COMPARISON OF TRANSPORTATION OPTIONS
IN A CARBON-CONSTRAINED WORLD:
HYDROGEN, PLUG-IN HYBRIDS AND BIOFUELS

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1. Introduction

Most automobile and energy company executives, academics and government planners acknowledge the long-term promise of hydrogen-powered fuel cell vehicles (FCVs). Some organizations are now promoting plug-in hybrid electric vehicles (PHEVs), and biofuels such as ethanol or butanol. These near-term options are desirable and should be pursued to reduce our demand for imported oil, but they should not be taken as a substitute for much better mid- to long-term solutions to curb urban air pollution, climate change gases and oil consumption. The national security and environmental imperatives for action are so strong that we should be vigorously pursuing all plausible transportation alternatives without delay.

We have developed an extensive computer model to simulate the societal benefits of various alternative transportation options including hybrid electric vehicles (HEVs) and plug-in hybrids fueled by gasoline, diesel fuel, ethanol and hydrogen, including both internal combustion engines (ICEs) and fuel cell (FC) power sources. These simulations compare the societal benefits of each vehicle/fuel combination in terms of reduced local air pollution, reduced greenhouse gas pollution, and reduced oil consumption.

2. Key Findings

The major conclusions from these computer simulations are:

- Greenhouse gas reductions: **the hydrogen-powered fuel cell vehicle is the only option that can achieve the goal of reducing GHGs by 60% or more below 1990 levels** in the transportation sector; the second-best option, cellulosic ethanol[1] PHEVs, could at best achieve a 20% reduction, and even then not until 2090.
- Urban air pollution: **the hydrogen-powered fuel cell vehicle is the only option that would virtually eliminate urban air pollution** from the transportation sector by 2100; all other vehicle/fuel options including both gasoline and ethanol PHEVs would produce essentially the same or greater urban air pollution as the existing car fleet due to increased vehicle miles traveled.
- Petroleum consumption: **hydrogen-powered vehicles (FC or hydrogen ICE) are the only option that could achieve energy "quasi-independence[2],"** reaching that milestone by mid-century; the second-best option, ethanol PHEVs would still consume over 5 million barrels oil per day by the end of the century.

[1] Existing corn ethanol could not even reach this level of GHG reduction.
[2] "Quasi-independence" is defined here as reducing oil consumption in the transportation sector to the level that US domestic oil production could supply all petroleum needs in a crisis, assuming no growth in non-transport oil consumption and no further decline in US oil production capacity.

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- Hydrogen infrastructure: **hydrogen infrastructure cost is not an issue:** the cost of installing a hydrogen infrastructure is small compared to current costs for maintaining the existing gasoline and diesel fueling systems, and hydrogen infrastructure costs are dwarfed by the societal cost savings from deploying fuel cell vehicles[3].
- Societal cost savings[4]: **hydrogen-powered fuel cell vehicles will provide greater societal cost savings than any other alternative**: each FCV sold will cut societal costs by a factor of 7.6 relative to conventional gasoline cars in the near-term (now to 2020), by a factor of 9.5 in the mid-term (2021 to 2050) and by a factor of 15.5 in the long-term (2051 to 2100); second-best option is the hydrogen-powered ICE HEV (reduction factors of 5.0, 6.2, 11.7); third-best the battery EV (4.2, 4.6, 10.6); fourth-best the ethanol plug-in hybrid (3.8, 4.8, 6.8) and fifth-best the gasoline plug-in hybrid (1.7, 2.1, 2.9) (See Figure 7 below).

3. Basis of Key Findings

We have focused on five vehicle/fuel scenarios to illustrate our key findings:

- Reference Case: 100% gasoline ICEVs
- Base Case: Gasoline HEV Scenario (including ICEVs)
- Gasoline PHEV Scenario (including gasoline ICEVs and HEVs)
- Cellulosic Ethanol PHEV Scenario (including gasoline ICEVs and HEVs)
- Hydrogen FCV Scenario (including all of the above in the early years)

3.1. Greenhouse gas results

Figure 1 shows the projected greenhouse gas emissions from the four scenarios plus a reference case with 100% conventional gasoline ICEVs (no hybrids of any kind). In the

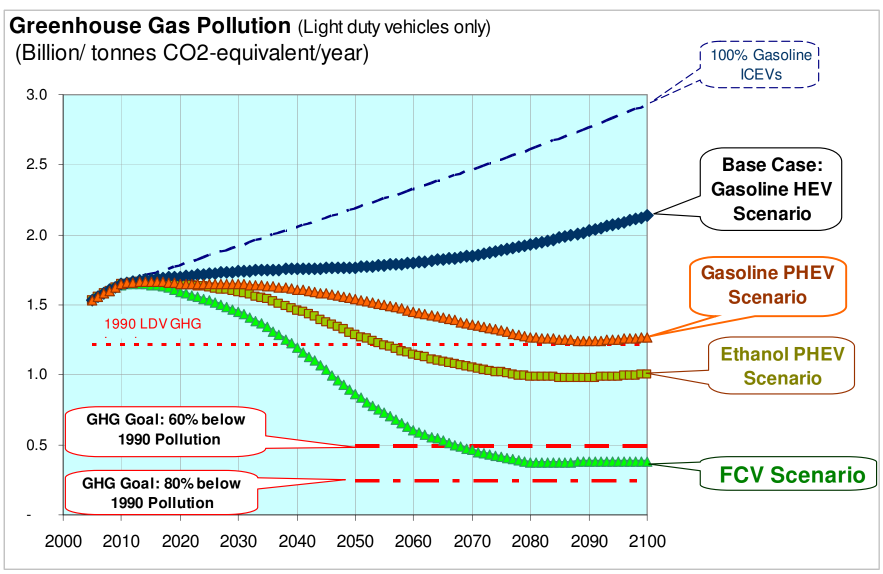

Figure 1. Greenhouse gas emissions for the four scenarios

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[3] Incentives will most likely be required, however, to reduce the initial FCV costs

[4] Societal costs include the health costs of urban air pollution, greenhouse gas emissions (varying linearly from \$25/metric tonne of CO_2 in 2010 to \$50/tonne in 2100) and the added societal costs of oil consumption (taken as \$60/barrel; this societal cost is *not the price* paid for oil)

base case with gasoline HEVs, GHGs are reduced from the reference case, but continue to rise through the century. The climate change goals of reducing GHGs to 60% or 80% below 1990 levels[5] are also shown at the bottom of Figure 1 for light duty vehicles. With the assumptions in this model, the fuel cell vehicle is the only scenario to achieve reductions of 60% below 1990 levels; the (cellulosic) ethanol PHEV cuts GHGs 20% below 1990 levels. Without substantial ethanol use, the gasoline PHEV would barely return GHGs to 1990 levels by 2100, and GHG pollution would increase for both PHEVs after 2090 as vehicle miles traveled continued to rise.

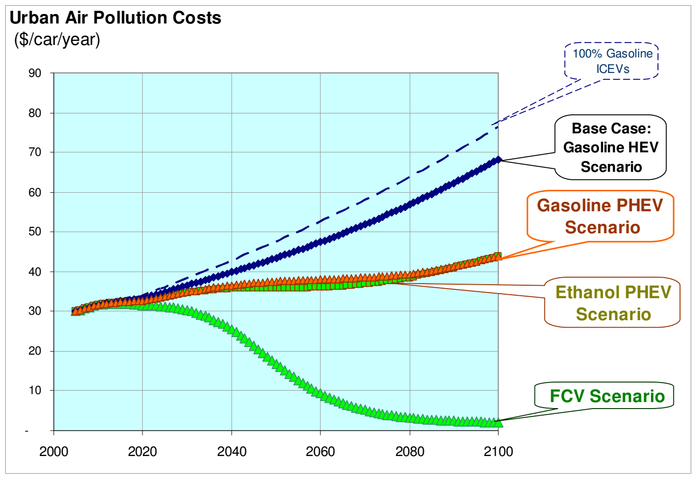


Figure 2. Urban air pollution costs (sum of grams/mile for each pollutant times $/kg societal cost) for each scenario

3.2. Urban air pollution results

The FCV is the only alternative that would reduce urban air pollution according to the Argonne GREET model.

3.3. Oil consumption results

The horizontal line near the bottom of Figure 3 labeled energy "quasi-independence" is the level where the projected US oil production of 7.5 million barrels/day in 2030 could meet all non-transportation needs (6.2 Mbbl/d, assuming no growth), leaving 1.3 Mbbl/d (or 0.5 billion barrels/year on the graph) for transportation needs. Only the FCV achieves this quasi-energy independence (by 2055).

