"How Green are Electric Vehicles?"

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Abstract

Battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) are often labeled "green", implying that they will significantly reduce greenhouse gas (GHG) emissions. But actual GHG reductions will depend on two factors: the number of electric vehicles that can be sold to Americans that are fond of driving large vehicles long distances, and the GHGs emitted by the electrical power plants that charge the EV batteries. This article evaluates the maximum potential of EVs to cut GHG emissions and oil consumption in the U.S. and compares them with the GHG and oil reduction potential of hydrogen-powered fuel cell electric vehicles. Even if all US light duty vehicles (LDVs) (cars and trucks) were replaced by a combination of battery EVs for small vehicles and plug-in hybrids for all other LDVs (100% electric vehicles!), then GHGs could at most be reduced by 26% and oil consumption could be reduced by less than 67%. But if all LDVs in the U.S. were replaced by fuel cell electric vehicles powered by hydrogen made from natural gas, then GHGs would be immediately reduced by 51% and oil consumption by nearly 100%.

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1 Introduction

Major reductions in greenhouse gas emissions in the light duty vehicle (LDV) transportation sector will be required to achieve the climate change community goal of reducing GHGs by 80% below 1990 levels by 2050; to achieve this goal, McKinsey & Company [1] postulated that the GHGs from road transport in Europe would have to be reduced by 95%, since other sectors are constrained in their ability to cut GHGs as summarized in Table 1.

In the United States, the light-duty vehicle (LDV) sector [cars and trucks] accounted for 17.7% of all GHG emissions[1] in 2009 according to the latest EPA GHG inventory[2]. In order to reach the goal of cutting GHGs to 80% below 1990 levels, all US transportation emissions would have to be reduced by 83% below 2009 levels, and LDV emissions would have to be reduced by 83.1% below 2009 levels in the US as summarized in Table 2. Since sectors such as rail, aviation and ships may be hard-pressed to achieve their "fair-share" reductions of 70% to 82%, the LDV sector may have to achieve more than an 83% reduction to reach the overall goal.

Table 1. GHG reduction percentages by sector postulated by McKinsey & Company to achieve an overall 80% GHG reduction below 1990 levels in Europe

Power	95% to 100%
Road Transport	95%
Air & Sea Transport	50%
Industry	40%
Buildings	95%
Waste	100%
Agriculture	20%

In the United States, battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) have replaced fuel cell electric vehicles (FCEVs) as the alternative vehicle promoted and funded by the Federal government to cut GHGs and oil consumption.

Table 2. GHG emissions (million metric tonnes or terragrams of CO2-equivalent) in 1990 and 2009 for the US transportation sector and % reductions from 2009 levels to reach the goal of 80% below 1990 level.

	1990	2009	LDV % of all GHGs 2009	% change 1990 to 2009	80% Reduction Goal	% Reduction from 2009
Passenger Cars	657.3	622.4	9.4%	-5.3%	131.46	-78.9%
Light Duty Trucks	336.6	551.1	8.3%	63.7%	67.32	-87.8%
All LDVs	993.9	1173.5	17.7%	18.1%	198.78	-83.1%
Med & Heavy trucks	231.1	365.6	5.5%	58.2%	46.22	-87.4%
Buses & motorcycles	10.1	13	0.2%	28.7%	2.02	-84.5%
Aviation	181.2	139.5	2.1%	-23.0%	36.24	-74.0%
Ships	45.1	30.5	0.5%	-32.4%	9.02	-70.4%
Rail	38.9	43.3	0.7%	11.3%	7.78	-82.0%
Other	47.8	43.7	0.7%	-8.6%	9.56	-78.1%
Transport Totals:	1548.1	1809.1	27.3%	16.9%	309.62	-82.9%
Total all sources:	6181.8	6633.2				

President Bush enthusiastically promoted and supported the development of FCEVs, but President Obama has set a goal of placing one million "electric vehicles[2]" on the road by 2015, and the US

[1] Passenger cars accounted for 9.4%, and light duty trucks (vans, SUVs, pickups) emitted 8.3% of all US GHGs in 2009.

2 While FCEVs are "electric vehicles," as used by the Obama administration, "electric vehicle" refers exclusively to battery EVs (BEVs) and PHEVs.

Secretary of Energy, Steven Chu, declared in a 2009 interview that FCEVs would require "four miracles" to succeed [3], attempting to eliminate all funding for FCEVs in 2009[3]. The Obama administration is counting on BEVs and PHEVs as the primary option to cut greenhouse gas (GHG) emissions and oil consumption in the light duty vehicle sector. But even if American drivers were convinced to purchase only BEVs and PHEVs in the future, what would be the impact on GHG emissions and oil consumption? And how would BEVs and PHEVs compare with FCEVs with respect to GHGs and oil use?

