for estimating energy use for platinum production and the energy inputs for each step are defined in the Mat_Inputs sheet and should not be changed in this sheet. However, the user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.20 VANADIUM SHEET

This worksheet consists of the following three sections:

1. **Shares of combustion processes for each stage.** These are used for emissions calculations.
2. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for

each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.

3. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of virgin and recycled vanadium. The user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.21 ZIRCONIUM SHEET

This worksheet consists of the following three sections:

1. **Shares of combustion processes for each stage.** These are used for emissions calculations.
2. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
3. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of virgin and recycled zirconium. The user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.22 TITANIUM SHEET

This worksheet consists of the following three sections:

1. **Shares of combustion processes for each stage.** These are used for emissions calculations.
2. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
3. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of virgin and recycled titanium. The user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.23 CHROMIUM SHEET

This worksheet consists of the following three sections:

1. **Shares of combustion processes for each stage.** These are used for emissions calculations.
2. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
3. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of virgin and recycled chromium. The user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.24 RARE EARTH SHEET

This worksheet consists of the following three sections:

1. **Shares of combustion processes for each stage.** These are used for emissions calculations.
2. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
3. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of virgin and recycled rare earth metals. The user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.25 MANGANESE SHEET

This worksheet consists of the following three sections:

1. **Shares of combustion processes for each stage.** These are used for emissions calculations.
2. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
3. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of manganese. The user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.26 FC MATERIALS SHEET

This worksheet consists of the following three sections:

1. **Shares of combustion processes for each stage,** which are used for emissions calculations.
2. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
3. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of Nafion$^{©}$ 117 sheet, Nafion$^{©}$ dry polymer, and polytetrafluoroethylene. The user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.27 MAT_SUM SHEET

This worksheet consists of the following two sections:

1. **Key input parameters.** The values in this section derive from the Mat_Inputs sheet. Thus, this section is the interactive link between the Mat_Inputs sheet and this sheet.
2. **Summary of energy consumption and emissions of material products.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents a summary of all energy use and emissions calculations for each material in GREET 2.7. The shares of virgin and recycled steel, wrought aluminum, cast aluminum, lead, and nickel used in the vehicles are defined in the Mat_Inputs sheet and should not be changed in this sheet.

7.28 VEHI_FLUIDS SHEET

This worksheet consists of the following five sections:

1. **Key input parameters.** The values in this section derive from both the Veh_Inputs and Mat_Inputs sheets. Thus, this section is the interactive link between the Veh_Inputs/Mat_Inputs sheets and this sheet.
2. **Shares of combustion processes for each stage.** These are used for emissions calculations.
3. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
4. **Summary of energy consumption and emissions.** Section 5 uses the key input parameters, along with the summary results for the per-vehicle lifetime calculations.
5. **Per-vehicle lifetime energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the production of engine oil, power steering fluid, brake fluid, transmission fluid, powertrain coolant, windshield fluid, and adhesives. The weight of each fluid per vehicle and the number of replacements per lifetime are defined in the Veh_Inputs sheet, while the ratio of waste to product and fluid shares are defined in the Mat_Inputs sheet and should not be changed in this sheet. However, the user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.29 BATTERY ASSEMBLY SHEET

This worksheet consists of the following three sections:

1. **Shares of combustion processes for each stage.** These are used for emissions calculations.
2. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
3. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in the assembly of a Pb-Ac battery, Ni-MH battery, and Li-ion battery. The user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.30 VEHI_ADR SHEET

This worksheet consists of the following three sections:

1. **Shares of combustion processes for each stage.** These are used for emissions calculations.
2. **Calculation of energy consumption and emissions for individual stages.** In this section, GREET executes calculations of energy use and emissions for each individual stage by considering energy efficiency, fuel use by type, fuel use by combustion technology, etc.
3. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for each step in vehicle assembly, disposal, and recycling. The user can adjust the combustion share if a residual oil boiler, NG boiler, or coal boiler is used; this will alter the GREET 1.7 emission factors used in the emissions calculations. In addition, the user can enter different values for the shares of process fuels used in each step.

7.31 BATTERY_SUM SHEET

This worksheet consists of the following three sections:

1. **Key input parameters.** The values in this section derive from both the Veh_Inputs and Mat_Inputs sheets. Thus, this section is the interactive link between the Veh_Inputs/Mat_Inputs sheets and this sheet.
2. **Calculation of energy consumption and emissions for each battery type.** In this section, GREET executes calculations of energy use and emissions for each battery by determining its material composition and using each material's values in the Mat_Sum sheet. Thus, this section is the interactive link between the Mat_Sum sheet and this sheet.
3. **Summary of energy consumption and emissions.** Other GREET sheets use the summary results from this sheet for individual vehicle-cycle calculations.

This sheet presents energy use and emissions calculations for the production of a Pb-Ac battery, Ni-MH battery, and Li-ion battery. The type of battery selected for HEV and FCV simulation, peak battery output, number of battery replacements, battery specific power, and weight of each battery are defined in the Veh_Inputs sheet, while the material composition is defined in the Mat_Inputs sheet and should not be changed in this sheet.

7.32 VEHI_COMP_SUM SHEET

This worksheet consists of the following three sections:

1. **Key input parameters.** The values in this section derive from both the Veh_Inputs and Mat_Inputs sheets. Thus, this section is the interactive link between the Veh_Inputs/Mat_Inputs sheets and this sheet.
2. **Summary of energy consumption and emissions for vehicle materials.** In this section, the weight of each material in each vehicle component is displayed, along with the energy use and emissions totaled for the all the components in each vehicle.
3. **Summary of energy consumption and emissions by vehicle component.** In this section, the energy use and emissions are disaggregated for each component in each vehicle.

7.33 VEHI_SUM SHEET

This worksheet consists of the following three sections:

1. **Summary of energy consumption and emissions per vehicle lifetime.** In this section, the energy use and emissions are displayed for each vehicle's components, ADR, batteries, and fluids; these four values are then totaled to estimate the total vehicle-cycle energy use and emissions for each vehicle.

2. **Summary of energy consumption and emissions of vehicle cycles per-mile.** In this section, the vehicle-cycle energy use and emissions for each vehicle are converted to per-mile results.
3. **Vehicle-cycle energy and emissions changes.** In this section, the vehicle-cycle energy use and emissions are shown as percentages relative to the conventional-material ICEV.

7.34 TEC_RESULTS SHEET

This worksheet consists of the following two sections:

1. **Contribution of each stage to fuel-cycle (well-to-pump), vehicle-cycle, and vehicle-operation energy use and emissions.** In this section, the fuel-cycle (well-to-pump) and vehicle-operation values are derived from GREET 1.7; however, the lightweight values do not come from GREET 1.7 directly, rather they are scaled by using the ratio of the fuel economy between the lightweight vehicle and its conventional-material counterpart. The vehicle-cycle results are added together with the results from GREET 1.7 to estimate the total energy-cycle results for each vehicle.
2. **Fuel-cycle (well-to-pump), vehicle-cycle, and vehicle-operation total energy-cycle energy and emissions changes.** In this section, the total energy-cycle energy use and emissions are shown as percentages relative to the conventional-material ICEV powered by RFG.

7.35 TEC_GRAPHS SHEET

This worksheet consists of the following two sections:

1. **Per-mile fuel-cycle (well-to-pump), vehicle-cycle, and vehicle-operation energy use and emissions.** This section presents bar charts for the shares of energy use and emissions of fuel cycle (well to pump), vehicle cycle, and vehicle operations for each simulated fuel/vehicle type.
2. **Reductions in energy use and emissions by vehicle type.** This section presents bar charts (by individual vehicle technology) as percentages relative to the conventional-material ICEV powered by RFG.

8 ENERGY USE AND EMISSIONS RESULTS

8.1 VEHICLE-CYCLE RESULTS

Figures 7 through 9 show the total, fossil, and petroleum energy use per vehicle, respectively, of the six vehicle types examined in this study (conventional ICEV, HEV, and FCV and lightweight ICEV, HEV and FCV). The results show that production of vehicle materials represents the most energy-intensive activity in the vehicle cycle. The total and fossil energy use from vehicle materials production increases as we move from the ICEV to advanced-powertrain vehicles; however, there is not a significant difference between the conventional and lightweight vehicles. There is a minimal increase in total and fossil energy use from the ICEV to the HEV. This results from the reduction in vehicle component weight for the HEV, which reduces component materials energy use, but the manufacturing of the Ni-MH battery considered in both the HEV and FCV is associated with higher energy use compared with the Pb-Ac battery in the ICEV. The contribution for the battery category is highest for the FCV, which has a larger Ni-MH battery than the HEV. The large total and fossil energy use for the FCV is attributable to the energy-intensive materials in the fuel cell stack and auxiliaries, such as graphite composite for the bipolar plates, aluminum for the current collector, and carbon paper for the electrode's gas diffusion layers. While the lightweight vehicles use a larger percentage of energy-intensive materials, such as aluminum and advanced composites, the significant reduction in total weight of these vehicles compared with their conventional counterparts offsets the increased energy intensity for the materials. For example, each lightweight vehicle has a lower energy use for its batteries compared with the conventional vehicles because the batteries do not need to be as large for the lighter vehicle to provide the same performance.

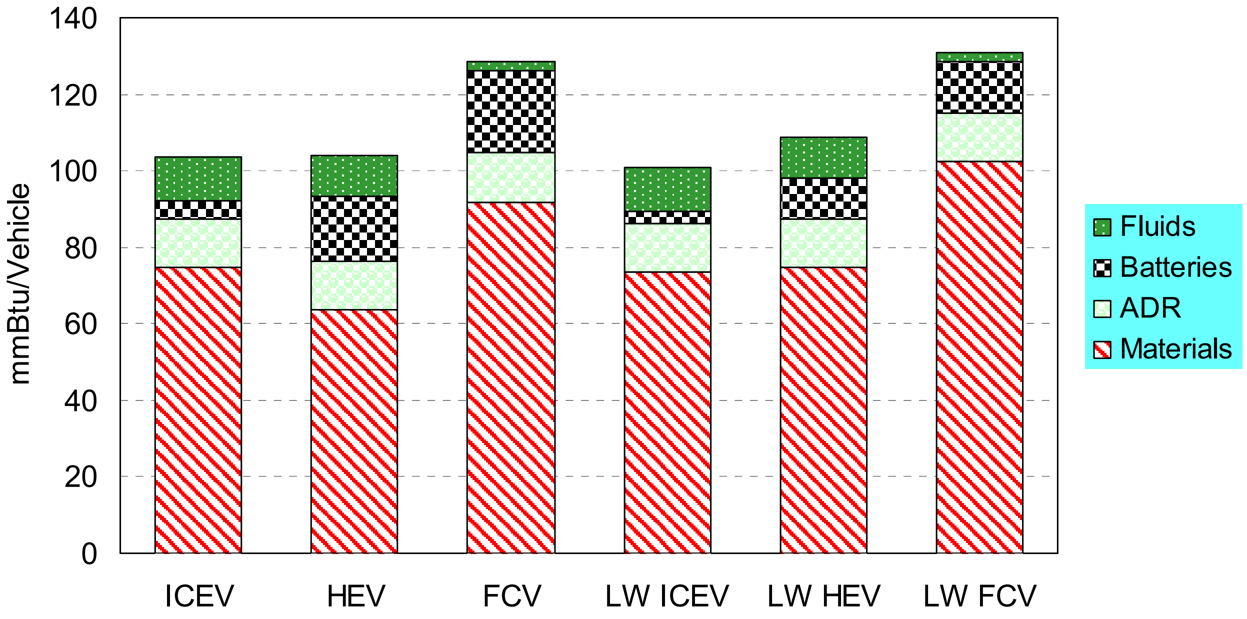

FIGURE 7 Vehicle-Cycle Results: Total Energy Use per Vehicle (mmBtu/vehicle)

