Summary Comparison of Alternative Vehicles

Alternative vehicles for the 21st century should be compared in terms of:

- Vehicle cost
- Total life cycle cost (LCC) or total cost of ownership (TCO)
- Fuel infrastructure cost
- Greenhouse gas (GHG) emissions
- Local air emissions
- Oil consumption
- Commercial Readiness

This document will show that the hydrogen-powered fuel cell electric vehicle (FCEV) is superior in all seven criteria compared to other options such as battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and biofuel PHEVs.

Vehicle Cost. Kromer and Heywood at MIT[1] have estimated that by 2030 a mass-produced FCEV with 350 miles range will cost $3,600 more than a conventional car, while a BEV with only 200 miles range will cost $10,200 more, and a PHEV with 40 miles all-electric range will cost approximately $5,000 more. The highly respected McKinsey & Company issued a report[2] in 2010 showing that, by 2030, the J-size (SUV) FCEV would cost less to own and operate than either a BEV or a PHEV; this result is particularly credible, since 10 major automobile companies[3] shared their proprietary cost data with the McKinsey analysts in a “clean room”. Note in figure 1 that the TCO includes the cost of the hydrogen infrastructure (small purple bar at top of each main bar--even though this cost would be

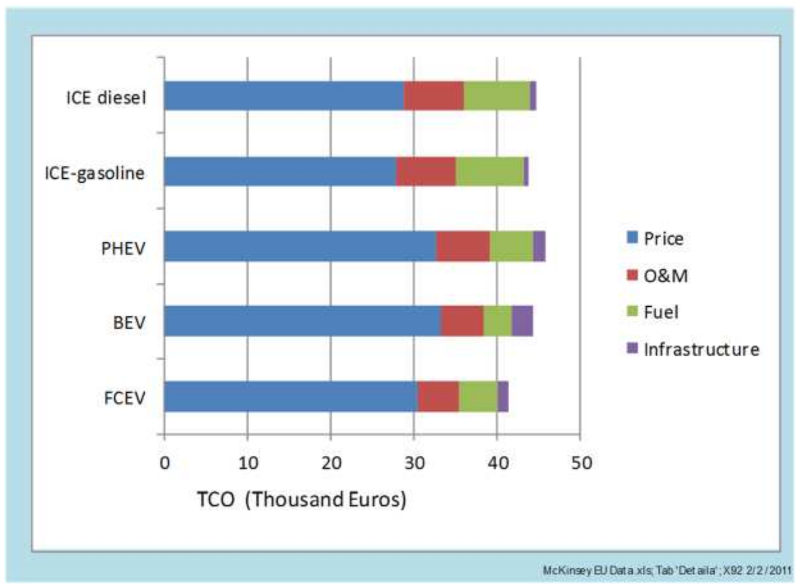

Figure 1. McKinsey estimate of vehicle total cost of ownership (TCO) in 2050 for SUV-sized vehicles

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[1] http://web.mit.edu/sloan-auto-lab/research/beforeh2/files/kromer_electric_powertrains.pdf

[2] For our summary of the McKinsey report, see:
http://www.cleancaroptions.com/McKinsey_EU_Report_key_points.pdf
The full Mckinsey report “A Portfolio of power-trains for Europe: a fact-based analysis- the Role of battery electric vehicles, plug-in hybrid electric vehicles and fuel cell electric vehicles” can be downloaded from
http://www.zeroemissionvehicles.eu/uploads/Power_trains_for_Europe.pdf

[3] BNW, Daimler AG, Ford, GM LLC, Honda R&D, Hyundai Motor Corp., Kia Motor Corp., Nissan, Renault, Toyota Motor Corp., Volkswagen.

buried in the price of hydrogen in the real world); this illustrates that hydrogen infrastructure is a very small portion of total costs.

Fuel infrastructure cost. The McKinsey report (Figure 2) also estimated that installing an electrical charging network for BEVs and PHEVs in the entire EU would cost 540 Billion Euros, while the cost for installing an EU-wide hydrogen infrastructure would be five times less at "only" 101 Billion Euros over the next 40 years.

