WELL-TO-WHEELS EMISSIONS DATA FOR PLUG-IN HYBRIDS AND ELECTRIC VEHICLES: AN OVERVIEW

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Plug-in Hybrids: The Cars that Will Recharge America

(Coming Dec. 22, 2006 from New Society Publishers)

Contents

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
EV = electric vehicle (plugs in to recharge batteries)
W2W = well-to-wheels (or "lifecycle") analyses of emissions from both the vehicle and fuel production

Greenhouse gas acronyms:

GHG = greenhouse gases
CO_2 = carbon dioxide
CH_4 = methane
N_2O = nitrous oxides
HC = hydrocarbons

Criteria air pollutant acronyms:

CO = carbon monoxide
VOC = volatile organic compounds
ROG = reactive organic gases
SOx = sulfur oxides
NOx = nitrogen oxides
PM = particulate matter
PM_{10} = particulate matter with a mean aerodynamic diameter of 10 microns or less

SUMMARY OF FINDINGS:

This is an overview of all analyses available as of March, 2006 looking at emissions produced by vehicles and by their power sources (called well-to-wheels analyses). The analyses range from sophisticated studies to informal estimates by experts. The most authoritative data come from the first study listed, performed by the U.S. Department of Energy's Argonne National Laboratory. A much abbreviated summary of results appears in my book, *Plug-in Hybrids: The Cars that Will Recharge America.*

Overall:

PHEVs reduce CO_2 emissions by 37%-67% compared with ICEs and by 19%-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 CO_2 by 11%-100% compared with ICEs and by 24%-54% 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. Using electricity strictly from coal, EVs still would reduce CO_2 by 0%-59% compared with ICEs (one analysis found 0% change; six others found reductions of 17%-59%) and might produce 30%-49% more CO_2 than HEVs (based on only two analyses). 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.

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 final paragraph of summary.) Most analyses of criteria pollutants look only at EVs and ICEs; numbers for PHEVs or HEVs may be based on only one study.
Overall:

NOx – Compared with ICEs, PHEVs decrease NOx by as much as 67% or increase it up to 83%; EVs decrease it by 32%-99%. Compared with HEVs, PHEVs may decrease NOx by 100% or increase it up to 108%; EVs increase it 384%.

PM – Compared with ICEs, PHEVs increase it by 2%; EVs may decrease PM by as much as 97% or increase it up to 122%. Compared with HEVs, PHEVs increase it 130% and EVs increase it 483%.

SOx – Compared with ICEs, PHEVs increase it by 53%; EVs increase it by 17%-296%. Compared with HEVs, PHEVs may increase SOx by 283% and EVs by 1120%.

Regulations are in place and technology exists to contain any of these criteria pollutant emissions that power plants create. Scrubbers can handle SOx, selective catalytic reduction technology can handle NOx 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 SOx 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 CO_2 comes from burning gasoline. 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.

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 200 million tailpipes.

Overall, PHEVs and EVs create fewer emissions by using cleaner, cheaper, domestic electricity.

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

EMISSIONS USING NATIONAL MIX OF POWER PLANTS for PHEVS and EVs vs. ICEs and/or HEVs:

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.

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
Total energy	-29%	-41%	-46%
CO_2	-29%	-40%	-45%
CH_4	-26%	-39%	-50%
N_2O	- 1%	-31%	-89%
GHGs	-28%	-40%	-46%
VOCs	-20%	-46%	-90%
CO	- 1%	-34%	-98%
NOx	-25%	- 2%	+71%
PM_{10}	- 6%	+ 2%	+23%
SOx	-29%	+53%	+266%

2) CalCars.org: Says an Argonne 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.)

3) Gilbert Masters, Ph.D., professor of civil and environmental engineering, Stanford University, Calif., 2006.

Grid assumptions for carbon emissions: Average U.S. grid (52% coal, 3% oil, 16% natural gas) = 700 g CO_2/kWh. Natural gas, combined cycle, 50% efficiency = 425 g CO_2/kWh. Gasoline, 80% WTP (well to pump) = 11.2 kg/CO_2/gallon. Hydrogen, 60% WTP, 57 miles/gallon = 200 g CO_2/mile. Fuel cell/electrolysis = 663 g CO_2/mile (average grid) or 402 g CO_2/mile (natural gas combined cycle).

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 CO_2 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 153 g/mile. EV on average grid 175 g/mile. EV on natural gas combined cycle 106 g/mile. Honda FCX on natural gas reformer 200 g/mile. Honda FCX on average grid 663 g/mile. Honda FCX from electrolysis by natural gas combined cycle 402 g/mile.

Compared with ICE CO_2: PRIUS+ PHEV average grid 60% less. PRIUS+ PHEV natural gas 67% less. EV 77% less. FCX natural gas 56% less. FCX average grid increases CO_2 42%. FCX electrolysis 14% less.

