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Chapter 6: Comparing Greenhouse Gas Emissions

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We turn now to comparing the environmental impacts of our alternative fuel / advanced vehicle pathways. Reducing greenhouse gas (GHG) emissions from vehicles and fuels is one key to lessening transportation's contribution to the climate change problem. This chapter presents much of what is known about the relative emissions of GHGs from battery, fuel cell, and plug-in hybrid electric vehicles versus conventional internal combustion engine vehicles.

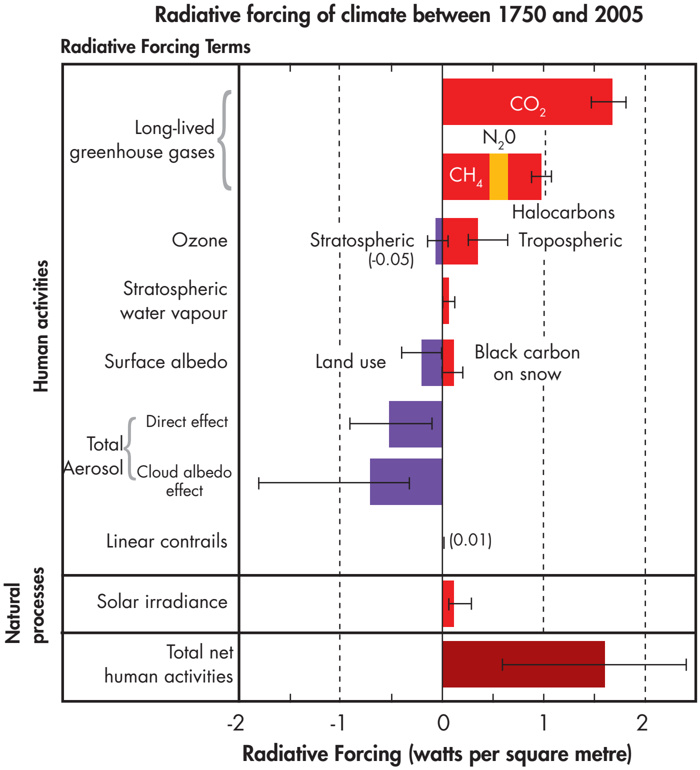
We first give some background on the issue of GHG emissions and their climate impact, and review previous research. We then discuss how GHG emissions from electric vehicle (EV) fuel cycles are estimated, before reviewing and comparing recent estimates of GHG emissions from the fuel cycles of various types of EVs. (Note that researchers generally distinguish emissions related to the life cycle of fuels and energy used to power the vehicle—the fuel cycle—from emissions related to the life cycle of the vehicle and the materials it is made from—the vehicle life cycle. In this chapter we focus mainly but not exclusively on fuel-cycle emissions, because there has been relatively little work on vehicle life-cycle emissions.) We next examine the potential for EVs to rapidly scale up to meet the climate challenge, and finally we discuss key uncertainties, areas for further research, and conclusions.

Background and Previous Research

GHGs are a number of different gases and aerosols that have climatic impacts. For EVs of various types that are fueled with electricity and/or hydrogen, the GHGs of greatest interest are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), nitrogen oxides (NO_X), the latest automotive refrigerants (HFC-134a, HFO-1234yf, and so on), ozone (O_3), and direct and secondary particulates from power production. Some other gases with apparently lesser significance (due in part to their relatively weak global warming potentials) but that also contribute are carbon monoxide (CO) and various nonmethane hydrocarbons (NMHCs).

Scientists compare the climatic impact of these various gases in terms of what is called radiative forcing. Radiative forcing is a direct measure of the imbalance between the energy flowing into the earth's atmosphere from the sun and the energy being reflected and radiated back out into space; if there is more energy coming into than leaving the atmosphere, the earth is going to heat up. The year 1750, before world industrialization began, is used by many scientists and the Intergovernmental Panel on Climate Change as the baseline or zero point in relation to which radiative forcing is computed. When we look at radiative forcing, CO_2 has had the single largest effect, but various other gases and atmospheric species are significant as well. For example, ozone and aerosols—which are omitted from most analyses of GHG emissions from EVs—have had a greater absolute radiative forcing effect than nitrous oxide.

RADIATIVE FORCING 1750–2005 FROM GREENHOUSE GASES CAUSED BY HUMAN AND NATURAL ACTIVITIES



When we look at radiative forcing (the imbalance between the energy flowing into the earth's atmosphere from the sun and the energy being reflected and radiated back out into space) between 1750 and 2005, human-generated CO_2 has had the single largest effect, but various other gases and atmospheric species are significant as well.

KEY GREENHOUSE GASES: INCREASES IN ATMOSPHERIC CONCENTRATIONS 1750–2007 AND RADIATIVE FORCING EFFECTS

This table summarizes the pre-industrial (1750) and current (2007) atmospheric levels in parts per million of four key GHGs, as well as their total increase and their radiative forcing effect in watts per square meter. CO_2 accounts for the largest radiative forcing effect, but the others also make significant contributions. Source: Oak Ridge National Laboratory, Carbon Dioxide Information Analysis Center (2009), http://cdiac.ornl.gov.

Greenhouse Gas	Pre-Industrial Level	Current Level	Increase Since 1750	Radiative Forcing (W/m2)
Carbon dioxide	280 ppm	385 ppm	105 ppm	1.66
Methane	700 ppb	1741 ppb	1045 ppb	0.48
Nitrous oxide	270 ppb	321 ppb	51 ppb	0.16
Ozone	25 ppb	34 ppb	9 ppb	0.35
CFC-12	0 ppt	533 ppt	533 ppt	0.17

Research on GHG emissions from fuel cycles related to electric vehicle use dates back to at least the early 1990s, when the introduction of battery electric vehicles (BEVs) by major automakers and growing concern about climate change spurred interest. At that point, most studies focused on criteria air pollutants (carbon monoxide, lead, nitrogen dioxide, ozone, particulate matter, and sulfur dioxide), but some GHGs were occasionally included. Significant research efforts in the 1990s included those by university and government lab research groups[1] and consulting firms.[2] The next decade saw major efforts by automakers,[3] industry research organizations,[4] and other groups. More recently, there has been a series of more sophisticated efforts based on further developments in electric vehicle technology and the concept of plug-in hybrid electric vehicles (PHEVs).

Among the most useful tools for analyzing and comparing emissions from a wide range of vehicle and fuel combinations are two models developed by academic researchers: the Life-cycle Emissions Model (LEM) from UC Davis and the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model from Argonne National Lab. Both of these are well developed with long histories and are also relatively well documented. Other studies have examined more specific vehicle and fuel pathways involving EVs with regard to their GHG emissions and have yielded interesting insights. Several of these are also discussed in this chapter.

RECENT TRANSPORTATION FUEL-CYCLE OR LIFE-CYCLE MODELING EFFORTS

Various efforts have examined the emissions of GHGs from electric vehicle fuel cycles or life cycles, but focusing on different types of vehicles and fuel feedstock options, and at varying levels of detail. Here we compare the structure and coverage of several of these modeling efforts. This table gives a good sense of key aspects of emission comparisons and the extent to which each of the models encompasses or addresses them.

Project	**GM-ANL U.S.**	**GM–LBST Europe**	**MIT 2020/2035**	**EUCAR**
Region **Time frame**	North America Near term (about 2010)	Europe 2010	Based on U. S. data 2020/2035	Europe 2010 and beyond
Transport modes	LDV (light-duty truck)	LDV (European mini-van)	LDV (mid-size family passenger car)	LDV (compact 5-seat European sedan)
Vehicle drive-train type	ICEVs, HEVs, BEVs, FCVs	ICEVs, HEVs, FCVs FCVs	ICEVs, HEVs, BEVs,	ICEVs, HEVs, FCVs
Motor fuels	Gasoline, diesel, naptha, FTD, CNG, methanol, ethanol, CH2, LH2, electricity	Gasoline, diesel, naptha, FTD, CNG, methanol, ethanol, CH2, LH2	Gasoline, diesel, FTD, methanol, CNG, CH2, electricity (2020)/plus ethanol (2035)	Gasoline, diesel, FTD, CNG, ethanol, FAME, DME, aptha, methanol, CH2, LH2
Fuel feedstocks	Crude oil, natural gas, coal, crops, ligno-cellulosic biomass, renewable and nuclear power	Crude oil, natural gas, coal, crops, ligno-cellulosic biomass, waste, renewable and nuclear power	Crude oil, natural gas, renewable and nuclear power (2020)/ plus corn, cellulose, tar sands (2035)	Crude oil, natural gas, coal, nuclear, wind, sugar beets, wheat, oil seeds, wood
Vehicle energy-use modeling, including drive cycle	GM simulator, U.S. combined city/ highway driving	GM simulator, European Drive Cycle (urban and extra-urban driving)	MIT simulator (2020)/ Advisor (2035), U.S. combined city and highway driving (2020)/various cycles (2035)	Advisor (NREL simulator), New European Drive Cycle
Fuel life cycle	GREET model	LBST E2 I-O model and database	literature review (2020)/ GREET and other sources (2035)	LBST E2 I-O model and database (review & update of GM et al. [2002])
Vehicle and material life cycle	Addressed in GREET 2.7	Addressed in GREET 2.7	Detailed literature review and analysis (2020)/GREET 2.7 (2035)	Not included
GHGs [CEFs]	CO_2, CH_4, N_2O [IPCC] (other pollutants included as non-GHGs)	CO_2, CH_4, N_2O [IPCC]	CO_2, CH_4 (2020)/ CO_2, CH_4, N_2O (2035) [IPCC]	CO_2, CH_4, N_2O [IPCC]
Infrastructure	Not included	Not included	Not included	Not included
Price effects	Not included	Not included	Not included	Not included

Project	**ADL AFV LCA**	**EcoTraffic**	**CMU I-O LCA**	**Japan AFVs CO_2**	**LEM**
Region	United States	Generic, but weighted toward European conditions	United States	Japan	Multi-country (primary data for U.S.; other data for up to 30 countries)
Time frame	1996 baseline, future scenarios	Between 2010 and 2015	Near term	Near term?	Any year from 1970 to 2050
Transport modes	Subcompact cars	LDVs (generic small passenger car)	LDVs (midsize sedan)	LDVs (generic small passenger car)	LDVs, HDVs, buses, light-rail transit, heavy-rail transit, minicars, scooters, offroad vehicles
Vehicle drive-train type	ICEVs, BEVs, FCVs	ICEVs, HEVs, FCVs	ICEVs	ICEVs, HEVs, BEVs	ICEVs, BEVs, FCVs
Motor fuels	Gasoline, diesel, LPG, CNG, LNG, methanol, ethanol, CH2, LH2, electricity	Gasoline, diesel, FTD, CNG, LNG, methanol, DME, ethanol, CH2, LH2	Gasoline, diesel, biodiesel, CNG, methanol, ethanol	Gasoline, diesel, electricity	Gasoline, diesel, LPG, FTD, CNG, LNG, methanol, ethanol, CH2, LH2, electricity
Fuel feedstocks	Crude oil, natural gas, coal, corn, ligno-cellulosic biomass, renewable and nuclear power	Crude oil, natural gas, ligno-cellulosic biomass, waste	Crude oil, natural gas, crops, ligno-cellulosic biomass	Crude oil, natural gas, coal, renewable and nuclear power	Crude oil, natural gas, coal, crops, lignocellulosic biomass, renewable and nuclear power
Vehicle energy-use modeling, including drive cycle	Gasoline fuel economy assumed; AFV efficiency estimated relative to this	Advisor (NREL simulator), New European Drive Cycle	Gasoline fuel economy assumed; AFV efficiency estimated relative to this	None; fuel economy assumed	Simple model based on SIMPLEV-like simulator, U.S. combined city/ highway driving
Fuel life cycle	Arthur D. Little emissions model, revised	Literature review	Own calculations based on other models (LEM, GREET)	Values from another study	Detailed internal model
Vehicle and material life cycle	Not included	Not included	Economic Input-Output Life Cycle Analysis software (except end-of-life)	Detailed part-by-part analysis	Internal model based on detailed literature review and analysis
GHGs [CEFs]	CO_2, CH_4 [partial GWP] (other pollutants included as non-GHGs)	None (energy efficiency study only)	CO_2, CH_4, N_2O? [IPCC] (other pollutants included as non-GHGs)	CO_2	CO_2, CH_4, N_2O, NO_x, VOC, SO_x, PM, CO, H_2, HFCs, CFCs [own CEFs, also IPCC CEFs]
Infrastructure	Not included	Not included	Not included	Not included	Crude representation
Price effects	Not included	Not included	Not included (fixed-price I-O model)	Not included	A few simple quasi-elasticities

