

THE CLEANEST CARS: WELL-TO-WHEELS EMISSIONS COMPARISONS

Updated May 2008

by Sherry Boschert, author of

Plug-in Hybrids: The Cars That Will Recharge America

(New Society Publishers, 2006)

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Guide to acronyms

Vehicle acronyms:

ICE = gasoline car (internal combustion engine)

HEV = hybrid gas-electric car (uses gasoline to recharge batteries)

PHEV = plug-in hybrid (can be plugged in or use gasoline to recharge batteries)

PHEV20, PHEV40, PHEV60 = plug-in hybrids with all-electric ranges of 20, 40, or 60 miles

PRIUS+ PHEV = CalCars PHEV conversion with real-world data

EV = electric vehicle (plugs in to recharge batteries)

HFCEV = hydrogen fuel cell electric vehicle

W2W = well-to-wheels analyses of emissions from both the vehicle operation and fuel source

Greenhouse gas acronyms:

GHG = greenhouse gases

CO₂ = carbon dioxide

CH₄ = methane

N₂O = nitrous oxide

HC = hydrocarbons

Criteria air pollutant acronyms:

CO = carbon monoxide

VOC = volatile organic compounds

ROG = reactive organic gases

SO_x = sulfur oxides

NO_x = nitrogen oxides

PM = particulate matter

PM_{2.5} = particulate matter with a mean aerodynamic diameter of 2.5 microns or less

PM₁₀ = particulate matter with a mean aerodynamic diameter of 10 microns or less

SUMMARY:

This is an overview of all the analyses that I could find as of September 2007 looking at emissions produced by vehicles with electric drive and by their power sources (called well-to-wheels analyses). There's quantity, and there's quality – both the overwhelming preponderance of the data and the conclusions of the best-designed studies show that

plug-in hybrids (PHEVs) and electric vehicles (EVs) produce fewer greenhouse gas emissions and pollutants than conventional cars, hybrids, or hydrogen fuel-cell vehicles.

The intent of this summary is to compare vehicles with partial or complete electric drive to conventional internal combustion engine (ICE) vehicles running on gasoline. Biofuels are not included in this summary, but some of the studies listed do assess emissions from vehicles running on liquid fuels other than gasoline.

The analyses range from sophisticated studies to informal estimates by experts. The studies are listed within each category from the newest to the oldest, with two exceptions. The two best-designed, most sophisticated studies are listed first. The most authoritative data come from a 2001 study performed by the U.S. Department of Energy's Argonne National Laboratory and by a 2007 study conducted jointly by the Natural Resources Defense Council (NRDC) and the Electric Power Research Institute (EPRI). Both use the sophisticated Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) model for analysis.

Because of the variety of study designs, the results are not directly comparable between all studies. The two gold-standard studies illustrate differing methodologies. The 2001 Argonne National Lab study compared well-to-wheels (W2W) emissions between vehicles. The 2007 NRDC/EPRI study contained multiple scenarios (and different ones for assessing greenhouse gas emissions or pollutants) and looked at how introduction of PHEVs would change W2W emissions in a U.S. fleet containing both ICEs and HEVs. Other studies included the effects of PHEVs on wind energy markets and resulting changes in W2W emissions.

The range in the results reflects the variety of study designs and also reflects the different assumptions within studies. For example, EVs and hydrogen fuel-cell electric vehicles (HFCEVs) are the only two cars that can reach zero W2W emissions, because they have no tailpipe emissions and can use electricity from renewable sources (solar, wind, etc.) to either drive the EV or to make hydrogen through electrolysis. Most hydrogen today, however (and for the foreseeable future), is made by reforming natural gas. Most U.S. electricity comes from coal-fired power plants, but California's grid is considerably cleaner, using very little coal. One study looks at the W2W benefits of using renewable electricity or natural gas to replace coal-fired power plants instead of using these to make hydrogen for cars. The choice of scenarios affects the outcomes.

Regardless of these differences, strong trends emerge from this overview, as outlined below. Other aspects related to these vehicles that are not covered in this overview are worth mentioning. HFCEVs are included as a theoretical, futuristic scenario which assumes that progress can be made in overcoming lingering significant obstacles such as improving the vehicle technology, designing a safe and effective way to store and transport gaseous hydrogen, vastly reducing the costs of the vehicles, and building a new multi-billion-dollar infrastructure. No experts believe that HFCEVs will be ready in any significant numbers soon enough (if ever) to reduce greenhouse gases within the

time frame in which society needs to act in order to avoid the worse effects of global warming.

A much abbreviated summary of all these results appears in my book, *Plug-in Hybrids: The Cars That Will Recharge America*. (See www.sherryboschert.com.)

Greenhouse gases (GHGs):

PHEVs reduce carbon dioxide (CO₂) emissions by 37%-67% compared with ICEs and by 7%-54% compared with HEVs in well-to-wheels (W2W) analyses assuming fueling with gasoline and electricity from the U.S. mix of power plants (and ignoring one or two outliers in the data). PHEVs reduce all other greenhouse gas emissions too.

EVs reduce CO₂ by 11%-100% compared with ICEs and by 24%-65% compared with HEVs, and significantly reduce all other greenhouse gas emissions, using the U.S. grid mix. If all U.S. cars were EVs, we'd reduce global warming emissions even on today's mostly coal grid. Using electricity strictly from coal, EVs still would reduce CO₂ by 0%-59% compared with ICEs (two analyses found 0% change; seven others found reductions of 17%-59%) and might produce 30%-49% more CO₂ than HEVs (based on only two analyses) on today's grid. On the other hand, if electricity comes from solar or wind power, EVs eliminate all emissions. Using natural gas to make electricity, emissions fall in between those from coal and renewable power.

HFCEVs using hydrogen from reformed natural gas may reduce GHGs by up to 56% or increase emissions up to 7% (excluding one outlier in the data) compared with ICEs. Compared with HEVs, HFCEVs on reformed natural gas may reduce GHG emissions by up to 20% or increase them by up to 76%. HFCEVs using hydrogen made from electrolysis may reduce GHGs by up to 80% (or 100% with renewable electricity) or increase GHG emissions by up to 532% compared with ICEs. Compared with HEVs, HFCEVs using electrolysis may reduce GHGs by 9% (one study) or increase emissions by 190%-300% (four studies) unless the electricity comes from renewable power. Using strictly renewable power, driving a HFCEV would require 60%-400% more windmills or solar panels compared with driving an EV.

Pollutants:

As for criteria air pollutants – the emissions that cause smog or acid rain – the data are mixed on whether using electricity for fuel would create more or less emissions compared with using gasoline. In either case, however, these emissions won't necessarily enter the atmosphere. (See "Note" below.) Most analyses of criteria pollutants look only at EVs and ICEs; numbers for PHEVs or HEVs or HFCEVs may be based on only one or two studies.

Nitrogen oxides (NO_x) – Compared with ICEs, PHEVs decrease NO_x by as much as 67% or increase it up to 83%; EVs decrease it by 32%-99%, HFCEVs using reformed natural gas for hydrogen may decrease it by 34%, and HFCEVs using electrolysis on

the U.S. grid may increase emissions 320%. Compared with HEVs, PHEVs may decrease NO_x by 100% or increase it up to 108%; EVs increase it 384%.