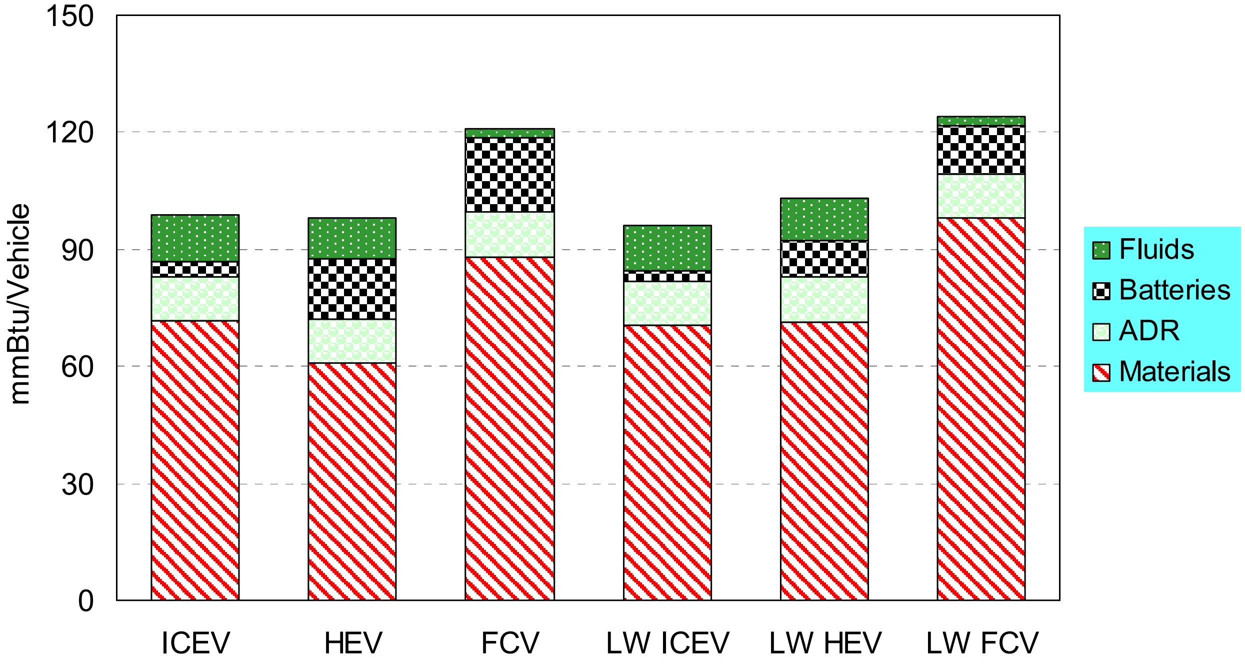

FIGURE 8 Vehicle-Cycle Results: Fossil Energy Use per Vehicle (mmBtu/vehicle)

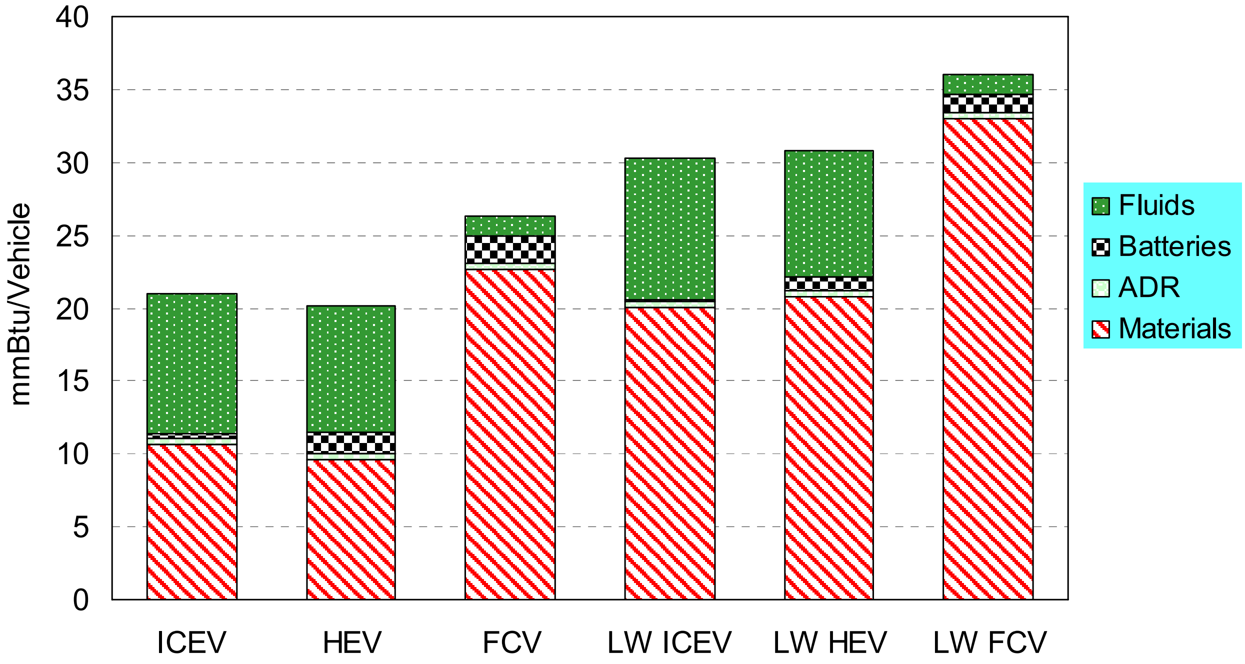

FIGURE 9 Vehicle-Cycle Results: Petroleum Energy Use per Vehicle (mmBtu/vehicle)

Figure 10 shows GHG emissions per vehicle and reveals a trend similar to that for total and fossil energy use. Because of data limitations, we assumed for all these simulations that the ADR remained constant for these vehicles. This issue certainly needs further research. In the case of the FCV, again, these emissions values are further increased by the contribution of emissions from production of materials in the fuel cell stack and accessories. Figures 11 through 13 show the CH_4, N_2O, and CO_2 emissions, respectively, which are used to calculate the GHG emissions.

Conversely, an opposite trend in PM_{10} emissions for lightweight vehicles is observed in Figure 14. This figure shows that replacing steel with composite material results in a decrease in PM_{10} emissions for lightweight vehicles; taconite mining and coke production emit a large amount of the PM_{10} emissions that are accounted for in the steel production processes.

The modeling results show that production of the battery component of both the conventional-material and lightweight HEVs represents about 30% of the total vehicle-cycle SO_x emissions (Figure 15). In addition, the results show that production of the battery component of both the conventional material and lightweight FCVs represents about 20% of the total vehicle-cycle SO_x emissions. The SO_x emissions associated with the Ni-MH battery are mainly attributable to the emissions that result from mining and production of nickel, copper, and rare earth metals. Again, we see that the lightweight vehicles have lower SO_x emissions than the conventional vehicles because of the decreased battery size needed to power the lightweight vehicles.

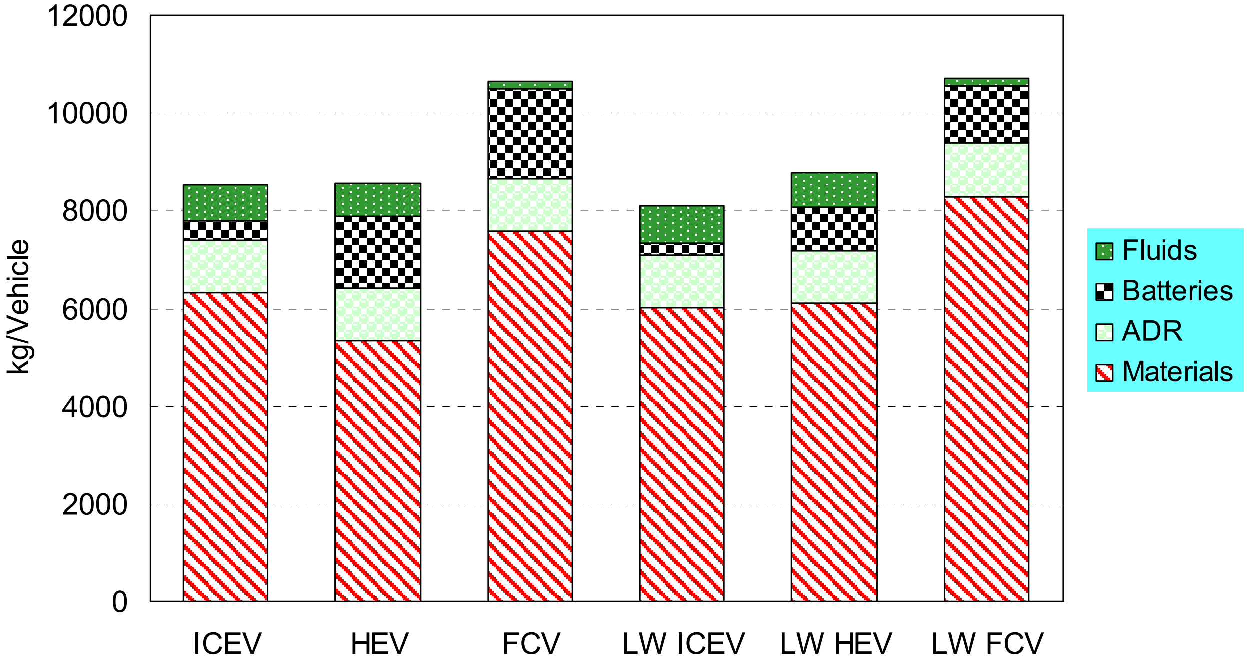

FIGURE 10 Vehicle-Cycle Results: GHG Emissions per Vehicle (kg/vehicle)

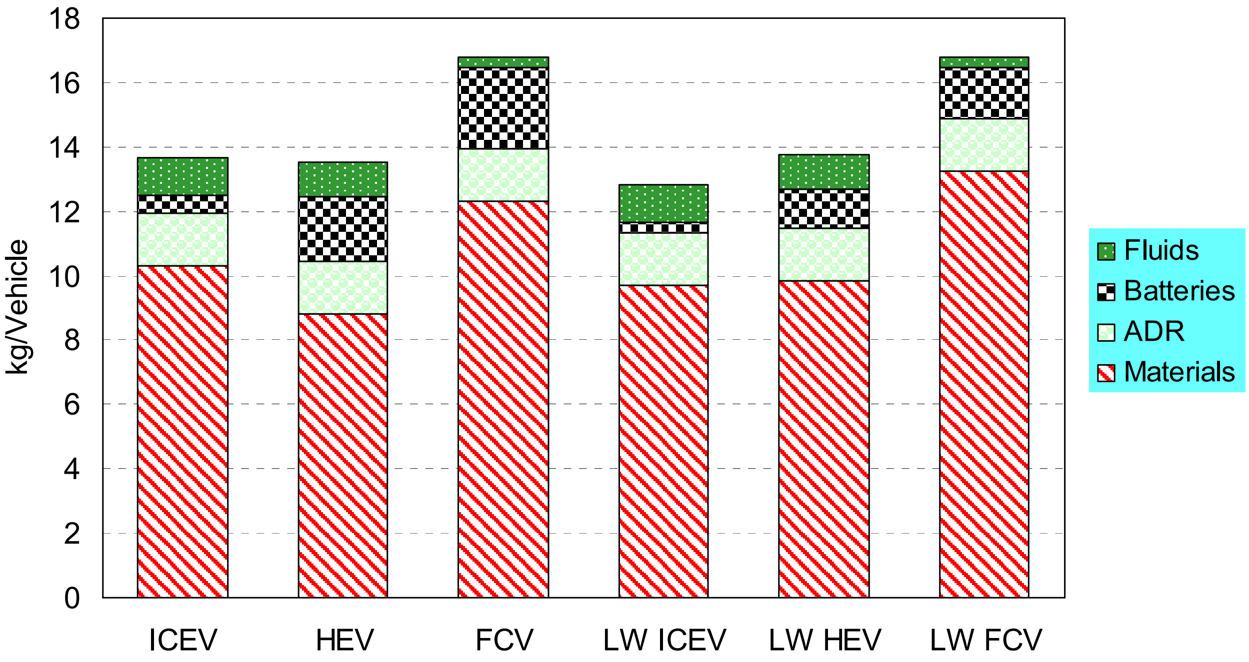

FIGURE 11 Vehicle-Cycle Results: CH_4 Emissions per Vehicle (kg/vehicle)