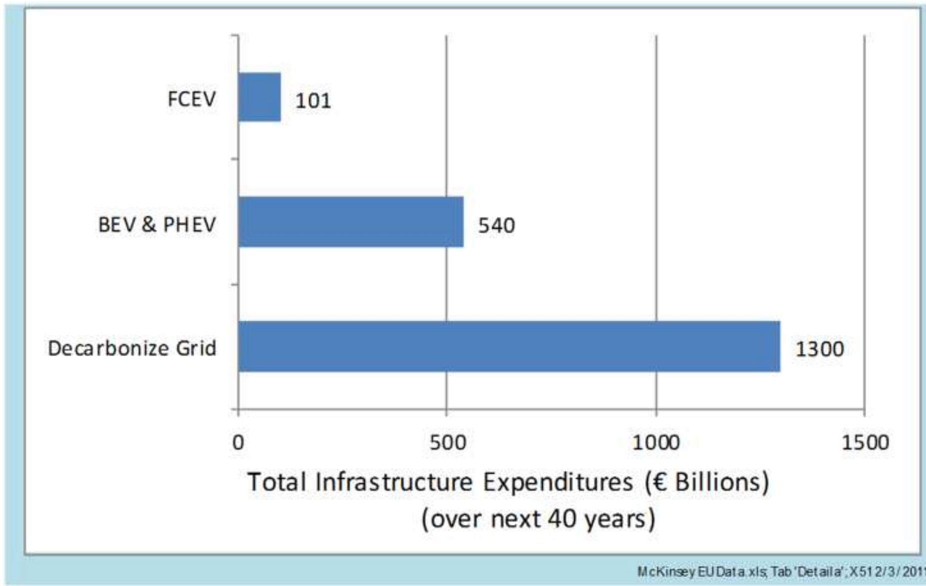


Figure 2. McKinsey estimated costs of installing hydrogen infrastructure for FCEVs and electrical charging infrastructure for BEVs and PHEVs for all of the EU over the next 40 years

The McKinsey report concluded that BEVs would be best suited for small vehicles[4] that traveled short distances; but they determined that 50% of all cars in the EU that generate 75% of vehicle GHGs are larger than average and travel more than average distances. They concluded that FCEVs have already demonstrated the ability to power large vehicles with long driving distances, and therefore hydrogen-powered FCEVs must be part of the vehicle mix to achieve the EU goal of cutting GHGs by 80% below 1990 levels by 2050.

Near-Term GHG Emissions. We have analyzed both the current greenhouse gas (GHG) and estimated long-term GHG emissions for various alternative vehicles. In the near-term (next 5 to 10 years), the GHGs from BEVs and PHEVs will be determined by the sources used to produce electricity to charge their batteries. In the U.S., most (45.6% in 2011) electricity was made by burning coal, the dirtiest (most carbon) fuel, and fossil fuels (Coal, natural gas and oil) accounted for 67.1% of all US electricity in 2011 according to the DOE's 2012 Annual Energy Outlook[5]. The EIA projects that fossil fuel used to generate electricity will only decline to 65.6% by 2035, the last year in their projections (40.7% coal; 0.6% oil and 24.3% natural gas) We have calculated the total possible number of BEVs that could be driven in the US, analogous to the McKinsey estimate that 50% of all EU vehicles that generate 75% of all GHGs are too large or travel too far to be affordably powered by batteries. We estimate that even if all small passenger vehicles, all small vans, all small pickup trucks, all small wagons, all small SUVs and *50% of all*

[4] McKinsey & Company estimated that small Class A&B cars would cost less to own and operation than small FCEVs