Particulate matter (PM) – Compared with ICEs, PHEVs increase it by 2% or decrease it by up to 29%; EVs may decrease PM by as much as 97% or increase it up to 122%; HFCEVs on reformed natural gas may decrease it by 33%, and HFCEVs using electrolysis may increase it 320%. Compared with HEVs, PHEVs increase it 130% and EVs increase it 483%.

Sulfur oxides (SO_x) – Compared with ICEs, PHEVs increase it by 53%-70%; EVs increase it by 17%-296%; HFCEVs using reformed natural gas may decrease it by 28%, and HFCEVs using electrolysis may increase it 800%. Compared with HEVs, PHEVs may increase SO_x by 107%-283% and EVs by 1120%.

NOTE: Regulations are in place and technology exists to contain criteria pollutant that power plants emit. Scrubbers can handle SO_x, selective catalytic reduction technology can handle NO_x and mercury, and baghouses and electrostatic precipitators can contain PM. The 1990 acid rain amendments to the Clean Air Act cap total acid rain emissions, so no matter how much electricity we generate, total SO_x emissions will continue declining if the Act is enforced. While there is no absolute cap on PM, federal rules are in place to ensure that these emissions – especially the smallest particulates – will decrease as well, regardless of the amount of electricity produced. (Source: Charles Garlow, U.S. Environmental Protection Agency Air Enforcement Division)

Indeed, power-plant criteria pollutants have been decreasing even as the U.S. generates more and more electricity. Greenhouse gases, which are not yet regulated, are a bigger concern. PHEVs certainly (and EVs almost surely) reduce W2W greenhouse gas emissions compared with ICEs or HEVs because so much of the CO₂ comes from burning gasoline. PHEVs and EVs produce fewer GHG emissions than HFCEVs because making hydrogen requires either reforming natural gas or applying vast amounts of electricity to water to extract the hydrogen via electrolysis. PHEVs and EVs get cleaner as the grid gets cleaner with the addition of more renewable power, but ICEs create more exhaust as they age. HFCEVs also get cleaner as the grid gets cleaner, but they need 2-4 times as much electricity to make the hydrogen and run the car compared with running an EV, making a hydrogen scenario inherently inefficient.

PHEVs and EVs have the added advantage of moving emissions away from population centers (where ICE tailpipes pollute the most). It is simpler to regulate emissions from a smaller number of power plants than from 240 million tailpipes.

Discussion:

The results of these various studies suggest that EVs and PHEVs are the most efficient vehicles and offer the greatest reductions in GHGs. Emissions of criteria pollutants will decrease under current regulations, and PHEVs will contribute to those reductions. Natural gas is more efficiently used (with greater GHG reductions) to make electricity

or to run compressed natural gas vehicles than to make hydrogen for cars. Renewable power (solar, wind, etc.) is more efficiently used (with greater emissions reductions) to make electricity than to make hydrogen for vehicles. Overall, PHEVs and EVs create fewer emissions than ICEs, HEVs, and HFCEVs by using cleaner, cheaper, domestic electricity in the most efficient manner.

Please send additions or corrections to info@sherryboschert.com.

EMISSIONS USING U.S. GRID MIX: Studies that include PHEVs

1) M.Q. Wang, Argonne National Laboratory, *Development and Use of GREET 1.6 Fuel-Cycle Model for Transportation Fuels and Vehicle Technologies*, June, 2001. Assume PHEVs drive electric 30% of time and on reformulated gasoline 70% of time and electricity comes from U.S. grid mix.

<http://www.transportation.anl.gov/pdfs/TA/153.pdf>

Table 2: Well-to-Wheels Energy and Emission Changes for Fuel/Vehicle Technologies Relative to Gasoline Vehicles Fueled with Reformulated Gasoline, pages 22-25. Note: In a phone interview, Dr. Wang acknowledged an artifact in one section of the GREET 1.6 analysis of EVs, and suggested averaging the figures that were reported as having a 20% or 80% probability of being correct. I used the averages as he suggested for EVs in this summary.

	Relative to ICEs:				
	HEVs	PHEVs	EVs	HFCEV (reformed natural gas)	HFCEV (electrolysis)
Total energy	-29%	-41%	-46%	-30%	+ 33%
CO ₂	-29%	-40%	-45%	-43%	+ 38%
CH ₄	-26%	-39%	-50%	-47%	+ 23%
N ₂ O	- 1%	-31%	-89%	-95%	- 73%
GHGs	-28%	-40%	-46%	-44%	+ 35%
VOCs	-20%	-46%	-90%	-96%	- 74%
CO	- 1%	-34%	-98%	-97%	- 95%
NOx	-25%	- 2%	+71%	-34%	+320%
PM ₁₀	- 6%	+ 2%	+23%	-33%	+136%
SOx	-29%	+53%	+266%	-28%	+800%

In an updated version of the GREET model (GREET 1.8), Argonne National Laboratory's Transportation Technology R&D Center posted Sample Results in the form of bar charts (date unknown):

http://www.transportation.anl.gov/software/GREET/sample_results.html

The GHG chart suggests that an ICE produces approximately 500 g/mile, compared with nearly 300 g/mile from HEVs, 220 g/mile from EVs on the U.S. grid, 200 g/mile from HFCEVs using hydrogen from natural gas reforming stations, 500 g/mile from HFCEVs using hydrogen from electrolysis, and nearly 1,000 g/mile from hydrogen ICEs (not FCEVs) using hydrogen from electrolysis.

2) Natural Resources Defense Council and Electric Power Research Institute, *Environmental Assessment of Plug-in Hybrid Electric Vehicles*, July 2007. <http://www.epri-reports.org/>

Part 1: Greenhouse Gas Emissions. The study looks at nine scenarios for the years 2010-2050 based on high, medium, or low penetration of PHEVs into the U.S. fleet and high, medium, or low levels of GHG emissions from power plants for electricity. The PHEVs modeled had 10, 20 or 40 miles of electric range in addition to gas engines. In every scenario, PHEVs significantly reduce GHG emissions, producing 40%-65% less GHGs compared with ICEs and 7%-46% less than HEVs.

Part 2: Air Quality Analysis. The study compares two scenarios for 2030, both nationally and in separate geographical regions: a U.S. fleet with no PHEVs, and a fleet that's 40% PHEVs (with electricity covering 20% of miles traveled). Assumes the use of coal for electricity increases to 60% of the grid (plus 16% nuclear, 13% natural gas, 9% renewables, 2% other) and that no new emissions controls or limits are added to existing regulations. Concludes that by 2030, PHEVs improve air quality, decrease depositions of air pollutants such as acids, nutrients, and mercury, decrease gaseous pollutants such as NO_x and SO_x, decrease total emissions of VOCs, and decrease overall PM concentrations.

More specifically:

- VOC emissions are reduced to 50% of 1970 values under existing regulations, and PHEVs then contribute an additional reduction of 338,000 tons/year.

- NO_x emissions are 40% of 1970 values, and PHEVs then contribute an additional reduction of 179,000 tons/year.