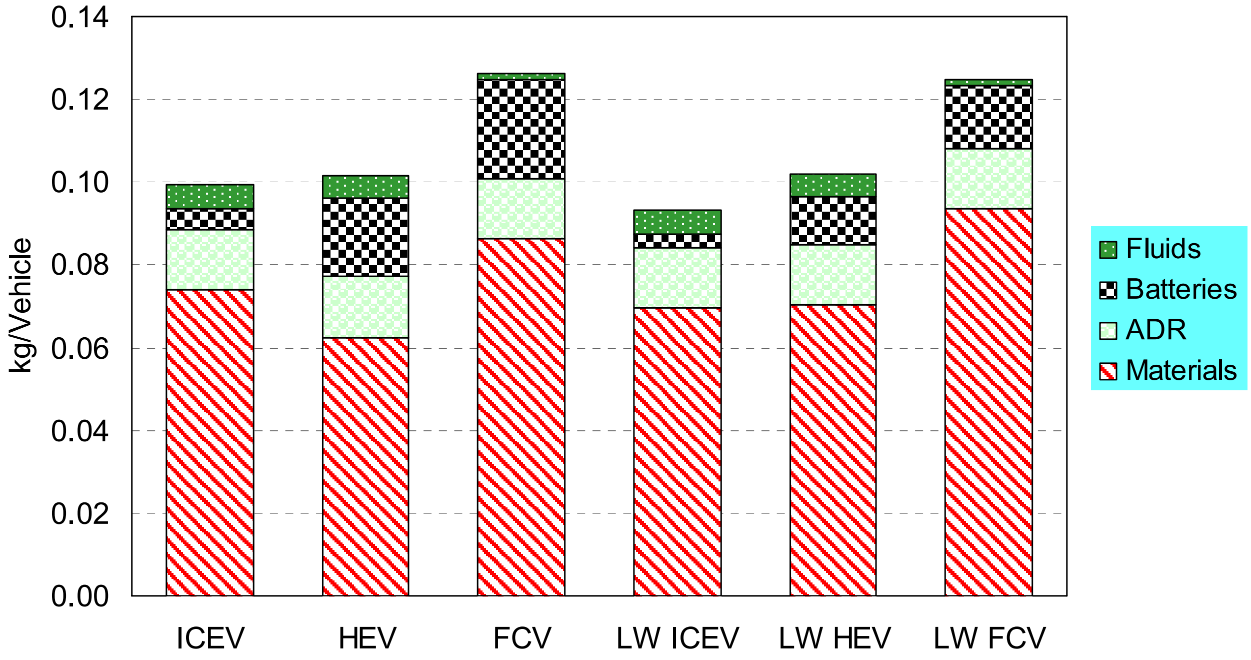

FIGURE 12 Vehicle-Cycle Results: N_2O Emissions per Vehicle (kg/vehicle)

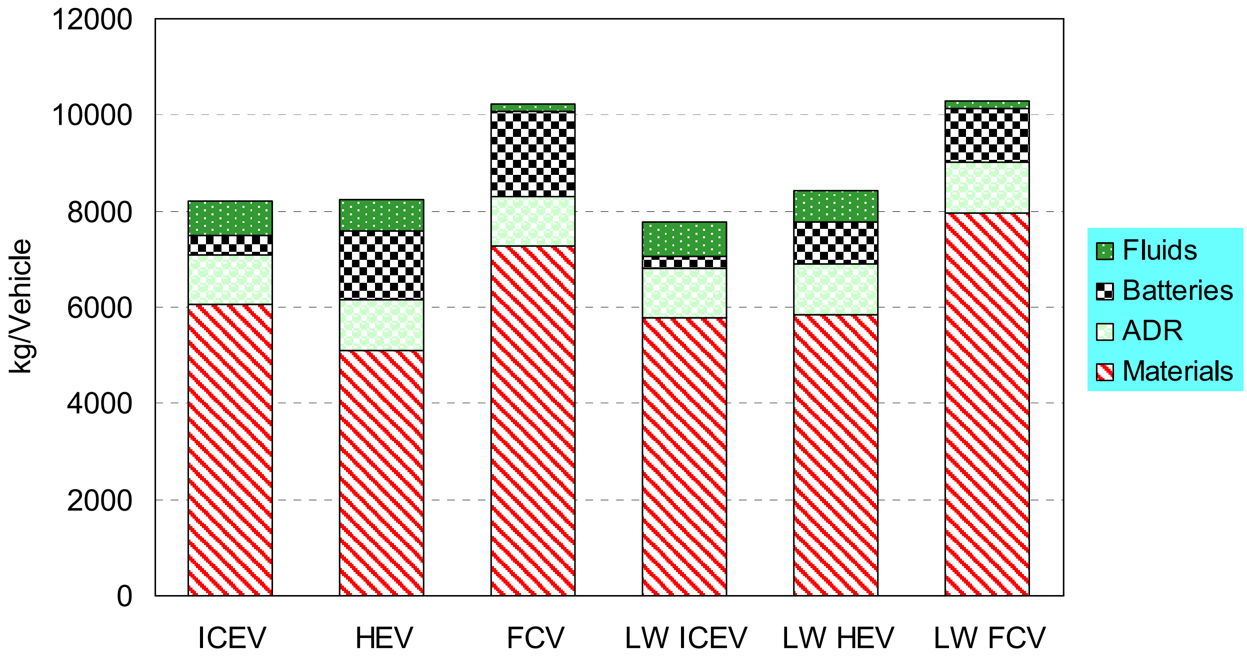

FIGURE 13 Vehicle-Cycle Results: CO_2 Emissions per Vehicle (kg/vehicle)

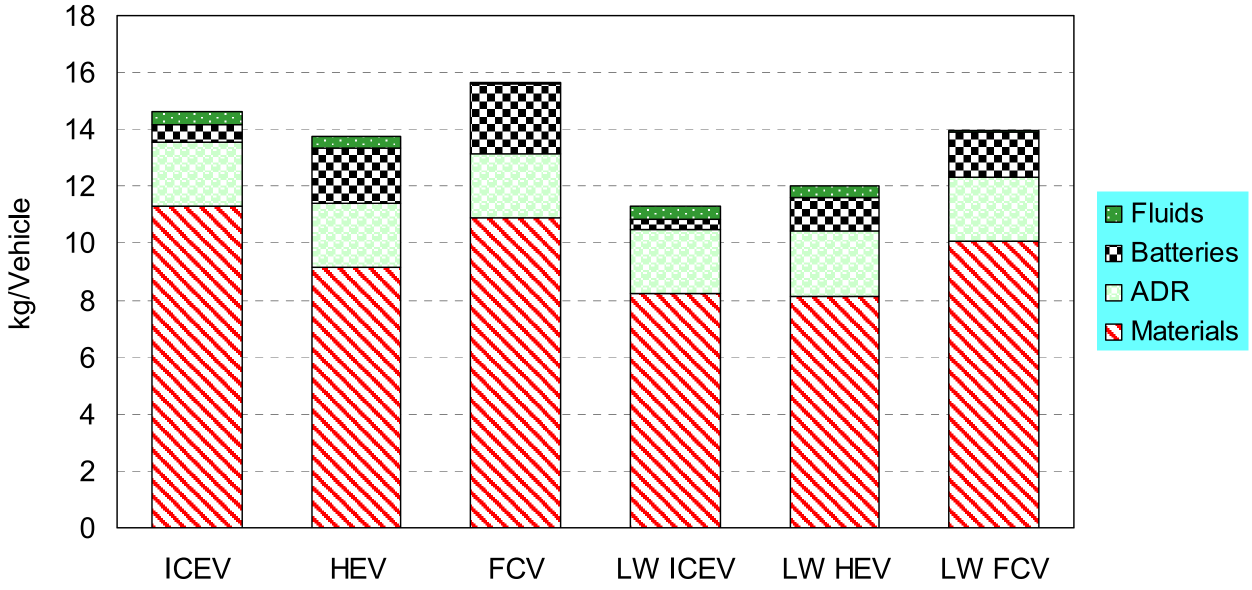

Figure 14 Vehicle-Cycle Results: PM_{10} Emissions per Vehicle (kg/vehicle)

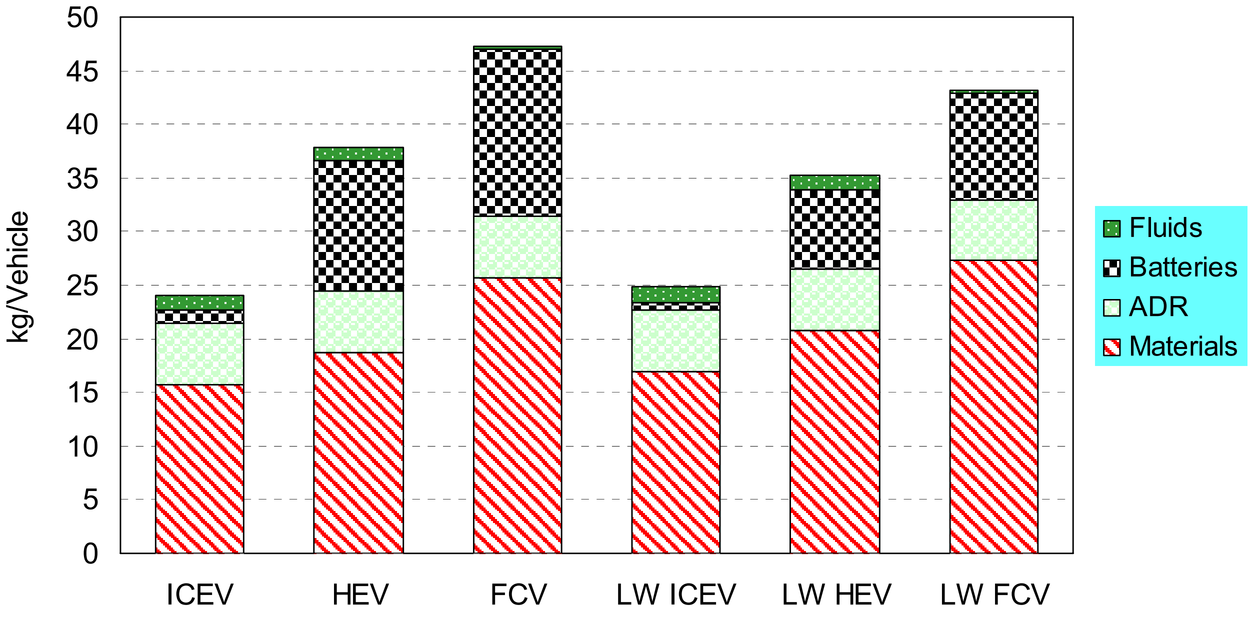

FIGURE 15 Vehicle-Cycle Results: SO_x Emissions per Vehicle (kg/vehicle)

Figures 16 through 18 show VOC, NO_x, and CO emissions, respectively. The VOC emissions are dominated by the release of methanol from the use of windshield wiper fluid. Figure 18 illustrates that replacing steel with composite material results in a large decrease in CO emissions for lightweight vehicles; sintering and BOP contribute a large amount of the CO emissions that result from the steel production processes.

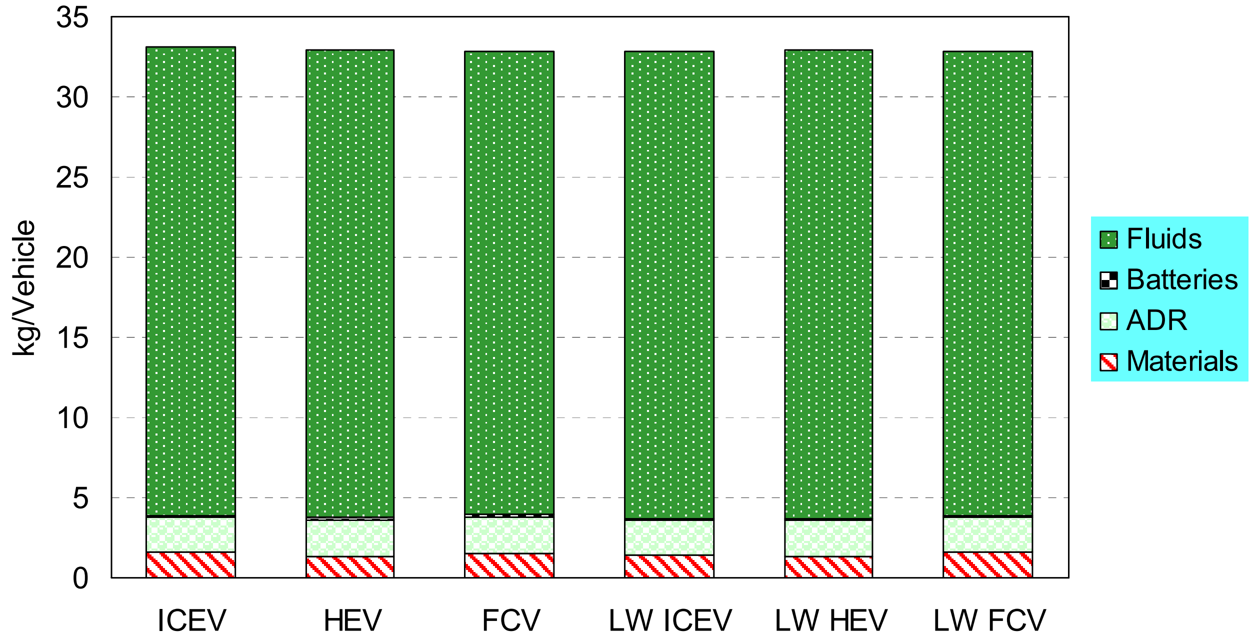

FIGURE 16 Vehicle-Cycle Results: VOC Emissions per Vehicle (kg/vehicle)