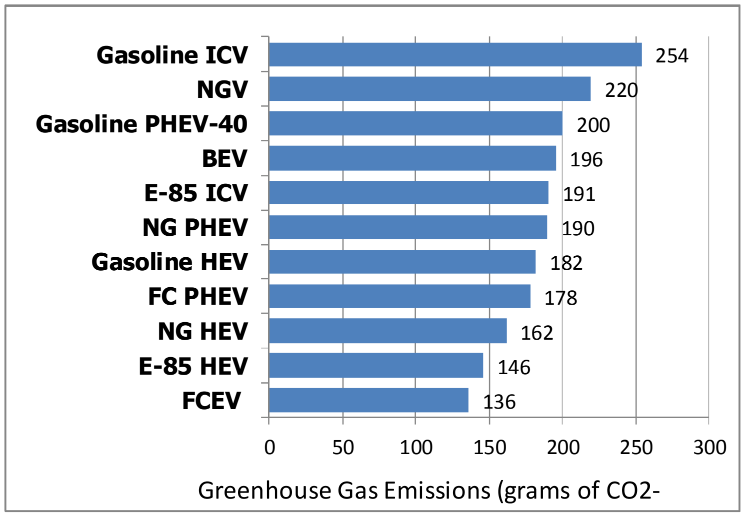
[5] The Annual Energy Outlook (AEO) 2012, the DOE's Energy Information Administration (EIA), available at: http://www.eia.gov/forecasts/aeo/.

midsize sedans are replaced by BEVs, then GHGs would be reduced[6] by at most 8.4% (compared to the goal of an 80% reduction from 1990 levels.)[7] Even if all other vehicles were gasoline PHEVs like the Chevy Volt (100% conversion to electric vehicles…either BEVs or PHEVs), GHGs would still only be reduced by 24.6%.

Long-term GHG emissions. We have also analyzed the GHG emissions and oil consumption for various alternative fueled vehicles (AFVs) by calculating the marginal grid mix in each region of the US to determine the GHG emissions for BEVs and PHEVs, and calculating the weighted average of GHGs over the entire US based on the number of light duty vehicles (LDVs—both cars and trucks) in each electrical grid region[8].

The estimated average LDV-weighted US GHG emissions for various AFVs are shown in Figure 3. The hydrogen-powered FCEV has the lowest emissions at 136 grams of CO_2-equivalent/mile.

We have also written a computer simulation model[9] that estimates the GHG emissions from various alternative vehicles over the 21st century. As shown in Figure 4, The FCEV scenario generates the least GHG emissions, reaching the 80% reduction goal by approximately 2070 with the market penetration rates assumed in the model[10]. BEVs cannot reach that level by the end of the century, primarily because of very low market penetration, on the order of 39.6% of all cars on the road today in the



papers/IHJE/Marginal grid mix figures & Tables.XLS, WS 'Tab 5' AA-58;5/26/2012

Figure 3. LDV-weighted average US GHG emissions for various alternative fueled vehicles based on 2010 marginal electrical generation mixes.

ICV = internal combustion engine vehicle; NGV = natural gas vehicle; E-85 = 85% ethanol in gasoline; NG = natural gas; HEV = hybrid electric vehicle; PHEV-40 = plug-in hybrid electric vehicle with 40 miles all-electric range; BEV = battery electric vehicle; FCEV = fuel cell electric vehicle.

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[6] These BEVs would represent approximately 39.6% of all US cars, which produce approximately 25.2% of LDV GHG emissions, but the power plants needed to charge the BEV batteries would emit 16.8% GHGs, for a net reduction of only 8.4%

[7] C.E. Thomas, "How Green are Electric Vehicles?" *International Journal of Hydrogen Energy*, Vol. 37, Issue 7, pages 6053-6062, April, 2012; available at: http://www.cleancaroptions.com/How__green__are_electric_vehicles-Final.pdf (See Table 6 for a list of the percentage of cars in each category.)