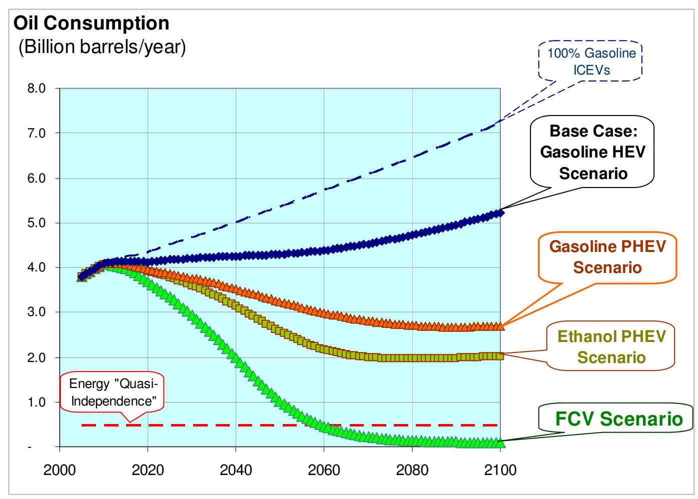


Figure 3. Petroleum consumption projections for the alternative vehicle scenarios, including the estimated oil consumption level such that US domestic production could supply all non-transportation petroleum requirements.

3.4. Hydrogen infrastructure cost results

The model calculates the cost of installing a distributed hydrogen infrastructure based on steam methane reforming of natural gas, using data from the DOE H2A cost model. The

[5] Senate Bill S.280 sets goal of 60% reduction below 1990 GHG levels by 2050; Senate Bill S.309 sets a goal of 80% below 1990 levels by 2050, and the states of California, Florida and Minnesota have enacted goals of 80% reduction by 2050, while New Mexico and Oregon has enacted 75% reductions by 2050.

total hydrogen infrastructure costs reach more than $35 billion per year by the end of the century. However, as shown in Figure 4, these costs are minimal compared to what the oil and gas industry spends today to maintain the existing gasoline and diesel fueling system. These costs are also similar to the $35 to $40 billion per year that will be required to reduce utility grid GHG pollution to at least 60% below 1990 levels (See Figure 13 below).

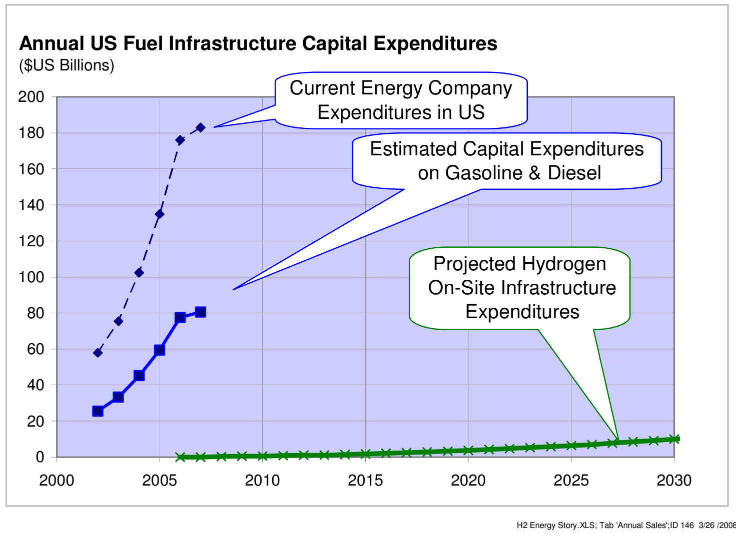


Figure 4. Projected hydrogen infrastructure costs compared to estimated costs of maintaining the current US gasoline and diesel fueling system

3.5. Societal cost savings results

The model also calculates the total societal cost savings relative to the base case of gasoline ICEVs and HEVs from reducing urban air pollution, reducing greenhouse gases, and reducing oil consumption. These societal savings exceed the hydrogen infrastructure costs by 2018, rising rapidly thereafter a shown in Figure 5 for the near-term, and in Figure 6 for the long-term. These graphs only refer to the costs of installing and maintaining a hydrogen infrastructure and do not address any incentives to offset the extra cost of the FCVs during early deployment.

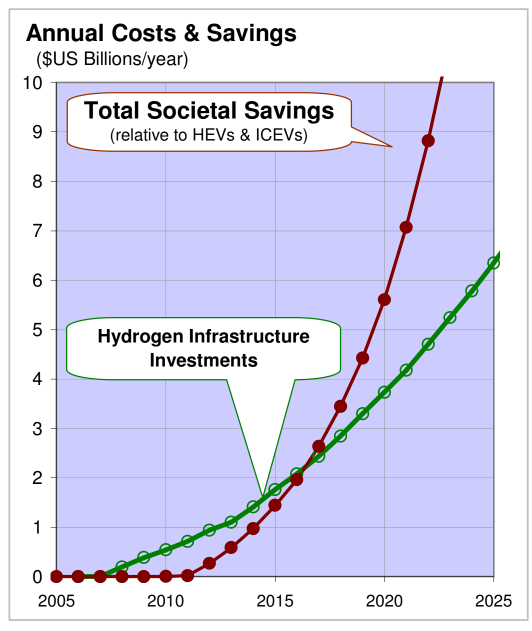
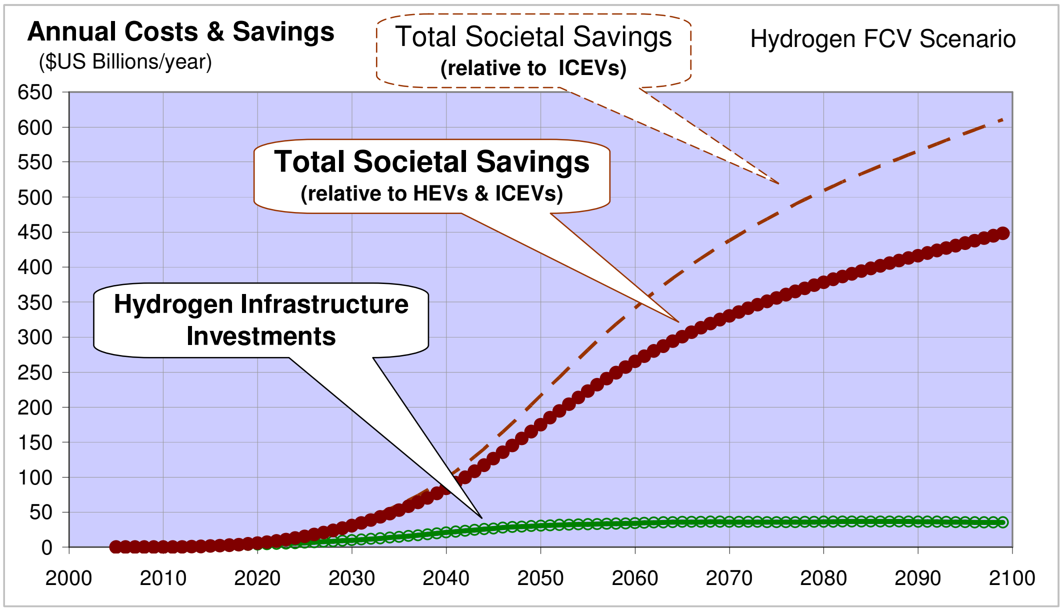


Figure 5. Projected near-term costs of a distributed hydrogen fueling system compared to the projected societal savings

The model sums the costs of urban air pollution, greenhouse gas emissions and oil consumption for each alternative vehicle/fuel combination. We then calculate a cost reduction factor, defined as the total societal costs attributed to a conventional gasoline (non-hybrid) car divided by the total societal costs of the alterative vehicle. These cost reduction factors change as the electrical grid and the sources of ethanol and hydrogen become greener over time. Figure 7 shows these cost reduction factors for each vehicle type averaged over three time periods: near-term (now to 2020), mid-term (2021 to 2050) and long-term (2051 to 2100).



	PM-10	PM-2.5	SOx	VOC	CO	NOx	CO2
Costs of Pollution:	53,739	134,041	29,743	6,592	1,276	13,844	25 to 50
($/metric tonne)			Crude Oil Price	$60/bbl			

H2 Energy Story.XLS; Tab 'Annual Sales';FL 26 3/21 /2008

Figure 6. Long-term projections of the hydrogen infrastructure costs compared to the total societal savings from deploying FCVs in terms of reduced urban air pollution, reduced greenhouse gases and reduced oil consumption with the costs listed above; the FCV would save up to $450 Billion per year compared to HEVs, and over $600 Billion per year compared to ICEVs by the end of the century.

We now turn to the assumptions and details behind these results.

4. Vehicles & Fuels Considered

We considered eight types of vehicle and five different fuels and analyzed in detail 12 different alternative vehicle/fuel combinations plus the gasoline ICEV reference case (Table 1). These alternatives represent vehicle/fuel combinations that have the best chance (or are being promoted as having a good chance) of achieving our transportation goals of reduced environmental and oil footprints. Detailed dynamic simulations were run for the four highlighted vehicle/fuel combinations.