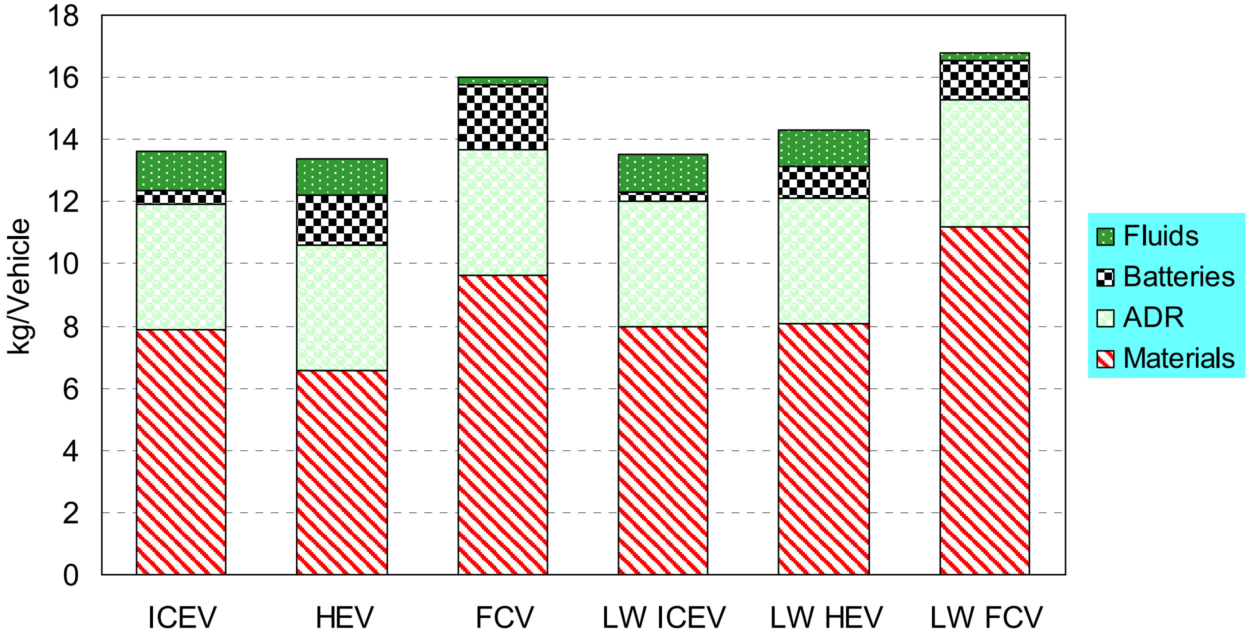

FIGURE 17 Vehicle-Cycle Results: NO_x Emissions per Vehicle (kg/vehicle)

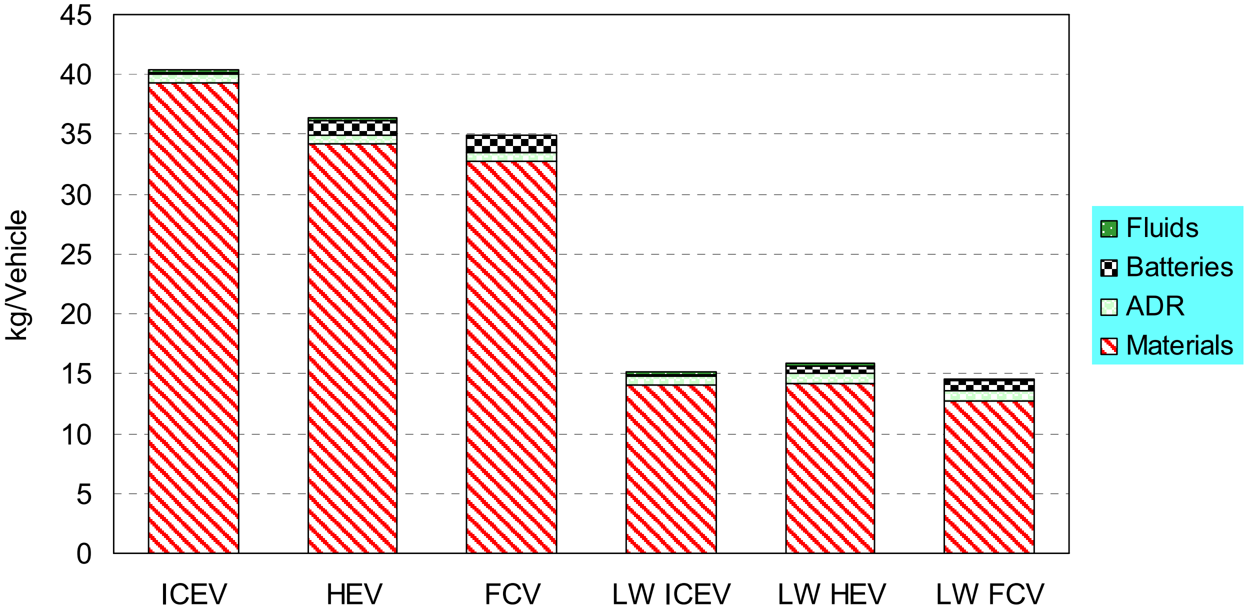

FIGURE 18 Vehicle-Cycle Results: CO Emissions per Vehicle (kg/vehicle)

8.2 TOTAL ENERGY-CYCLE RESULTS

The previous section presented the differences in vehicle-cycle energy use and emissions among the three vehicle powertrain systems (ICEV, HEV, and FCV) and material compositions (conventional vs. lightweight). In order to put the vehicle-cycle results into a broad perspective with energy use and emissions of fuel production and vehicle operation, we conducted a total energy-cycle analysis; the results are presented in this section. The total energy cycle includes the vehicle cycle (VC), fuel cycle (FC), and vehicle operation (VO) stages and provides a comprehensive view of energy use and emissions. With the vehicle-cycle simulations discussed in the preceding sections, we used GREET 1.7 to run simulations for the fuel-cycle and vehicle-operation stages.

The key fuel-cycle assumptions for these simulations included the following. Reformulated gasoline (with ethanol as an oxygenate) is used in ICEVs and HEVs, while FCVs are assumed to be powered with gaseous hydrogen (5,000 psi onboard storage) that was produced from steam methane reforming of North American NG at refueling stations. The key vehicle operation assumptions for these simulations were EPA Tier II Bin 3 emissions for ICEVs, Bin 2 emissions for HEVs, and Bin 1 emissions for FCVs.

Fuel economy values for the three vehicle technologies that employ conventional materials were from PSAT simulations for model year (MY) 2010 vehicles. For lightweight vehicles, the values were estimated from equations calculated by PSAT to estimate the change in fuel economy with a given change in vehicle weight. All of the fuel economy values, which are listed in Table 25, are based on on-road adjusted combined 55%/45% city/highway driving cycles. Besides the vehicle weights listed in Table 1, 80 lb of gasoline was added to the ICEV and HEV weights, and 10 lb of hydrogen was added to the FCV weight. For the ICEV, we calculated a 41% reduction in weight, with a resulting 32% improvement in fuel economy. For the HEV,we calculated a 25% reduction in weight, with a resulting 18% improvement in fuel economy. From those equations, we found that the ICEV has a larger improvement in fuel economy per unit of weight reduction than the HEV and FCV.

Another key assumption for the total energy-cycle analysis was the distance traveled by the vehicles during their lifetimes. This is an important issue for total energy-cycle analysis because GREET 1.7 fuel-cycle and vehicle-operation results are in per-distance-traveled, while vehicle-cycle results are on a per-vehicle basis. The VISION model developed at Argonne shows

TABLE 25 On-Road Adjusted Combined Fuel Economy Values for MY 2010 Vehicles

	ICEV	HEV	FCV	LW ICEV	LW HEV	LW FCV
Fuel Economy (mpgge)[a]	24.8	39.7	57.5	32.7	47.2	67.7
LW Weight Change (%)				41	29	25
LW Fuel Economy Change (%)				32	1.8	2.6

[a] mpgge = miles per gallon gasoline equivalent.

an average lifetime distance of 160,000 miles by a passenger car. We used this value for our analysis. However, each vehicle might have a different expected lifetime because of the materials and components used in each; these differences result from variations in rust resistance, the ability to repair a material after an accident, and other factors. At this point, we have not examined this topic extensively, but we have built in the flexibility to change the total distance each vehicle is driven as more data become available.

Figures 19 through 21 show that the per-mile total, fossil, and petroleum energy use for both HEVs and FCVs is significantly lower than that for ICEVs. In addition, the fuel economy improvement for the lightweight vehicles results in decreases of 22%, 13%, and 12% in total energy-cycle total energy use for the lightweight ICEV, HEV, and FCV, in that order, in comparison with their conventional-material counterparts.

As Figure 22 shows, the GHG emission patterns are similar to those of the total and fossil energy use; however, GHG emissions for the two FCV cases show a more significant reduction compared with the HEV cases. This is because hydrogen produced from NG is less carbon-intensive than petroleum-derived gasoline on a per-energy-unit basis. Furthermore, the fuel economy improvement of the lightweight vehicles results, again, in reductions of 22%, 13%, and 12% in GHG emissions by the ICEV, HEV, and FCV, in that order, compared with their conventional-material counterparts. Figures 23 through 25 show the CH_4, N_2O, and CO_2 emissions, respectively, that were used to calculate the GHG emissions.

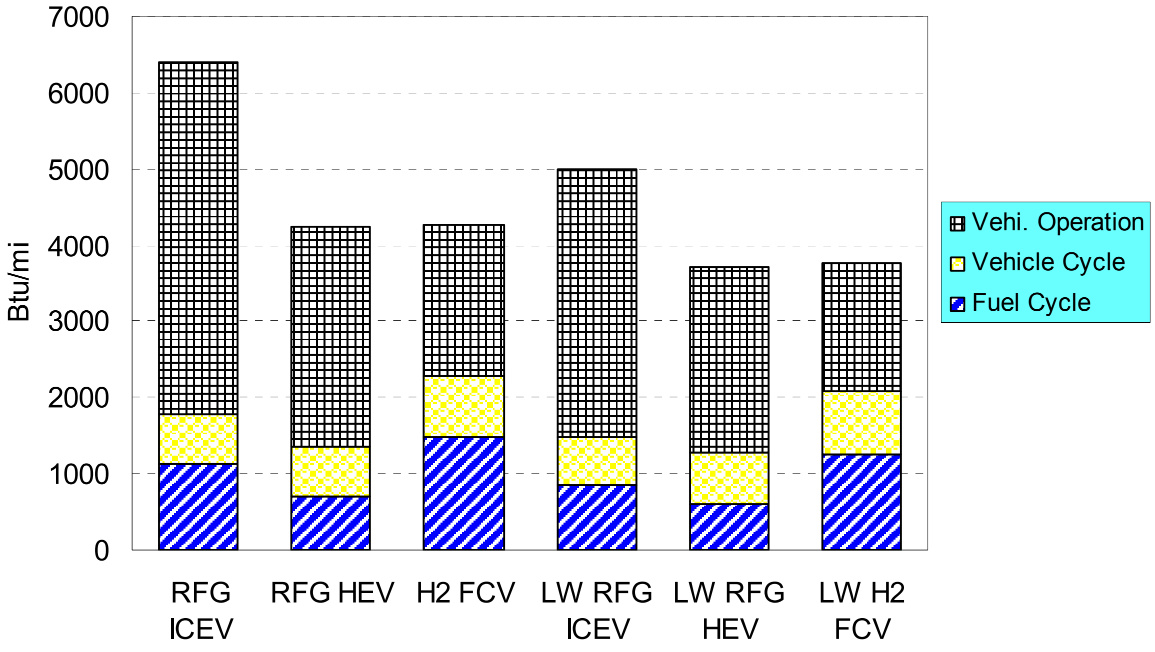

FIGURE 19 Total Energy-Cycle Results: Total Energy Use (Btu/mi)