[8] C. E. Thomas, "Marginal grid mix and GHGs for AFVs," Feb 11, 2012. available at: http://www.cleancaroptions.com/Marginal_grid_mix_and_GHGs_for_AFVs.pdf

[9] C.E. Thomas, "Fuel cell and battery electric vehicles compared", International Journal of Hydrogen Energy, 34 (2009) 6005-6020. [Note: the model in this earlier paper erroneously assumed that all sizes of vehicles including SUVs, vans and pickup trucks would be powered by batteries.] Available at: http://www.cleancaroptions.com/C.E._Thomas_Battery_vs_Fuel_Cell_EVs_Paper_for_Distribution.pdf

[10] For a description of the assumptions used in this model, see: http://www.cleancaroptions.com/html/simulation_assumptions.html

US. Note that, according the Argonne National Laboratory GREET model[11] used to estimate GHG emissions, gasoline plug-in hybrid electric vehicles (PHEVs) such as the Chevy Volt do not reduce GHG emissions significantly more than a more conventional gasoline hybrid electric vehicle (HEV) such as the Toyota Prius (The blue and orange lines nearly overlap in the last half of the century).

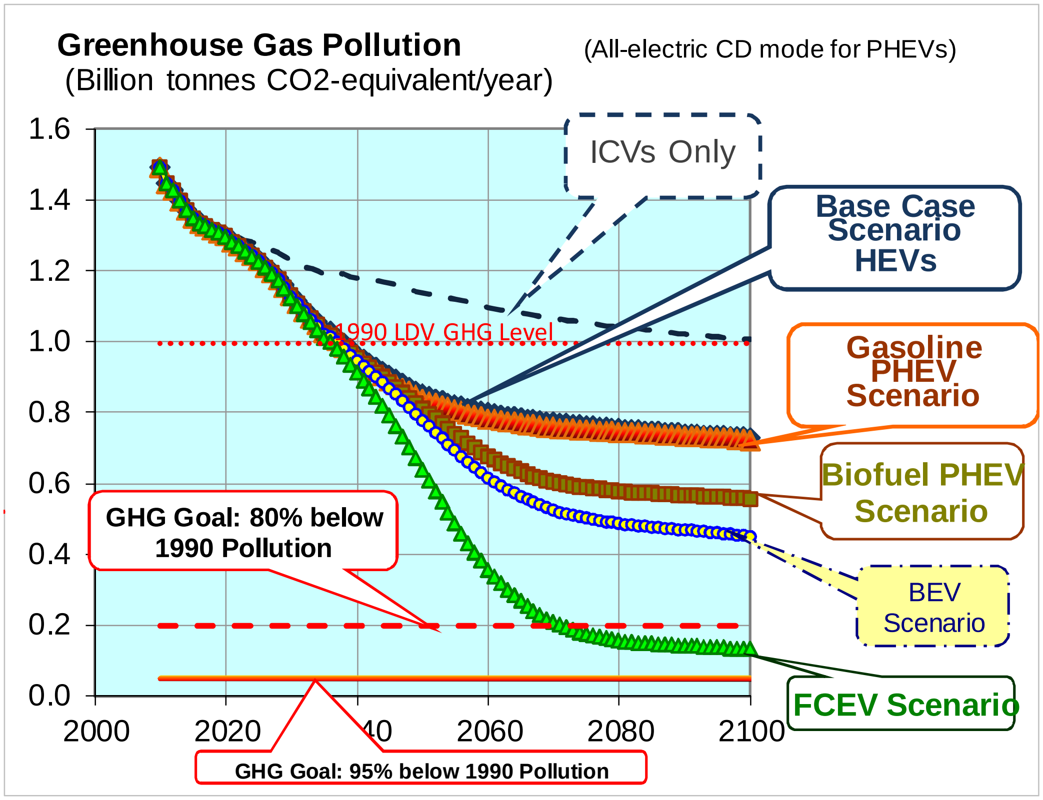

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Figure 4. Estimated greenhouse gas (GHG) emissions for various alternative vehicle scenarios over the 21st century

Some PHEV enthusiasts postulate that we need to deploy PHEVs now, since they can enter the marketplace immediately, while FCEVs must wait several years to establish the hydrogen fueling infrastructure. This model accepts this hypothesis, with the FCEV sales lagging PHEV sales by 5 to 6 years. Despite this 5- to 6-year head-start by PHEVs, the FCEVs will cut GHGs more than PHEVs beginning in the 2025. This is because the hydrogen-powered FCEV immediately reduces GHG by 50% compared to conventional gasoline cars if the hydrogen is made from natural gas, while a PHEV generates almost as much GHGs as a gasoline car with today's electricity generation mix which is mostly coal in the US. Therefore the PHEV only begins reducing GHGs when the electrical grid becomes "greener," which the model[12] assumes will occur slowly over the century, reaching near-zero GHGs by