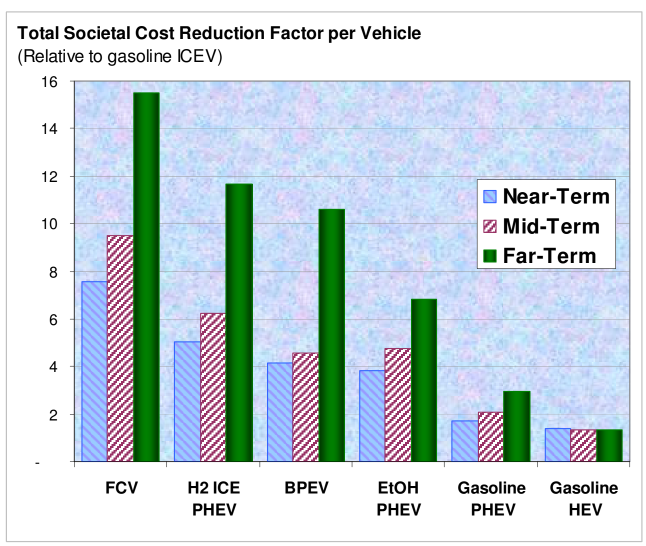


Figure 7. Societal cost reduction factors for alternative vehicle/fuel combinations over three time periods: near-term (now to 2020), mid-term (2021 to 2050) and far-term (2051 to 2100)

Table 1. Vehicle/fuel combinations analyzed in this report

Fuel:	SI ICEV	CIDI HEV	CIDI PHEV	ICE HEV	ICE PHEV	FC HEV	FC PHEV	BPEV
Gasoline	Reference			X	X			
Diesel		X	X					
Ethanol	X			X	X			
Hydrogen				X	X	X	X	
Grid Electricity			S		S		S	X

SI = spark ignition; ICEV = internal combustion engine vehicle; CIDI = compression ignition direct injection; PHEV = plug-in hybrid electric vehicle; FC = fuel cell' BPEV = battery-powered electric vehicle; X= primary fuel; S = Secondary fuel for PHEVs

5. Study Methodology

For each vehicle/fuel combination, we calculated the local air pollution (VOCs, NOx, CO, SOx, PM-2.5, PM-10), greenhouse gas (GHG) emissions and oil consumption using the GREET computer model developed by Michael Wang and associates at the Argonne National Laboratory [1]. We modified some of the GREET default input parameters over time to reflect the changing methods of producing ethanol, hydrogen and electricity, particularly when carbon constraints are introduced. Given the pollution and oil consumption estimates from GREET, our model then monetizes the externality costs associated with air pollution, greenhouse gas emissions and oil consumption.

To estimate the cost of building a national hydrogen infrastructure, we used the H2A cost model developed by the US Department of Energy and its contractors [2]. In particular, the H2A model projects that building small-scale steam methane reformers at the fueling station will be the least costly option initially, as summarized in Table 2. Eventually there will be enough FCVs on the road to justify building central steam methane reformer (SMR) plants and installing a hydrogen pipeline network, which may then be less expensive than building all on-site SMRs. So the assumption used here of all on-site hydrogen generators is conservative….hydrogen infrastructure costs could be less than shown here.

Table 2. Estimated cost for compressed hydrogen for early markets, using the DOE H2A model

($/kg) **Hydrogen Production Option**	Production Costs	Delivery Cost LH2 Truck	Total Delivered Cost
Forecourt** NG SMR	3.49		3.49
Forecourt** Electrolyzer	5.88		5.88
Central NG SMR	1.50	3.01	4.51
Central NG SMR with CCS	1.69	3.01	4.70
Central Coal Gasifier	1.34	3.01	4.35
Central Coal Gasifier with CCS	1.63	3.01	4.64
Central Wind + Electrolyzer	5.89	3.01	8.90
Cenral Biomass Gasifier	1.77	3.01	4.78

*Delievery costs assume 10% FCV market penetration in the Los Angeles basin; HDSAM 2.0 Beta
**Forecourt costs include compression, storage and dispensing

H2 Energy Story.XLS; Tab 'H2 Cost';F 18 3/22 /2008

6. Key Baseline Assumptions

Three key assumptions are the relative fuel economies of the alternative vehicles compared to the baseline gasoline ICEV, the externality costs of air pollution and the marginal electrical grid mix.

6.1. Relative Fuel Economy. Several studies have estimated the relative fuel economy for various alternative vehicle/fuel combinations. We used the average fuel economies of three sources: the GREET model, the National Research Council/National Academy of Engineering report on hydrogen[3], and an Auto/Oil report led by GM and Argonne[4].

Table 3. Average relative fuel economies used in model (last column)

Vehicle	Fuel	GREET	NRC/NAE	GM - Argonne	**Average**
SI ICEV	Gasoline	1.00	1.00	1.00	**1.000**
SI ICEV	EtOH	1.00		1.00	**1.000**
SI ICEV	H2	1.20		1.20	**1.201**
CIDI ICEV	Diesel	1.20		1.21	**1.206**
SI ICE HEV	Gasoline	1.48	1.45	1.24	**1.391**
SI ICE HEV	EtOH	1.48		1.24	**1.362**
SI ICE HEV	H2	1.60		1.48	**1.542**
CIDI ICE HEV	Diesel	1.60		1.45	**1.523**
FC HEV	H2	2.30	2.40	2.63	**2.445**

SI = spark ignition; ICEV = internal combustion engine vehicle; CIDI = compression ignition direct injection
HEV = hybrid electric vehicle; FC = fuel cell; H2 Energy Story.XLS; Tab 'Fuel Economy';F 17 2/1 /2008

6.2. Externality Costs. Similarly, we evaluated several reports that attempted to quantify either the health costs associated with urban air pollution or the costs of technology to reduce air pollution. As shown in Table 4, there are extremely divergent estimates, so we again took the average for this study, all converted to 2006 $/metric tonne [5,6,7,8,9].

Table 4. Average cost of urban air pollution (last column) used in model

	Delucchi US Urban (2006$/tonne)		Litman Urban	EU AEA (Ave. of 4)	EU (Holland & Watkiss)	Argonne National Lab Damage cost	Argonne National Lab Control cost	Average Air Pollution Costs
	Low	High	(2006$/tonne)	(2006$/tonne)	(2006$/tonne)	(2006$/tonne)	(2006$/tonne)	(2006$/tonne)
VOC	$179	$1,993	$17,706	$ 2,722	$ 3,413	$ 3,940	$ 16,195	$ 6,592
CO	$14	$137	$534				$ 4,420	$ 1,276
NOx	$2,185	$32,074	$18,934	$ 11,714	$ 6,825	$ 7,860	$ 17,319	$ 13,844
PM-10	$18,881	$257,633	$6,565		$ 22,750	$ 10,599	$ 6,005	$ 53,739
PM-2.5	$20,352	$309,687		$ 72,085				$ 134,041
SO2	$13,220	$124,969		$ 15,506	$ 8,450	$ 4,733	$ 11,581	$ 29,743

H2 Energy Story.XLS; Tab 'Emission costs'; W 14 2/1 /2008

6.3. Marginal Grid Mix. The source of grid electricity to charge PHEVs, BPEVs and to electrolyze water to make hydrogen is essential for calculating emissions. Some analysts calculate greenhouse gases based on the *average* grid mix, but this does not represent the reality of electric utility grid operation. For example, if a utility generated 50% of its electricity from nuclear and 50% from coal, then the GHGs for any new electrical load might be taken as the average of zero (nuclear) and approximately 1,000 grams of CO_2-equivalent/kWh from coal-based generators, or 500 gCO_2/kWh.

However, this does not mimic actual utility operation. To maximize profits, utilities operate their lowest operating cost plants first, and only turn on plants with higher operating costs to meet high demand. In the above example, since nuclear plants have lower operating costs than coal plants, the nuclear plants are run as baseload. The output from the coal plant would then be increased to accommodate any new electrical load. The net impact of adding a new load to the grid would generate 1,000 gCO_2/kWh, or twice the average GHG emissions in this example, unless the utility demand dipped below 50% of maximum capacity during the early morning hours, in which case the nuclear plant might have to be turned up slightly for a few hours at night.

This marginal grid mix effect is illustrated in Figure 8, showing a hypothetical US utility grid over a 24-hour period. The electrical generators are layered in order of increasing marginal operating costs. Hydro and renewables have the lowest operating cost, and are therefore run as baseload[6], followed by nuclear, then coal, and finally the natural gas generators that are used for peaking.