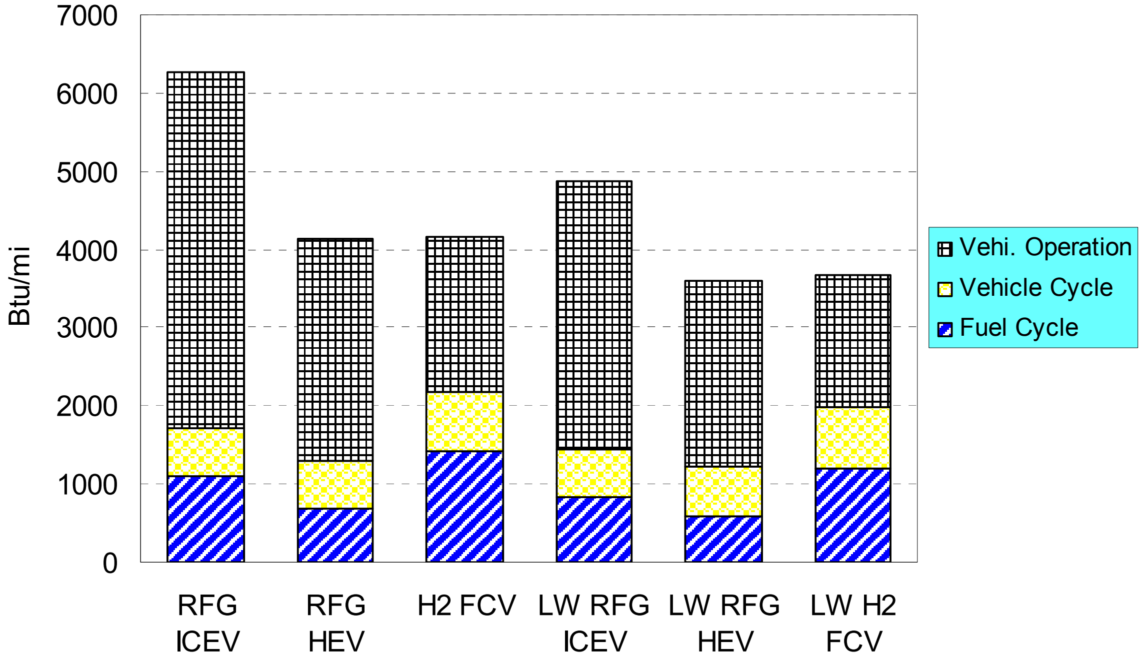

FIGURE 20 Total Energy-Cycle Results: Fossil Energy Use (Btu/mi)

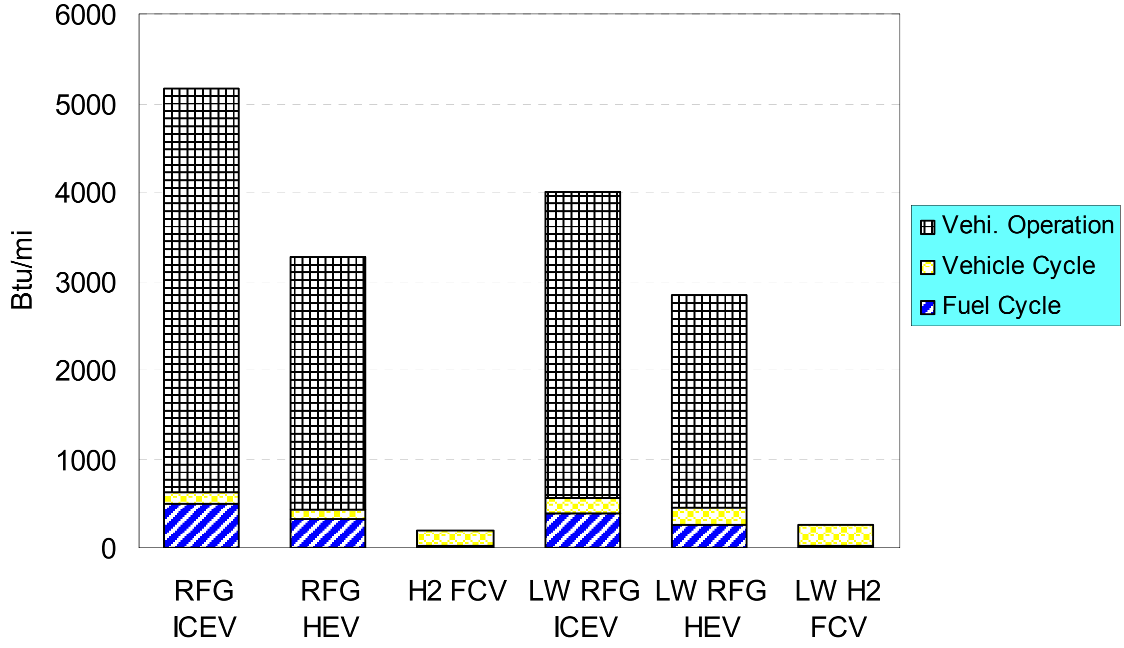

FIGURE 21 Total Energy-Cycle Results: Petroleum Energy Use (Btu/mi)

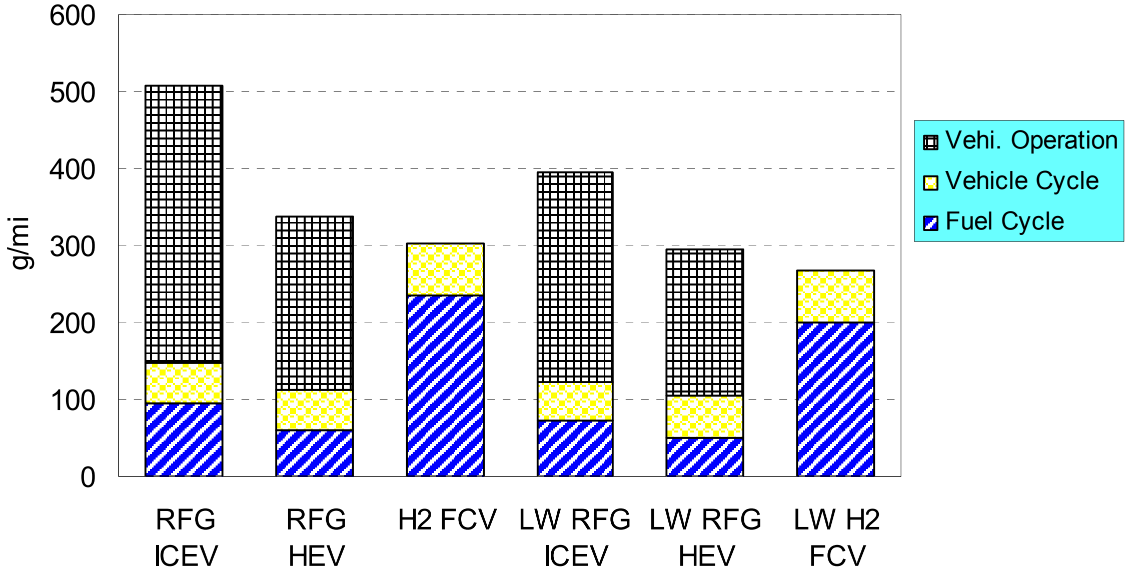

FIGURE 22 Total Energy-Cycle Results: GHG Emissions (g/mi)

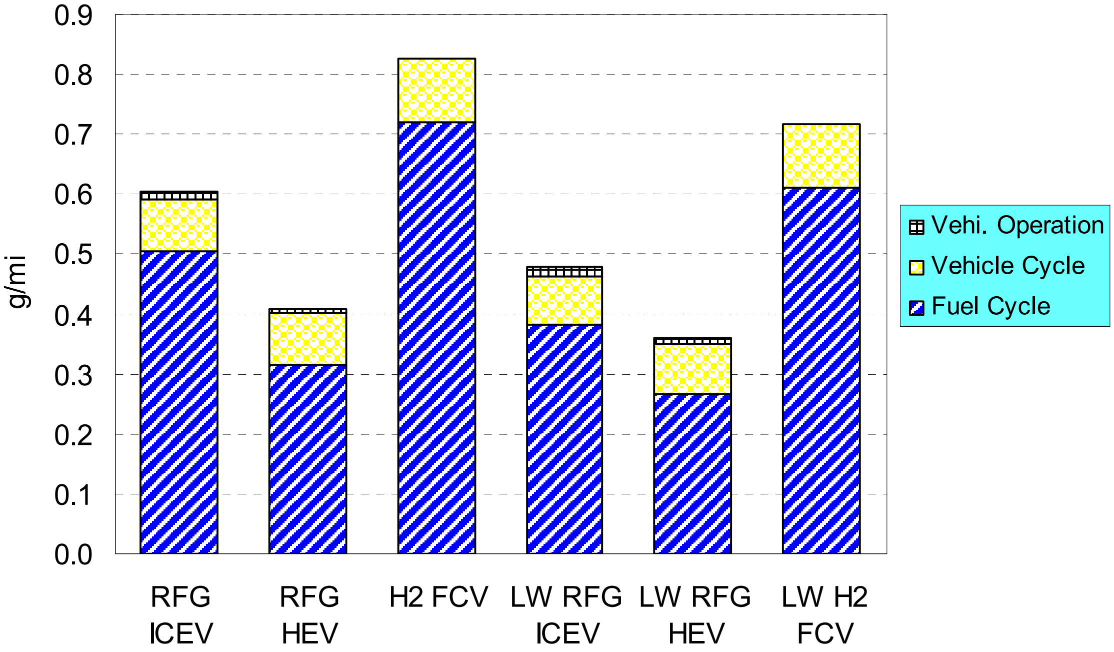

FIGURE 23 Total Energy-Cycle Results: CH_4 Emissions (g/mi)

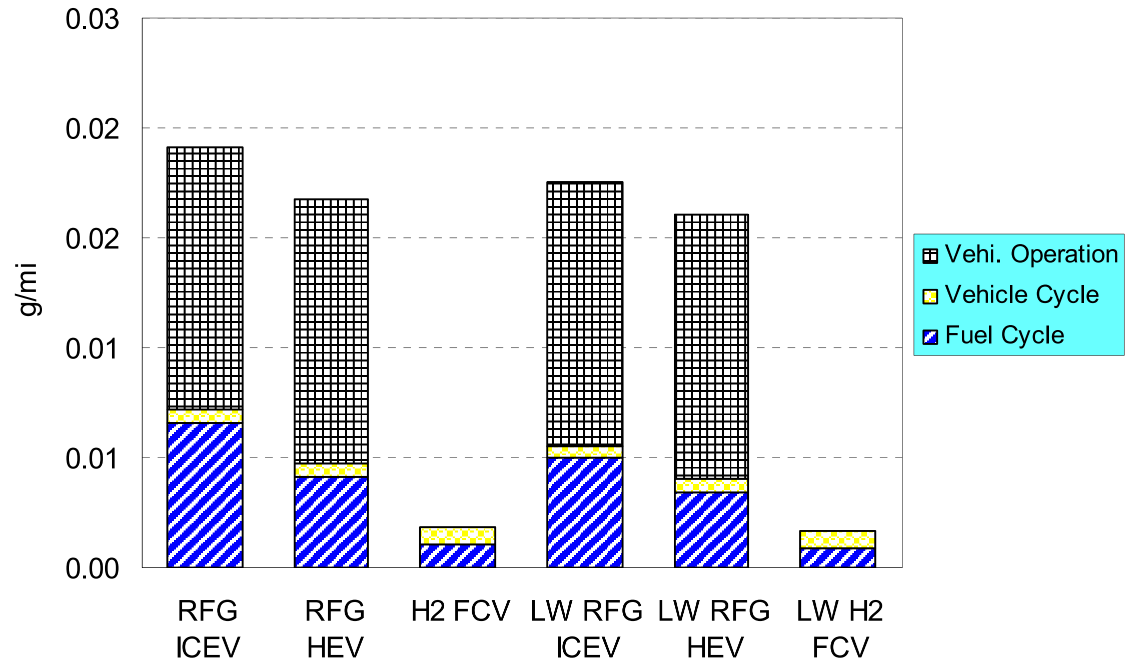

FIGURE 24 Total Energy-Cycle Results: N_2O Emissions (g/mi)

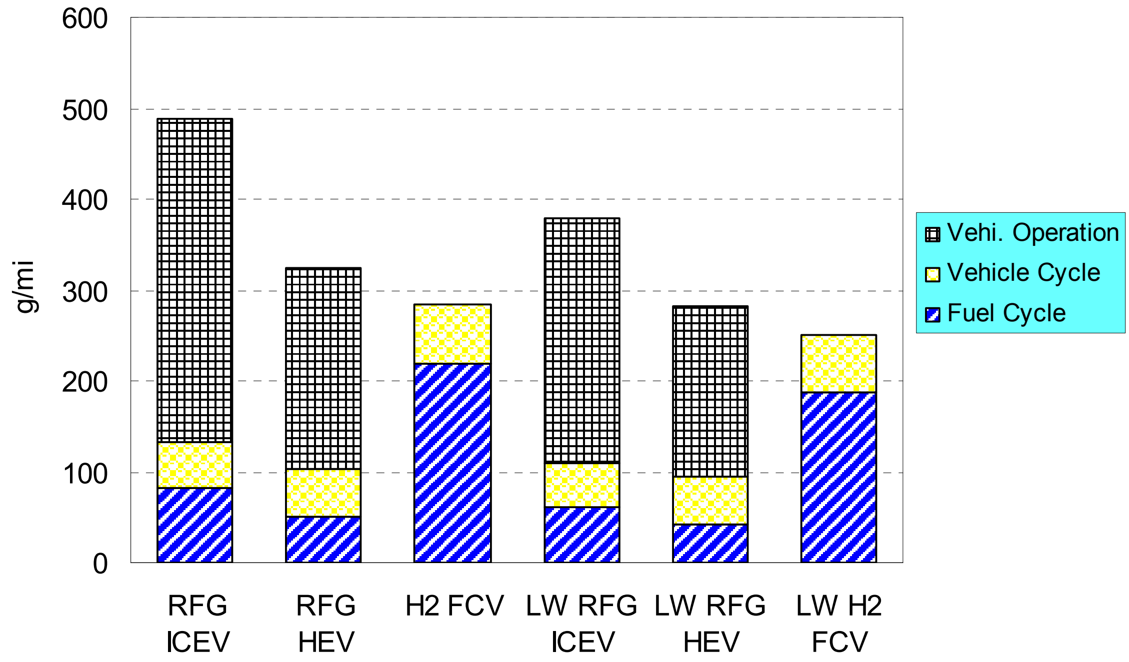

FIGURE 25 Total Energy-Cycle Results: CO_2 Emissions (g/mi)

Materials such as aluminum and carbon fiber composites can be used to reduce vehicle weight and improve fuel economy, which reduces the energy use and GHG emissions from the fuel-cycle and vehicle-operation stages. In addition, the use of these materials does not necessarily increase the energy use and GHG emissions of lightweight vehicles; rather, with a reduction in total weight, the results are about the same and could be improved with additional recycling. The results from our simulations do show that there can be a significant net benefit in substituting lightweight materials for conventional materials on a total energy-cycle basis.