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

Region	The countries or regions covered by the analysis.
Time frame	The target year of the analysis.
Transport modes	The types of passenger transport modes included. LDVs = light-duty vehicles, HDVs = heavy-duty vehicles.
Vehicle drivetrain type	ICEVs = internal combustion engine vehicles, HEVs = hybrid electric vehicles (vehicles with an electric and an ICE drivetrain), BEVs = battery electric vehicles, FCVs = fuel cell electric vehicles.
Motor fuels	Fuels carried and used by motor vehicles. FTD = Fischer-Tropsch diesel, CNG = compressed natural gas, LNG = liquefied natural gas, CH2 = compressed hydrogen, LH2 = liquefied hydrogen, DME = dimethyl ether, FAME = fatty acid methyl esters.
Fuel feedstocks	The feedstocks from which the fuels are made.
Vehicle energy-use modeling	The models or assumptions used to estimate vehicular energy use (which is a key part of fuel-cycle CO2 emissions), and the drive cycle over which fuel usage is estimated (if applicable).
Fuel life cycle	The models, assumptions, and data used to estimate emissions from the life cycle of fuels.
Vehicle and materials life cycle	The life cycle of materials and vehicles, apart from vehicle fuel. The life cycle includes raw material production and transport, manufacture of finished materials, assembly of parts and vehicles, maintenance and repair, and disposal.
GHGs and CEFs	The pollutants (greenhouse gases, or GHGs) that are included in the analysis of CO2-equivalent emissions, and the CO2-equivalency factors (CEFs) used to convert non-CO2 GHGs to equivalent amount of CO2 (IPCC = factors approved by the Intergovernmental Panel on Climate Change [IPCC]).
Infrastructure	The life cycle of energy and materials used to make and maintain infrastructure, such as roads, buildings, equipment, rail lines, and so on. (In most cases, emissions and energy use associated with the construction of infrastructure are small compared with emissions and energy use from the end use of transportation fuels.)
Price effects	The relationships between prices and equilibrium final consumption of a commodity (for example, crude oil) and an "initial" change in supply of or demand for the com modity or its substitutes, due to the hypothetical introduction of a new technology or fuel.

How Emissions Are Estimated

Although battery electric vehicles (BEVs) and fuel cell vehicles (FCVs) are often called zero-emission vehicles, and although most BEV and FCV fuel options do entail significant reductions in GHG and criteria pollutant emissions compared with conventional gasoline vehicles, this is not always the case—for example, if coal without carbon capture is the sole feedstock for the electricity for BEV charging. Here we take a closer look at the components of electric vehicle emissions and how they are estimated.

Emissions of GHGs from conventional gasoline internal combustion engine vehicles (ICEVs) are a combination of "upstream" emissions from fuel production and distribution, and "downstream" emissions from vehicle operation. By contrast, GHG emissions from the life cycle of fuels for BEVs and FCVs are entirely in the form of upstream emissions related to the production of electricity or hydrogen, with no emission from the vehicles themselves (except for water vapor in the case of FCVs, and any emissions related to heating and cooling sytems). The emissions from these vehicles are thus entirely dependent on the manner in which the electricity and/or hydrogen is produced, along with the energy efficiency of the vehicle (typically expressed in watt hours per mile or kilometer for BEVs, and miles or kilometers per kilogram for hydrogen-powered vehicles). For PHEVs emissions are a complex combination of upstream and in-use emissions since these vehicles use a combination of grid electrical power and another fuel that is combusted (or potentially converted with a fuel cell) onboard the vehicle. There can be significant tailpipe emissions depending on travel patterns and the type of plug-in hybrid, along with any strategies to prevent criteria pollutant emissions from the catalyst-based control system when it is periodically starting up from low temperatures.

Emissions of CO_2 from fuel combustion are comparatively easy to estimate since virtually all of the carbon in fuel oxidizes to CO_2. In contrast, combustion emissions of all the other greenhouse gases are a function of many complex aspects of combustion dynamics (such as temperature, pressure, and air-to-fuel ratio, among other factors) and of the type of emission control systems used, and hence cannot be derived from one or two basic characteristics of a fuel. Instead, we need to use published emission factors for each combination of fuel, end-use technology, combustion conditions, and emission control system. Likewise, noncombustion emissions of greenhouse gases as part of the fuel cycle (for example, gas flared at oil fields, or N_2O produced and emitted from fertilized soils) cannot be derived from basic fuel properties and instead must be measured and estimated source by source and gas by gas. We have provided a compendium of many of these emission factors,[14] but note that some of them have since been updated based on more recent data than were available at the time our compendium was published.

Upstream emissions

The emissions associated with fuel production, or upstream emissions, dominate the fuel cycles associated with BEVs and FCVs. For BEVs, upstream emissions consist of emissions from the production and delivery of electricity for vehicle charging. These emissions vary regionally based on the fuels and types of power plants used to generate electricity. For FCVs, emissions are again entirely upstream, from the production, delivery, and dispensing of gaseous or liquid hydrogen, with the exception of small amounts of water vapor emitted directly and any emissions of refrigerants used for air conditioning. For PHEVs, on the other hand, total emissions consist of a mix of upstream emissions from electricity generation (proportional to the extent that the vehicle is recharged with electricity) and both upstream and in-use emissions from fuel combustion from the vehicle engine (or potentially conversion in a fuel cell).

Various studies have examined the upstream emissions from vehicle fuel production, especially from gasoline and diesel fuel and electricity production but also for other fuels such as compressed natural gas, ethanol and methanol, hydrogen, and biodiesel. These have been conducted in various regions (mainly in the United States and Europe) and with various emphases (various vehicle type/technology combinations, CO_2 or a whole suite of gases, sometimes including criteria pollutants as well as GHGs, and so on). Emissions from electricity generation processes are generally well known and well studied; this is less true for hydrogen production, but in most cases these emissions also are well understood. Some novel hydrogen production methods, and those that are based on conversion from biofuels, have somewhat complex and certainly not completely understood and established levels of emissions of GHGs.

Combustion or "in-use" emissions

Emissions of GHGs from engine combustion processes result from a complex combination of combustion dynamics and emission controls, and vary widely by fuel type, engine operation, and emission control system applied (if any). For EVs, combustion emissions from the vehicle are limited to PHEVs that either use a combustion engine and generator as a "range extender" for what is fundamentally an electric vehicle driveline, or where the engine is connected in parallel to the driveline with the electric motor. Either way, the combustion engine operates periodically to supplement the electric motor operation and thereby produces GHG emissions. Additional in-use emissions from EVs include those that can occur from a supplemental fuel-fired heater in the passenger cabin for occasional use in colder climates, and from vehicle air-conditioning systems, where GHGs are often used as refrigerants.

Key GHG emission products from combustion engines include CO_2, CH_4, N_2O, CO, NO_x, soot, and various air toxics and other trace chemicals that can play roles in the formation of secondary particulates and other gases (such as ozone) that are known to have climatic effects.

A CLOSER LOOK AT ESTIMATING KEY GHG EMISSIONS

Carbon dioxide

Carbon dioxide is emitted directly from combustion engine vehicles, and these emissions are closely correlated with the total carbon in the vehicle fuel. The U.S. Environmental Protection Agency (EPA) uses a carbon content estimate of 2,421 grams of carbon per gallon of gasoline and 2,778 grams of carbon per gallon of diesel fuel for purposes of estimating CO_2 emissions from combustion of these fuels.[15] To approximate the CO_2 emissions resulting from combustion of these fuels, we multiply the fuel carbon content by an "oxidization factor" and by the ratio of molecular weights of CO_2 (44) to elemental carbon (12). This results in the following sample calculations, assuming a 99-percent oxidization factor (the value used by the EPA):

CO_2 emissions from a gallon (liter) of gasoline = 2,421 grams x 0.99 x (44/12) = 8,788 grams => 8.8 kg/gallon = 2.3 kg CO_2/liter

CO_2 emissions from a gallon (liter) of diesel = 2,778 grams x 0.99 x (44/12) = 10,084 grams => 10.1 kg/gallon = 2.7 kg CO_2/liter

These factors can be used for reasonable first-order approximations of the direct tailpipe emissions of CO_2 from combustion engine vehicles using gasoline and diesel fuel.[16]

Carbon dioxide is also emitted directly from electricity-generating power plants, particularly those that burn fossil fuels or biomass. In the case of biomass-powered facilities, the CO_2 emitted represents a partial or full closed loop, as biomass removes carbon dioxide from the atmosphere as it is grown. Renewable and nuclear facilities emit little or no CO_2 directly but may have significant emissions through other parts of their full fuel cycle (for example, during construction of nuclear plants, uranium mining, or construction of wind turbine systems). In general, these emissions are much lower than lifetime emissions of coal-fired power plants, which are used for up to 50 years and emit GHGs at a level locked in with each new plant built. For example, an estimated 100 million tons of CO_2 are generated by a 500 MW coal-fired power plant over a 40-year lifetime.[17] For purposes of comparison, a 2004 article reports that coal-fired power plants in the United States emit about 1,200 kg CO_2 per MWh, and natural gas combined-cycle plants emit about 700 kg CO_2 per MWh, while renewable and nuclear sources emit on the order of 25 to 75 kg CO_2 per MWh.[18]

Methane

Methane (CH_4) has a 100-year global warming potential (GWP) value of 25, meaning that each gram has 25 times the radiative-forcing impact of a gram of CO_2 over that time period.[19] It is emitted directly by both combustion engine vehicles and power plants.

Methane emissions from combustion engines are a function of the type of fuel used, the design and tuning of the engine, the type of emission control system, the age of the vehicle, and other factors. Although methane emissions per se are not regulated in the United States, the systems used to control emissions of nonmethane and total hydrocarbons from combustion engines do to some extent control CH_4 emissions. Not much data exists on CH_4 emissions from high-mileage gasoline light-duty vehicles, but these emissions seem to increase somewhat as a function of catalyst age, as do N_2O emissions.[20] There are many CH_4 emissions tests for gasoline vehicles, but comparatively few for diesel and alternative-fuel ones.