2 EV Market Penetration Potential

2.1 Battery Electric Vehicle Market Potential

Lithium-Ion batteries that are used in BEVs today are too heavy and occupy too much volume to be used in very large vehicles that travel long distances. In principle more batteries can be added to any BEV to extend range. But the weight and volume occupied by these batteries grows non-linearly with additional range due to a process called "mass compounding." For example, to double the range of a BEV from 161 km to 322 km might require the addition of 800 kg of batteries. But extra structure must be added to support those batteries. This extra mass will in turn require larger motors to provide the desired vehicle acceleration, and the brake system must be slightly larger to safely stop the vehicle. The vehicle frame and suspension systems must also be augmented to carry this additional mass, further increasing total vehicle mass. And, finally, additional batteries will be required to propel this heavier vehicle the required distance in an iterative, non-linear feedback process. Malen and Reddy have evaluated the mass compounding effects of 32 late-model (2002-2007) vehicles [4]. They found that adding a load such as 100 kg of batteries will require an additional 59.8 kg for 12 vehicle subsystems such as structure, brakes, and suspension systems. This added mass will require still more batteries to provide the desired range.

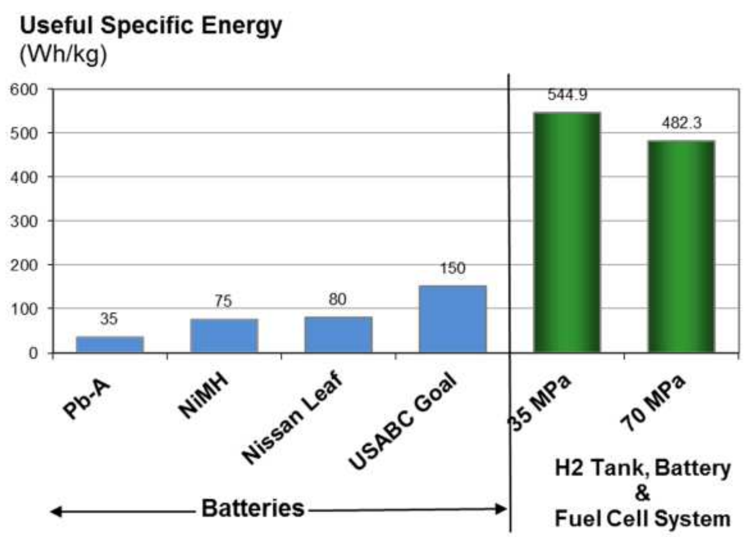

Figure 1. Useful specific energy (stored energy per unit mass—large is good!) for batteries and hydrogen/fuel cell systems

Table 3. Nissan Leaf BEV battery parameters comapared with the USABC long-term commercialization goals

	Specific Energy	Specific Power	Power Density	Energy Density
	Wh/kg	kW/kg	kW/L	kWh/L
Nissan Leaf Battery	80	0.3	0.3	0.0261
USABC long-term commercialization goals	150	0.46	0.46	0.230

The mass for any electric vehicle is limited by the useful specific energy (in Whkg^{-1}) of the complete storage system. As shown in Figure 1, the specific energy of battery systems has improved over the last

[3] The U.S. Congress restored most of the FCEV funding in 2009, but has since accepted the administration's plan to cut the FCEV program.

few decades, from 35 $Whkg^{-1}$ for the lead-acid (Pb-A) batteries used to start ICVs for a century to 75 Wh kg^{-1} for nickel-metal hydride (NiMH) batteries used in the original Prius hybrid electric vehicles, to the advanced lithium ion (Li-ion) batteries used in laptop computers, cell phones, and now BEVs such as the Nissan Leaf BEV[4]. As shown in Figure 1, the specific energy for a fuel cell energy storage system (hydrogen tanks, plus the fuel cell system plus a peak power battery system) is better (larger) than even advanced Li-ion batteries that meet the minimum goals for the U.S. Advanced Battery Consortium long-term commercialization goals [5] as summarized in Table 3 along with the Nissan Leaf characteristics.

Hydrogen systems are shown for two pressures in Figure 1. 35 MPa (350-bar or 5,250 psia) that was used in early FCEVs, and 70 MPa or 10,250 psia used in more recent FCEVs by several car companies. The higher pressure 70-MPa storage tanks require more carbon fiber to hold the higher pressure, so these tanks are slightly heavier and have lower specific energies than 35-MPa tanks.