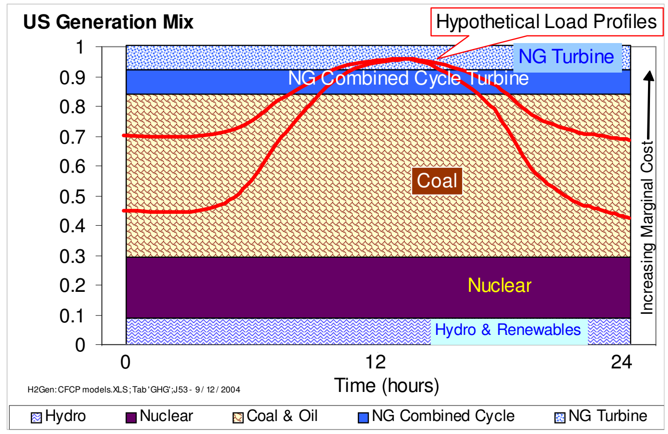


Figure 8. Illustration of marginal grid loads for a typical US electric utility

The red lines represent possible utility load profiles over 24 hours. Adding any new load will require this utility to increase the output from coal-based generators at night, and from natural gas generators during the peak day-time period. If vehicles are charged from the grid, greenhouse gases will increase based primarily on coal plants, particularly if the vehicles are charged at night.

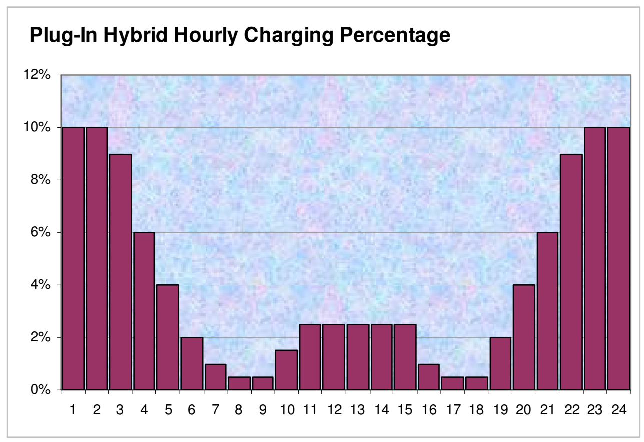


Figure 9. PHEV charging profile suggested by EPRI

To simulate vehicle charging, the model calculates the fraction of grid generators that will have to be turned on using a PHEV charging profile (Figure 9) developed by the Electric Power Research Institute [10]. Most (74%) PHEV charging is off-peak at night in the EPRI model. The resulting estimates of the current marginal grid mix compared to the average grid mixes for the US and California are summarized in Table 5. In both cases, there is no credit for renewables and nuclear, the two zero GHG sources. Our program estimates that 61.7% of electricity to charge vehicles in California will come from coal. For comparison, Mark Delucchi of UC-Davis estimates that 51.7% of electricity for charging car batteries in the West would come from coal and 15.2% from oil, or total of 66.9% high GHG emitting electricity [11].

Table 5. Comparison of average and marginal grid mixes

	Renewables & Nuclear	Coal	NG CC	NG GT
US Average	30.4%	50.1%	8.6%	10.9%
US Marginal	**0.0%**	**80.3%**	**3.9%**	**15.8%**
Cal. Average	39.0%	34.4%	11.7%	14.7%
Cal. Marginal	**0.0%**	**61.7%**	**21.5%**	**16.8%**

GHG.XLS, Tab 'Marginal Grid'; Q146;3/11/2008

[6] If water can be held behind dams without adversely affecting river flow or fisheries, then hydroelectricity can be used for peak shaving, which maximizes its value.

For the near-term (2010) time period, we assumed current sources for the fuels: ethanol from corn, electricity from the grid, and hydrogen from natural gas.

7. Key Dynamic Assumptions

The methods of producing hydrogen, ethanol and electricity are expected to change over time, particularly if greenhouse gas reduction becomes a major priority. Transportation and electricity currently account for over 73% of all US GHG pollution (Figure 10). Reducing GHGs by 60% to 80% below 1990 levels by 2050 will require significant reductions in coal use for electricity (or carbon capture and storage- CCS) and reductions in petroleum use for transportation.

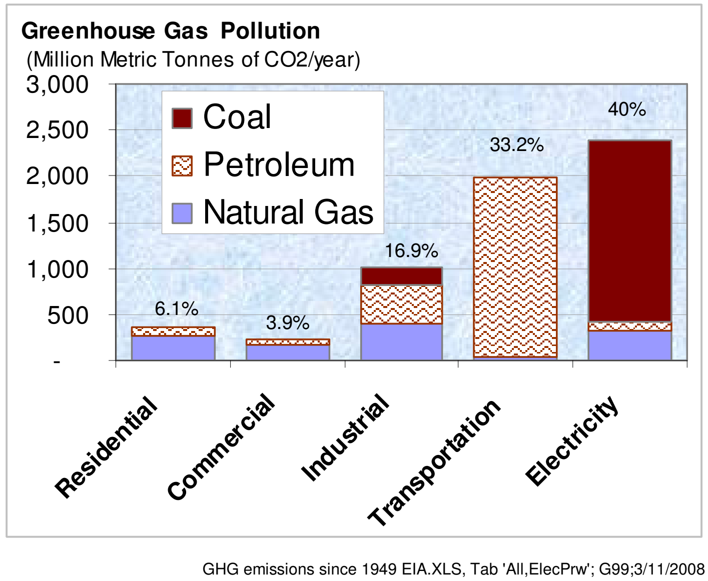


Figure 10. Current (2005) contributions to US greenhouse gas emissions from various sectors (all electricity was removed from residential, commercial and industrial sectors for this graphic)

Electric Grid Mix. To simulate possible electrical grids of the future with a strong commitment to curbing GHGs, we averaged two projections to 2030 by the EPA [12] and the DOE's Energy Information Administration (EIA) to implement the GHG reduction goals of Senate Bill S.280 [13]. To provide the best benefit to battery EVs and plug-in hybrids, we also started with the current California grid mix as represented by the Western Electricity Coordinating Council conglomerate of eleven western states. The electrical generators in these western states have a higher percentage of hydroelectricity and less coal-generated power than the rest of the nation. We then applied the average of the EPA and EIA projections for the grid mix to the year 2030, and then extrapolated out to the year 2100, phasing in increasing fractions of renewables and also sequestration of carbon at integrated gasification and combined cycle (IGCC) coal plants. This grid production mixture (Figure 11) was then

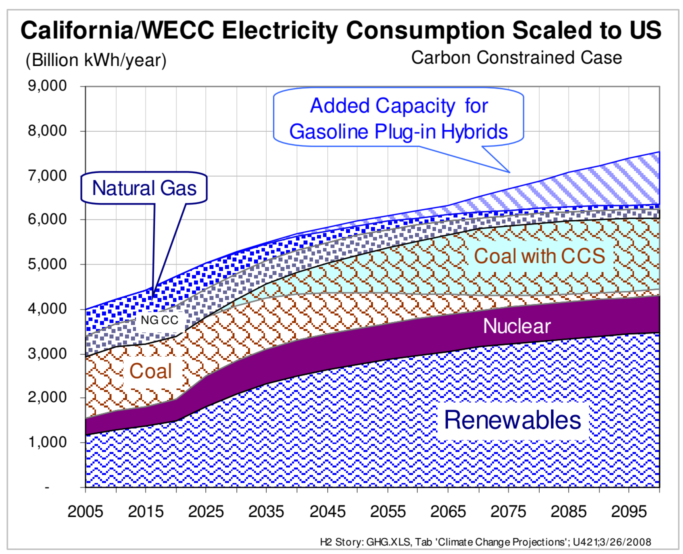


Figure 11. Electrical grid production sources projected to 2100 based on EPA and EIA projections to 2030, scaled from WECC with significant carbon constraints; extra consumption shown for plug-in hybrids

used to estimate the marginal grid mix over time for the purpose of charging car batteries, applied to all sections of the US[7].