Figures 26 through 30 show the total PM_{10}, SO_x, VOC, NO_x, and CO emissions, respectively.

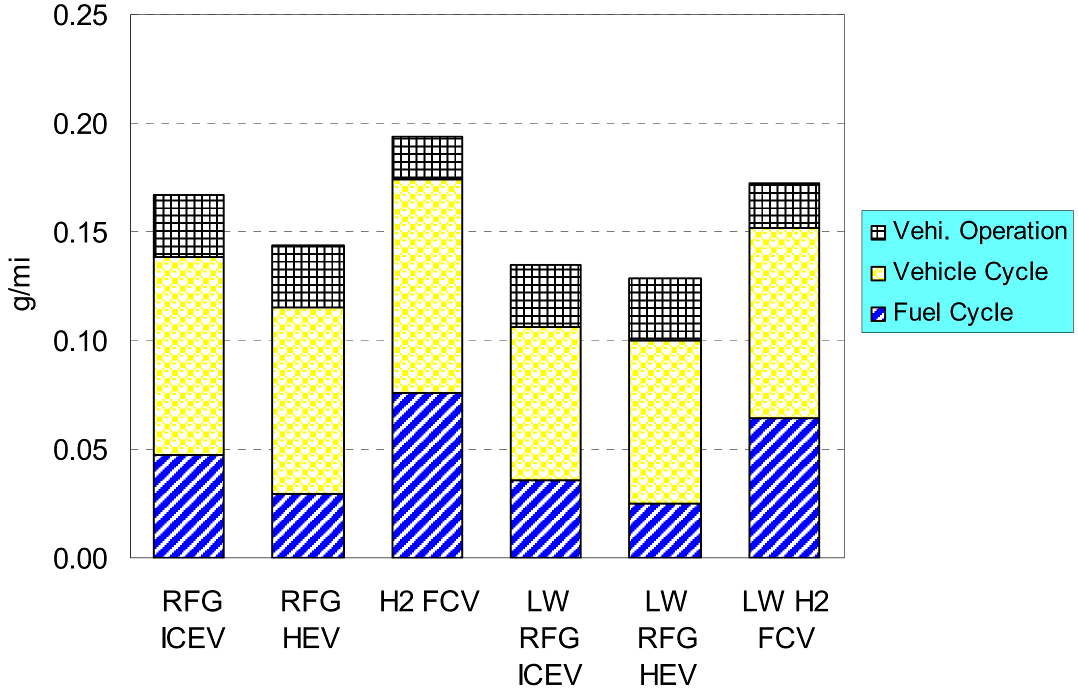

FIGURE 26 Total Energy-Cycle Results: Total PM_{10} Emissions (g/mi)

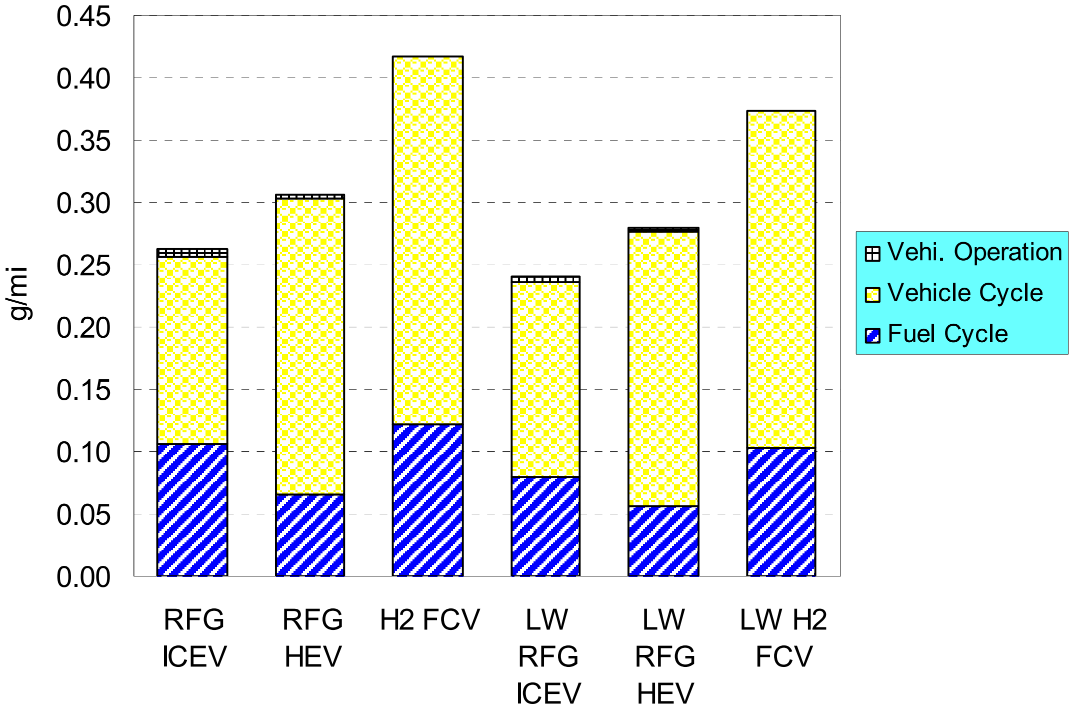

FIGURE 27 Total Energy-Cycle Results: Total SO_x Emissions (g/mi)

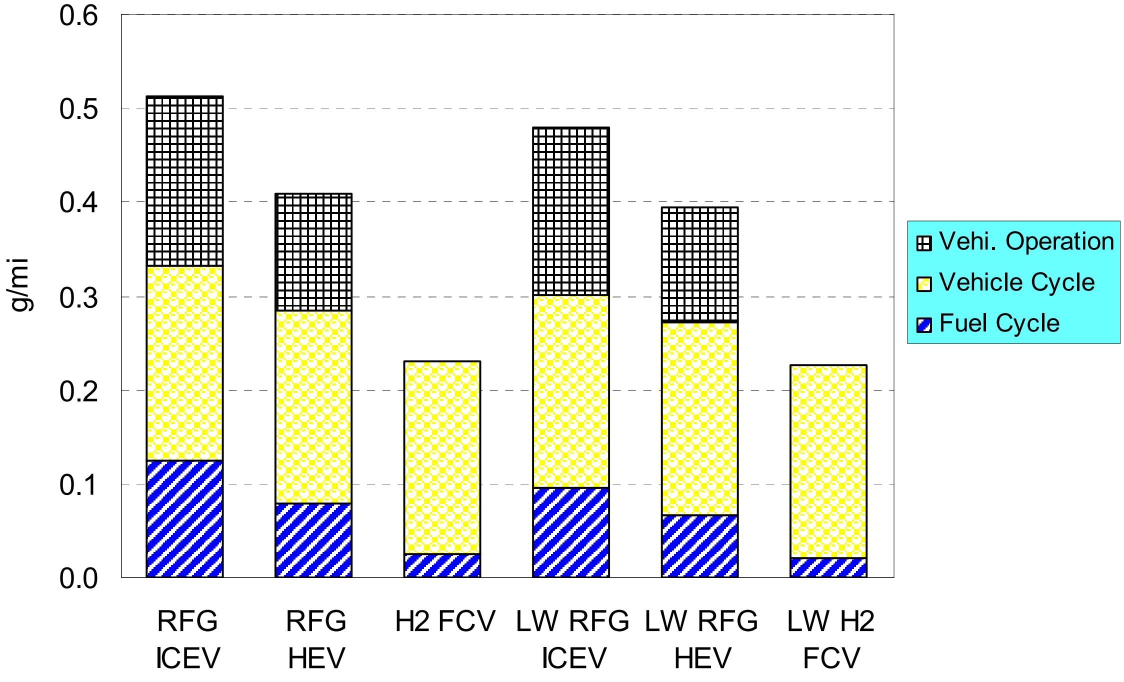

FIGURE 28 Total Energy-Cycle Results: Total VOC Emissions (g/mi)

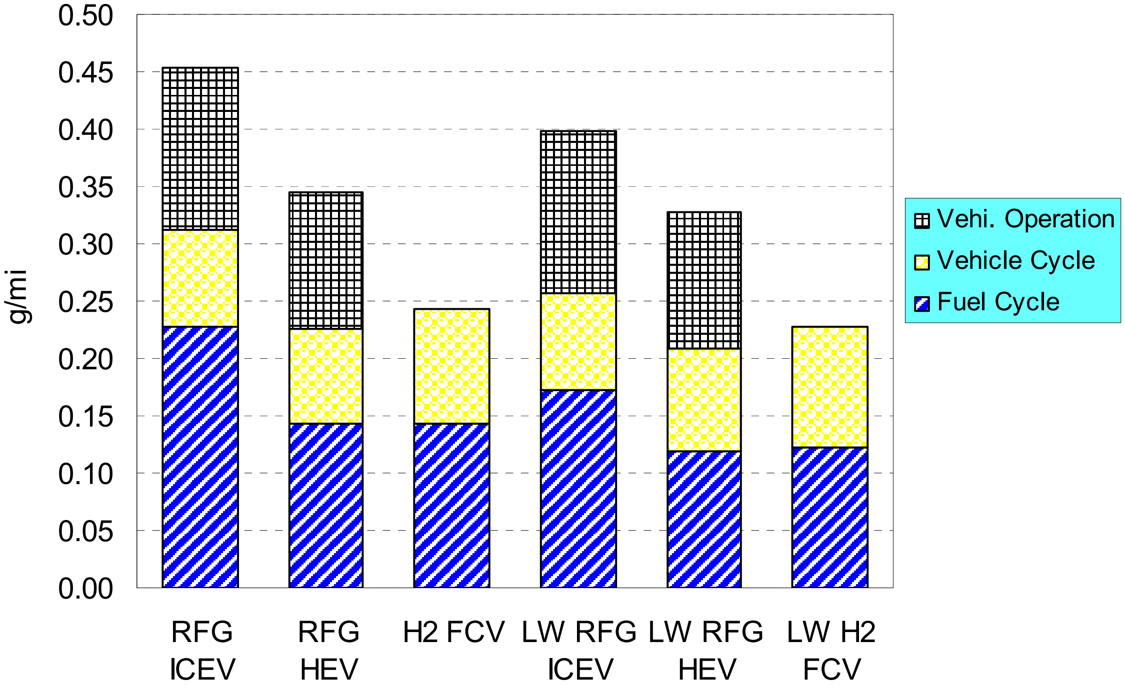

FIGURE 29 Total Energy-Cycle Results: Total NO_x Emissions (g/mi)

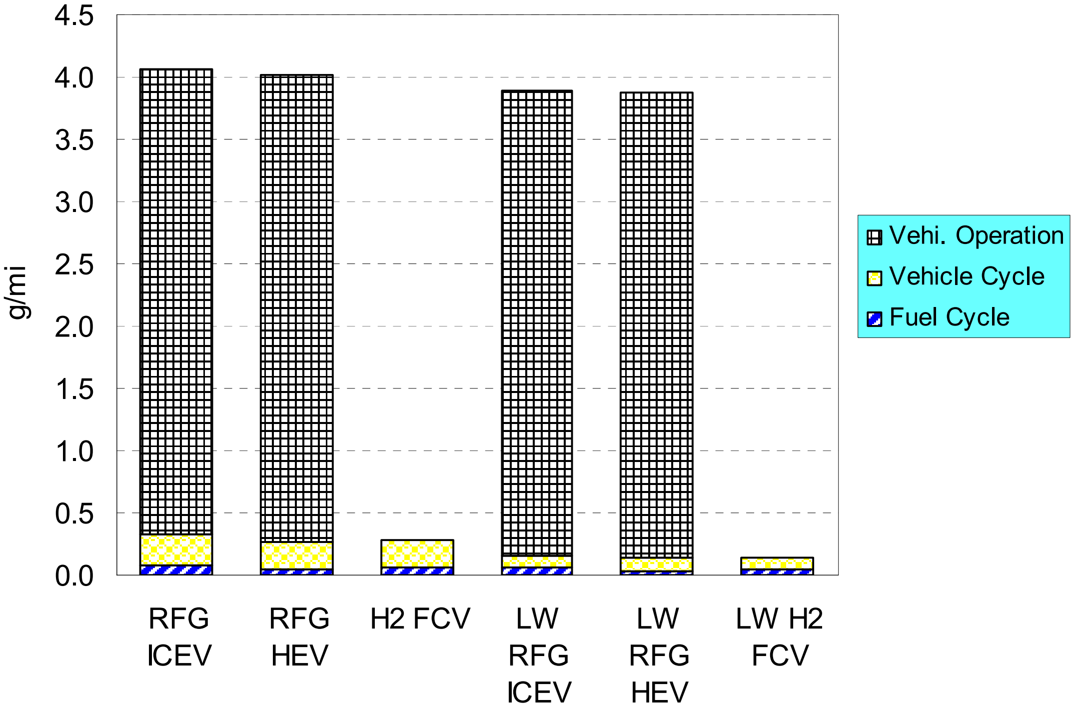

FIGURE 30 Total Energy-Cycle Results: Total CO Emissions (g/mi)

Figures 31 through 35 show the urban PM_{10}, SO_x, VOC, NO_x, and CO emissions, respectively.