- SO₂ emissions are 25% of 1970 values, and PHEVs then contribute an addition reduction of 24,000 tons/year.

- PM: PHEVs increase primary emissions from power plants by 10% but these are more than offset by the significant reductions in VOCs and NO_x emissions from the transportation sector, leading to less secondary particulate matter. Eastern Texas and Oklahoma see some increases in PM concentrations due to increased power plant emissions. PM concentrations decrease particularly across the Eastern U.S., California, and the Pacific Northwest. Daily PM_{2.5} concentrations decrease for 93% of the population and increase for 7%. Average annual PM_{2.5} concentrations decrease for 91% of the population and increase for 9%. Average annual PM₁₀ concentrations decrease for 92% of the population and increase for 8%.

- Ozone: PHEVs reduce ozone across the eastern U.S. and in major urban areas affecting 92% of the population. Ozone increases for 8% of the population near major power plants in eastern Texas, Western Georgia, Utah, Montana, and western North Dakota. Assuming a minimum detection limit of 0.25 parts per billion, ozone levels decrease for 61% of the population and increase for 1% of the population.

- Mercury emissions are 35% of 1990 values. PHEVs increase mercury emissions 2.4% from power plants compared with non-PHEV scenario, but overall mercury emissions remain well below 1990 values. The reductions in ozone produced by PHEVs cause more of the mercury to remain in its elemental form, thereby decreasing the amount deposited on the Earth's surface. By regions, mercury deposits decrease in 71% of land areas and increase in 29%.

- Sulfate deposits decrease with PHEVs for the U.S. as a whole. Deposit patterns change in many eastern regions. Sulfate deposits decrease in 92% of land areas and increase in 8%.

- Nitrate deposits decrease with PHEVs in the U.S. as a whole, especially near urban areas and throughout the eastern regions including the Ohio River valley. Nitrate deposits decrease in 86% of land areas and increase in 14%.

- Air quality: On a population weighted basis, the improvements in ambient air quality for ozone and particulate matter are small but numerically significant with PHEVs for most of the country.

- Visibility is improved by PHEVs in smoggy areas throughout the United States, substantially in California and the eastern regions (like the Appalachians) and unsubstantially in northern and central regions.

3) Constantine Samaras and Kyle Meisterling, *Life Cycle Assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles: Implications for Policy* (*Environ. Sci. Technol.* 2008; 42:3170-3176). Life cycle analysis is more extensive than W2W analysis and includes vehicle and fuel manufacture, use, and end-of-use impacts. Not counting battery manufacturing, PHEVs reduce GHG emissions by 38%-41% compared with ICEs and by 7%-12% compared with HEVs. Including battery manufacturing, GHG emissions are “slightly lower” than HEVs on today’s U.S. grid. If use of coal for electricity increases by grid GHG emissions by 42%, PHEVs would emit 9%-18% more GHGs than HEVs. If GHG emissions from the grid decrease by 70%, GHG emissions with PHEVs would be 51%-63% less than ICEs and 30%-47% less than HEVs.

<http://pubs.acs.org/cgi-bin/abstract.cgi/esthag/2008/42/i09/abs/es702178s.html>

4) John Shears, Center for Energy Efficiency and Renewable Technologies, *Hydrogen and Fuel Cells: A Comprehensive Solution in the Fight against Global Warming*, May 16, 2007. Well-to-wheels GHG emissions reductions compared with mid-sized ICE: HEV 25%-50% less; PHEV40 50% less; EV 0% -100% less (coal vs. renewable electricity); HFCEV 30%-100% less (reformulated natural gas vs. electrolysis using renewable electricity).

http://www.cleanpower.org/ceert_reports/CEEERT%20Hydrogen%20Fuel%20Cell%20Vehicles%2005%2015%2007.pdf

5) Minnesota Pollution Control Agency, *Air Emissions Impacts of Plug-in Hybrid Vehicles in Minnesota’s Passenger Fleet*, March 2007. If electricity is generated by 60% coal and 40% wind power, PHEVs would decrease all emissions compared with ICEs and most emissions vs. HEVs but increase GHG and SO_x (if not contained at power plant). Emissions compared with ICEs:

CO₂: HEV 59%; PHEV20 65%; PHEV60 66%.

VOC: HEV 69%; PHEV20 42%; PHEV 60 18%.

CO: HEV 100%; PHEV20 60%; PHEV60 25%.

NO_x: HEV 80%; PHEV20 62%; PHEV60 48%.

PM_{2.5}: HEV 76%; PHEV20 71%; PHEV60 66%.

SO_x: HEV 63%; PHEV20 170%; PHEV60 265%.

http://www.state.mn.us/mn/externalDocs/Commerce/Air_Emissions_Impacts_of_Plugin_Hybrid_Vehicles_in_Minnesotas_Pass_032907013010_PCA_PHEV_emissions_FIN_AL_2.pdf

6) Peter Lilienthal, Ph.D. and Howard Brown, National Renewable Energy Laboratory, *Potential Carbon Emissions Reductions from Plug-in Hybrid Electric Vehicles by 2030*, in *Tackling Climate Change in the U.S.*, American Solar Energy Society, January 2007.
<http://www.ases.org>

PHEVs that get 3 miles per kWh and 25 miles per gallon would reduce CO₂ emissions by 42% if charged on the present U.S. grid, compared with ICEs. Greenhouse gas reductions in 49 states range from 4% to 80% less CO₂ per state from vehicles. One state – North Dakota – would see no change in GHG emissions with PHEVs. Making PHEVs bi-directional so some of the stored electricity could be fed back to homes or the grid would double U.S. capacity to use wind power by 2050.

7) Michael Kintner-Meyer et al, Pacific Northwest National Laboratory, *Impacts Assessment of Plug-in Hybrid Vehicles on Electric Utilities and Regional U.S. Power Grids, Part 1: Technical Analysis*, 2006. PHEVs compared with ICEs: GHG 27% less; VOC 93% less; CO 98% less; NO_x 31% less; PM₁₀ 18% more; Sox 125% more. Emissions in urban areas are found to improve across all pollutants and regions as the emission sources shift from millions of tailpipes to a small number of large power plants in less-populated areas.

http://www.pnl.gov/energy/eed/etd/pdfs/phev_feasibility_analysis_combined.pdf

8) James Kliesch and Therese Langer, American Council for an Energy-Efficient Economy, *Plug-in Hybrids: An Environmental and Economic Performance Outlook*, Report Number T01, September 2006. Comparing HEV (50 mpg) with PHEV40 on current U.S. grid: PHEV produces 15% less CO₂, 23% less NO_x, 57% more SO_x. Factoring in federal laws that require reduced emissions from power plants over the next two decades, a 2020 comparison on the U.S. grid finds the PHEV40 would produce 16% less CO₂, 39% less NO_x, and 12% more SO_x, assuming no changes in auto technology or institution of greenhouse gas limits.

<http://www.aceee.org/pubs/t061.htm>

9) W. Short and P. Denholm, National Renewable Energy Laboratory, *A Preliminary Assessment of Plug-in Hybrid Electric Vehicles on Wind Energy Markets*, April 2006. Introduction of PHEV20s or PHEV60s would boost installation of wind energy.