Compared with HEV CO_2: PRIUS+ PHEV average grid 19% less. PRIUS+ PHEV natural gas 33% less. EV 24% less. FCX natural gas 13% less. FCX average grid 190% more. FCX electrolysis 76% more.

4) 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 CO_2/gallon lifecycle = 5,000 pounds CO_2.

PRIUS+ PHEV = 250 Wh/mile = 2,500 kWh X 1.2 pounds CO_2/kWh = 3,000 pounds CO_2. If PRIUS+ PHEV = 300 Wh/mile = 3,600 pounds CO_2. 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 calcars.org. For 12,000 miles traveled (typical vehicle/year):

Prius HEV = 240 gallons = 6,000 pounds CO_2 (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 CO_2

PHEV on U.S. grid = 3,000 kWh = 3,900 pounds CO_2 (based on 1.3 lbs/kWh average emissions) = 35% better than Prius HEV, 65% better than ICE

EV on 100% coal = about double the CO_2 = 7,800 pounds CO_2, 29% better than ICE but 30% worse than the Prius HEV.

EMISSIONS USING NATIONAL GRID MIX, for EVs (NOT PHEVs):

5) Therese Langer and Daniel Williams, *Greener Fleets: Fuel Economy Progress and Prospects, December, 2002 (Report Number T024),* American Council for an Energy-Efficient Economy, Washington, D.C. 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% improvement in GHGs).

6) Daryl Slusher of Austin Energy at Electric Drive Transportation Association meeting, Dec. 8, 2005 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:

CO_2: ICE 10,000 pounds; EV on coal power 7,000 pounds (30% less); EV on wind power 0 (100% less).
NOx: 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.
SOx: ICE emits trace amounts; EV on coal 25 pounds (250% increase); EV on wind 0 pounds.

In an update later in 2005, the Austin's Mark Kapner included figures for electricity from natural gas, and for two kinds of ICEs – average, or new. Approximate numbers (based on bar charts):
CO_2: Average ICE 11,000 pounds; new ICE 11,000 pounds; EV on coal power 7,000 pounds (36%) less; EV on natural gas 4,000 pounds (64% less); EV on wind power 0 pounds (100% less).
NOx: Average ICE 38 pounds; new ICE 5 pounds; coal EV 7.5 pounds; natural gas EV 4 pounds.
HCs: Average ICE 77 pounds; new ICE 4 pounds; coal or natural gas EVs emit trace amounts.
SOx: Average or new ICEs emit trace amounts; coal EV 25 pounds; natural gas EV 2.5 pounds.

7) *Debunking the Myth of EVs and Smokestacks,* Chip Gribben, Electric Vehicle Association of Greater Washington, D.C., circa 1997. Referenced the following studies:

A) EVs on coal would reduce CO_2 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 NOx 67%, but increase SO_2 (from SOx) 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 CO_2 (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 CO_2 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 POWER MIX:

8) *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), California Environmental Protection Agency Air Resources Board: August 6, 2004.

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 CO_2 emissions by 62%. EV would reduce CO_2 emissions by 67%.

(An advanced HEV would reduce CO_2 by 54% compared with ICE. So compared with an HEV, a PHEV20 would decrease CO_2 15% more and an EV would decrease CO_2 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 same percentages as above. Total CO_2 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).

9) *Draft Technology and Cost Assessment for Proposed Regulations to Reduce Vehicle Climate Change Emissions Pursuant to Assembly Bill 1493*, California Air Resources Board Mobile Source Control Division, El Monte, Calif., April 1, 2004, Table II-13, p. II-31: PHEVs would reduce lifetime CO_2 equivalent emissions by 50% vs. ICEs.

10) "Choose a car to stabilize the climate and your wallet," Stephen Heckeroth, Energy Conversion Devices, Inc., Rochester Hills, Mich. 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 CO_2; all ICEs or HEVs hold 5 passengers and have a 350-mile gas range; and EV1 has 120-mile range. Results: Total CO_2 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).

11) *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options,* Electric Power Research Institute Report 1000349, July, 2001. Using average driving patters determined from survey.
CO_2 emissions vs. ICE: HEV = 28%; PHEV20 = 44%; PHEV 60 = 57%.
Criteria (smog precursor) emissions vs. ICE: HEV = 15%; PHEV20 = 35%; PHEV60 = 52%.

12) *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options for Compact Sedan and Sport Utility Vehicles,* Electric Power Research Institute Technical Report 1006892, July 2002.
Compared to Saturn compact sedan ICE:

HEV: 21% less CO_2; 10% less NOx;

PHEV: 40% less CO_2; 32% less NOx;

PHEV VS. HEV: 90% greater CO_2 reduction, 220% greater NOx reduction
Compared with Explorer mid-size SUV:

HEV: 31% less CO_2; 19% less NOx;

PHEV: 46% less CO_2; 37% less NOx;

PHEV vs. HEV: 48% greater CO_2 reduction; 10% greater NOx reduction.