Power plants also produce relatively small amounts of methane as unburned hydrocarbons, with emission factors that are available in comprehensive databases from the U.S. EPA and the Intergovernmental Panel on Climate Change (IPCC).[21] Natural gas power plants can also produce fugitive methane emissions from pipelines, purging, and venting procedures.[22]

Nitrous oxide

N_2O is a potent GHG with a 100-year GWP value of 298[23] that is emitted directly from motor vehicles and power plants. Emission factors for both sources are available in comprehensive databases from the U.S. EPA and the Intergovernmental Panel on Climate Change (IPCC).[24] Emissions of N_2O from combustion engines have been estimated by other research centers as well.[25] Generally, N_2O emissions from power plants are a small fraction of total fuel-cycle CO_2-equivalent (CO_2e) GHG emissions from vehicles.

N_2O emissions from catalyst-equipped gasoline light-duty vehicles depend significantly on the type and temperature of catalyst, rather than total oxide of nitrogen (NO_x) levels or fuel nitrogen content. Gasoline contains relatively little nitrogen and therefore fuel NO_x and N_2O emissions from autos are low; as a result, cars without catalytic converters produce essentially no net N_2O. However, cars with catalytic converters can produce significant N_2O when the catalyst starts out cold. Essentially, as a vehicle warms up and the catalyst temperature increases, a "pulse" of nitrous oxide is released. This occurs until the catalyst temperature increases beyond the temperature window for N_2O formation, after which emissions of N_2O are minimal. Older catalysts have a wider window for formation, hence older three-way catalyst equipped vehicles tend to emit more N_2O than newer vehicles.

This temperature dependence of N_2O formation has important implications regarding potential emissions from PHEVs. If the combustion engine in a PHEV is cycling on and off, the catalyst may be cooling off and reheating multiple times during a trip instead of a single time, which could result in increased emissions of N_2O. One way to mitigate this would be to electrically heat the catalyst to keep it from cooling off, but this would come at some (perhaps small) net energy penalty for the vehicle. This issue of potentially increased emissions of N_2O from PHEVs appears to be a significant issue for further study.

Power plants also emit N_2O. Although the power plant combustion chemistry of N_2O is quite complex, several general trends are apparent. Higher N_2O emissions are generally associated with lower combustion temperatures, higher-rank fuels, lower ratios of fuel oxygen to fuel nitrogen, higher levels of excess air, and higher fuel carbon contents.[26]

Other greenhouse gases

Emissions of other GHGs from the production and use of EVs include criteria pollutants, such as CO, NMHCs, NO_X, and SO_X, and automotive refrigerants such as CFC and HFC-134a. Criteria pollutants typically have weak direct-forcing GWP values and are emitted in much lower quantities than CO_2 but can contribute to the formation of compounds that do have a strong radiative forcing effect, such as ozone and sulfate aerosol.

Also potentially important are the refrigerants used in automotive air conditioners, which can be released during accidents or improper maintenance procedures, and which can have very high GWP values. Automotive air conditioners used the refrigerant R-12 throughout the 1970s and 1980s and transitioned to HFC-134a in the 1990s, primarily to help protect the earth's ozone layer. HFC-134a is still a potent GHG, however, with a 100-year GWP value of 1430.[27] Other non-ozone-depleting refrigerants such as HFO-1234yf and CO_2 are being investigated as lower GWP options that can still be effective in automotive applications.

Emissions of CO_2 and other GHGs from the vehicle life cycle

What we call the vehicle life cycle includes producing the materials that compose a vehicle and the life cycle of the vehicle itself. The life cycle of automotive materials, such as steel, aluminum, and plastics, extends from production of raw ore to delivery of finished materials to assembly plants, and includes recycled materials as well as materials made from virgin ore. The life cycle of the vehicle itself includes vehicle assembly, transportation of finished motor vehicles and motor-vehicle parts, and vehicle disposal, but not the operational emissions from the vehicle, which we consider separately.

In the vehicle life cycle there are two broad sources of GHG emissions, similar to the emissions sources in the industrial sector in general: (1) emissions related to the use of process energy (for example, fuels burned in industrial boilers to provide process heat), and (2) noncombustion emissions from process areas (for example, emissions from the chemical reduction of alumina to aluminum, or NMHC emissions from painting auto bodies). Energy use and process areas can produce CO_2, CH_4, N_2O, CO, NMHCs, SO_X, NO_X, particulate matter, and other pollutants relevant to life-cycle analysis of GHG emissions. The most extensive of the vehicle life-cycle assessment models, including the LEM and the GREET model, include characterization of these vehicle manufacturing emissions and their contribution to the overall emissions from various vehicle/fuel life cycles.

In general, manufacturing emissions can be somewhat higher for some types of EVs (such as those that use large nickel-based batteries) than for conventional vehicles. The vehicle manufacturing emissions for EVs are often proportionately larger than for conventional vehicles because of their lower vehicle-operation life-cycle (i.e., fuel cycle) emissions. A key point is that because vehicle operational emissions dominate, EVs are often much cleaner than conventional vehicles in an overall sense even if they have slightly to somewhat higher vehicle manufacturing emissions.

PHEV emissions

PHEVs generate GHG emissions from three distinct sources: the life cycle of fuels used in the ICE, the life cycle of electricity used to power the electric drivetrain, and the life cycle of the vehicle and its materials. A number of studies, reviewed later, have estimated GHG-emission reductions from PHEVs relative to conventional ICEVs considering the life cycle of fuels and the life cycle of electricity generation. Because energy use and emissions for the vehicle life cycle are an order of magnitude smaller than energy use and emissions for the fuel and electricity life cycle,[28] and because there are relatively few studies of emissions from the PHEV vehicle life cycle, we do not consider the vehicle life cycle in much detail here.

Various vehicle design and operational strategies are available for PHEVs, and these can have important emissions implications. For example, PHEVs can be designed to be either charge-depleting (CD) or charge-sustaining (CS), and this affects the relative levels of electricity and gasoline used.[29] PHEVs with true all-electric range (AER) could allow drivers to make some trips without the engine turning on at all (or at least very little), relying almost entirely on the energy stored in the battery. However, some PHEVs are not designed for this and instead employ "blended mode" operation, where the engine turns off and on periodically even at relatively high states of battery charge. And in other cases, even for "series type" PHEVs with extensive AER, some engine operation is to be expected both on longer trips and in other cases where the PHEV battery becomes discharged before it can be charged again.

With regard to GHG emissions from the life cycle of petroleum fuels used in ICEs for PHEVs, these depend mainly on the fuel use of the engine and the energy inputs and emission factors for the production of crude oil and finished petroleum products. A number of studies estimate the fuel use of ICEs in PHEVs; for example, Bradley and Frank[30] found a variety of simulated and tested PHEVs to reduce gasoline consumption by 50 percent to 90 percent. GHG emissions from the use of electricity by PHEVs depend mainly on the energy use of the electric drivetrain, the efficiency of electricity generation, and the mix of fuels used to generate electricity.

The energy use of the electric drivetrain in a PHEV is a function of the size and technical characteristics of the electric components (battery, motor, and controller), the vehicle driving and charging patterns, and the control strategy that determines when the vehicle is powered by the battery and when it is powered by the ICE. The studies reviewed here consider two basic control strategies: all-electric and blended. In a PHEV with a large all-electric range (AER), the electric drivetrain is sized to have enough power to be able to satisfy all power demands over the drive cycle without any power input from the engine. By contrast, in the blended strategy, the electric drivetrain and the engine work together to supply the power over the drive cycle. The blended strategy can be either "engine dominant," in which case the electric motor is used to keep the engine running at its most efficient torque/rpm points, or "electric dominant," in which case the engine turns on only when the power demand exceeds the capacity of the electric drivetrain.[31]

The efficiency of electricity generation can be estimated straightforwardly on the basis of data and projections in national energy information systems, such as those maintained by the Energy Information Administration (for the U.S.) (www.eia.doe.gov/fuelelectric.html) or the International Energy Agency (for the world) (www.iea.org). Life-cycle models, such as the GREET model and the LEM, also have comprehensive estimates of GHG emissions from the life cycle of electricity generation for individual types of fuels.

However, it is not straightforward to estimate the mix of fuels used to generate the electricity that actually will be used to charge batteries in PHEVs. The "marginal" generation fuel mix depends on the interaction of supply-side factors, such as cost, availability, and reliability, with anticipated hourly demand patterns, and can vary widely from region to region.[32] This supply-demand interaction can be represented formally with models that attempt to replicate how utilities actually dispatch electricity to meet demand. A few studies, reviewed below, have used dispatch models to estimate the mix of fuels used to generate electricity for charging PHEVs. However, as dispatch models generally are not readily available, most researchers either have assumed that the actual marginal mix of fuels is the year-round average mix or else have reported results for different fuel-mix scenarios.

OVERVIEW OF THE LEM, THE GREET MODEL, AND OTHER MAJOR EFFORTS

The Life-cycle Emissions Model (LEM) uses life-cycle analysis (LCA) to estimate energy use, criteria air-pollutant emissions, and CO_2-equivalent greenhouse-gas emissions from a wide range of energy and material life cycles. It includes life cycles for passenger transport modes, freight transport modes, electricity, materials, heating and cooling, and more. For transport modes, it represents the life cycle of fuels, vehicles, materials, and infrastructure. It calculates energy use and life-cycle emissions of all regulated air pollutants plus GHGs. It includes input data for up to 30 countries, for the years 1970 to 2050, and is fully specified for the United States.

For motor vehicles, the LEM calculates life-cycle emissions for a variety of combinations of end-use fuel, fuel feedstocks, and vehicle types. The fuel and feedstock combinations included in the LEM for light-duty vehicles are shown in the table below.

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

ICEV = internal combustion engine vehicle; FCV = fuel cell vehicle; BEV = battery electric vehicle. Cells with BEVs and FCVs are highlighted in blue.

The LEM estimates emissions of CO_2, CH_4, N_2O, carbon monoxide (CO), total particulate matter (PM), PM less than 10 microns in diameter (PM10), PM from dust, hydrogen (H_2), oxides of nitrogen (NOx), chlorofluorocarbons (CFC-12), nonmethane organic compounds (NMOCs, weighted by their ozone-forming potential), hydrofluorocarbons (HFC-134a), and sulfur dioxide (SO_2). These species are reported individually and aggregated together weighted by CO_2 equivalency factors (CEFs).

These CEFs are applied in the LEM the same way that global warming potentials (GWPs) are applied in other LCA models but are conceptually and mathematically different from GWPs. Whereas GWPs are based on simple estimates of years of radiative forcing integrated over a time horizon, the CEFs in the LEM are based on sophisticated estimates of the present value of damages due to climate change. Moreover, whereas all other LCA models apply GWPs to only CH_4 and N_2O, the LEM applies CEFs to all of the pollutants listed above. Thus, the LEM is unique for having original CEFs for a wide range of pollutants. The following table compares LEM CEFs with IPCC GWPs.