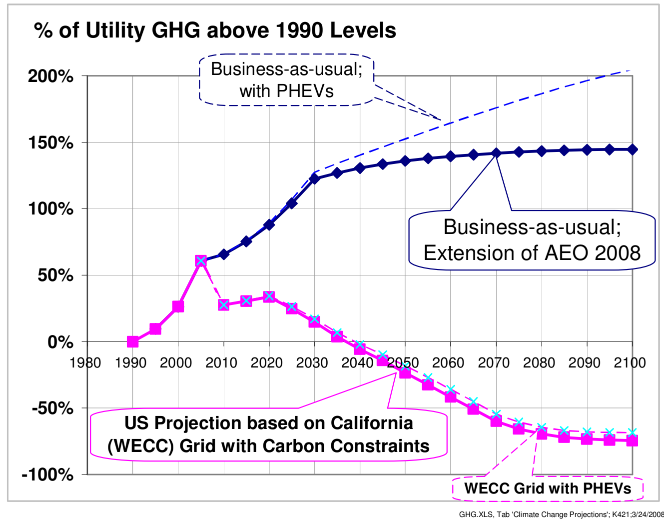


Figure 12. Estimated percentage change of grid greenhouse gas emissions relative to the 1990 US level assuming business as usual EIA projections through 2030, compared with the assumptions used here based on the California/WECC grid mix and significant carbon constraints over the century

The impact of these electrical generation changes on GHG pollution is shown in Figure 12, all relative to the 1990 US grid GHG's. With the EIA's 2008 Annual Energy Outlook projection to 2030, and a decrease in the rate of electricity growth from 2030 to 2100 (excluding PHEV grid demand), the US utility GHGs would rise to 2.5 times the 1990 levels (150% increase) by 2100. With PHEVs, GHGs would rise to 200% above 1990 levels. With the assumptions used here, starting with the California/WECC grid mix (immediate drop in 2005-2010), the grid GHGs would fall to 60% of 1990 levels by 2070 and to 75% below 1990 levels by 2090. With the low-carbon grid, adding PHEVs would have marginal impact. Even with this aggressive introduction of low-carbon generators, the GHGs from the grid would fall to only 20% below 1990 levels by 2050.

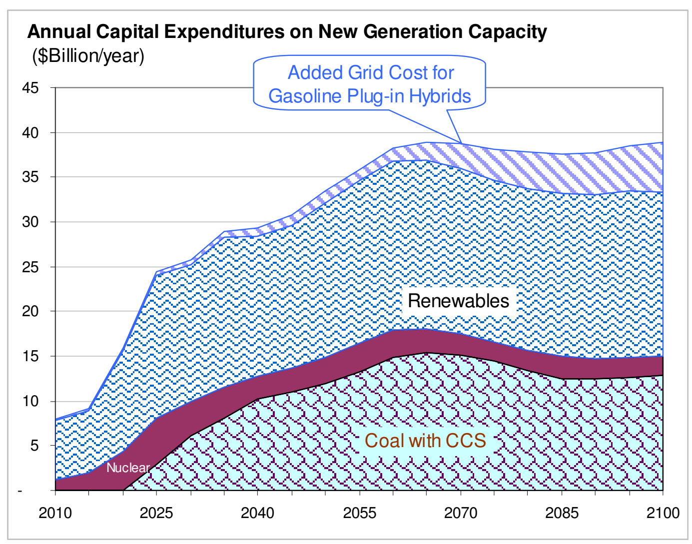


Figure 13. Estimated capital costs per year to install the new, low-carbon generators postulated in this model; also shown is the added cost to support plug-in hybrids

<u>Electric Grid Capital Costs</u>. We estimated the gross cost of installing these new low-carbon electrical generators using the capital expenditure costs and capacity factors for new generator technologies from the Electric Power Research Institute [14]. As shown in Figure 13, the electric utility industry would have to spend up to $30 billion per year by 2030 to install the new generators postulated for this assessment. This does not

[7] The extra electricity to charge PHEVs is assumed to come from the same mixture of generators as shown without the PHEV consumption; extra grid capacity is needed with the EPRI charging schedule for PHEVs to accommodate 26% new on-peak demand; up to 700 billion kWh/year of off-peak power is assumed to be available from the grid for charging PHEVs at night

include any cost for new transmission and distribution equipment, but does include generator replacement after 30 years, assuming 20% salvage value. Note that we have assumed rather stringent energy conservation (Figure 11) in this model, with the rate of electricity consumption growth falling significantly after 2030 (without the added PHEV demand for electricity). If these energy conservation efforts fail to achieve these reductions, cost for new generator capacity would rise proportionately.

<u>Hydrogen Sources</u>. We have also assumed that the sources for hydrogen become greener over time. Hydrogen is made from natural gas initially as the least costly option for producing vehicle fuel, which immediately cuts GHGs by approximately 50% for FCVs compared to burning gasoline in a regular car. Further reductions in the hydrogen carbon footprint will be required, however, to meet the goals of a 60% to 80% reduction below 1990 levels.

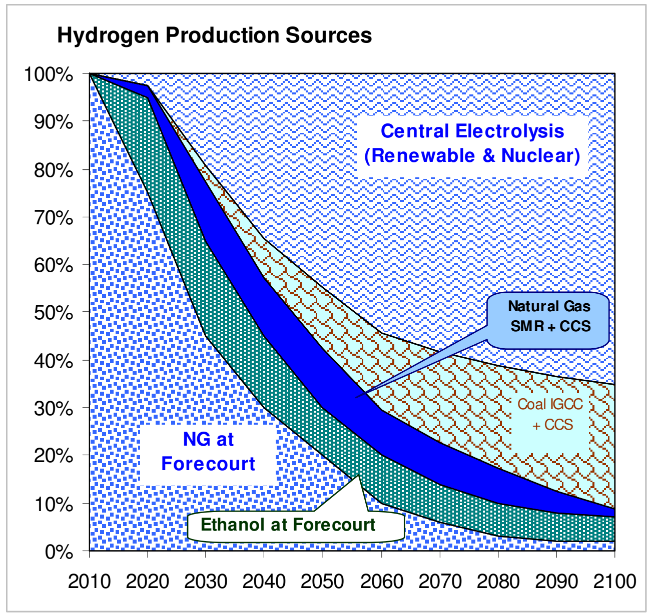


Figure 14. Postulated sources of hydrogen over time

The first move toward greener hydrogen postulated here is reforming ethanol at the fueling station. We assume that ethanol is made from corn initially, transitioning to cellulose and hemi-cellulose, starting with corn stover…the corn stalk and root residue that is currently left on the field. As fuel cell vehicles increase demand for hydrogen, we assume that hydrogen is made from natural gas and from coal gasification with carbon capture and storage (CCS). Finally, we assume that the bulk of the hydrogen is eventually made by electrolysis using green electricity from renewables or nuclear power, and from biomass gasification as shown in Figure 14.

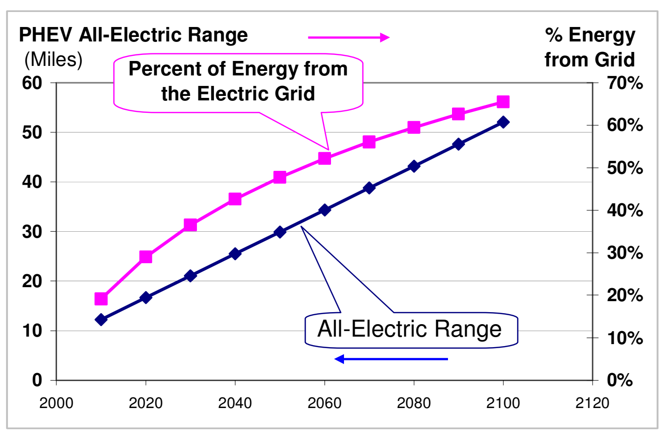


Figure 15. The all-electric range and percentage of energy drawn from the electrical grid for plug-in hybrids

<u>Plug-in Hybrid Performance</u>. The urban air and GHG pollution and petroleum consumption of PHEVs will depend on both their all-electric range (AER) and the percentage of energy drawn from the electrical grid. The AER is determined by the energy storage capacity of the PHEV's battery bank. The larger the AER, the longer the vehicle can travel on grid electricity

alone and the less frequently the vehicle will need to turn on its on-board power source. Figure 15 shows the AER and the corresponding fraction of PHEV energy drawn from the grid used in this model. The AER varies linearly from 12 to 52 miles, while the fraction of energy from the grid varies from 18% to 65% over the century. These data were derived from a report on PHEVs by the Electric Power Research Institute and the Natural Resources Defense Council where they estimated the fraction of grid energy for PHEVs with 10, 20 and 40 mile AER as a function of the annual vehicle miles traveled [15]. We extrapolated out to 52 miles range based on their data, using the vehicle miles traveled in this model.

8. Key Static Transportation Results

Total Societal Cost. We have devised a single figure-of-merit to compare all vehicle/fuel combinations: the total societal costs including the costs of urban air pollution, greenhouse gas pollution, and the cost of oil imports. To account for GHG pollution, the model assumes a cost of \$25/metric tonne of CO_2 in 2010, rising linearly to \$50/tonne by 2100. The model assumes a societal cost of \$60/barrel[8] for oil to account for balance of trade and other macroeconomic costs and the military costs of protecting our oil supplies. This societal cost figure-of-merit changes over time as the relative "greenness" of fuel sources and the costs of GHGs vary. This figure-of-merit does not include any market acceptability information, but compares each vehicle on a one-for-one basis.