Assumes the rest of electricity comes mainly from coal. Compares with fleet containing ICEs and HEVs but no PHEVs.

- If half of cars in 2050 are PHEV20 (using 50% less gasoline as ICEs), annual fleet CO₂ emissions decrease 5% vs. ICEs.

- If half of cars in 2050 are PHEV60 (using 80% less gasoline as ICEs), annual fleet CO₂ emissions decrease 11% vs. ICEs

- If entire 2050 fleet consists of HEVs, annual fleet CO₂ emissions decrease 9% vs. ICEs.

- If 2050 fleet is half HEVs and half PHEV20s, annual fleet CO₂ emissions decrease 10% vs. ICEs or 1% vs. all-HEVs.

- If 2050 fleet is half HEVs and half PHEV60s, annual fleet CO₂ emissions decrease 15% vs. ICEs or 7% vs. all-HEVs.

The authors provide an alternative way of interpreting the results: “All the electricity from PHEV60s is derived from carbon-free wind enabled by the vehicles; and the additional carbon reduction in the electric sector of 53 million tons/year due to the introduction of PHEVs is a large fraction of the PHEV fleet’s 142 million tons of ICE emissions. As a result, the PHEV60 fleet is nearly carbon neutral.”

<http://www.nrel.gov/docs/fy06osti/39729.pdf>

10) Gilbert Masters, Ph.D., professor of civil and environmental engineering, Stanford University, Calif., March 2006. (Personal communication.)

Grid assumptions for carbon emissions: Average U.S. grid (52% coal, 3% oil, 16% natural gas) = 700 g CO₂/kWh. Natural gas, combined cycle, 50% efficiency = 425 g CO₂/kWh. Gasoline, 80% WTP (well to pump) = 11.2 kg/CO₂/gallon. Hydrogen, 60% WTP, 57 miles/gallon = 200 g CO₂/mile. Fuel cell/electrolysis = 663 g CO₂/mile (average grid) or 402 g CO₂/mile (natural gas combined cycle for grid electricity).

Vehicle assumptions: Drive cycle = 15,600 miles/year. Weekdays = 50 miles/day, 13,000 miles/year, ½ city, ½ highway. Weekends = 25 miles/day, local streets, 2,600 miles/year. Fuel prices: Gas \$2.50/gallon. Electricity 12.5 cents/kW or 6 cents/kW off peak. Hydrogen \$3/kg. Fuel efficiency: Ford Focus 24 mpg. Toyota Prius HEV 49 mpg. PRIUS+ PHEV 45 mpg highway plus 200 Wh/mile. EV (generic) 250 Wh/mile. Honda FCX (fuel cell) 57 miles/kg hydrogen.

Results: W2W CO₂ emissions: Focus 467 g/mile. Prius HEV 229 g/mile. PRIUS+ PHEV on average grid 185 g/mile. PRIUS+ PHEV on natural gas combined cycle electricity 153 g/mile. EV on average grid 175 g/mile. EV on natural gas combined cycle electricity 106 g/mile. Honda FCX using reformed natural gas for hydrogen 200 g/mile. Honda FCX HFCEV using average grid for electrolysis 663 g/mile. Honda FCX HFCEV using natural gas combined cycle grid for electrolysis 402 g/mile.

Compared with ICE CO₂: PRIUS+ PHEV average grid 60% less. PRIUS+ PHEV natural gas grid electricity 67% less. EV 77% less. HFCEV on reformed natural gas 56% less. HFCEV using average grid increases CO₂ 42%. HFCEV using natural gas combined cycle electrolysis 14% less.

Compared with HEV CO₂: PRIUS+ PHEV average grid 19% less. PRIUS+ PHEV natural gas grid 33% less. EV 24% less. HFCEV using reformed natural gas 13% less. HFCEV using average grid electrolysis 190% more. HFCEV using natural gas combined cycle grid for electrolysis 76% more.

11) Joseph Romm, Ph.D., energy consultant, Capital E Group; executive director, Center for Energy and Climate Solutions, Washington, D.C.

A) *Interviewed* Feb. 2, 2006: Back-of-the-envelope calculation. Assumptions: 10,000 miles traveled, U.S. grid mix.

Prius HEV real-world 50 mpg (generous: Consumer Reports says 44 mpg) = 200 gallons X 25 pounds CO₂/gallon lifecycle = 5,000 pounds CO₂.

PRIUS+ PHEV = 250 Wh/mile = 2,500 kWh X 1.2 pounds CO₂/kWh = 3,000 pounds CO₂. If PRIUS+ PHEV = 300 Wh/mile = 3,600 pounds CO₂. So 28%-40% less than Prius HEV, and even greater reduction than other hybrids, and far greater reduction than “average” ICE.

B) Romm's post to <http://www.calcars.org>. For 12,000 miles traveled (typical vehicle/year):

Prius HEV = 240 gallons = 6,000 pounds CO₂ (based on lifecycle GHG emissions of burning 1 gallon of gas = 25 pounds, 20 from car and 5 from petroleum production chain; these numbers would be slightly higher for reformulated gasoline and considerably higher for oil from tar sands). ICE = 11,000-12,000 pounds CO₂. PHEV on U.S. grid = 3,000 kWh = 3,900 pounds CO₂ (based on 1.3 lbs/kWh average emissions) = 35% less than HEV, 65% less than ICE. EV on 100% coal = about double the CO₂ = 7,800 pounds CO₂, 29% less than ICE but 30% more than the HEV.

12) Patrick Mazza and Roel Hammerschlag, Institute for Lifecycle Environmental Assessment, *Carrying the Energy Future: Comparing Hydrogen and Electricity for Transmission, Storage and Transportation*, June 2004. Using electricity directly in EV rather than converting it into hydrogen yields twice the miles per kilowatt hour. PHEV charged by natural gas-fired electricity would produce 60% less CO₂ vs. HEV. Using natural gas to make electricity for an EV would produce 68% less CO₂ vs. reformulating natural gas for a HFCEV.

<http://www.ilea.org/downloads/MazzaHammerschlag.pdf>

13) CalCars.org: Says an Argonne National Laboratories researcher reached consensus with researchers from other national labs, universities, California Air Resources Board (CARB), automakers, utilities and AD Little to estimate in July, 2002 that PHEVs using nighttime power reduce GHGs by 46%-61%. (Summarized in Nov. 2003 presentation by Electric Power Research Institute.) <http://www.calcars.org>

EMISSIONS USING U.S. GRID MIX: Studies that include EVs but not PHEVs

14) Argonne National Laboratory, GREET 1.8 Sample Results. GHG emissions compared with ICEs: HEVs 63%; BEVs 52%; HFCEVs using hydrogen made from natural gas 42%; HFCEVs using hydrogen made from electrolysis 104%.

http://www.transportation.anl.gov/software/GREET/sample_results.html

15) Ulf Bossel, Ph.D., *On the Way to a Sustainable Energy Future*, presented to the European Fuel Cell Forum, October 2006. Using 100 MJ of electricity generated at a power plant, an EV would travel 130 km and a HFCEV (using electrolysis) would travel 27 km. Implies 52% greater GHG emissions with HFCEV.