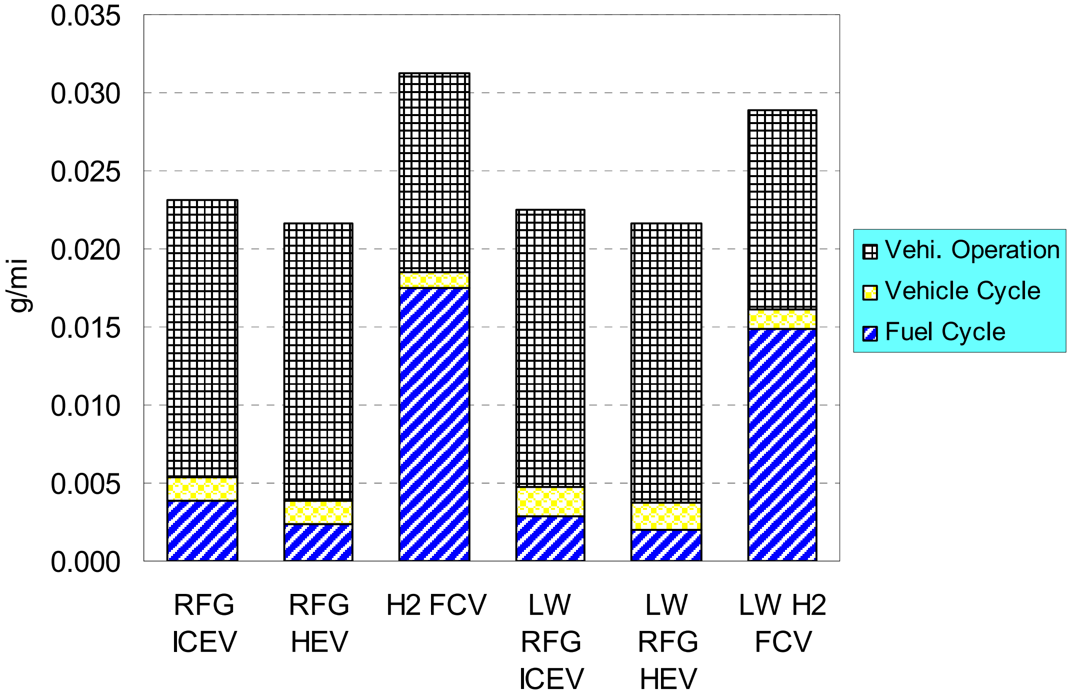

FIGURE 31 Total Energy-Cycle Results: Urban PM_{10} Emissions (g/mi)

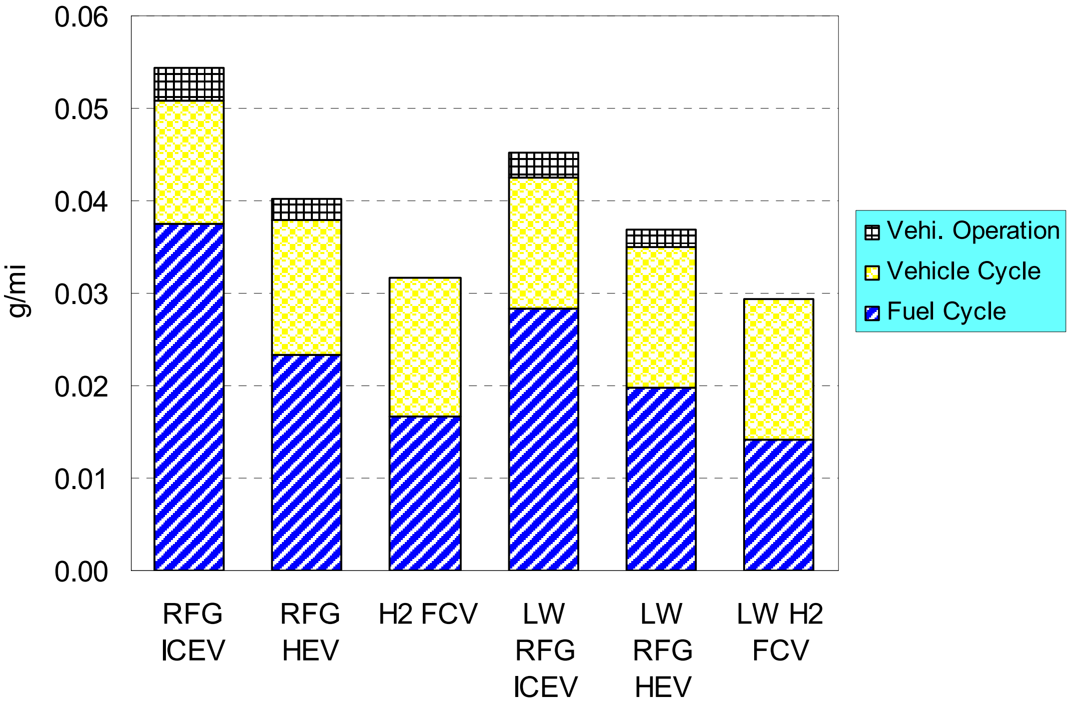

FIGURE 32 Total Energy-Cycle Results: Urban SO_x Emissions (g/mi)