The useful energy density of the storage system determines how much *space* must be occupied on the vehicle to obtain the required range. Figure 2 illustrates the significant improvements in battery energy density, but again shows that a hydrogen/fuel cell/battery system has slightly higher energy density than even an advanced Li-ion battery system meeting the USABC long-term goals, particularly with 70-MPa tank pressure. However, since the battery system has much lower specific energy, it will be heavier than a FCEV and will therefore have to store more energy than the hydrogen system for a given range, and the total volume of the battery system would be larger than the total volume for the hydrogen/fuel cell system even if the two systems had equal energy densities.

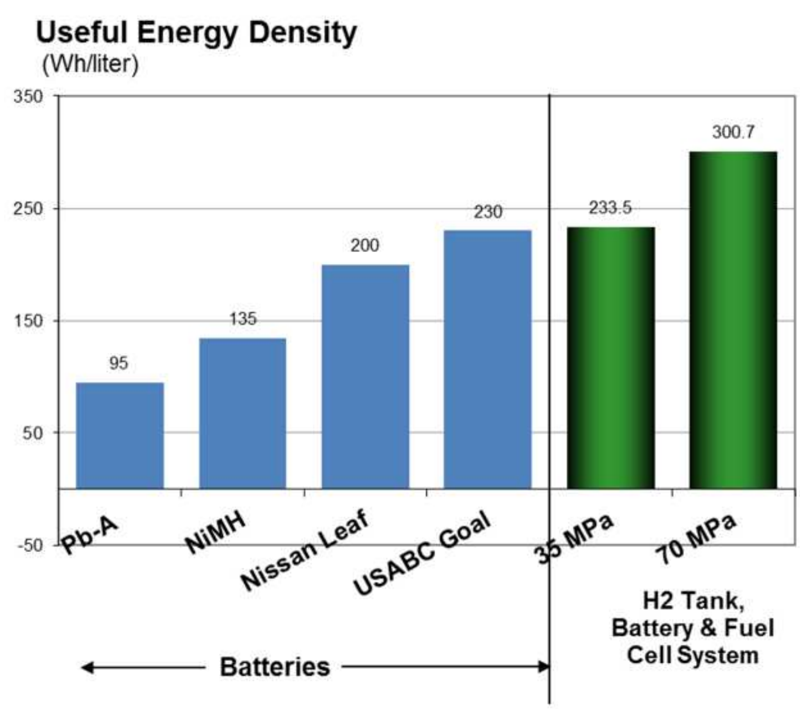

Figure 2Useful Energy density (energy per unit volume--Large is good!) for batteries and for hydrogen/fuel cell systems

As a result of the mass and volume required for the battery system, BEVs will be limited to relatively small vehicles such as the BEVs sold or under development by auto companies as summarized in Table 4.

[4] Nissan lists their battery pack with a 24 kWh energy storage capacity. With a mass of 300 kg, this corresponds to a specific energy of 80.2 $Whkg^{-1}$ which we use in this model for the Leaf; however, this may not be the *useful* energy capacity, since batteries can typically only utilize 70% of the stored energy, which would decrease the specific energy to only 56 $kWhkg^{-1}$.

Table 4. Current BEVs available or under development

			EPA range		Charging Hours	
		Type	(km)	(miles)	120-V	240-V
Nissan	Leaf	5-passenger	117.5	73	21	8
Ford	Transit Connect	Small van	128.7	80	27	8
Toyota	RAV4	Small SUV	129-193	80-120	28*	12*
Smart	Fortwo	2-seater	113-161	70-100		3.5**
Wheego	Life	2-seater	160.9	100		5***
Mitsubishi	i-MiEV	4-passenger	99.8	62	14	7
Think	City	4-passenger	160.9	100	18	8 to 10

*RAV4 charging times for prototype; production unit charging time expected to be shorter

**Smart Fortwo charging from 20% to80% SOC; 8 hours for full charge

***Wheego charging time for 50% to 100% SOC

To assess the likely market share for BEVs in the U.S., we need to know the proportion of vehicles of various sizes and classes on the road, but we were not able to find such data in the literature. We therefore estimated the number of light duty vehicles in the different EPA size classes on the road in the US today by analyzing LDV sales numbers for the last 30 years[4]. For each class of vehicle, we then multiplied the annual sales times the survival rates (See Table 5 for passenger car survival rates) for LDVs to determine the fraction of vehicles on the road today [7]; note that survival rates are increasing. Thus for model year 1970 cars, only 9.6% would still be on the road after 20 years, while the 20-year survival rates for 1980 model year (MY) cars increased to 13,8% and to 35.4% for 1990 MY cars.

Table 6 summarizes the results of this analysis showing the estimated number of vehicles on the road, along with the number of vehicles in each class sold in 2010.