Pollutant	LEM CEFs (year 2030)	IPCC 100-yr. GWPs
NMOC-C	3.664	3.664
NMOC-03/CH4	3	not estimated
CH4	14	23
CO	10	1.6
N2O	300	296
NO2	-4	not estimated
SO2	-50	not estimated
PM (black carbon)	2,770	not estimated
CFC-12	13,000	8,600
HFC-134a	1,400	1,300
PM (organic matter)	-240	not estimated
PM (dust)	-22	not estimated
H2	42	not estimated
CF4	41,000	5,700
C2F6	92,000	11,900
HF	2000	not estimated

CEF = CO_2-equivalency factor; GWP = global warming potential. Source: LEM CEFs from the year 2005 version of the LEM; IPCC GWPs from Intergovernmental Panel on Climate Change, Climate Change 2001: The Scientific Basis, *ed. J. T. Houghton, Y. Ding, et al.*

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model has been under development at Argonne National Laboratory since about 1995. The model assesses more than 100 fuel production pathways and about 75 different vehicle technology / fuel system types, for hundreds of possible combinations of vehicles and fuels. It has more than 10,000 users worldwide and has been adapted for use in various countries around the world.[33] GREET estimates emissions of CO_2, plus CO_2-equivalent emissions of CH_4 and N_2O (based on the IPCC's GWPs), from the fuel cycle and the vehicle life cycle.

GREET 1.8c, released in 2009, is noteworthy for its much expanded treatment of PHEVs along with updated projections of electricity grid mixes in the United States based on the latest projections by the Energy Information Administration. This latest version of the model analyzes PHEVs running on various fuels—not just gasoline and diesel—along with electricity. The additional fuels it analyzes include corn-based ethanol (E85—85 percent blend with gasoline), biomass-derived ethanol (E85), and hydrogen produced by three different methods: (1) steam methane reforming of natural gas (distributed, small scale); (2) electrolysis of water using grid power (distributed, small scale); and (3) biomass-based hydrogen (larger scale). The analysis also examines different regions of the United States, and the United States on average, for power plant mixes and emission factors for BEV and PHEV charging and other electricity demands.

Various other studies of the relative GHG emission benefits of different types of EVs have been done by other university and national laboratory research groups, consulting firms, government agencies, nongovernmental organizations, and industry research groups. Key organizations that have been involved include the Japanese Ministry of Economy, Trade, and Industry; Japanese research universities including the University of Tokyo; the International Energy Agency; the European Union; Natural Resources Canada; and many other government and research organizations around the world. In the United States, in addition to the national laboratories and the University of California, key efforts have been led by the Massachusetts Institute of Technology, Carnegie Mellon University, Stanford University, the Pacific Northwest Laboratory, the National Renewable Energy Laboratory, General Motors, and the Electric Power Research Institute, among others. The results of several of these efforts are discussed and compared below. In our review we emphasize the most extensive studies that included BEVs and FCVs as well as PHEVs, but we note that there are carefully performed studies that look at a narrower range of vehicle technologies (for example, that only compare BEVs to ICEVs).

Estimates of GHG Emissions from EVs

Now that we have explored how the various GHG emissions from EVs are estimated, we will look at the results of a few of the major modeling efforts. We first examine the results of the well-developed Life-cycle Emissions and GREET models regarding emissions of BEVs and FCVs. Then we look at results for BEVs and FCVs from other major modeling efforts, before considering the results of major studies of potential emission reductions from PHEVs.

LEM emission results for BEVs and FCVs

Using the LEM, we find that in the United States in the year 2010, BEVs reduce fuel-cycle GHG emissions by 20 percent (in the case of coal) to almost 100 percent (in the case of hydro and other renewable sources of power). If the vehicle life cycle is included, the reduction is lower, in the range of 7 percent to 70 percent, because emissions from the BEV life cycle are larger than emissions from the gasoline ICEV life cycle due to the production of materials used in the battery. The emission reduction percentages are generally higher in the year 2050, mainly because of the improved efficiency of vehicles and power plants. The emission reductions in Japan, China, and

Germany are similar to those in the United States, except that in those cases the reduction using coal power is higher, due to the greater efficiency of coal plants in Germany and Japan, and to high SO_2 emissions from coal plants in China (SO_2 has a negative CEF).

In the United States in 2010, FCVs using "reformed" gasoline or methanol made from natural gas offer roughly 50-percent reductions in fuel-cycle GHG emissions. FCVs using methanol or hydrogen made from wood reduce fuel-cycle GHG emissions by about 85 percent; FCVs using hydrogen made from natural gas reduce emissions by about 60 percent, and FCVs using hydrogen made from water (using clean electricity) reduce fuel-cycle GHG emissions by almost 90 percent. Again, the reductions are slightly lower if the vehicle life cycle is included, and slightly higher in the year 2050. The patterns in Japan, China, and Germany are essentially the same, because the vehicle technology and the fuel production processes are assumed to be the same as in the United States.

LEM: ELECTRIC VEHICLE VS. GASOLINE ICEV EMISSIONS FOR FOUR COUNTRIES, 2010 AND 2050

These tables present the final gram-per-km emission results from the LEM by vehicle/fuel/feedstock, and percentage changes relative to conventional gasoline vehicles, for the United States, China, Japan, and Germany, for the years 2010 and 2050.

ICEV = internal combustion engine vehicle; BEV = battery electric vehicle; FCV = fuel cell vehicle; NG = natural gas; Hydro = hydro power; Other = solar, geothermal power; RFG = reformulated gasoline; Ox = oxygenate (ETBE, MTBE, ethanol, methanol) (volume percent in active gasoline); M = methanol (volume percent in fuel for methanol vehicle; remainder is gasoline); CNG = compressed natural gas; LNG = liquefied natural gas; CH2 = compressed hydrogen; E = ethanol (volume percent in fuel for ethanol vehicle; remainder is gasoline).

The vehicle life cycle includes emissions from the life cycle of materials used in vehicles, vehicle assembly and transport, the life cycle of refrigerants, the production and use of lube oil, and brake wear, tire wear, and road dust.

Baseline ICEV

2010	**U.S.**	**Japan**	**China**	**Germany**
Fuel cycle (g/km)	332.5	329.4	337.8	333.0
Fuel and vehicle life cycle (g/km)	392.9	389.8	408.6	392.3
2050				
Fuel cycle (g/km)	280.0	273.3	281.0	273.4
Fuel and vehicle life cycle (g/km)	316.5	307.8	321.5	306.9

United States—BEVs—By Type of Power Plant Fuel

2010	Coal	Fuel Oil	NG Boiler	NG Turbine	Nuclear	Biomass	Hydro	Other
Fuel cycle (g/km)	266.0	231.9	141.3	143.6	14.6	24.2	10.4	7.7
Fuel cycle (% change)	-20%	-30.2%	-57.5%	-56.8%	-95.6%	-92.7%	-96.9%	-97.7%
Fuel and vehicle life cycle (g/km)	365.9	331.8	241.2	243.5	114.5	124.0	110.3	107.6
Fuel and vehicle life cycle (% change)	-6.9%	-15.5%	-38.6%	-38.0%	-70.9%	-68.4%	-71.9%	-72.6%
2050								
Fuel cycle (g/km)	227.5	197.2	105.9	107.8	7.8	(-3.2)	5.2	3.0
Fuel cycle (% change)	-18.7%	-29.6%	-62.2%	-61.5%	-97.2%	-101.1%	-98.1%	-98.9%
Fuel and vehicle life cycle (g/km)	262.4	232.1	140.8	142.7	42.7	31.7	40.1	37.9
Fuel and vehicle life cycle (% change)	-17.1%	-26.7%	-55.5%	-54.9%	-86.5%	-90.0%	-87.3%	-88.0%

United States—FCVs—By Fuel and Feedstock

General fuel -->	Gasoline	Methanol	Methanol	Ethanol	H2	H2	H2	H2
Fuel spec -->	RFG-Ox10	M100	M100	E100	CH2	CH2	CH2	CH2
Feedstock -->	Crude oil	NG	Wood	Grass	Water	NG	Wood	Coal
2010								
Fuel cycle (g/km)	163.9	164.1	47.9	85.4	35.7	135.1	47.8	83.6
Fuel cycle (% change)	-50.7%	-50.7%	-85.6%	-74.3%	-89.3%	-59.4%	-85.6%	-74.8%
Fuel and vehicle life cycle (g/km)	223.6	224.1	107.9	145.3	96.6	196.0	108.7	144.6
Fuel and vehicle life cycle (% change)	-43.1%	-43.0%	-72.5%	-63.0%	-75.4%	-50.1%	-72.3%	-63.2%
2050								
Fuel cycle (g/km)	134.0	122.6	18.3	13.2	27.5	113.3	24.3	61.6
Fuel cycle (% change)	-52.1%	-56.2%	-93.5%	-95.3%	-90.2%	-59.5%	-91.3%	-78.0%
Fuel and vehicle life cycle (g/km)	163.7	152.5	48.1	43.0	59.7	145.6	56.6	93.9
Fuel and vehicle life cycle (% change)	-48.3%	-51.8%	-84.8%	-86.4%	-81.1%	-54.0%	-82.1%	-70.3%

Japan—BEVs—By Type of Power Plant Fuel

2010	Coal	Fuel Oil	NG Boiler	NG Turbine	Nuclear	Biomass	Hydro	Other
Fuel cycle (g/km)	215.2	185.0	175.8	140.0	11.2	17.7	10.3	7.8
Fuel cycle (% change)	-34.7%	-43.8%	-46.6%	-57.5%	-96.6%	-94.6%	-96.9%	-97.7%
Fuel and vehicle life cycle (g/km)	305.6	275.4	266.2	230.5	101.7	108.1	100.7	98.2
Fuel and vehicle life cycle (% change)	-21.6%	-29.3%	-31.7%	-40.9%	-73.9%	-72.3%	-74.2%	-74.8%
2050								
Fuel cycle (g/km)	175.4	142.0	130.5	111.8	5.4	(-1.0)	5.2	3.0
Fuel cycle (% change)	-35.8%	-48.1%	-52.2%	-59.1%	-98.0%	-100.4%	-98.1%	-98.9%
Fuel and vehicle life cycle (g/km)	207.3	173.8	162.4	143.7	37.3	30.9	37.1	34.9
Fuel and vehicle life cycle (% change)	-32.6%	-43.5%	-47.2%	-53.3%	-87.9%	-90.0%	-88.0%	-88.7%

Japan—FCVs—By Fuel and Feedstock

General fuel -->	Gasoline	Methanol	Methanol	Ethanol	H2	H2	H2	H2
Fuel spec -->	RFG-Ox10	M100	M100	E100	CH2	CH2	CH2	CH2
Feedstock -->	Crude oil	NG	Wood	Grass	Water	NG	Wood	Coal
2010								
Fuel cycle (g/km)	161.6	169.9	45.0	106.4	27.3	138.8	39.2	79.4
Fuel cycle (% change)	-50.9%	-48.4%	-86.3%	-67.7%	-91.7%	-57.9%	-88.1%	-75.9%
Fuel and vehicle life cycle (g/km)	221.0	229.5	104.6	165.9	87.9	199.5	99.9	140.1
Fuel and vehicle life cycle (% change)	-43.3%	-41.1%	-73.2%	-57.4%	-77.4%	-48.8%	-74.4%	-64.1%
2050								
Fuel cycle (g/km)	130.3	126.1	10.6	36.8	17.1	111.9	12.0	51.2
Fuel cycle (% change)	-52.3%	-53.8%	-96.1%	-86.5%	-93.7%	-59.1%	-95.6%	-81.3%
Fuel and vehicle life cycle (g/km)	158.2	154.2	38.6	64.8	47.7	142.5	42.5	81.7
Fuel and vehicle life cycle (% change)	-48.6%	-49.9%	-87.5%	-78.9%	-84.5%	-53.7%	-86.2%	-73.5%