<http://www.efcf.com/reports/E17.pdf>

16) Daryl Slusher of Austin Energy at Electric Drive Transportation Association meeting, Dec. 8, 2005 in Vancouver, Canada compared emissions from a gallon of gasoline and an equivalent “gallon” of electricity obtained from the utility’s coal power plant or from the utility’s wind energy. Combined with tailpipe emissions, if the car drove 12,500 miles/year:

CO₂: ICE 10,000 pounds; EV on coal power 7,000 pounds (30% less); EV on wind power 0 (100% less).

NO_x: ICE 41 pounds; EV on coal 7.5 pounds (82% less); EV on wind 0 pounds.

CO: ICE 606 pounds; EV on coal 1.1 pounds (99% less); EV on wind 0 pounds.

HCs: ICE 80 pounds; EV on coal 0.13 pounds (99% less); EV on wind 0 pounds.

SO_x: ICE emits trace amounts; EV on coal 25 pounds (250% increase); EV on wind 0 pounds.

17) Mark A. Delucchi, Institute of Transportation Studies, University of California, Davis, *Lifecycle Environmental Impacts of Alternative-Fuel Vehicles*, October 29, 2004. GHG emissions vs. light-duty ICE: EV using electricity from natural gas 55% less. EV using electricity from coal 19% less. HFCEV using reformed natural gas 53% less. HFCEV using electrolysis 80% less.

[http://www.its.ucdavis.edu/education/classes/pathwaysclass/9-LCA\(Delucchi\).pdf](http://www.its.ucdavis.edu/education/classes/pathwaysclass/9-LCA(Delucchi).pdf)

18) Stephen S. Eaves and James E. Eaves, *Fuel-Cell Vehicles: Solution or Shell Game?* April 7, 2003. Survey of government studies and auto manufacturer reports finds that HFCEVs need 2.4-2.6 times more electricity well-to-wheels compared with EVs, resulting in more greenhouse gas emissions or greater need for renewable power. Using hydrogen made from reformed natural gas at stations, EVs are still 8% more efficient and generate less greenhouse gases compared with HFCEVs. If the building and maintaining of a hydrogen infrastructure are included, the differences in pollution are even greater. http://www.evuk.co.uk/EAVES_BEV_VS_FCV%20040703.pdf

19) Therese Langer and Daniel Williams, American Council for an Energy-Efficient Economy, Washington, D.C. *Greener Fleets: Fuel Economy Progress and Prospects, December, 2002 (Report Number T024)*, Table 1 on page 4: Characteristics of Selected Alternative Fuels, includes data on EVs: Full-fuel-cycle GHG (on a per-mile basis) as % of conventional ICE: 69% (so 31% less GHGs).

<http://www.aceee.org/pubs/t024full.pdf>

20) Malcolm A. Weiss et al, Massachusetts Institute of Technology Energy Laboratory, *On the Road in 2020: A life-cycle analysis of new automobile technologies*, October 2000. GHG emissions compared with ICE: EV 30% less; HFCEV 30%. Notes that the technology is not ready to implement a fuel cell scenario. http://lees-web.mit.edu/public/In_the_News/el00-003.pdf

21) Chip Gribben, Electric Vehicle Association of Greater Washington, D.C., *Debunking the Myth of EVs and Smokestacks*, circa 1997.

<http://www.evadc.org/pwrplnt.pdf> He referenced the following studies:

A) EVs on coal would reduce CO₂ by 17-22% (Cites *The Keys to the Car*, James J. MacKenzie, World Resources Institute, Baltimore, Md., May, 1994, p. 92).

B) EVs on U.S. grid would decrease HCs 96%, CO 99%, and NO_x 67%, but increase SO₂ (from SO_x) by 203% and PM 122% (Cites “The Case for Electric Vehicles,” Daniel Sperling, *Scientific American*, November, 1996.)

C) EVs in Los Angeles would produce 10 tons of CO₂ (72% less) vs. 35 tons from ICEs for each 100,000 miles (Cites California Air Resources Board, “Draft Technical Document for the Low-Emission Vehicle and Zero-Emission Vehicle Workshop on March 25, 1994, Zero-Emission Vehicle Update,” 1994, Table C-6, p. 68)

D) EVs in Arizona (67% coal-fired grid) would reduce GHGs by 71% (cites “Emissions, Quantifying the Air Quality Impact of EV Recharging,” *Green Car Journal*, October, 1993, p. 116)

E) EVs in the northeast would reduce CO₂ by as much as 60% (cites Center for Technology Assessment Transportation Technology Review, “CTA Findings Reveal Carnegie-Mellon Study Misrepresents Environmental Impacts of Electric Vehicles,” 1996, p.5).

EMISSIONS USING CALIFORNIA GRID MIX:

22) TIAX LLC, *Full Fuel Cycle Assessment: Well-to-wheels Energy Inputs, Emissions, and Water Impacts*, revised 8/1/2007. Prepared for California Energy Commission for State Plan to Increase the Use of Non-petroleum Transportation Fuels, Assembly Bill 1007. Compared with ICEs, EVs reduce GHG emissions by 68%, PHEVs reduce it by 44%, and HFCEVs using hydrogen produced from natural gas steam reforming reduce GHGs by 54%.

<http://www.energy.ca.gov/2007publications/CEC-600-2007-004/CEC-600-2007-004-REV.PDF>

23) Jennifer Pont et al, TIAX LLC, *Full Fuel Cycle Analyses for AB1007*, presented at CEC-ARB Workshop on Developing a State Plan to Increase the Use of Alternative Transportation Fuels, May 31, 2007. GHG emissions compared with mid-sized ICE: HEV 25% less; PHEV 42%-48% less; EV 70%-85% less; HFCEV using reformed natural gas 40%-50% less. So GHG reductions compared with HEV: PHEV is 20% less; EV is 53% less; HFCEV using reformed natural gas is 15%-25% less.

http://www.energy.ca.gov/ab1007/documents/2007-06-27_business_meeting/2007-06-27_JACKSON_TIAX.PDF

24) Martin Eberhard and Marc Tarpenning, Tesla Motors, Inc., *The 21st Century Electric Car*, updated April 17, 2007. CO₂ emissions: ICE 141.7 g/km; HEV 130.4 g/km (8% less); Tesla Roadster EV 46.1 g/km (67% less vs. ICE, 65% less vs. HEV); HFCEV 151.7 g/km (7% more vs. ICE, 16% more vs. HEV).

http://www.teslamotors.com/display_data/twentyfirstcenturycar.pdf

25) Jon Leonard, TIAX LLC (R&D consultants), presented at Electric Drive Transportation Association Dec. 7, 2005, Vancouver: A 2005 update of 2002 study for California Electric Transportation Coalition. *TIAX Update to 2002 ADL LEV EV Market Assessment*, October 25, 2005.

Assumptions: Calculated emissions improvements from new (not existing) plug-in vehicles, assuming each replaced a gas car, and including upstream emissions from production of gasoline or electricity.