To further consolidate the data, we calculated the societal cost reduction factor for each alternative vehicle/fuel combination; the reduction factor is the total societal cost of the baseline gasoline ICEV averaged over each time period divided by the societal cost of the alternative vehicle over that period. Thus if a gasoline ICEV generated \$1,000 per year societal costs and a FCV produced \$100 per year costs, then the FCV would have a 10 to one cost reduction factor. These cost reduction factors are summarized for the key vehicle/fuel combinations[9] in Figure 7 above for the near-term (now to 2020), the mid-term (2021 to 2050) and the far-term (2051 to 2100.) These cost reduction factors are all based on the carbon constraints placed on the grid starting with the relatively clean California/WECC grid as described above.

As shown in Figure 7, the hydrogen-powered FCV reduces the total societal costs per car more than any other vehicle/fuel combination in all time periods. The FCV cuts societal costs by an average of 7.6 to one in the near-term compared to gasoline cars, rising to 15.5 to one in the far-term. The relative advantage of the FCV over the PHEVs would be even greater for the US electrical grid instead of the California/WECC grid mix assumed in this model.

[8] This is not the price paid for oil, but an estimate of the additional societal cost in terms of economic loss through trade imbalance, the cost of defending our oil supply, etc.

[9] To reduce the data presented, we show only the best options in a given category. Thus the ethanol PHEV is superior to either the ethanol ICEV or the ethanol HEV, so we do not show the latter two. Similarly, the FC HEV is superior to FC PHEV, while the hydrogen ICE PHEV is better than the hydrogen ICE HEV. The diesel PHEV is similar to the gasoline PHEV, slightly better in some attributes and slightly worse in others, so we did not show the diesel PHEV.

The hydrogen-powered ICE plug-in hybrid is second-best, cutting societal costs by a factor of 5 initially, growing to 11.7 in the far-term.

The battery-powered electric vehicle (BPEV) is third-best, cutting societal costs between 4 to 10.6 to one over time. We have assumed here that the BPEV uses advanced lithium-ion batteries that have achieved the DOE specific energy goal of 150 Wh/kg, which is a 50% improvement over the best Li-Ion energy battery developed to date[16][10]. For widespread consumer acceptance, these BPEVs would also have to reduce the long charging times to qualify for long-distance travel.

The fourth-best option is the ethanol-powered plug-in hybrid (PHEV). While ethanol supply will be limited, less would be needed for a PHEV than an ICEV.

The fifth-best option is the gasoline plug-in hybrid. Note that the average cost reduction factor for the gasoline PHEV, even in the long-term, is only 2.9 to one, compared to 15.5 to one for the FCV.

Finally, the gasoline (non-plug-in) hybrid offers the least advantage on a per-vehicle basis. The gasoline HEV essentially can only improve costs by the increased fuel economy compared to a conventional car, assumed to be 1.39 to one in this model.

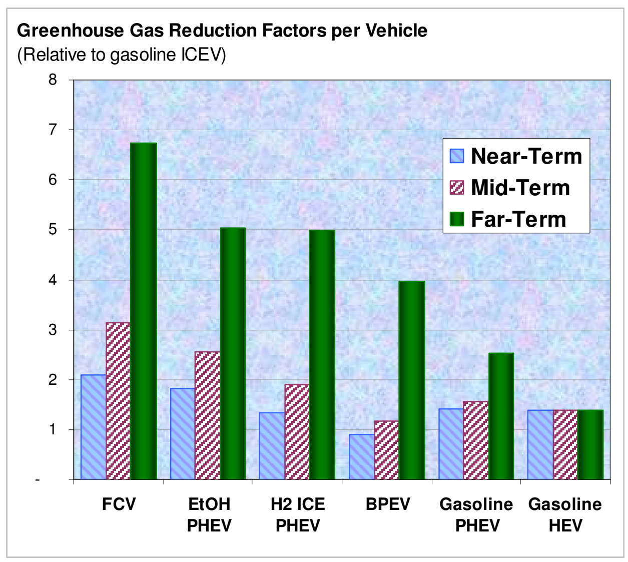


Figure 16. Greenhouse gas reduction factors compared to gasoline ICEVs

We now consider each of the three vehicle criteria separately:

<u>Greenhouse Gas Pollution</u>. The reduction factors for greenhouse gases (defined as the ratio of ICEV GHGs to the alternative vehicle GHGs) are shown in Figure 16. The data are similar to the societal cost reduction factors, but the ethanol PHEV has jumped to second place. Once again the hydrogen-powered FCV is superior for all time periods, cutting GHGs by factors of 2 to 6.7 compared to the gasoline ICEV. The BPEV actually has higher GHG emissions than a gasoline car in the near-term, before the electrical grid carbon constraints take effect, so the reduction factor is slightly less than one.

[10] Although a 2008 DOE energy storage R&D progress report [17] listed 100 wh/kg as the goal for PHEV batteries, in which case the 150 Wh/kg assumed here would be 50% above the DOE goal.

Urban Air Pollution. The static urban air pollution reduction factors are shown in Figure 17, with the FCV superior to all the others. Surprisingly, the BPEV has lower air pollution reduction factors (more pollution) than the ethanol PHEVs and gasoline PHEVs in the near-term. One normally thinks of the BPEV as a zero emission vehicle. However, the Argonne GREET model calculates substantial urban air pollution from BPEVs. Much of this pollution is due to SOx and NOx from electrical power plants either in or up wind of the urban airshed. Some particulates are also generated by the tires and brakes of a BPEV.

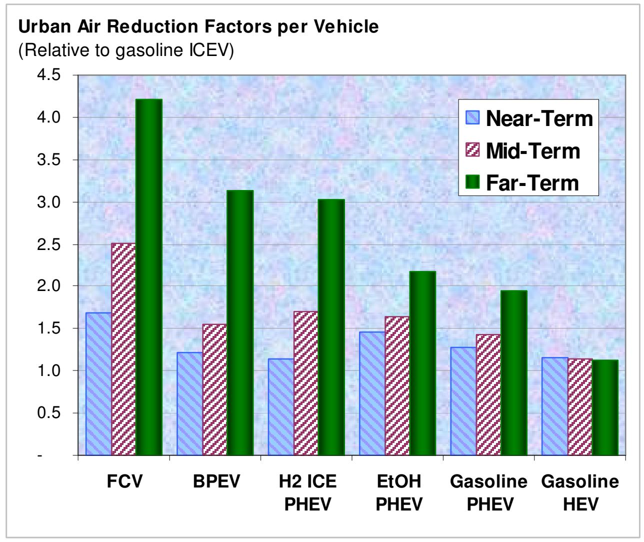


Figure 17. Urban air pollution reduction factors relative to gasoline ICEVs

Oil Consumption. The oil consumption reduction factors are huge for the FCV, hydrogen ICE PHEV and the BPEV, since they use virtually no oil (nearly division by zero!) We put them off-scale in Figure 18 to show the relative comparison of the ethanol and gasoline PHEVs and the gasoline HEVs. Significant petroleum is used to grow corn or other biomass, to transport the biomass and ethanol, etc., so the ethanol oil reduction factors are limited to the range between 6 and 12 to one.

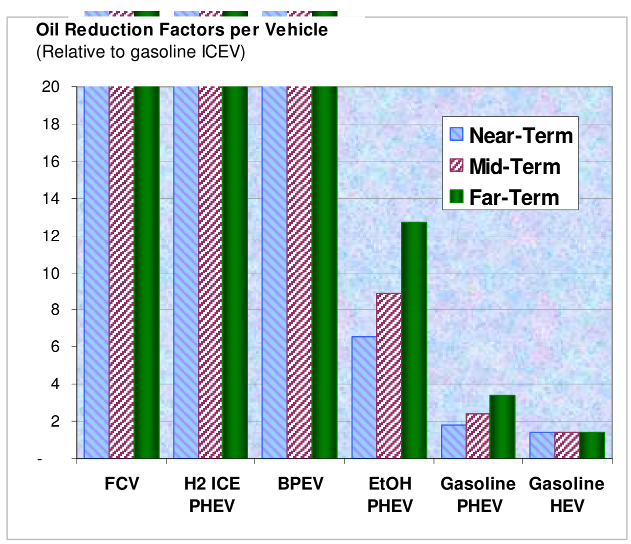


Figure 18. Oil consumption reduction factors

9. Dynamic Transportation Simulation Assumptions

The static per vehicle data in Section 8 above did not take into account the marketability of the various alternative vehicle/fuel combinations. The gasoline HEVs and ethanol (E-85) ICEVs are already on the road in limited numbers. Others such as PHEVs and FCVs will require further technical development and cost reductions before they satisfy a large segment of consumers. Battery EVs may take even longer to overcome the limited range/refueling time dilemma. To account for these differences in technical/ economic readiness, we have simulated the gradual introduction of advanced vehicles into the fleet according to the modified logistic market share curves shown in Figure 19.

We have analyzed four different vehicle/fuel scenarios (plus gasoline ICEV case):

- Base Case gasoline HEV Scenario
- Ethanol PHEV Scenario
- Gasoline PHEV Scenario
- Hydrogen FCV Scenario

In addition we analyzed a gasoline ICEV-only case, excluding all hybrids. The mix of new car sales for each scenario is illustrated in Figures 20 through 23.