China—BEVs—By Type of Power Plant Fuel

2010	Coal	Fuel Oil	NG Boiler	NG Turbine	Nuclear	Biomass	Hydro	Other
Fuel cycle (g/km)	216.2	217.5	183.0	133.5	15.3	55.5	9.8	7.3
Fuel cycle (% change)	-37.2%	-36.8%	-46.8%	-61.2%	-95.5%	-83.9%	-97.1%	-97.9%
Fuel and vehicle life cycle (g/km)	321.2	322.5	288.1	238.5	120.3	160.5	114.9	112.3
Fuel and vehicle life cycle (% change)	-21.4%	-21.1%	-29.5%	-41.6%	-70.5%	-60.7%	-71.9%	-72.5%
2050								
Fuel cycle (g/km)	201.9	155.4	132.9	97.2	7.3	3.9	4.9	2.8
Fuel cycle (% change)	-28.1%	-44.7%	-52.7%	-65.4%	-97.4%	-98.6%	-98.3%	-99.0%
Fuel and vehicle life cycle (g/km)	240.6	194.1	171.6	135.8	46.0	42.5	43.5	41.4
Fuel and vehicle life cycle (% change)	-25.2%	-39.6%	-46.6%	-57.7%	-85.7%	-86.8%	-86.5%	-87.1%

China—FCVs—By Fuel and Feedstock

General fuel -->	Gasoline	Methanol	Methanol	Ethanol	H2	H2	H2	H2
Fuel spec -->	RFG-Ox10	M100	M100	E100	CH2	CH2	CH2	CH2
Feedstock -->	Crude oil	NG	Wood	Grass	Water	NG	Wood	Coal
2010								
Fuel cycle (g/km)	151.3	151.6	65.8	117.9	44.6	124.1	62.0	82.2
Fuel cycle (% change)	-56.0%	-55.9%	-80.9%	-65.7%	-87.0%	-63.9%	-82.0%	-76.1%
Fuel and vehicle life cycle (g/km)	215.7	216.5	130.6	182.5	109.9	189.4	127.4	147.5
Fuel and vehicle life cycle (% change)	-47.2%	-47.0%	-68.0%	-55.3%	-73.1%	-53.6%	-68.8%	-63.9%
2050								
Fuel cycle (g/km)	122.0	114.1	23.6	27.8	31.0	106.2	29.4	60.9
Fuel cycle (% change)	-56.6%	-59.4%	-91.6%	-90.1%	-89.0%	-62.2%	-89.5%	-78.3%
Fuel and vehicle life cycle (g/km)	155.2	147.5	57.1	61.1	66.8	142.0	65.1	96.6
Fuel and vehicle life cycle (% change)	-51.7%	-54.1%	-82.3%	-81.0%	-79.2%	-55.8%	-79.7%	-69.9%

Germany—BEVs—By Type of Power Plant Fuel

2010	Coal	Fuel Oil	NG Boiler	NG Turbine	Nuclear	Biomass	Hydro	Other
Fuel cycle (g/km)	239.5	188.0	164.3	131.1	28.3	23.3	10.4	7.8
Fuel cycle (% change)	-28.1%	-43.5%	-50.7%	-60.6%	-91.5%	-93.0%	-96.9%	-97.7%
Fuel and vehicle life cycle (g/km)	333.8	282.4	258.6	225.4	122.6	117.6	104.7	102.0
Fuel and vehicle life cycle (% change)	-14.9%	-28.0%	-34.1%	-42.6%	-68.8%	-70.0%	-73.3%	-74.0%
2050								
Fuel cycle (g/km)	200.5	144.7	121.5	104.2	15.3	(-0.3)	5.2	3.0
Fuel cycle (% change)	-26.7%	-47.1%	-55.6%	-61.9%	-94.4%	-100.1%	-98.1%	-98.9%
Fuel and vehicle life cycle (g/km)	230.7	174.9	151.7	134.4	45.5	29.9	35.5	33.2
Fuel and vehicle life cycle (% change)	-24.8%	-43.0%	-50.6%	-56.2%	-85.2%	-90.3%	-88.5%	-89.2%

Germany—FCVs—By Fuel and Feedstock

General fuel -->	Gasoline	Methanol	Methanol	Ethanol	H2	H2	H2	H2
Fuel spec -->	RFG-Ox10	M100	M100	E100	CH2	CH2	CH2	CH2
Feedstock -->	Crude oil	NG	Wood	Grass	Water	NG	Wood	Coal
2010								
Fuel cycle (g/km)	163.8	168.7	48.9	100.5	65.5	134.2	49.0	80.9
Fuel cycle (% change)	-50.8%	-49.3%	-85.3%	-69.8%	-80.3%	-59.7%	-85.3%	-75.7%
Fuel and vehicle life cycle (g/km)	222.2	227.5	107.7	159.1	125.1	193.9	108.7	140.6
Fuel and vehicle life cycle (% change)	-43.4%	-42.0%	-72.5%	-59.5%	-68.1%	-50.6%	-72.3%	-64.2%
2050								
Fuel cycle (g/km)	130.4	125.1	9.7	45.7	31.8	96.9	11.8	37.3
Fuel cycle (% change)	-52.3%	-54.3%	-96.4%	-83.3%	-88.4%	-64.6%	-95.7%	-86.4%
Fuel and vehicle life cycle (g/km)	157.2	152.0	36.8	72.6	61.0	126.1	41.1	66.6
Fuel and vehicle life cycle (% change)	-48.8%	-50.5%	-88.0%	-76.3%	-80.1%	-58.9%	-86.6%	-78.3%

GREET emission results for BEVs and FCVs

The GREET model results for BEVs and FCVs are broadly similar to the LEM results discussed above. GREET shows that emission reductions of about 40 percent can be expected from BEVs using the average electricity grid mix in the United States, compared with emissions from conventional vehicles, and that BEVs using a California electricity grid mix would produce reductions of about 60 percent. FCVs using hydrogen derived from natural gas would reduce emissions by just over 50 percent. FCVs using the average grid mix of U.S. electricity to produce hydrogen through the electrolysis process would result in an increase in emissions of about 20 percent. As shown by the LEM as well, BEVs and FCVs using entirely renewable fuels to produce electricity and hydrogen would nearly eliminate GHGs from the fuel cycle.[34]

Emission results for BEVs and FCVs from other major modeling efforts

The various efforts to model electric vehicle fuel-cycle emissions are challenging to compare because of the many different dimensions that they encompass, and because they rarely overlap very well in that regard. Hence there is often the challenge of trying to make "apples to apples" rather than "apples to oranges" comparisons. Later (under "Comparison of GHG emission reductions from various electric vehicle types") we include a figure that does compare the results from a few of the most detailed studies; however we caution that no attempt has been made to correct for key differences in their underlying assumptions (for example, assumed vehicle driveline efficiencies).

Several studies were conducted for California in the 1990s when the introduction of BEVs was being mandated by the state. These studies generally found significant benefits from BEVs in terms of GHG emission reductions, along with more mixed results for the criteria pollutants that were the main focus of the studies.[35] However, the studies were often limited to CO_2 only, as far as the GHGs examined, sometimes along with CH_4 and several air pollutants that were more of concern at the time.

Other studies have been done more recently comparing BEVs and FCVs as alternatives to ICEVs, with results based on more modern assumptions that are better comparisons to the recent work on emissions from PHEVs. One such study by MIT concludes that conventional ICEVs emit about 252 grams of CO_2e per km and that by 2030 this might be reduced to about 156 grams per km. In comparison, 2030 FCVs could emit about 89 grams per km, BEVs could emit 116 grams per km, and a PHEV-30 (with a 30-mile/50-km AER) might emit about 86 grams of CO_2e per km. Thus, the study finds that the PHEV-30s and FCVs have the largest emission reductions relative to the 2030 ICEV (44 percent and 42 percent), followed closely by the BEVs (26 percent). Hence, all three options (as well as a 2030 advanced conventional hybrid in this analysis) are significantly better than the advanced 2030 ICEV.[36]

Another recent comparison of BEVs and FCVs found that GHG emissions from lithium-ion BEVs were much lower than from either nickel-metal hydride or lead-acid battery based vehicles, ranging from about 235 grams per km for a 100-km-range vehicle to about 375 grams per km for a 600-km-range vehicle. This study found that FCV emissions are relatively unchanged by driving range, at about 180 grams per km. This assumes the electricity is from the U.S. marginal grid mix and that hydrogen for the FCVs is made from natural gas. Hence this study suggests that FCVs operating on hydrogen from natural gas can have lower GHG emissions than even relatively low-range BEVs in the United States,[37] a finding that is consistent with most other studies.

A major ongoing European study, the EUCAR study, makes detailed estimates of life-cycle GHG emissions from alternative-fuel ICEVs, hybrid vehicles, and FCVs.[38] The study estimated life-cycle emissions for methanol FCVs, using wood, coal, and natural gas as feedstocks, and for compressed-hydrogen vehicles, using wood and natural gas as feedstocks. FCVs using hydrogen made from natural gas had about 55 percent lower well-to-wheels GHG emissions than a conventional gasoline ICEV, and FCVs using hydrogen made from wood had about 90 percent lower emissions.

Emission results for PHEVs from major modeling efforts

What have major modeling efforts revealed about GHG emission reductions that can be expected from PHEVs? We summarize the results of key studies here.

A 2001 report by the Electric Power Research Institute (EPRI) assumed that the marginal electricity load for PHEVs would be met by combined-cycle natural gas plants. The study estimated a grid GHG intensity of 427 grams of CO_2 per kWh, which is the average of the high and low estimates of marginal emissions made by the consulting firm AD Little Inc. for the California Air Resources Board in 2000. In EPRI's average-driving-schedule case with nightly charging, the PHEV-32 emits 144 grams of CO_2 per km and the PHEV-96 emits 112 grams of CO_2 per km, both of which are much lower than the estimated ICEV CO_2 emissions of 257 grams per km.[39]

Samaras and Meisterling[40] performed a hybrid life-cycle analysis of PHEV GHG emissions using GREET 1.7 along with results from the Economic Input-Output Life Cycle Assessment Model developed at Carnegie Mellon University.[41] They defined the low, average, and high electricity grid GHG intensities as 200, 670, and 950 grams of CO_2-eq/kWh, respectively. They estimated that PHEVs would have only 15 percent lower GHG emissions than a comparable ICEV in the high-grid-emissions case, but 63 percent lower emissions in the low-grid-emissions case.

Kromer and Heywood[42] forecasted that the average GHG intensity of the 2030 U.S. electricity grid will be 769 grams of CO_2e GHGs per kWh, based on projections from the Energy Information Administration and emissions calculations from Groode.[43] Gasoline well-to-tank emissions of 21.2 gCO_2e/MJ were adopted from a GM/ANL study,[44] and tank-to-wheels emissions were modeled in the vehicle simulation program ADVISOR, over standard EPA driving cycles. With these assumptions, PHEVs were estimated to have about 45 percent lower GHG emissions than ICEVs.

Another study of PHEVs by Silva et al.[45] concludes that for the United States, charge-depleting (CD) PHEVs with 15 kWh of battery capacity can have GHG emissions on the order of 70–80 grams per km, or about 40 percent less than a conventional baseline vehicle. The reductions would be greater in Japan and Europe, which have a lower-carbon fuel mix for electricity generation than the United States does. Charge-sustaining (CS) PHEVs were found to have considerably higher emissions than the CD designs—in fact, higher than baseline vehicles in the study for the United States and Europe. The study also found that the proportion of emissions attributable to vehicle fueling versus cradle-to-grave manufacturing and maintenance varies strongly with distance driven. For example, for a CS PHEV driving a total of 300,000 km, 15 percent of the emissions are attributable to the vehicle manufacturing and maintenance and 85 percent to fuel use; for lower total mileage of 150,000 km, the proportion is 25 percent to manufacturing and maintenance and 75 percent to fuel use. Silva et al. assumed NiMH batteries and used ADVISOR to do the simulation modeling and GREET for emissions estimates.