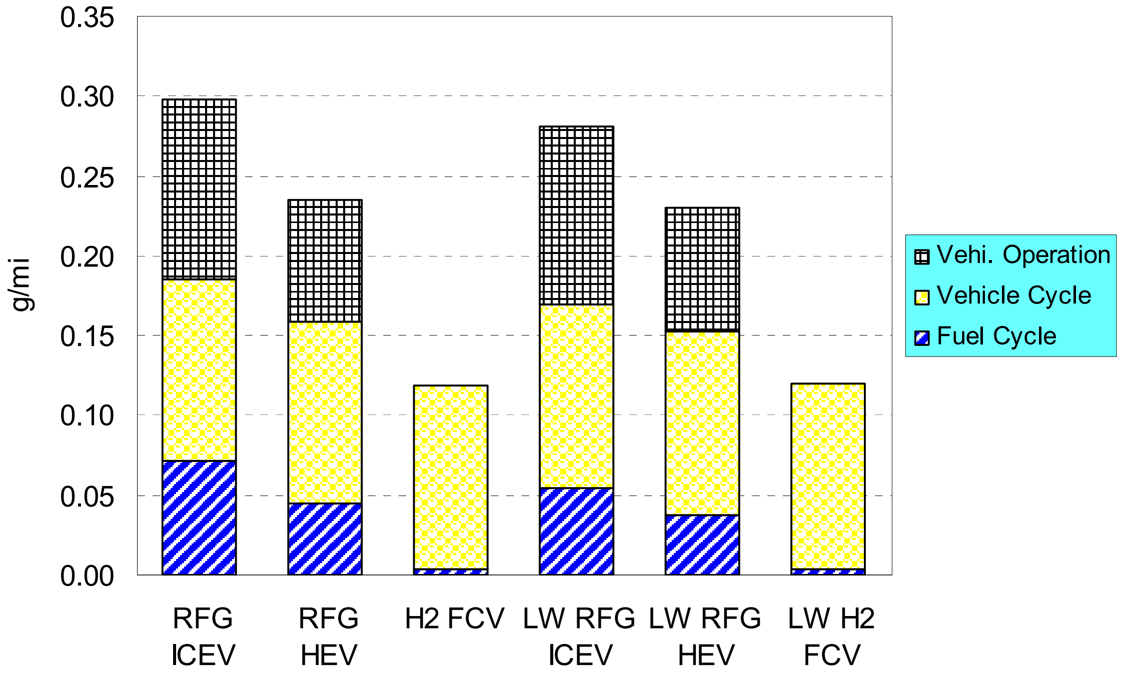

FIGURE 33 **Total Energy-Cycle Results: Urban VOC Emissions (g/mi)**

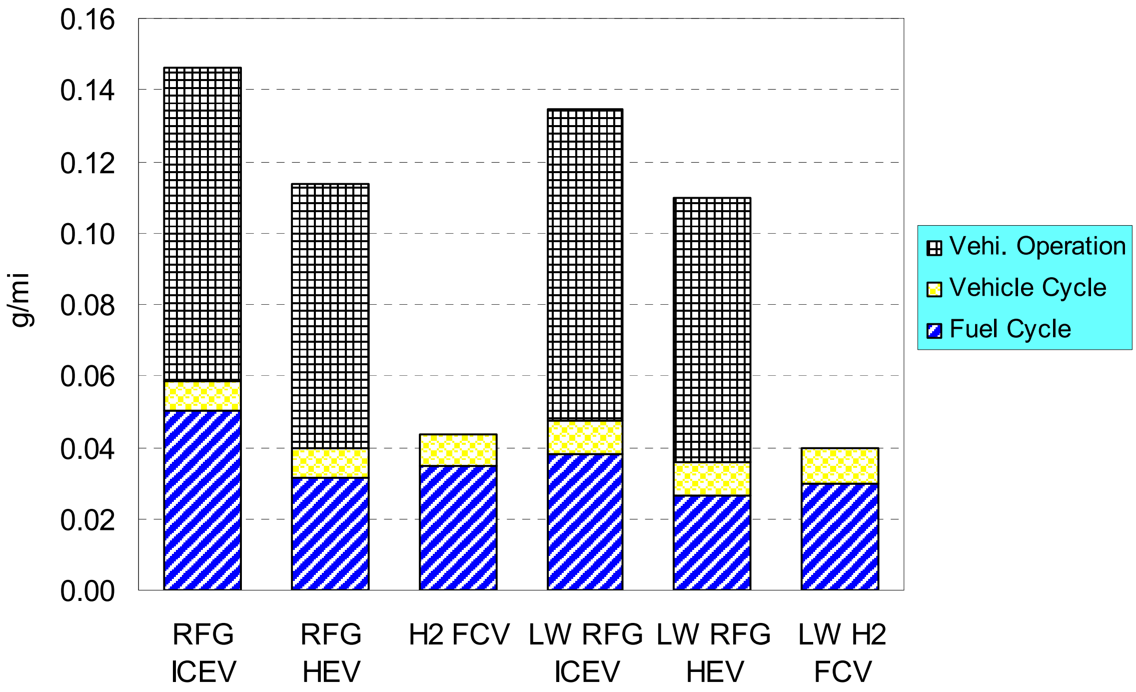

FIGURE 34 **Total Energy-Cycle Results: Urban NO$_x$ Emissions (g/mi)**

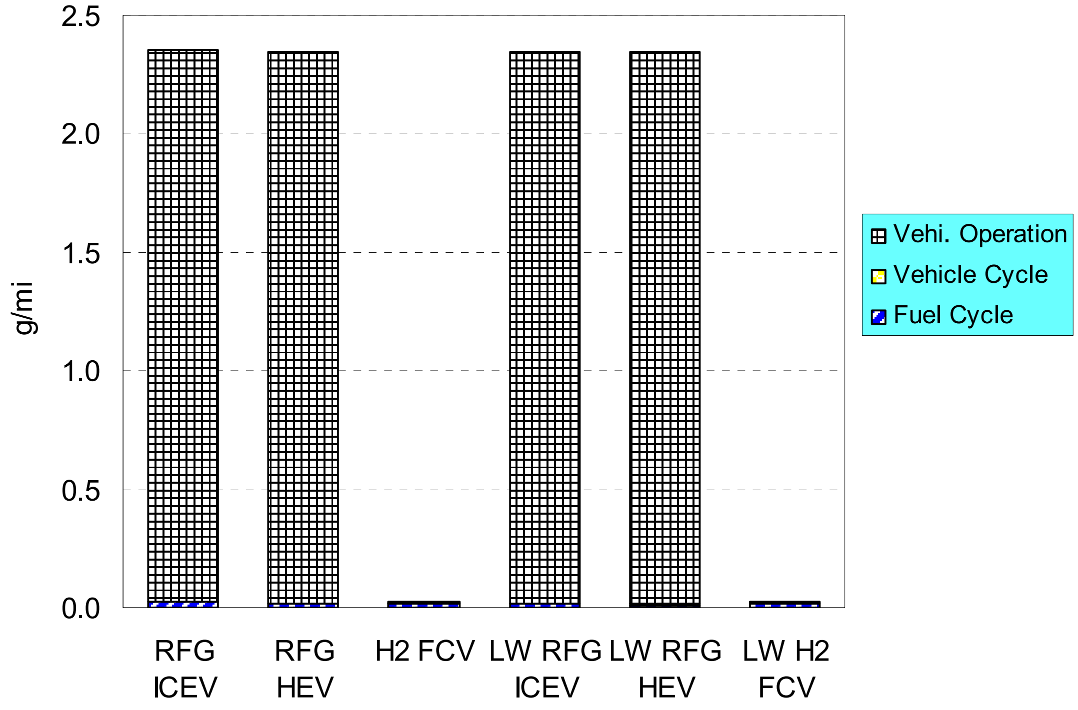

FIGURE 35 Total Energy-Cycle Results: Urban CO Emissions (g/mi)

9 CONCLUSIONS

We added the vehicle cycle to the GREET model to provide a more comprehensive life-cycle analysis of the energy use and emissions associated with ICEVs, HEVs, and FCVs. By using this model, we evaluated the total energy use, fossil energy use, petroleum energy use, GHG (CH_4, N_2O, CO_2) emissions, and criteria air pollutant (PM_{10}, SO_x, VOC, NO_x, CO) emissions that result from production and disposal of a mid-size passenger car. For each vehicle type, we also compared the energy use and emissions of conventional-material vehicles and lightweight-material vehicles.

Our vehicle-cycle results revealed that the production of materials accounts for a majority of the energy use and emissions associated with all the vehicles. The energy use and GHG emissions that result from vehicle production and disposal of advanced-powertrain vehicles (HEV and FCV) may be greater than those for ICEVs because of (1) the use of energy-intensive materials in the fuel cell system of the FCV, and (2) the increased use of aluminum in both the HEV and FCV. However, the use of recycled materials can reduce these impacts. Conversely, the use of energy-intensive materials such as aluminum and carbon fiber composites does not necessarily increase the vehicle-cycle energy use and GHG emissions of lightweight vehicles; with a reduction in total weight, the results are about the same and could be improved with additional recycling.

To put vehicle-cycle results into a broad perspective, we conducted a total energy-cycle analysis that included the vehicle-cycle, fuel-cycle, and vehicle-operation stages. Our vehicle-cycle analysis revealed that lightweight materials can reduce the weight of a vehicle and improve its fuel economy, but that production of these materials can be energy intensive if recycled materials are not used. Our total energy-cycle analysis further shows that, when examining vehicle technologies and lightweight materials on a total energy-cycle basis, there can be a significant net benefit in terms of energy use and emissions reduction by substituting lightweight materials for conventional materials.

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APPENDIX A:

BREAKDOWN OF VEHICLE ENERGY USE AND EMISSIONS VALUES BY VEHICLE COMPONENT

TABLE A.1 ICEV: Conventional Material

	Percentage of Energy Consumption and Emissions per Component							
	Body	Powertrain System	Transmission System	Chassis (w/o battery)	Traction Motor	Generator	Electronic Controller	Fuel Cell Auxiliary
Energy use								
Total energy	34.9	26.5	11.0	27.6				
Fossil fuels	34.8	26.5	10.7	28.0				
Petroleum	36.9	22.4	8.2	32.6				
Total Emissions								
VOC	16.0	17.3	6.5	60.2				
CO	45.2	16.6	3.4	34.8				
NO_x	32.0	29.6	11.6	26.7				
PM_{10}	30.9	30.9	13.8	24.4				
SO_x	36.4	33.4	10.3	19.8				
CH_4	35.2	26.9	10.2	27.7				
N_2O	34.0	27.5	12.3	26.2				
CO_2	34.1	27.5	11.3	27.0				
Urban Emissions								
VOC	36.9	22.0	7.8	33.3				
CO	36.1	25.2	13.3	25.4				
NO_x	35.8	25.5	13.5	25.1				
PM_{10}	36.4	23.7	10.6	29.2				
SO_x	36.0	26.1	15.3	22.6				

TABLE A.2 ICEV: Lightweight Material

	Percentage of Energy Consumption and Emissions per Component							
	Body	Powertrain System	Transmission System	Chassis (w/o battery)	Traction Motor	Generator	Electronic Controller	Fuel Cell Auxiliary
Energy use								
Total energy	45.1	20.0	8.4	26.4				
Fossil fuels	45.5	19.8	8.1	26.5				
Petroleum	65.4	9.5	3.5	21.6				
Total Emissions								
VOC	20.1	11.1	4.4	64.4				
CO	16.1	42.7	5.9	35.4				
NO_x	48.4	17.7	7.3	26.5				
PM_{10}	31.4	27.1	12.8	28.7				
SO_x	46.0	24.8	7.3	21.9				
CH_4	43.2	21.1	8.2	27.5				
N_2O	41.9	21.3	9.8	27.0				
CO_2	45.1	20.2	8.4	26.3				
Urban Emissions								
VOC	66.7	8.8	3.1	21.4				
CO	51.9	16.7	8.4	23.1				
NO_x	51.2	17.0	8.6	23.1				
PM_{10}	60.8	11.9	5.3	22.1				
SO_x	44.1	20.8	11.4	23.7				

TABLE A.3 HEV: Conventional Material

	Percentage of Energy Consumption and Emissions per Component							
	Body	Powertrain System	Transmission System	Chassis (w/o battery)	Traction Motor	Generator	Electronic Controller	Fuel Cell Auxiliary
Energy use								
Total energy	35.1	16.4	11.5	27.8	3.2	3.2	2.6	
Fossil fuels	35.2	16.4	11.3	28.2	3.2	3.2	2.6	
Petroleum	36.0	12.7	9.8	31.8	3.3	3.3	3.2	
Total Emissions								
VOC	17.0	10.9	4.4	64.0	1.2	1.2	1.3	
CO	44.3	12.5	6.5	34.0	1.2	1.2	0.2	
NO_x	33.4	18.4	11.2	27.9	3.2	3.2	2.7	
PM_{10}	32.9	20.1	12.6	26.0	3.0	3.0	2.4	
SO_x	25.2	13.5	24.9	13.7	9.6	9.6	3.5	
CH_4	35.9	16.9	10.5	28.3	3.0	3.0	2.3	
N_2O	34.2	16.9	12.7	26.2	3.6	3.6	2.9	
CO_2	34.9	17.2	11.4	27.6	3.2	3.2	2.5	
Urban Emissions								
VOC	36.0	12.3	9.5	32.4	3.3	3.3	3.3	
CO	35.2	14.8	14.1	24.8	3.9	3.9	3.3	
NO_x	35.0	15.1	14.2	24.5	3.9	3.9	3.3	
PM_{10}	35.5	13.6	11.9	28.4	3.6	3.6	3.4	
SO_x	34.9	15.5	15.9	21.9	4.2	4.2	3.4	

TABLE A.4 HEV: Lightweight Material

	Percentage of Energy Consumption and Emissions per Component							
	Body	Powertrain System	Transmission System	Chassis (w/o battery)	Traction Motor	Generator	Electronic Controller	Fuel Cell Auxiliary
Energy use								
Total energy	46.1	13.7	7.4	27.6	1.8	1.8	1.5	
Fossil fuels	46.5	13.6	7.2	27.6	1.8	1.8	1.5	
Petroleum	66.2	5.9	3.4	21.5	1.0	1.0	1.0	
Total Emissions								
VOC	21.0	7.7	3.1	65.9	0.7	0.7	0.9	
CO	16.0	32.1	12.0	35.6	1.9	1.9	0.4	
NO_x	49.5	11.9	6.4	27.6	1.6	1.6	1.4	
PM_{10}	32.3	19.5	10.6	31.3	2.2	2.2	1.8	
SO_x	37.9	12.9	16.8	18.8	5.7	5.7	2.2	
CH_4	44.1	14.6	7.4	28.8	1.8	1.8	1.5	
N_2O	42.8	14.7	8.2	28.5	2.0	2.0	1.7	
CO_2	46.0	13.9	7.5	27.5	1.8	1.8	1.5	
Urban Emissions								
VOC	67.4	5.4	3.1	21.2	1.0	1.0	1.0	
CO	52.8	11.2	7.1	24.0	1.7	1.7	1.5	
NO_x	52.1	11.4	7.3	24.1	1.7	1.7	1.6	
PM_{10}	61.6	7.7	4.7	22.3	1.3	1.3	1.2	
SO_x	44.9	14.3	9.3	25.3	2.1	2.1	1.9	

TABLE A.5 FCV: Conventional Material

	Percentage of Energy Consumption and Emissions per Component							
	Body	Powertrain System	Transmission System	Chassis (w/o battery)	Traction Motor	Generator	Electronic Controller	Fuel Cell Auxiliary
Energy use								
Total energy	25.4	18.1	3.2	19.9	4.5		3.7	25.2
Fossil fuels	25.3	18.4	3.1	20.1	4.4		3.7	25.1
Petroleum	16.4	30.8	1.7	14.4	2.9		2.9	30.9
Total Emissions								
VOC	15.3	8.3	1.5	57.1	2.1		2.4	13.4
CO	46.5	1.3	2.6	35.4	2.4		0.5	11.3
NO_x	22.9	20.8	2.9	18.9	4.2		3.7	26.7
PM_{10}	28.7	11.7	4.2	22.5	5.0		4.1	23.8
SO_x	19.1	10.2	7.2	10.3	13.8		5.3	34.1
CH_4	27.5	16.6	3.1	21.5	4.4		3.5	23.4
N_2O	25.3	17.1	3.6	19.2	5.1		4.3	25.5
CO_2	25.6	17.8	3.2	20.0	4.4		3.7	25.3
Urban Emissions								
VOC	15.7	31.8	1.6	14.0	2.8		2.9	31.2
CO	21.6	22.0	3.3	15.0	4.6		4.1	29.4
NO_x	21.8	21.6	3.4	15.1	4.6		4.1	29.4
PM_{10}	18.0	27.8	2.3	14.3	3.5		3.4	30.6
SO_x	24.2	17.4	4.2	15.1	5.5		4.7	28.9

TABLE A.6 FCV: Lightweight Material

	Percentage of Energy Consumption and Emissions per Component							
	Body	Powertrain System	Transmission System	Chassis (w/o battery)	Traction Motor	Generator	Electronic Controller	Fuel Cell Auxiliary
Energy use								
Total energy	37.5	13.5	2.2	22.6	2.9		2.4	18.8
Fossil fuels	37.8	13.7	2.2	22.5	2.9		2.3	18.7
Petroleum	47.6	17.1	0.9	14.5	1.4		1.4	17.2
Total Emissions								
VOC	20.3	6.5	1.1	58.7	1.4		1.6	10.5
CO	19.0	3.0	5.5	41.5	4.7		1.0	25.3
NO_x	39.3	14.2	1.9	21.9	2.5		2.1	18.2
PM_{10}	28.1	10.5	3.5	29.4	3.9		3.1	21.4
SO_x	31.1	8.0	5.3	16.1	9.4		3.5	26.6
CH_4	36.7	13.1	2.3	24.1	3.0		2.4	18.5
N_2O	35.2	12.8	2.5	24.2	3.3		2.7	19.2
CO_2	37.5	13.4	2.3	22.6	2.9		2.3	19.0
Urban Emissions								
VOC	48.1	17.3	0.8	14.1	1.3		1.3	17.0
CO	40.8	14.3	2.0	18.9	2.6		2.2	19.1
NO_x	40.4	14.2	2.1	19.1	2.6		2.3	19.2
PM_{10}	45.4	16.2	1.3	15.9	1.8		1.7	17.8
SO_x	36.1	12.4	2.8	21.8	3.4		2.9	20.6

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