For PHEVs, “expected” numbers assume introduction in 2009 and sales following pattern of Toyota Prius growth. Range of benefit based on PHEV20 on low end and PHEV60 on high end. For EVs (full-size, city, and neighborhood EVs [NEVs]), “expected” numbers assume that automakers choose to meet the California Zero Emission Vehicle program’s gold category with half fuel-cell vehicles and half EVs, and that the EVs will be divided between full-size and city cars. NEVs assumed to grow by 1,000-2,000/year. After 2010, 5% market growth assumed. “Achievable” numbers assume very aggressive incentive programs and regulations.

Bottom line: CO₂, NO_x, ROG, and PM reduced in all PHEV and EV scenarios compared with gas cars.

Results for “expected” scenario by 2020, compared with ICEs:

CO₂: PHEVs 1.12-1.63 million tons/year; EVs 0.03-0.05 million tons/year.

NO_x: PHEVs 0.21-0.44 tons/day; EVs 0.01-0.02 tons/day.

ROG: PHEVs 0.34-0.73 tons/day; EVs 0.02-0.03 tons/day.

PM: PHEVs 0.03-0.07 tons/day; EVs 0 tons/day.

Results for emissions reduction with “achievable” scenario by 2020:

CO₂: PHEVs 10-12.99 million tons/year; EVs 1.24 million tons/year.

NO_x: PHEVs 1.8-3.5 tons/day; EVs 0.43 tons/day.

ROG: PHEVs 0.37-0.7 tons/day; EVs 0.73 tons/day.

PM: PHEVs 0.8-0.88 tons/day; EVs 0.07 tons/day.

Combined with expected increases in truck stop electrification, alternative electric marine power, electrified transportation refrigeration units, off-road electric industrial vehicles (like forklifts), and hydrogen fuel cell vehicles by 2020, the “expected” total could reduce greenhouse gases by 4 million tons/year and criteria pollutants by 72 tons/day. (Note: 72 tons/day is equivalent to taking off the road 1.7 million cars made in 2000.)

Under the “achievable” scenario, expansion of all these electric-drive technologies could reduce greenhouse gases by 20.5 million tons/year (five times as much) and criteria pollutants by 194.5 tons/day (three times as much).

26) Alec Brooks, AeroVironment, *Energy and Greenhouse Gas Considerations for Various ZEV Alternatives*, to CARB ZEV Technology Symposium Sept. 26, 2006. CO₂ emissions: ICE 444 g/mile; HEV Prius 206 g/mile (54% less); RAV4-EV 134 g/mile (70% less than ICE, 35% less than HEV); HFCEV Prius using reformed natural gas 287-363 g/mile (18%-35% less than ICE, but 39%-76% more vs. HEV); HFCEV Prius using electrolysis on Calif. grid 634 g/mile (comparable to 641 g/mile of Hummer ICE, 43% more vs. average ICE, 208% more vs. HEV).

<http://www.arb.ca.gov/msprog/zevprog/symposium/presentations/brooks.pdf>

27) Mark Duvall, Electric Power Research Institute, *Plug-in Hybrid Electric Vehicles*, presented at American Public Power Association PHEV Symposium, Nov. 17, 2005. A PHEV20 compared with HEV in lifetime of car would: Produce 20%-30% less CO₂; produce 30%-40% less NO_x and ROG; use 42% less petroleum.

28) William Glauz, Los Angeles Department of Water and Power, *A Vision of the Future: A Global Perspective of PHEVs and the Impact on Electric Utilities and Generation*, presented at American Public Power Association PHEV Symposium, Nov. 17, 2005. Annual emissions:

CO₂: ICE 11,000 pounds; HEV 7,300 pounds (34% less); PHEV 3,700 pounds (66% less). PHEV vs. HEV: 49% less.

NO_x: ICE 45 pounds; HEV 30 pounds (33% less); PHEV 15 pounds (67% less). PHEV vs. HEV: 50% less.

EV (electricity from coal): CO₂ 11,000 pounds (0 reduction vs. ICE, 49% increase vs. HEV); NO_x 20 pounds (56% less vs. ICE, 33% less vs. HEV); (no figures for CO or HC)

EV (electricity from natural gas): CO₂ 5,500 pounds (50% less vs. ICE, 25% less vs. HEV); NO_x <1 pound (98% less vs. ICE, 97% less vs. HEV); (no figures for CO or HC)

EV (electricity from renewables): 0 / 0 / 0 / 0 = 100% reduction in all emissions

29) Alec Brooks, *Why Hydrogen?* presented November 2, 2005 to California Air Resources Board Hydrogen Highway Network Workshop. Assumes 33% of the energy used to make hydrogen via electrolysis comes from “new renewables” and 68% from the California grid at marginal emissions rate. CO₂ emissions: Honda Civic ICE 321 g/mile; Honda FCX HFCEV 341 g/mile (6% more). Feed that renewable power to the grid to displace fossil fueled electricity and drive a Honda Civic ICE, 153 g/mi (52% less CO₂ vs. ICE). Feed renewables to grid and drive a Prius HEV, -6 g/mile (102% less vs. ICE). Feed renewables to grid and drive a Toyota RAV4 EV, -27 g/mile (108% less vs. ICE). http://www.evworld.com/library/abrooks_carb_nov2_05.pdf

30) Alec Brooks, *Comments to CARB on the AB1493 Draft Staff Report*, July 5, 2004, based on data published by Honda, Stuart Energy Systems, Proton Energy Systems, and CARB Final Report FR-00-101. Well-to-wheels CO₂: Average ICE (at 27 mpg) 410 g/mile. HEV Prius 197 g/mile (52% less vs. ICE). RAV4 EV compact SUV on California grid 131 g/mile (68% less vs. ICE and 33% less vs. HEV). Honda HFCEV on reformed natural gas at station 255 g/mile (38% less vs. ICE but 29% more vs. HEV). HFCEV using combined cycle power plant (similar to Calif. grid) for electrolysis 591 g/mile (44% more vs. ICE and 200% more vs. HEV).

31) Mark Duvall, Electric Power Research Institute, presentation Nov. 15, 2003 at American Public Power Association conference: Fuel cycle CO₂ emissions estimated: A) Compact sedan = ICE 300 g/mile; HEV 240 g/mile (70% vs. ICE); PHEV20 190 g/mile (37%); PHEV60 140 g/mile (53%). (PHEV20 is 21% less than HEV. PHEV60 is 42% less than HEV.)

B) Midsize sedan = ICE 400 g/mile; HEV 290 g/mile (27% less); PHEV20 220 g/mile (45%); PHEV60 170 g/mile (57%). (PHEV20 is 24% less vs. HEV; PHEV60 is 41% less.)

C) Midsize SUV = ICE 500 g/mile; HEV 360 g/mile (28% less); PHEV20 280 g/mile (44%); PHEV60 200 g/mile (60%). (PHEV20 is 23% less vs. HEV; PHEV60 is 45% less.)

D) Fullsize SUV = ICE 650 g/mile; HEV 440 g/mile (32%); PHEV20 320 g/mile (51%); PHEV60 250 g/mile (61%). (PHEV20 is 27% less vs. HEV; PHEV60 is 43% less.)