In another study, Jaramillo et al.[46] compare the GHG emissions of PHEVs with those of FCVs and conventional vehicles, assuming that PHEVs are operated either on conventional gasoline or coal-to-liquids (CTL) fuels and electricity and that FCVs use hydrogen made from coal gasification. Under varying assumptions about the level of carbon capture and sequestration from the CTL and gasification processes, they find that PHEVs could reduce emissions by up to 46 percent compared with conventional vehicles and up to 31 percent compared with hybrid vehicles. FCVs could decrease GHG emissions by up to 50 percent compared with conventional vehicles or could increase them considerably, depending on the level of carbon capture and the source of electricity used for hydrogen compression. Meanwhile, CTL fuels used in conventional and hybrid vehicles would significantly increase emissions compared with conventional gasoline and diesel vehicles.

Analysts at Pacific Northwest National Laboratory (PNNL)[47] used a simplified dispatch model to estimate the impacts of PHEV charging on GHG emissions. PNNL estimated the average hourly demand for an average winter day and an average summer day in each of twelve electricity-generating regions of the United States, with no PHEV recharging. The analysts then assumed that the difference between the available hourly electricity-generating capacity and the estimated hourly electricity demand without PHEVs would be used to charge PHEVs. They assumed that only natural gas and coal power would be available to supply this "marginal" electricity demand. They used version 1.6 of the GREET model to estimate fuel-cycle GHG emissions for a gasoline vehicle and for electricity generation. With these assumptions and methods, they estimated that PHEVs operating in all-electric mode would have 0 to 40 percent lower fuel-cycle GHG emissions than gasoline vehicles, with the reduction depending on the share of coal in the regional available capacity mix. (PNNL did not model emissions from operation of the ICE in a PHEV.) For the whole United States, the average reduction was 27 percent.

The approach of Stephan and Sullivan[48] is similar to that of PNNL. They assumed that PHEVs would be supported by "spare utility capacity," which they defined as the difference between 90 percent of peak generating capacity and the actual nighttime demand. However, rather than use a simplified dispatch approach to estimate electricity fuel mix and emissions by region, the authors used what they called "empirical" estimates of CO_2 emission rates in various regions. They estimated that fuel-cycle CO_2 emissions from PHEVs operating in electric mode would be 40 to 75 percent lower than emissions from gasoline vehicles, in the 12 electricity-generating regions of the United States. With the U.S. average electricity generation fuel mix, the reduction would be about 60 percent. They also reported CO_2 emission impacts for current-technology and new-technology coal and natural gas plants.

Parks et al.[49] used the characteristics of Colorado's Xcel energy system in 2004 for their analysis of CO_2 emissions from PHEV charging and use. They used a chronological dispatch model called PROSYM, developed by Global Energy Decisions, to model the operation of the electricity grid. The Xcel region's electricity grid is primarily fossil fuel-based and had an average CO_2 emissions intensity of 884.5 grams of CO_2/kWh (1,950 lb/MWh) in 2004. The study calculated CO_2 emissions under four charging scenarios:

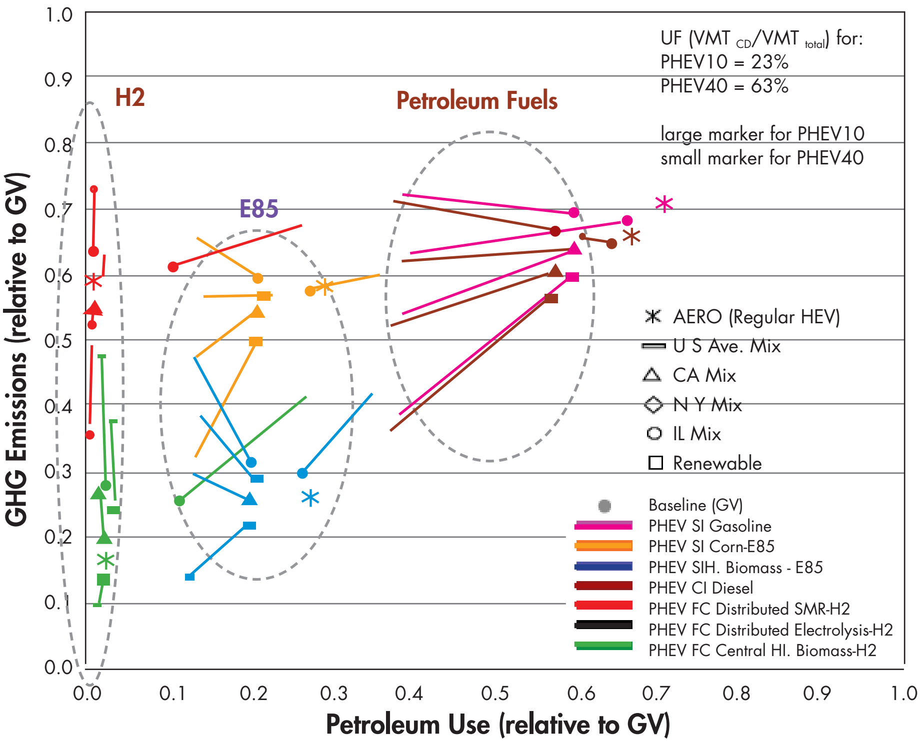
- uncontrolled—no time restrictions, peak around 4 to 6 p.m., 1.4 kW rate
- delayed—charging starts at 10 p.m., 1.4 kW rate
- off-peak—controlled charging starts after 10 p.m. and ends by 7 a.m., 3.2 kW rate
- continuous charging—charging allowed all day, charging stations available, 1.4 kW rate

They found that the CO_2 emissions from PHEV-32 charging were about 454 g/kWh (1,000 lbs/MWh) under all of these scenarios, which results in per-mile emissions of 251 g CO_2/km, about 40 percent lower than the estimated ICEV emissions.

The GREET model has been used to analyze life-cycle GHG emissions from various types of PHEVs. As an example of results from this model, one Argonne National Laboratory (ANL) study[50] focused on three regions (Illinois, New York, and California) that provide a wide range of marginal electricity generation mixes, plus a U.S. average generation case and an all-renewable generation case. To estimate the marginal mix of fuels used to generate electricity in the regions, the study used the results of the region-specific dispatch modeling of Hadley and Tsvetkova.[51] The study examined a scenario in which charging took place in the late evening in the year 2020 at a 2-kW charging rate. It estimated that the GHG emissions of a petroleum-fueled PHEV are 30 to 50 percent lower than those of an ICEV, with the greater reduction corresponding to lower grid emissions. It also estimated the impacts of the grid GHG intensity on the overall emissions of PHEVs powered by other fuels, including biofuels and hydrogen. It found that while the California generation mix reduced CO_2 emissions from all PHEVs relative to the U.S. average mix, PHEVs powered by biomass-based fuels were not affected as greatly. The study also shows that PHEVs charged on a GHG-intensive electricity grid can have greater well-to-wheels GHG emissions than regular HEVs and that this is exacerbated by increasing the battery capacity.[52]

Another set of GREET results for various types of PHEVs—fueled by gasoline, ethanol, or hydrogen fuel cells—shows that use of renewable hydrogen in fuel cells and biomass-derived ethanol result in the largest reductions in both GHG emissions and petroleum use. Fuel cell PHEVs using natural gas-derived hydrogen can also offer significant benefits, along with those using petroleum fuels but with relatively clean electricity—for example, from renewables or the California grid mix.

GREET: GHG EMISSIONS AND PETROLEUM USE OF PHEVS USING VARIOUS FUELS



One set of GREET results shows that use of renewable hydrogen in fuel cells and biomass-derived ethanol result in the largest reductions in both GHG emissions and petroleum use. Source: A. Elgowainy, A. Burnham, M. Wang, J. Molburg, and R. Rousseau, Well-to-Wheels Energy Use and Greenhouse Gas Emissions Analysis of Plug-In Hybrid Electric Vehicles*, ANL/ESD/09-2 (Argonne National Laboratory, 2009).*

A 2007 report by EPRI and the Natural Resources Defense Council (NRDC) combines dispatch modeling with scenario analysis to estimate PHEV GHG emissions for the years 2010 and 2050.[53] Grid emissions in this study—97, 199, and 412 grams per kWh in 2050—are much lower than the emissions estimated in the other studies mentioned here because EPRI and NRDC assumed that grid emissions will decrease over time as older plants are retired and are replaced by more efficient ones. Their analysis shows that life-cycle GHG emissions decrease as the range of the PHEV increases, even in the high-grid-emissions case. This is different from the result of (for example) Samaras and Meisterling, who estimate that increased CD range results in higher emissions in their high-grid-emissions case. This difference is due to the large difference in the grid GHG intensities assumed in the two studies.

In sum, PHEVs promise significant reductions in GHG emissions in most regions and under most conditions. This is especially the case in the longer term, when the electricity grid is likely to be cleaner and vehicles are likely to have greater battery storage capacities.

PHEV GHG EMISSION REDUCTIONS PROJECTED BY KEY STUDIES

This table summarizes the results of key PHEV emission studies that can be reasonably compared directly. These studies indicate that PHEVs have 20 to 60 percent lower GHG emissions than their ICEV counterparts, with the lower-end reductions corresponding mainly to relatively low-carbon fuel mixes for electricity generation.

Studies using dispatch modeling of the electricity grid indicate a narrower range of reductions, 30 to 50 percent. By comparison, studies tabulated by Bradley and Frank[54] indicate slightly greater reductions, about 40 to 60 percent. To put the grid GHG emission numbers into perspective, the LEM estimates that in the United States in the year 2020, life-cycle emissions from coal-fired plants are 1,030 grams of CO_2e per kWh generated, and from gas-fired plants are 520 grams of CO_2e per kWh generated, using IPCC GWPs.

CD = charge-depleting; GHG = greenhouse gas; CO_2e = CO_2 equivalent; ICEV = internal combustion engine vehicle; PHEV = plug-in hybrid electric vehicle; AE = all-electric (meaning the vehicle operates solely on the battery until a certain state of charge is reached); blended = vehicle is designed to use both the engine and battery over the drive cycle; n.s. = not specified; n.e. = not estimated; NG = natural gas; C = coal.