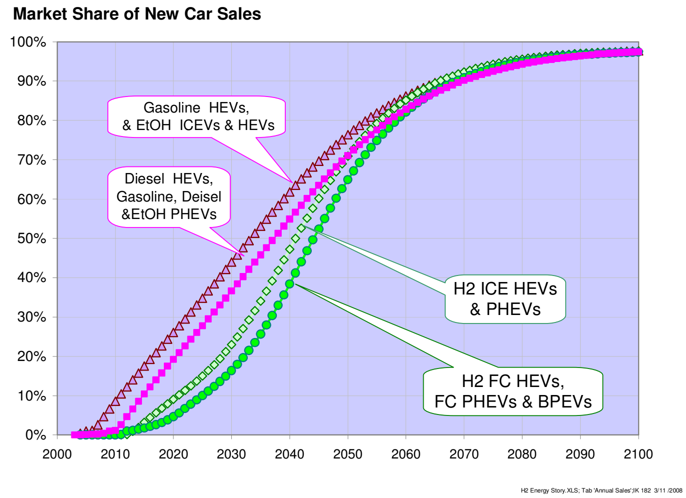


Figure 19. Percentage market share of new vehicles sold in the US for each of the alternative vehicles

For the base case, we assume that gasoline hybrids continue their current ramp-rate in sales, reaching 50% market share by 2024, with the remainder of all cars sold conventional gasoline ICEVs (Figure 20).

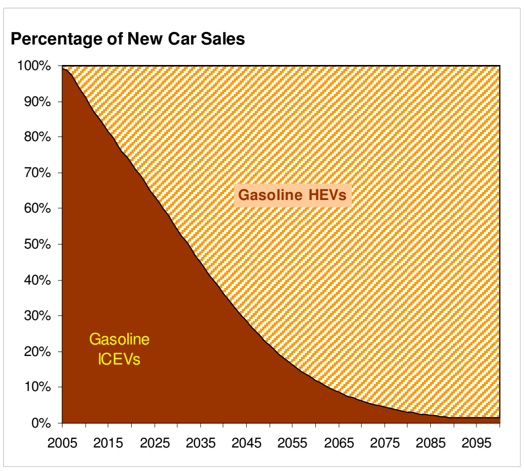


Figure 20. Annual market share of gasoline ICEVs and gasoline HEVs for the base case scenario

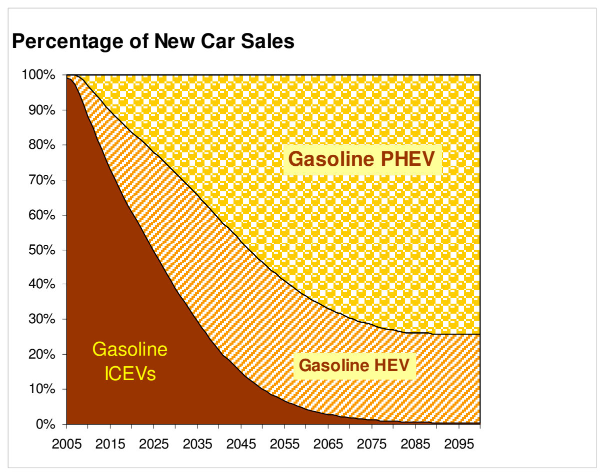


Figure 21. Market share of new cars sold for the gasoline plug-in hybrid scenario

For the gasoline PHEV scenario, we assume that the plug-in hybrids have a sales curve delayed by six years, or 50% sales share by 2032. We assume that 75% of all vehicles have access to night-time power outlets[11]. Gasoline HEVs continue to be sold as shown in Figure 21. Ethanol PHEVs enter the marketplace with the

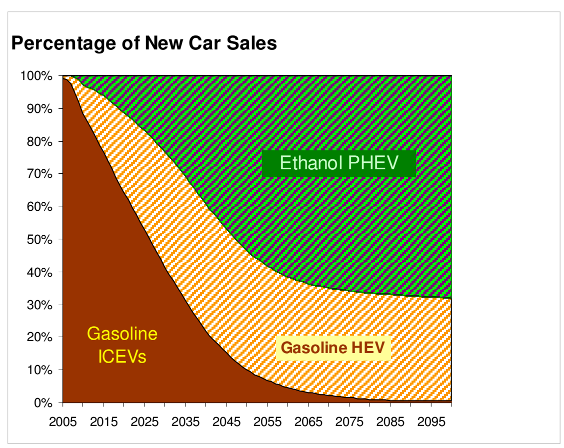


Figure 22 Market share of new cars sold for the ethanol plug-in hybrid scenario

[11] EIA and Census Bureau data estimate that 45% to 50% of car owners have garages or carports (some of which may actually still have cars inside!); assume that another 25% have driveways or assigned off-street parking places that could accommodate an outdoor charging port.

same basic sales share potential as gasoline PHEVs, but with the added constraint of limited ethanol production capacity. Ethanol consumption ramps up to 14 billion gallons by 2022 (limited by PHEV sales), less than the 36 billion gallons/year administration goal, and continues up to a level of 110 billion gallons per year, by 2060. NRDC suggested that up to 120 billion gallons/year of cellulosic ethanol could be produced in the US, equivalent to 7.9 million barrels/day of gasoline on an energy basis [18].

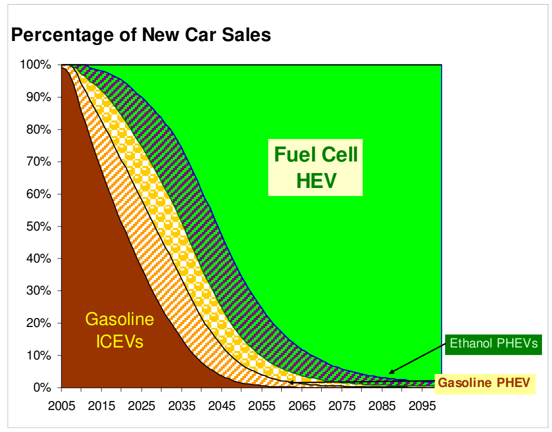


Figure 23. Market share of new vehicles sold for the fuel cell vehicle scenario

The fuel cell vehicle scenario assumes that FCVs are sold into the existing gasoline HEV/PHEV and ethanol PHEV markets. The FCV market penetration curve is also delayed relative to the gasoline PHEV market curve, such that FCVs reach 50% of all new cars sold by 2035, with market share increasing over time as shown in Figure 23.

10. Hydrogen Infrastructure Costs

The U.S. Department of Energy and its contractors have developed the H2A hydrogen infrastructure cost estimating model. This model predicts that the cost of providing hydrogen will be minimized initially by installing steam methane reformers at fueling stations to convert natural gas and water to hydrogen. This avoids the necessity of installing a costly hydrogen pipeline system that would be severely under-utilized when there are very few hydrogen vehicles on the road. Hydrogen fueling stations are added when and where they are needed to match the introduction of hydrogen vehicles in each region of the country.

For purposes of estimating GHGs and urban pollution, we have assumed that hydrogen production shifts gradually from on-site distributed generation to central production with either truck or pipeline delivery. For costing purposes, however, it is easier to estimate costs for on-site production only and avoid the complexity of deciding when and where to begin building large central hydrogen production plants and hydrogen pipeline distribution systems. We assume that the shift to central production will occur when there are enough FCVs in a given region to make central production and hydrogen delivery by either truck or pipeline less costly than on-site distributed generation. Hence the costs calculated here should be considered an upper bound on the hydrogen infrastructure system.

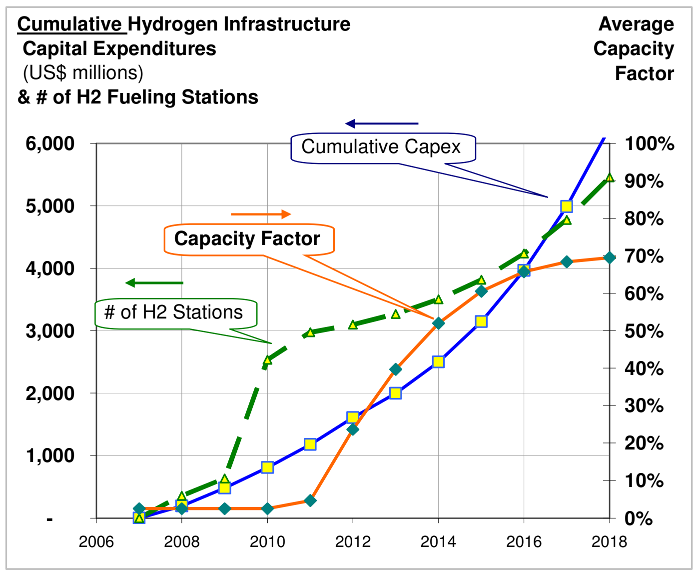
The fueling equipment has an expected life of 20 years. At the end of its useful life, all equipment is replaced with zero assumed salvage value (another conservative assumption.) By the last quarter of the century, the annual costs reach $38 billion per year including both expansions of the hydrogen infrastructure as well as replacement of older fueling systems. This is approximately the same as the cost of converting the electrical grid to low-carbon sources, especially if extra grid capacity must be installed to support plug-in hybrids (See Figure 13).