32) Stephen Heckerath, Energy Conversion Devices, *Choose a car to stabilize the climate and your wallet*, distributed at California Public Utilities Commission “Climate Change Policy En Banc,” Feb. 23, 2005, San Francisco. Assumptions: upstream emissions for both electricity and gasoline; gasoline costs \$2.50/gallon; time-of-use off-peak electricity is 5 cents/kWh; there are 40 kWh of energy in a gallon of gasoline; burning 1 gallon produces 23 pounds of CO₂; all ICEs or HEVs hold 5 passengers and have a 350-mile gas range; and EV1 has 120-mile range. Results: Total CO₂ emissions (tailpipe and upstream) per year of driving 50 miles/day = 24 tons for 20-mpg ICE; 12 tons for 40-mpg HEV; 5.5 tons for PHEV25 that gets 40 mpg (77% less vs. ICE, 54% less vs. HEV), and 0.2 tons for EV (99% less vs. ICE, 98% less vs. HEV).

33) California Environmental Protection Agency Air Resources Board, *Climate Change*. (Staff Report: Initial Statement of Reasons for Proposed Rulemaking, Public Hearing To Consider Adoption of Regulations to Control Greenhouse Gas Emissions from Motor Vehicles), August 6, 2004. <http://arb.ca.gov/regact/grnhsgas/isor.pdf>

Table 5.3-7, p. 95, Incremental Costs of Alternative Fuel Vehicles includes these figures: Compared with ICE, if electricity came mostly from natural gas plants: PHEV20 would reduce CO₂ emissions by 62%. EV would reduce CO₂ emissions by 67%.

(An advanced HEV would reduce CO₂ by 54% compared with ICE. So compared with an HEV, a PHEV20 would decrease CO₂ 15% more and an EV would decrease CO₂ 24% more.)

Table 5.2-13, page 78 and Table 5.2-3, page 59 were mined for a chart created in 2005 by David Modisette, executive director of the California Electric Transportation Coalition and reprinted on EVworld.com Dec. 30, 2005, in Bill Moore’s column, “Why Well-to-Wheel Matters.” It shows the same percentages as above. Total CO₂ equivalent emissions (well to wheels): Conventional ICE 449 g/mile. Advanced HEV 210 g/mile (53% reduction). PHEV20 (primarily natural gas electricity) 171 g/mile (62% less vs. ICE, 19% less vs. HEV). EV (natural gas) 150 g/mile (67% less vs. ICE, 29% less vs. HEV). HFCEV on reformed natural gas 275 g/mile (39% less vs. ICE, 31% more vs. HEV).

34) California Air Resources Board Mobile Source Control Division, El Monte, Calif., *Draft Technology and Cost Assessment for Proposed Regulations to Reduce Vehicle Climate Change Emissions Pursuant to Assembly Bill 1493*, April 1, 2004, Table II-13, p. II-31: PHEVs would reduce lifetime CO₂ equivalent emissions by 50% vs. ICEs (45

tons vs. 91 tons). HFCEVs or hydrogen ICEs on reformulated natural gas would provide CO₂ reductions similar to PHEV.

<http://www.arb.ca.gov/cc/042004workshop/final-draft-4-1-04.pdf>

35) Alec N. Brooks, AC Propulsion, *Perspectives on Fuel Cell and Battery Electric Vehicles*, presented at the California Air Resources Board ZEV Workshop December 5, 2002. Using natural gas to make either electricity or hydrogen, a HFCEV would use 39% more natural gas vs. an EV. Using electricity either directly or to make hydrogen, a HFCEV would use 400%-632% vs. an EV.

<http://www.arb.ca.gov/msprog/zevprog/2003rule/1202wkshp/brooks.pdf>

36) Electric Power Research Institute, *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sport Utility Vehicles*, Technical Report 1006892, July 2002. http://www.evworld.com/library/EPRI_sedan_options.pdf

Compared to Saturn compact sedan ICE:

HEV: 21% less CO₂; 10% less NO_x;

PHEV: 40% less CO₂; 32% less NO_x;

PHEV VS. HEV: 90% greater CO₂ reduction, 220% greater NO_x reduction

Compared with Explorer mid-size SUV:

HEV: 31% less CO₂; 19% less NO_x;

PHEV: 46% less CO₂; 37% less NO_x;

PHEV vs. HEV: 48% greater CO₂ reduction; 10% greater NO_x reduction.

37) Electric Power Research Institute, *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options*, Report 1000349, July, 2001. Using average driving patterns determined from survey. http://www.evworld.com/library/EPRI_hev_options.pdf

CO₂ emissions vs. ICE: HEV = 28% less; PHEV20 = 44% less; PHEV 60 = 57% less. Criteria (smog precursor) emissions vs. ICE: HEV = 15% less; PHEV20 = 35% less; PHEV60 = 52% less.

38) Phil Karn, EV1 driver, compared on-road emissions from ICEs with upstream emissions from electricity production for an EV getting 4 miles/kWh. EV emissions in g/mile compared with ICE: 99% less CO and VOCs; 99% less NO_x; 95% less SO_x, and 97% less PM and PM₁₀. http://www.ka9q.net/ev/ev_emissions.html

CANADIAN EMISSIONS STUDY:

39) Electric Vehicle Association of Canada, *Full Fuel Cycle Emissions Reductions through the replacement of ICEVs with BEVs*, July 10, 2000. Prepared for Health Canada, Air and Waste Section. <http://evworld.com/library/CanadaFuelCycle.pdf>

EVs using 1999 technology reduce GHGs 55%-99.9% depending on the electricity source, compared with “average” of conventional ICEs on road in 2005 (new & used). Comparing 1999-era EVs with new 2005 ICEs, GHG emissions would not change but non-CO₂ would be less.

Electricity from coal, EVs reduce GHGs 55%-59% and non-GHGs by 80%-92%.

Electricity from conventional natural gas, reduce GHGs by 74% and non-GHGs by 99.5%.

Electricity from combined cycle natural gas, reduce GHGs by 85% and non-GHGs by >99.5%.

OTHERS:

40) Dr. Ben Lane, Ecolane Transport Consultancy, *Life Cycle Assessment of Vehicle Fuels and Technologies*, March 2006, for the London Borough of Camden. GHG emissions compared with petrol vehicles: HEV or EV on average UK grid 23%-26% lower, EV on renewable grid 70% lower.

http://www.ecolane.co.uk/content/dcs/Camden_LCA_Report_FINAL_10_03_2006.pdf

41) Bill Moore, editor, EV World, *The Promise of Plug-in Hybrids*, September 21, 2005 and in October/November 2005 issue of Mother Earth News. An ICE on one gallon of gasoline travels about 24 miles and releases 24 pounds of CO₂. To go the same distance on electricity strictly from coal would require 6 pounds of coal and create 12 pounds of CO₂ (50% vs. ICE). If electricity came instead from the U.S. grid mix (with about 30% from non-CO₂-producing sources), driving on electricity would produce about 8 pounds of CO₂ (33% vs. ICE).