Report	Emissions Estimation	CD Range (km)	Control Strategy	Year	Grid GHGs (gCO2e/kWh)	PHEV GHGs (gCO2e/km)	ICEV GHGs (gCO2e/km)	Percent Reduction (vs. ICEV)
EPRI 2001	Average	32.2	AE	2010	427	144	257	44%
		96	AE	2010	427	112	257	57%
Samaras and Meisterling	Scenario	30	AE	NR	200	126	257	51%
					670	183	269	32%
					950	217	276	21%
		90	AE	NR	200	96	257	63%
					670	183	269	32%
					950	235	276	15%
Kromer and Heywood	Average	48	Blended	2030	769	86.2	156	45%
		96	Blended	2030	769	89.8	156	43%
Silva et al.	Average	~57	AE	n.s.	543 (U.S.)	~110	n.s.	n.e.
					387 (Eur.)	~105	n.s.	n.e.
					428 (Japan)	~108	n.s.	n.e.
Jaramillo et al.	Scenario	60	AE	n.s.	883 (coal)	~125–220	~230	~4%–46%
PNNL	Simplified dispatch	53	n.s.	2002	94% NG/6% C	n.s.	n.s.	40%
					1% NG/99% C	n.s.	n.s.	-1%
					U.S. average	n.s.	n.s.	27%
Stephan and Sullivan	Scenario	63	n.s.	current / long term	598 (current NG)	184/119	432	57%/72%
					954 (current coal)	274/192	432	37%/56%
					608 (U.S. average)	177	432	59%
Parks et al.	Dispatch	32	Blended	2004	454	154	251	39%
ANL	Dispatch/ scenario	32	Blended	2020	U.S. average	146	233	37%
					California	140	233	40%
					Illinois	162	233	30%
					Renewable	115	233	51%
EPRI and NRDC	Dispatch/scenario	16	AE	2050	97	140	233	40%
					199	143		39%
					412	147		37%
		32.2	AE	2050	97	103	233	56%
					199	109		53%
					412	119		49%

Notes on Table:

In the "Emissions Estimation" column, "Average" = annual average emissions from the entire national electric grid; "Scenario" = the study considered different fuel-mix and hence emission scenarios for the electric grid; "Dispatch" = the study estimated marginal fuel mixes and emissions for PHEV charging based on a dispatch model.

In the "Control Strategy" column, PNNL and Stephan and Sullivan estimate emissions from electric operation only; they do not estimate emissions from the ICE in a PHEV.

In the "Year" column, for Silva et al. and Jaramillo et al. the year of analysis is not specified but appears to be roughly current.

GHG emissions and CO_2 equivalency are estimated as follows:

- *For EPRI 2001, Silva et al., Stephan and Sullivan, and Parks et al.: CO_2 only.*
- *For ANL: 2007 IPCC GWPs for CH_4 and N_2O.*
- *For Samaras and Meisterling, Jaramillo et al., and EPRI-NRDC: 2001 IPCC 100-year GWPs for CH_4 and N_2O.*
- *For Kromer and Heywood and PNNL: 1995 IPCC GWPs for CH_4 and N_2O.*

Samaras and Meisterling and Jaramillo et al. do not explicitly state which GHGs they include in their CO_2e measure; however, they refer to CO_2e estimates from the GREET model, which considers CH_4 and N_2O. Similarly, PNNL does not state which CO_2e measure it uses, but it does state that it uses GREET version 1.6, with year 2001 documentation, so we assume that the 1995 IPCC GWPs apply.

For EPRI 2001, the 32.2 km CD range uses the "unlimited" case, which allows the maximum number of electric miles.

For Silva et al., the numbers preceded by "~" were estimated from Figures 2 and 4 of the study report; for Jarmillo et al., from Figure 4 of the study report.

For Stephan and Sullivan, where there are two numbers given, the number before the slash is the result for "current technology" electricity generation, and the number after the slash is the result for "new technology" electricity generation, in the long term. The new technology is more efficient than the current technology.

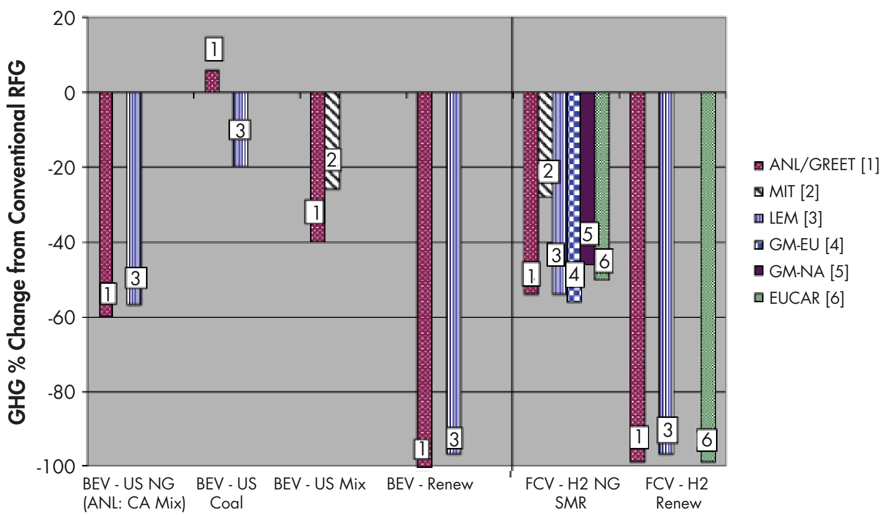
Some of the results shown in this table merit further explanation. For example, Kromer and Heywood report a higher grid GHG intensity than several other cases, but lower emissions per km than Samaras and Meisterling and EPRI 2001. The high grid GHG intensity comes from DOE-EIA projections, and the lower emissions per km are likely due to the assumed improvement in efficiency and emissions in the 2030 ICEV. The relatively large reductions estimated by Stephan and Sullivan are due to several factors: (1) they start with a relatively high-emitting gasoline vehicle; (2) they consider electric operation of the PHEV only; (3) they assume relatively efficient power plants in the long term; and (4) they consider only CO_2 emissions.

Comparison of GHG emission reductions from various electric vehicle types

Now that we have reviewed the results of various specific studies, we can make an overall comparison of the emission reductions estimated for the various types of EVs. However, again we note that these emissions vary widely by location and vehicle type/design and are only generally characterized in the following discussion.

BEVs have the potential to reduce well-to-wheels GHG emissions by about 55 to 60 percent using either natural gas power plants or the California grid mix (which is heavily dependent on natural gas). Using coal-based power, BEVs may reduce emissions by about 20 percent or slightly increase them (model results vary somewhat), and using the U.S. grid mix (which is about half coal-based) emission reductions on the order of 25 to 40 percent appear possible. For FCVs using hydrogen produced from natural gas steam reformation, GHG emissions can be reduced by 30 to 55 percent according to the various studies. Once again, when entirely or almost entirely powered by completely renewable fuels such as wind, solar, and hydro, GHG emissions from both BEVs and FCVs can be almost entirely eliminated.

COMPARISON OF GHG EMISSION-REDUCTION ESTIMATES FOR BEVS AND FCVS



When we compare estimates of the well-to-wheels GHG reductions (from conventional reformulated gasoline) to be expected from BEVs and FCVs, we see that findings vary by study and that emission reductions vary by energy source. When entirely or almost entirely powered by completely renewable fuels such as wind, solar, and hydro, GHG emissions from both BEVs and FCVs can be almost entirely eliminated.

BEV = battery electric vehicle; CA = California; FCV = fuel cell vehicle; H2 = hydrogen; NG = natural gas; Renew = renewable fuel; SMR = steam methane reforming.

Sources:

1. M. Wang, Y. Wu, and A. Elgowainy, GREET1.7 Fuel-Cycle Model for Transportation Fuels and Vehicle Technologies *(Argonne National Laboratory, 2007); M. Wang, "Well to Wheels Energy Use Greenhouse Gas Emissions and Criteria Pollutant Emissions—Hybrid Electric and Fuel Cell Vehicles," presented at the SAE Future Transportation Technology Conference, Costa Mesa, CA, June 2003.*

2. M. A. Kromer and J. B. Heywood, Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet*, LEFF 2007-02 RP (Sloan Automotive Laboratory, MIT Laboratory for Energy and the Environment, May 2007).*

3. LEM.

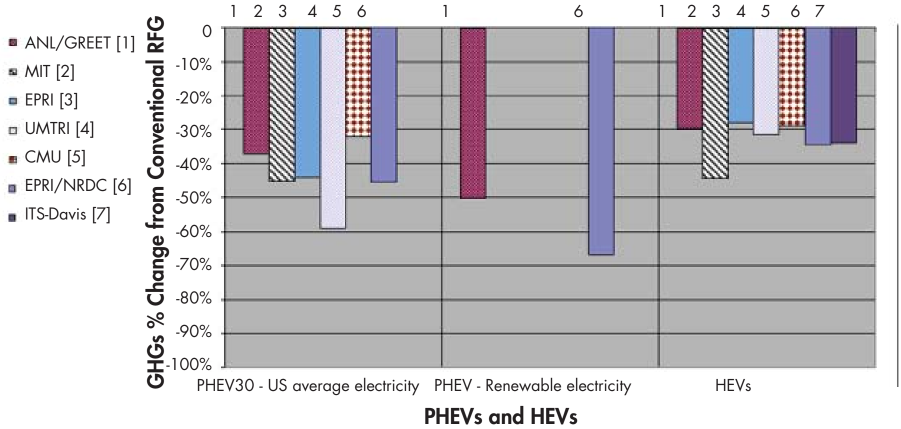
4. General Motors et al., GM Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems—A European Study*, L-B-Systemtechnik GmbH, Ottobrunn, Germany, September 27, 2002.*

5. General Motors, Argonne National Lab, et al., Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems*, in three volumes, published by Argonne National Laboratory, June 2001.*

6. EUCAR (European Council for Automotive Research and Development), CONCAWE, and ECJRC (European Commission Joint Research Centre), Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context*, Well-to-Wheels Report, Version 2c, March 2007.*

Emission reductions possible from PHEVs are somewhat more modest than for some BEV and FCV configurations. For a PHEV type considered in several studies that has a 30-mile/50-km electric range, GHG emission reductions compared with a conventional vehicle are estimated to be in the range of 30 to 60 percent using the U.S. grid mix. For the California electricity mix, a range of 40 to 55 percent has been estimated. Also, one estimate shows a 50-percent reduction potential with PHEV-30s running on renewables-based electricity. We note that for PHEVs in particular, these relative emission reduction results vary by assumed driving patterns and distances as well as underlying emission factors for electricity and gasoline used. This leads to further sources of potential variation amongst the studies, along with other variables such as the assumed driveline efficiencies, upstream emission factors, and the type and size of the vehicle itself.

COMPARISON OF GHG EMISSION-REDUCTION ESTIMATES FOR PHEVS AND HEVS



When we compare estimates of the well-to-wheels GHG reductions (from conventional reformulated gasoline) to be expected from PHEVs and HEVs, we see that findings vary by study. For a PHEV that has a 30-mile/50-km electric range, GHG emission reductions compared with a conventional vehicle are estimated to be 30 to 60 percent using the U.S. grid mix. PHEVs running on renewables-based electricity offer greater reductions, in the range of 50 percent to almost 70 percent. For HEVs, most studies typically estimate reductions of about 30 percent, although one study estimates a reduction of about 45 percent.