[11] The Greenhouse gases, Regulated emissions, and energy use in Transportation model GREET1_2012, the Argonne National Laboratory, available at: http://greet.es.anl.gov/

[12] For details of the assumptions used in the model, see : (note that some of the assumptions in this earlier report have been updated with 2012 data) http://www.cleancaroptions.com/Alternative_Vehicle_Simulation_Paper_by_C._E._Thomas__for_distribution_.pdf

the 2070 from the electricity used to charge the PHEV batteries time period when all coal-based power plants are either shut down or augmented with carbon capture and storage (CCS) technology[13].

<u>Local air pollution</u>. While some people believe that PHEVs are low emission vehicles, the California Air Resources Board[14] has determined that a PHEV-40 like the Chevy Volt will actually generate 20 times more carbon monoxide emissions than the non-plug-in Toyota Prius HEV as shown in Figure 6. The PHEV will also generate more NOx and NMOGs.

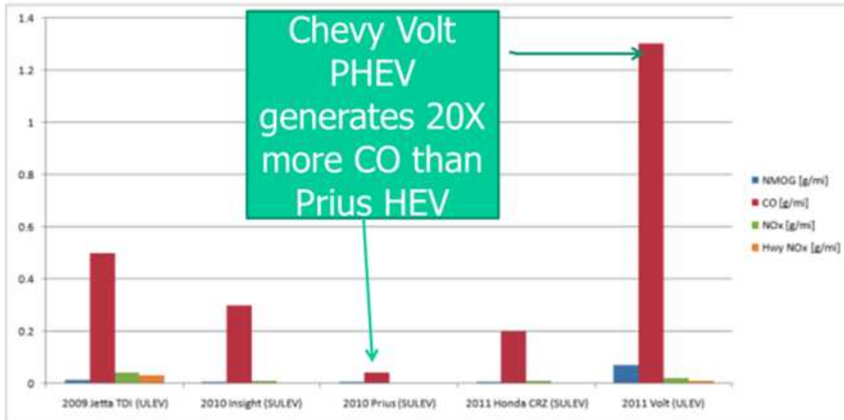

Figure 5 Estimated local air pollution from HEVs like the Toyota Prius and PHEVs like the Chevy Volt, estimated by the California Air Resources Board

<u>Oil Consumption</u>. One popular assumption is that PHEVs and BEVs will cut oil consumption more than FCEVs. But, as shown in Figure 7, FCEVs will cut oil consumption much more than PHEVs or BEVs. BEV sales are limited to 36.9% of small cars, vans, pickup trucks, SUVs and 50% of all midsize sedans. Also, with maximum possible BEV market penetration in the US as mentioned above, oil consumption would only be reduced by less than 15%[15].

