The Cleanest Cars: Well-to-wheels Emissions

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ABSTRACT

A review of more than 40 studies and analyses compares the well-to-wheels emissions of conventional internal combustion engine (ICE) vehicles, hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and hydrogen fuel-cell electric vehicles (HFCEVs). BEVs and PHEVs are the most efficient vehicles and offer the greatest reductions in greenhouse gases (GHGs). Emissions of criteria pollutants that cause smog, acid rain, and lung disease will decrease under current regulations, and PHEVs will contribute to those reductions. Renewable power (solar, wind, etc.) is more efficiently used (with greater emission reductions) to make electricity than to make hydrogen for vehicles. Overall, BEVs and PHEVs create fewer emissions than the other vehicles by use of cleaner, cheaper, domestic electricity in the most efficient manner.

Keywords: vehicle, electric, plug-in, fuel-cell, emissions

1 SUMMARY

This is an overview of more than 40 studies and analyses as of March 2008 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 battery electric vehicles (BEVs) 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. Descriptions of the individual studies are listed in a document on the FAQ page of my website, www.sherryboschert.com. 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) system 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, or looked at lifecycle emissions (W2W plus emissions from manufacturing and recycling or disposing of cars and their components.)

The range in the results reflects the variety of study designs and also reflects the different assumptions within studies. For example, BEVs 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 theoretical, futuristic scenarios which assume that progress can be made in overcoming lingering significant obstacles such as improving the vehicle technology, designing a safe and effective way to store gaseous hydrogen, vastly reducing the costs of the vehicles, and building a new multi-billion-dollar infrastructure. No experts believe that HFCEVs will

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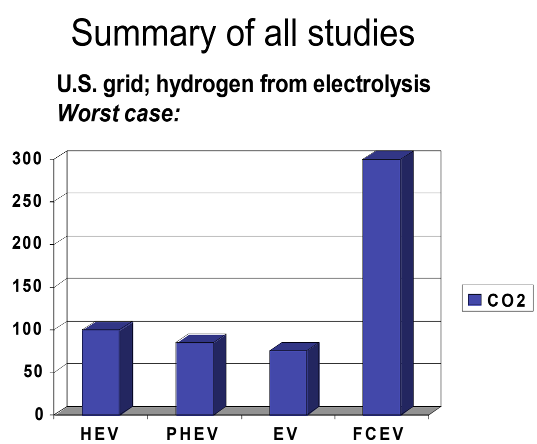
be ready in any significant numbers soon enough (if ever) to reduce greenhouse gases within the time frame in which society needs to act in order to avoid the worse effects of global warming.

2 GREENHOUSE GASES

The studies suggest that PHEVs reduce carbon dioxide (CO_2) emissions by 37%-67% compared with ICEs and by 7%-54% compared with HEVs in 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.

Figure 1: Worst-case U.S. greenhouse gas results



BEVs reduce CO_2 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 BEVs, we'd reduce global warming emissions even on today's mostly coal grid. Using electricity strictly from coal, BEVs still would reduce CO_2 by 0%-59% compared with ICEs (two analyses found 0% change; seven others found reductions of 17%-59%) and might produce 30%-49% more CO_2 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 BEV.

Figure 2: Best-case U.S. greenhouse gas results

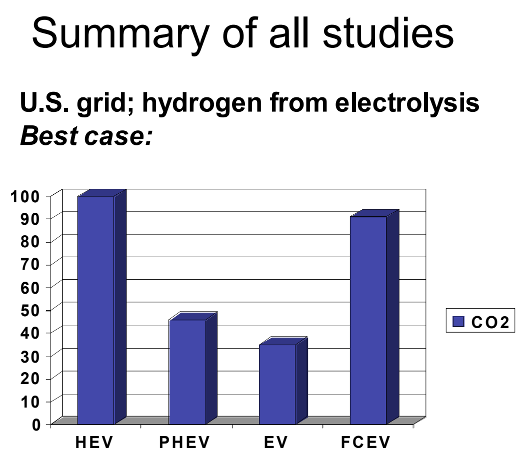
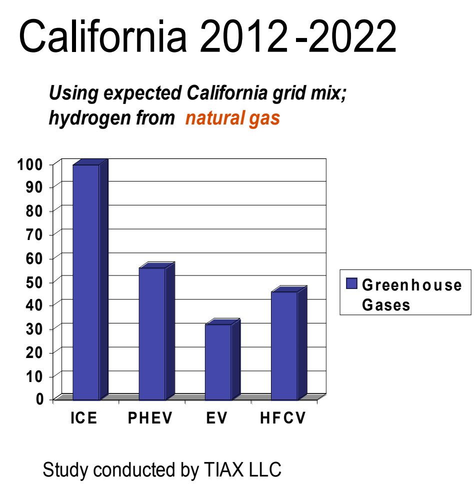


Figure 3: California scenario, natural gas stock



3 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 BEVs and ICEs; numbers for PHEVs or

HEVs or HFCEVs may be based on only one or two studies.

3.1 Nitrogen oxides (NOx)

Compared with ICEs, PHEVs decrease NOx by as much as 67% or increase it up to 83%; BEVs 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 NOx by 100% or increase it up to 108%; BEVs increase it 384%.

3.2 Particulate matter (PM)

Compared with ICEs, PHEVs increase PM by 2%; BEVs 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 BEVs increase it 483%.

3.3 Sulfur oxides (SOx)

Compared with ICEs, PHEVs increase SOx by 53%; 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 SOx by 283% and BEVs by 1120%.

3.4 Subject to regulations

Regulations are in place and technology exists to contain criteria pollutant that power plants emit. 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 BEVs 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 BEVs 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 BEVs 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 a BEV, making a hydrogen scenario inherently inefficient.

PHEVs and BEVs 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.

4 CONCLUSIONS

The results of these various studies suggest that BEVs 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 BEVs create fewer emissions than ICEs, HEVs, and HFCEVs by using cleaner, cheaper, domestic electricity in the most efficient manner.