Sources:

1. M. Wang, Y. Wu, and A. Elgowainy, GREET1.7 Fuel-Cycle Model for Transportation Fuels and Vehicle Technologies *(Argonne National Laboratory, 2007); M. Wang, "Well-to-Wheels Analysis of Biofuels and Plug-In Hybrids," presentation at Argonne National Laboratory, June 3, 2009. We calculate GHG reductions for HEVs by weighting their estimated city mpg 55 percent and their estimated highway mpg 45 percent.*

2. M. A. Kromer and J. B. Heywood, Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet, *LEFF 2007-02 RP (Sloan Automotive Laboratory, MIT Laboratory for Energy and the Environment, May 2007). Estimates from Table 50, year-2030 U.S. average electricity mix, year-2030 gasoline vehicle, 30-mi PHEV range.*

3. R. Graham, Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options, *Report 1000349 (Electric Power Research Institute, 2001). Estimates from Table 3-21, U.S. average electricity mix, 20-mi PHEV range.*

4. C. H. Stephan and J. Sullivan, "Environmental and Energy Implications of Plug-in Hybrid-Electric Vehicles," Environmental Science and Technology *42 (2008): 1185–90. Estimates from Table 4, U.S. average electricity mix, current technologies, 20- to 40-mi PHEV range.*

5. C. Samaras and K. Meisterling, "Life Cycle Assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles: Implications for Policy," Environmental Science and Technology *42 (2008): 3170–76. Estimates from Table 1, U.S. average electricity mix ca. 2007, baseline scenario, 30-mi PHEV range.*

6. Electric Power Research Institute and Natural Resources Defense Council, Environmental Assessment of Plug-In Hybrid Electric Vehicles, Volume 1: Nationwide Greenhouse Gas Emissions, *Report No. 1015325 (EPRI and NRDC, 2007). Estimates from Figure 5-1, year 2010, 20-mi PHEV range. We estimate the U.S. average electricity* *case by scaling the electricity emissions in the "old 2010 CC" results in Figure 5-1 by the ratio of emissions from U.S. average electricity (Table 3-2) to emissions from "old NG CC" (Table 2-1).*

7. Based on Burke et al., Chapter 4 in this volume. The reduction shown here is the reduction in fuel use per mile, which we calculate by weighting their estimated city mpg 55 percent and their estimated highway mpg 45 percent, for midsize 2015 vehicles.

How Fast Can the GHG Reductions Promised by EVs Be Achieved?

The emission estimates just discussed demonstrate that EVs can offer significant GHG reductions when compared on a one-to-one basis with conventional vehicles. How fast, then, can the electric vehicle industry scale up? When we pose this question we run into a major issue: the availability of advanced electric vehicle battery packs in the numbers needed for a major commercial launch of vehicles by several automakers at once.

A 2009 analysis examined the potential of various options to scale up to become a "gigaton solution"—that is, to account for reducing CO_2 by a gigaton on a global annual basis—by 2020.[65] The study found that achieving "gigaton scale" with a strategy based largely on a massive introduction of grid-connected EVs would require about 1,000 times as many batteries in the near term as are expected to be available (that is, tens of millions globally rather than tens of thousands), growing to a need for hundreds of millions of battery packs by 2020. This implies a massive investment in battery production capacity at a time when battery designs are still being improved and perfected to the point where commercially acceptable PHEVs and BEVs can be produced—which suggests that achieving gigaton scale with EVs is not possible by 2020. However, much larger gains are possible by 2030 and especially 2050, given the relative slowness of motor vehicle fleet stock turnover.[66]

The need to scale up battery production in the cell sizes and configurations required for different types of EVs is accompanied by several other needs to support the introduction of elecric vehicles into consumer households. These include:

- improving the procedures for installing recharging facilities for EVs at household and other sites,
- better understanding of the utility grid impacts of significant numbers of grid-connected vehicles,
- better understanding of the consumer and utility economics of electric vehicle ownership (and/or leasing of car or battery), and
- better education of consumers and tools to assist them to determine whether their driving habits would be a good fit for the characteristics of the different types of EVs.

These and other related issues are being explored by the University of California and other groups as new EVs are being introduced into the market.[67]

Additional issues related to vehicle scale-up include provision of hydrogen for FCVs, currently an expensive proposition for low volumes of dispensed fuel, development and dissemination of appropriate safety procedures for first responders in dealing with accidents with vehicles with high voltage electrical systems and/or hydrogen fuel storage, and additional education and outreach programs for mechanics and fleet managers.[68] These measures will be needed to help EVs become more established and acceptable to consumers in various market segments.

Still, it is important to note that more generally, PHEV and other electric vehicle technologies can scale fairly rapidly. Typical automotive volumes run to several hundred thousand units per year for individual popular models (for example, the combined U.S. and Japanese sales of the Toyota Prius are around 275,000 to 300,000 per year), and there is the potential to incorporate electric drive technology into many vehicle models. The rate of scaling is mainly limited by the growth of supplier networks and supply chains, and by the dynamics of introducing new vehicles with 15-year lives into regional motor vehicle fleets, along with economic and market response constraints on the demand side.

Given these dynamics of the transportation sector and that a significant percentage of new vehicles sold today will still be on the road in the next 10 years, it is much easier to foresee large reductions in LDV emissions by 2030, 2040, and 2050 than by 2020. For example, the EPRI-NRDC study noted earlier concludes that under the most optimistic U.S. scenario assessed—high PHEV fleet penetration and low electric sector CO_2 intensity—612 million megatons of emissions could be reduced annually by 2050. Extrapolated globally, these emission reductions could be on the order of 2 to 3 gigatons annually.

ANNUAL GREENHOUSE GAS REDUCTIONS POSSIBLE FROM PHEVS IN THE YEAR 2050

The EPRI-NRDC study noted earlier includes scenario estimates of future GHG reductions from vehicle fleets in the United States and finds that reductions of up to about 500 megatons per year are possible by 2050, depending on the level of PHEV fleet penetration and the CO_2 intensity of the electricity sector. This table presents some of the key results of the study. Source: Electric Power Research Institute and Natural Resources Defense Council, Environmental Assessment of Plug-In Hybrid Electric Vehicles, Volume 1: Nationwide Greenhouse Gas Emissions*, Report No. 1015325 (EPRI and NRDC, 2007).*

2050 Annual GHG Reduction (million metric tons)		**Electric Sector CO2 Intensity**		
		High	Medium	Low
PHEV Fleet Penetration	Low	163	177	193
	Medium	394	468	478
	High	474	517	612

KEY UNCERTAINTIES AND AREAS FOR FURTHER RESEARCH

Because GHGs are produced in myriad ways from electric-vehicle fuel cycles, including both upstream and vehicle-based emissions (in the case of PHEVs and HEVs), and because electric-vehicle technologies are still evolving, there are considerable uncertainties involved in the analysis of life-cycle CO_2e GHG emissions from advanced EVs. Since 1990 many of these uncertainties have been narrowed—for example, the manufacturing cost and performance of electric vehicle motors and motor controllers has become better established—but many still remain. Exploring these uncertainties in much detail is beyond the scope of this chapter but is done to some extent in some of the studies referenced here. The GREET model in particular now has the ability to include estimates of the levels of uncertainty in key input variables, and it incorporates this capability through a graphical user interface version of the model that runs in a PC Windows environment. This can be useful, but of course we can still benefit from additional efforts to characterize and narrow the remaining uncertainties themselves.

Some of the key remaining uncertainties are these:

- Emission rates of high-GWP-value gases (such as N_2O, CH_4, and refrigerants) that are emitted in lower quantities than CO_2 from vehicle fuel cycles but that can still be significant
- Emission impacts of the increased use of power plants to charge BEVs and PHEVs
- Secondary impacts such as the "indirect land use change" impacts of biofuels, where production of biofuels implies cultivation of land that in some cases can displace its use for other purposes, and how emissions from power plants and other combustion sources actually result in exposures and potential harm to humans and the Climate impacts of emissions of typically overlooked but potentially important pollutants such as oxides of sulfur, ozone precursors, and particulate matter
- Rate of future vehicle and fueling-system performance improvements
- Driveline efficiencies of various types of alternative fuel vehicles, and efficiencies
- involved in key upstream fuel production processes
- Potential "wild cards" in future fuel-production processes, such as the successful introduction of carbon capture and sequestration
- Breakthroughs in electricity, advanced biofuel, or hydrogen production

Uncertainty about the exact levels of emissions is compounded by uncertainty about the overall impacts of GHGs, as some aspects of climate dynamics are still not completely understood. But as time goes on, we can expect more to be learned about these key areas, and for the remaining uncertainties to be narrowed. At the same time, new fuel cycles based on evolving technology (for instance, diesel-type fuels from algae, new types of PHEVs running on various fuels, other new types of synthetic Fischer-Tropsch process and bio-based fuels) are likely to become available but with potentially significant uncertainties until more is learned about them in turn. The significant amount of research currently under way is encouraging, but given the pressing nature of the energy and climate challenges facing many nations, one could argue that more attention should be paid to this critical area.

Summary and Conclusions

- Electric-drive vehicles, based on batteries, plug-in hybrid, and fuel cell technology, have been found to significantly reduce emissions of GHGs compared to conventional vehicles in most cases and settings studied. Various types of hybrid-electric and all-electric vehicles can offer significant GHG reductions when compared to conventional vehicles on a full fuel-cycle basis. In fact, most EVs used under most conditions are expected to significantly reduce life-cycle CO_2e GHG emissions. Under certain conditions, EVs can even have very low to zero emissions of GHGs when based on renewable fuels. However, at present this is more expensive than other options that offer significant reductions at lower costs based on the use of more conventional fuels.

- BEVs reduce GHGs by a widely disparate amount depending on the type of power plant used and the particular region involved, among other factors. Reductions typical of the United States for BEVs are on the order of 20 to 50 percent, depending on the relative level of coal versus natural gas and renewables in the regional power plant feedstock mix. However, much deeper reductions of more than 90 percent are possible for vehicles using renewable or nuclear power sources. PHEVs running on gasoline can reduce emissions by 20 to 60 percent, again depending strongly on electricity source. FCVs are found to reduce GHGs by 30 to 50 percent when running on natural gas-derived hydrogen and up to 95 percent or more when the hydrogen is produced using renewable feedstocks.

- Emissions from all of these electric-vehicle types are highly variable depending on the details of how the electric fuel or hydrogen is produced. When coal is heavily used to produce electricity or hydrogen, GHG emissions for EVs tend to increase significantly compared with conventional fuel alternatives. Unless carbon capture and sequestration (CCS) becomes a reality, using electric-drive systems in conjunction with a heavily coal-based fuel supply offers little or no benefit.

- Overall, EVs offer the potential for significant and even dramatic reductions in GHGs from transportation fuel cycles. Pursuing further development of this promising set of more efficient technologies is thus of paramount importance, given the rapidly spiraling growth in motor vehicle ownership and use around the globe.

Notes

1. See M. A. Delucchi, "Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity," ANL/ESD/TM-22 (Argonne National Laboratory, 1991); M. Q. Wang, "GREET 1.0 – Transportation Fuel Cycles Model: Methodology and Use," ANL/ESD-33 (Argonne National Laboratory, 1996); M. A. Delucchi, "Emissions of Non-CO_2 Greenhouse Gases from the Production and Use of Transportation Fuels and Electricity," UCD-ITS-RR-97-05 (Institute of Transportation Studies, UC Davis, 1997); and J. M. Ogden and R. H. Williams, *Solar Hydrogen* (World Resources Institute, Washington DC, 1989).
2. See S. Unnasch, L. Browning, M. Montano, S. Huey, and G. Nowell, *Evaluation of Fuel-Cycle Emissions on a Reactivity Basis: Volume 1 - Main Report*, FR-96-114 (Mountain View, CA: Acurex Environmental Corporation, 1996); S. Unnasch, "Greenhouse Gas Analysis for Fuel Cell Vehicles," 2006 Fuel Cell Seminar, Honolulu, HI (2006); and C. E. Thomas, B. D. James, F. Lomax, and I. F. Kuhn, "Fuel Options for the Fuel Cell Vehicle: Hydrogen, Methanol or Gasoline?" *International Journal of Hydrogen Energy* 25 (2000): 551–67.
3. See General Motors and Argonne National Lab, *Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems* (2001); and General Motors et al., *Well-to-Wheel Analysis of Energy use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems—A European Study* (2002).
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