<u>Fueling Station Capacity Factor</u>. As shown in Figure 24, the capacity factor approaches 70% by 2018 in this model after a *cumulative* hydrogen infrastructure investment of $6.2 billion for 5,500 hydrogen stations. At this point, the energy companies will start making the 10% real, after-tax return on the capital investments that is assumed in the model to calculate the price of hydrogen to drivers. In other words, no additional government incentives would be required to continue building the hydrogen infrastructure after the 2016-2018 time period.

Table 6. Costs for distributed hydrogen fueling systems

Capacity	Fueling Station Costs	
	Single Qty	500 Qty
100 kg/day	$ 772,800	$ 535,000
500 kg/day	$ 2,212,000	$ 1,534,000
1,500 kg/day	$ 4,181,700	$ 2,900,000

H2 Energy Story.XLS; Tab 'Annual Sales';EC 18 3/22 /2008



H2 Energy Story.XLS; Tab 'Annual Sales';DB 24 3/1 /2008

Figure 24. Number of hydrogen fueling stations, the *cumulative* capital costs for those stations, and the average capacity factors in the early years of FCV deployment

<u>Hydrogen vs. Gasoline Infrastructure Costs</u>. To put the hydrogen infrastructure expenditures in perspective, Figure 4 (shown above) compares the hydrogen infrastructure cost with the recent history of actual energy company capital investments in the US gasoline and diesel fuel infrastructure. In 2007, the Oil and Gas Journal estimates that the energy companies spent over $180 billion in the US on capital items [19]. Some of these expenditures were for natural gas and some for non-fuel uses of crude oil. We have not located a source for the fraction of these capital expenditures that should be attributed to gasoline and diesel fuel, so we estimated that fraction as follows.

The energy companies produced more natural gas (19 quads) in the US than oil (13.2 quads). However, the production of gasoline from crude oil is much more capital intensive than the production of line natural gas from well-head gas. One measure of this cost is the price charged for these two products. In 2006, natural gas prices averaged $6.24/MBTU, while gasoline averaged $21.06/MBTU, including highway taxes. Subtracting 48 cents/gallon ($3.84/MBTU) highway taxes, gasoline cost $17.22/MBTU. If we apply these costs times the production of oil and gas, the net revenues from natural gas were $119 billion and $227 billion for oil turned into gasoline.

By this revenue measure, natural gas accounted for 34% of the total capital expenditures, so we can associate 66% of the $180 billion spend in 2007 to petroleum, or $118 billion. Gasoline and diesel fuel account for approximately 67% of the output from US oil refineries[20], so the final estimate of their share of capital expenditures for 2007 is $79 billion as shown in Figure 4. Thus 2007 capital expenditures for gasoline & diesel infrastructure far exceed the expected 2030 costs for the hydrogen infrastructure.

11. Natural Gas Resources

Some observers have suggested that by replacing gasoline with hydrogen made from natural gas we would just be switching from one foreign fossil fuel dependency to another. Several relevant points on natural gas usage for hydrogen production include:

- Natural gas would be a temporary transition energy source for hydrogen until lower carbon sources such as biofuels, electrolysis of water using renewables, biofuels, nuclear or coal with sequestration become practical and affordable.
- US natural gas consumption would increase temporarily by less than 12% to supply hydrogen for fuel cell vehicles in this scenario, falling thereafter as hydrogen is made from other sources
- Every BTU of natural gas used to make hydrogen for a FCV displaces approximately two BTUs of crude oil, so hydrogen from natural gas would cut total fossil fuel use by a factor of two[12]
- The world has slightly more natural gas resources than crude oil resources, and the world is consuming oil faster than natural gas. Therefore cutting some petroleum use and increasing natural gas consumption by a lesser amount actually helps to correct the imbalance developing between global oil and gas resources.
- The Middle East holds 55% of oil resources but only 31% of natural gas resources, so slightly shifting from oil to gas at least diminishes dependence on fossil fuels from this unstable region.

If we assume constant natural gas consumption after 2030 based on the AEO2008 projections, then the addition of fuel cell vehicles according to the scenarios reported here would temporarily increase US natural gas consumption by less than 12% (right-hand scale of Figure 25) in the 2060 time period, then falling rapidly thereafter.

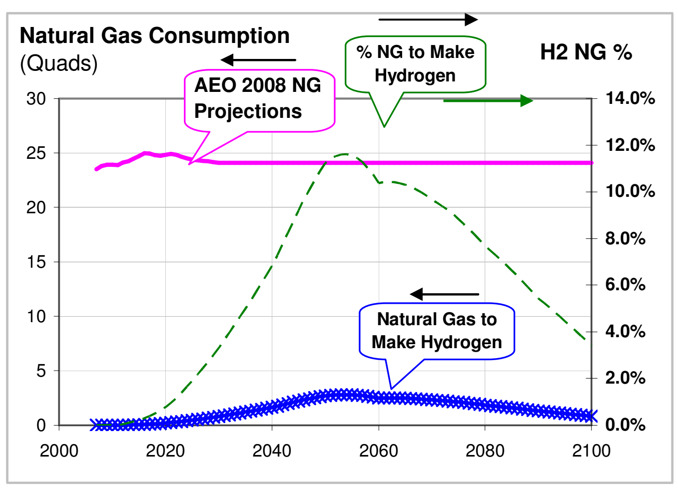


Figure 25. Comparison of projected US natural gas consumption assuming a flat rate after 2030 and the natural gas needed to make hydrogen in the FCV scenario, which is less than 12% of US consumption.

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[12] Crude oil BTU consumption / natural gas BTU consumption = 2.45 x .75/.86 = 2.1, assuming FCV fuel economy is 2.45 times that of ICEVs, SMR efficiency =75% and gasoline refinery efficiency = 86%.

Natural gas vs. crude oil resources. The global natural gas resources (proved reserves, reserve growth, and undiscovered natural gas) are slightly larger than the crude oil resources. The curves in Figure 26 assume that no new oil or gas is found, and the world consumption of both fuels continues at current rates. The two extra curves assume that 50% of all the world's cars sold are FCVs by 2050 (rising to 100% by 2100) and all hydrogen is made from natural gas.

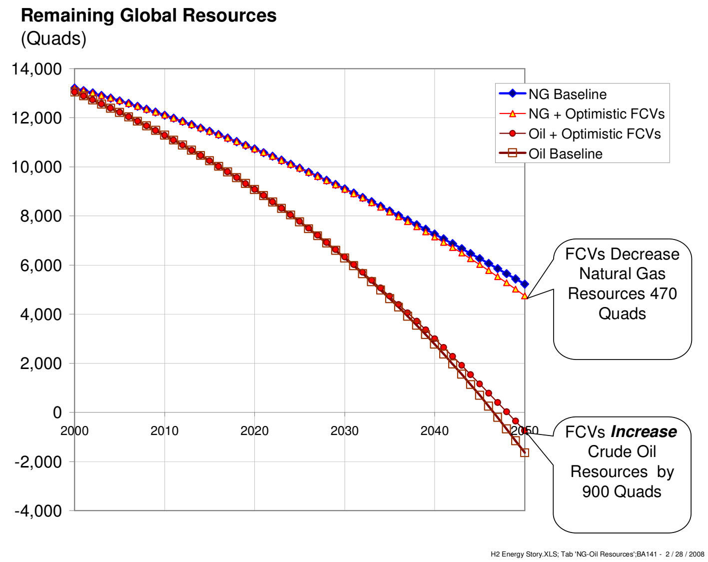

Figure 26. Hypothetical illustration of the impact of 50% FCV global sales by 2050, showing that world's crude oil resources would increase much more than natural gas resources would decrease, tending to right the imbalance that would otherwise occur

Under these conditions, the world's supply of oil and gas would follow the trajectories shown in Figure 26. Without any new discoveries, the world would run out of petroleum before 2050. By adding FCVs, we would save approximately 900 quads of oil by 2050, adding a few years more global consumption. Natural gas reserves would decrease by approximately 470 quads under these worst-case conditions.

We conclude that even if all FCVs use hydrogen from natural gas, the impact on natural gas resources would be minimal on a global scale, and the slight decrease in natural gas consumption is more than offset by the larger increase in oil resources. The net effect is to partially improve the balance between natural gas and oil consumption while cutting total fossil fuel use in half.

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