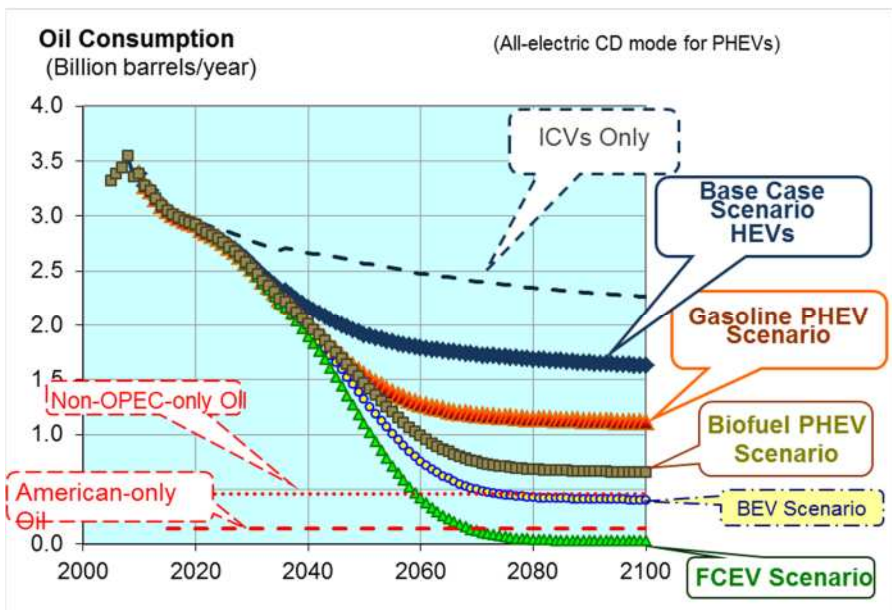

Figure 7. Oil consumption over the 21st century from various alternative vehicle scenarios

As with GHGs, the advantage of FCEVs for reducing oil consumption becomes

[13] However, PHEVs will still consume gasoline for long trips (and when the owner's teenage son or daughter forgets to plug in the vehicle when returning home!)

[14] Available at: http://green.autoblog.com/2010/10/23/carb-rules-the-chevy-volt-is-a-ulev-emits-more-than-prius-or-j/

[15] See 6/23/2011 report at: http://www.cleancaroptions.com/Distribution_of_US_Car_Fleet_by_Car_Class.pdf

apparent by the 2025 time period. PHEVs still consume some gasoline, while FCEVs eliminate all gasoline use. BEVs do not use any gasoline directly[16], but they cannot displace as many gasoline cars as FCEVs and PHEVs.

Commercial Readiness. The Department of Energy's National Renewable Energy Laboratory has documented[17] the on-road performance of 155 FCEVs over several years, driven by ordinary U.S. citizens in their daily routines. These FCEVs have operated for 131,000 hours under NREL monitoring, logging more than 3 million miles of travel. These FCEVs have been fueled with high pressure hydrogen 28,000 times without major incident, with an average fueling time of 4.4 minutes. No such data exist for BEVs or PHEVs since the major automobile companies just started producing those vehicles in 2011. Questions remain about the actual range and refueling times of BEVs and PHEVs in real-world driving conditions, including the impact of car heaters and air conditioners, as well as the impact of ambient temperature extremes, and the cost of the vehicles and the cost of the electrical infrastructure as described above and the ability of batteries to affordably power a majority of American cars, SUVs, vans and pickup trucks, which will be essential to make large reductions in GHGs and oil consumption.

Several major auto companies have declared that they will begin serial production of FCEVs on or before 2015. Hyundai has announced that they will produce 2,000 FCEVs by 2014. Daimler has announced that they will build a $50 million fuel cell manufacturing plant in Burnaby, British Columbia, with a goal of increasing their current fleet of 100 FCEVs to 10,000 FCEVs. This is how McKinsey & Company judged the commercial readiness of FCEVs in the EU context:

> "Given satisfactory testing in a customer environment - with more than 500 cars [FCEVs] covering over 15 million kilometres and 90,000 refuellings - the focus has now shifted from demonstration to planning commercial deployment so that FCEVs, like all technologies, may benefit from mass production and the economies of scale."

Conclusion: we need a *mixture* of alternative vehicles to meet our environmental and energy security goals: BEVs for small vehicles with short driving distances, FCEVs for larger vehicles and longer driving ranges, and PHEVs to bridge the gap.

The imperatives to cut GHG emissions and cut our addiction to oil are too great to "pick winners and losers" at this point of time, which is what the Obama administration has done by attempting to eliminate all funding for hydrogen and FCEV projects while lavishing billions of dollars on batteries, BEVs and PHEVs and electric charging outlets.

The need for a mixture of vehicles is illustrated by the plans of the California Air Resources Board as they seek to implement California's goal of cutting GHGs by 80% by 2050. Figure 8 is a slide presented by

[16] Although gasoline and diesel fuel are used to search for, mine and particularly deliver coal to the electrical power plants, so the Argonne GREET model does attribute some oil use to BEVs.