<http://www.evworld.com/article.cfm?storyid=897>

42) Don Francis, product manager, EV Infrastructure and Service, Georgia Power, Atlanta. Posted on listserv, June 30, 2005: Compared a Toyota RAV4 ICE with a Toyota RAV4-EV using electricity from primarily coal-powered plants. Assumes ICE gets 25 mpg, EV goes 4 miles per kWh (0.25 kWh/mile). A 100-mile trip consumes 4 gallons of gasoline or 25 kWh of electricity. EPA data say the ICE would emit 0.8 pounds of CO₂ per mile. The mainly-coal plants emit 1,500 pounds/MWh. Results: RAV4-ICE: 0.8 pounds/mile x 100 miles = 80 pounds CO₂ per 100 miles. RAV4-EV: 25 kWh x 1,500 pounds/MWh x 0.001 = 37.5 pound CO₂ per 100 miles (or 47% less than the ICE).

43) Mark Kapner, Austin Energy, presented to Electric Auto Association chapters meeting, April, 2005. Assumptions: Driving 12,500 miles/year, and EV charges using ¼ kW per hour:

A) If electricity solely from coal:

CO₂: ICE = 11,450 pounds/MWh; EV = 7,000 pounds/MWh (39% less).

NO_x: ICE = 38 pounds/MWh; EV = 8 pounds/MWh (79% less).

HCS: ICE = 77 pounds/MWh; EV = 0.13 pounds/MWh (99% less).

CO: ICE = 575 pounds/MWh; EV = 1 pounds/MWh (99% less).

SO_x: (EPA didn't list SO_x for ICE); EV = 25 pounds/MWh.

B) If charge on mix from Calif. South Coast Air Basin (mostly natural gas-fired electricity):

CO₂: ICE = 11,450 pounds/MWh; EV = 3,965 pounds/MWh (65% less).

NO_x: ICE = 6 pounds/MWh; EV = 4 pounds/MWh (33% less).

HCs: ICE = 3 pounds/MWh; EV = 0.08 pounds/MWh (97% less).

CO: ICE = 192 pounds/MWh; EV = 0.4 pounds/MWh (99% less).

Sox: ICE = 1.2 pound/MWh; EV = 2.5 pounds/MWh (108% increase).

44) Dr. Peter Van Den Bossche et al, *Prospective Research for Brussels – Integrated modelling of the urban development, mobility and air pollution analysis in the Brussels-Capital region: Policy measures based on environmentally friendly vehicle technologies*, March 31, 2004. Compared with ICEs, the “direct and indirect” (W2W) emissions with EVs are: CO₂ 26% of ICE emissions; CO 0.4%; HC 2%; NO_x 10%; SO_x 40%, and PM 17%.

45) Peter Hendriksen et al, Audi, *Audi Duo Demonstration Project: Environmental Comparison and User Survey*, presented at EVS-17, Montreal, Canada, October, 2000. Study compared diesel-electric PHEV with diesel ICE, and found that under some (but not all) driving conditions, the PHEV may increase CO₂ or other emissions.

<http://www.automotive.tno.nl/VM/EST/publicaties/paper%20EVS-17%20AUDI%20Duo.pdf>

46) Broward County (Fla.) Board of County Commissioners, Department of Planning and Environmental Protection, *The Future of Electric Transportation in Broward County, Florida*, 1999, p. 6-7 and 13: Estimates that EVs would reduce vehicular air emissions by 95% and CO₂ by 28% vs. gasoline vehicle. If EVs replaced 10% of the conventional fleet, an extra 20 million gallons of gasoline (out of 2 billion) per year would be saved because of less need to transport, store, and distribute gasoline, besides what’s saved by the EVs themselves.

47) Todd Litman, Victoria (B.C.) Transport Policy Institute, *A Critical Evaluation of Electric Vehicle Benefits*, Nov. 28, 1999. He referenced the following studies:

A) *Driving Out Pollution: The Benefits of Electric Vehicles*, Roland Hwang et al, Union of Concerned Scientists, 1994. Compared lifetime emissions for ultra-low-emission ICE with EV in the Los Angeles area (including electric power generation resources outside the South Coast Air Basin): Carbon = ICE 19,200 kg vs. EV 5,509 kg (71% less). ROG = ICE 46-54 kg vs. EV 0.49 kg (99% less). CO = ICE 198-478 kg vs. EV 2.76 kg (99% less). NO_x = ICE 60-66 kg vs. EV 24.28 kg (60% less). PM₁₀ = ICE 2.5 kg vs. EV 1.1 kg (56% less). SO_x = ICE 11.8 kg vs. EV 13.8 kg (17% more).

B) EVs would reduce CO₂ by 50%, per *Magnitude and Value of Electric Vehicle Emissions Reductions for Six Driving Cycles in Four U.S. Cities*, Quanlu Wang and Danilo Santini, Transportation Research, Argonne National Laboratory, Argonne, Ill. Record 1416, March 1993, p. 22-42. Compared with mid-1990s ICE, an EV would reduce HCs and CO by 98% or more and reduce NO_x in all four cities. CO₂ emissions reductions are uniformly large at low speed but variable at high speed.
<http://pubsindex.trb.org/document/view/default.asp?Ibid=388959>.

C) *Texas Transportation Energy Savings: Assessment of Control Measures, Technologies and Policies*, Texas Sustainable Energy Development Council, Austin,

Tex., 1995, p. 99. Compared with ICE, EV produces 33% of air pollution using electricity from natural gas, 80% if from coal.

D) *Transport and Greenhouse Gas Costs and Options for Reducing Emissions*, Bureau of Transport and Communications Economics, Australian Gov. Publishing Service (Canberra), July 1996, p. 296. Electric vehicle would reduce lifecycle CO₂-equivalent gases 11% vs. petroleum car.

E) *The Role of Electric Cars in Amsterdam's Transport System in the year 2015*, Sytze Rienstra and Peter Nijkamp, Transportation Research D, Vol. 3, No. 1, January 1998, p. 31. Estimates that EVs reduce CO₂ emissions by 20% compared with ICEs.

F) *Electric Vehicles: Technology, Performance and Potential*, Organization for Economic Co-operation and Development (OECD), Paris, France, 1993: Concluded that electric vehicles may increase CO₂ emissions if the electricity is generated with fossil fuels. (Assumptions and comparison vehicle unclear; no further information.)

HYDROGEN-ONLY COMPARISONS

48) Donald Anthrop, the Cato Institute, *Hydrogen's Empty Environmental Promise*, December 7, 2004. GHG emissions compared with ICE: HFCEVs using coal-fired electrolysis, 170% more. Using electrolysis on U.S. grid, 97% more. Using hydrogen from reformed natural gas would increase natural gas consumption by 66%.
<http://www.cato.org/pubs/briefs/bp90.pdf>

49) Joseph J. Romm, *The hype about hydrogen*, in *Issues in Science and Technology*, March 22, 2004 (and in Romm's book, *The Hype about Hydrogen*). CO₂ reductions are similar between HEVs and HFCEVs on reformed natural gas. Using that natural gas to replace coal-fired electricity would produce much greater carbon reductions than using it to make hydrogen. Using renewable energy to replace coal-fired electricity would create much greater carbon reductions than using it to make hydrogen.
<http://www.issues.org/20.3/romm.html>