13) Mark Duvall, Electric Power Research Institute, presentation Nov. 15, 2003 at American Public Power Association conference: Fuel cycle CO_2 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.)

14) 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: CO_2, NOx, ROG, and PM reduced in all PHEV and EV scenarios compared with gas cars.
Results for "expected" scenario by 2020, compared with ICEs:

CO_2: PHEVs 1.12-1.63 million tons/year; EVs 0.03-0.05 million tons/year.

NOx: 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:

CO_2: PHEVs 10-12.99 million tons/year; EVs 1.24 million tons/year.

NOx: 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).

15) "Plug-in Hybrid Electric Vehicles," presentation by Mark Duvall of Electric Power Research Institute at American Public Power Association Plug-in PHEV Symposium, Nov. 17, 2005. A PHEV20 compared with HEV in lifetime of car would: Produce 20%-30% less CO_2; produce 30%-40% less NOx and ROG; use 42% less petroleum.

16) "A Vision of the Future: A Global Perspective of PHEVs and the Impact on Electric Utilities and Generation," presentation by William Glauz, Los Angeles Department of Water and Power, at APPA PHEV Symposium, Nov. 17, 2005. Annual emissions:

CO_2: ICE 11,000 pounds; HEV 7,300 pounds (34% less); PHEV 3,700 pounds (66% less). PHEV vs. HEV: 49% less.

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

EV (electricity from coal): CO_2 11,000 pounds (0 reduction vs. ICE, 49% increase vs. HEV); NOx 20 pounds (56% less vs. ICE, 33% less vs. HEV)); (no figures for CO or HC)

EV (electricity from natural gas): CO_2 5,500 pounds (50% less vs. ICE, 25% less vs. HEV); NOx <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

17) 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 NOx; 95% less SOx, and 97% less PM and PM_{10}. http://www.ka9q.net/ev/ev_emisions.html

CANADIAN EMISSIONS STUDY:

18) *Full Fuel Cycle Emissions Reductions through the replacement of ICEVs with BEVs,* Electric Vehicle Association of Canada, July 10, 2000. Prepared for Health Canada, Air and Waste Section.

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-CO_2 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:

19) 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:

CO_2: ICE = 11,450 pounds/MWh; EV = 7,000 pounds/MWh (39% less).
NOx: 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).
SOx: (EPA didn't list SOx for ICE);EV = 25 pounds/MWh.

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

CO_2: ICE = 11,450 pounds/MWh; EV = 3,965 pounds/MWh (65% less).
NOx: 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).

20) 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 CO_2 per mile. The mainly-coal plants emit 1,500 pounds/MWh.
Results:
RAV4-ICE: 0.8 pounds/mile x 100 miles = 80 pounds CO_2 per 100 miles.
RAV4-EV: 25 kWh x 1,500 pounds/MWh x 0.001 = 37.5 pound CO_2 per 100 miles (or 47% less than the ICE).

21) Bill Moore, editor, EV World, "The Promise of Plug-in Hybrids," September 21, 2005, EVworld.com: An ICE on one gallon of gasoline travels about 24 miles and releases 24 pounds of CO_2. To go the same distance on electricity strictly from coal would require 6 pounds of coal and create 12 pounds of CO_2 (half as much as the ICE). If electricity came instead from the U.S. grid mix (with about 30% from non-CO_2-

producing sources), driving on electricity would produce about 8 pounds of CO_2 (a third as much as the ICE).

22) *The Future of Electric Transportation in Broward County, Florida,* Broward County Board of County Commissioners, Department of Planning and Environmental Protection, 1999, p. 6-7 and 13: Estimates that EVs would reduce vehicular air emissions by 95% and CO_2 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.

23) *A Critical Evaluation of Electric Vehicle Benefits,* Todd Litman, Victoria (B.C.) Transport Policy Institute, Nov. 28, 1999. 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). NOx = ICE 60-66 kg vs. EV 24.28 kg (60% less). PM_{10} = ICE 2.5 kg vs. EV 1.1 kg (56% less). SOx = ICE 11.8 kg vs. EV 13.8 kg (60% increase).

B) EVs would reduce CO_2 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 NOx in all four cities. CO_2 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 would produce 33% of air pollution if electricity came from natural gas and 80% if came 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 CO_2-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 CO_2 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 CO_2 emissions if the electricity is generated with fossil fuels. (Assumptions and comparison vehicle unclear; no further information.)

24) *Audi Duo Demonstration Project: Environmental Comparison and User Survey*, Peter Hendriksen et al, Audi, 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 CO_2 or other emissions.