[17] Click on "monitoring" link at http://www.cleancaroptions.com/html/ev_fueling_time.html for report by Keith Wipke, Sam Sprik, Jennifer Kurtz, & Todd Ramsden, "2011 Composite Data Products: National FCEV Learning Demonstration," NREL report presented to the Fuel Cell and Hydrogen Energy Association Conference, Washington, D.C., March 29, 2011.

CARB's Tom Cackette at the 2011 Hydrogen and Fuel Cell Association's conference[18] in Washington D.C., CARB assumes a portfolio of vehicle options starting with hybrids, then PHEVs, then BEVs, with the majority of vehicles on the road being FCEVs by the 2050 time period.

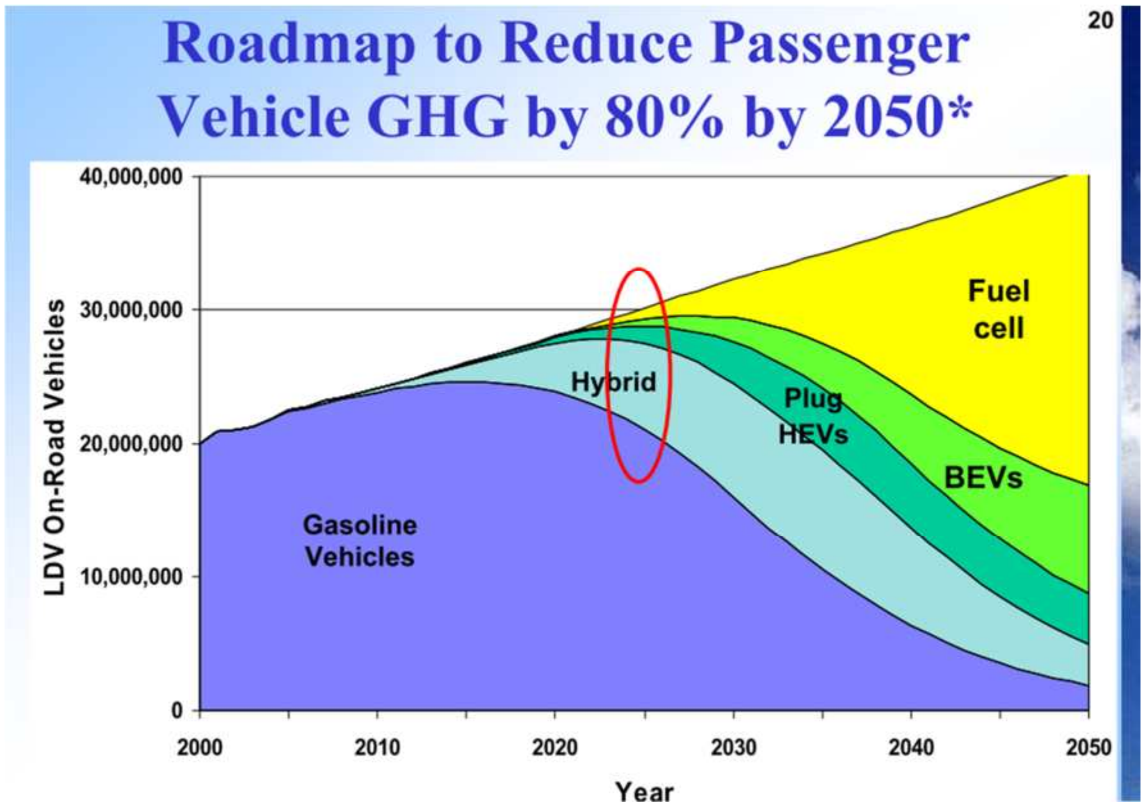

Figure 8. Mixture of alternative vehicles on the road suggested by CARB to achieve an 80% reduction in California GHGs by 2050

[18] Tom Cackette, "California climate change policy and the role of hydrogen," presented at the Fuel Cell and Hydrogen Energy Conference, Washington, D.C., February 1, 2011