We conclude that approximately 28.1% of all cars on the road today are small passenger vehicles, and 28.1% of all new passenger cars sold in 2010 were small vehicles. If we include all small vans, all small pickup trucks and all small SUVs, then the totals increase to 30.9% of all vehicles on the road and 28.7% of 2010 sales.

We also estimated the average vehicle kilometers traveled (VKT) for each model year, using VKT data provided by the Argonne National Laboratory [8], as summarized in Table 7. The Argonne National Laboratory provided the VKT data for the first 16 years (1994 to 2010), and we extrapolated the Argonne VMT data curves back to 1982.

To determine the possible market penetration of BEVs, we assumed that all small cars and wagons could be powered by batteries, along with all small vans, all small pickups, and all small SUVs. We also assumed that half of all midsize sedans could be powered by batteries, since the Nissan Leaf BEV is rated as a "midsize sedan" by the EPA, based on its internal volume of 113 cubic feet[5].

[5] The EPA defines a "midsize" sedan as those having between 110 and 119 cubic feet of interior space, so the Nissan Leaf falls into the lower 50% of the "midsize" sedan category [9].

Table 5. Estimated passenger vehicle survival rates

Age	1970 MY	1980MY	1990MY
30	0.4%	0.8%	6.6%
29	0.5%	1.1%	8.2%
28	0.8%	1.6%	10.0%
27	1.1%	2.2%	12.1%
26	1.6%	2.9%	14.5%
25	2.2%	3.9%	17.1%
24	3.1%	5.2%	20.2%
23	4.2%	6.7%	23.5%
22	5.6%	8.7%	27.2%
21	7.4%	11.0%	31.1%
20	9.6%	13.8%	35.4%
19	12.3%	17.0%	39.9%
18	15.5%	20.8%	44.6%
17	19.3%	25.0%	49.5%
16	23.7%	29.8%	54.6%
15	28.7%	35.1%	59.7%
14	34.2%	40.8%	64.9%
13	40.3%	46.9%	70.0%
12	46.9%	53.3%	75.0%
11	53.8%	60.0%	79.8%
10	60.9%	66.6%	84.4%
9	68.1%	73.3%	88.7%
8	75.2%	79.7%	92.7%
7	82.0%	85.7%	96.3%
6	88.4%	91.3%	99.4%
5	94.1%	96.3%	100.0%
4	99.0%	100.0%	100.0%
3	100.0%	100.0%	100.0%
2	100.0%	100.0%	100.0%
1	100.0%	100.0%	100.0%
0	100.0%	100.0%	100.0%

Table 6. Estimated percentage of vehicles on the road compared to the percentage of new cars sold in 2010

	% on the road	% of 2010 Sales
two-seaters	0.9%	0.8%
Minicompact	0.5%	0.4%
subcompact	8.2%	7.8%
Compact	16.7%	14.6%
Small wagons	1.8%	4.5%
All Small cars	28.1%	28.1%
Small vans	0.1%	0.1%
Small pickups	1.1%	0.0%
Small SUVs	1.6%	0.5%
All Small Vehicles	30.9%	28.7%
Midsize sedans	17.6%	21.9%
Midsize vans	7.2%	3.3%
Medium wagon	1.2%	0.8%
Large wagon	0.2%	0.1%
Midsize pickups	3.6%	1.4%
Midsize SUVs	12.0%	14.0%
Large cars	8.5%	8.0%
Large vans	0.7%	0.1%
large pickups	10.2%	11.2%
large SUVs	8.0%	10.4%

Table 7. Estimated vehicle kilometers traveled by model year							
Year	Large Cars	Midsize	Small cars	SUV	Vans	Pickups	
2010	18,583	21,538	20,358	22,048	27,452	27,285	
2009	23,747	23,191	22,597	23,699	24,916	25,803	
2008	21,779	23,258	22,259	23,736	25,045	23,385	
2007	19,875	20,923	18,826	21,580	23,089	21,691	
2006	19,277	20,289	18,696	22,202	22,186	20,995	
2005	20,683	20,522	19,584	21,446	22,872	20,548	
2004	17,832	18,705	19,628	21,477	21,375	19,978	
2003	19,199	18,430	17,698	20,469	23,442	19,013	
2002	16,666	17,878	17,933	19,309	20,527	20,506	
2001	18,503	17,566	17,561	20,427	20,357	17,737	
2000	17,935	17,014	18,380	19,631	20,616	18,268	
1999	16,475	16,287	17,508	17,762	15,646	18,757	
1998	15,369	16,148	18,718	16,890	16,642	17,416	
1997	15,532	15,002	16,081	16,528	18,046	16,166	
1996	16,026	15,183	15,144	15,529	16,847	15,290	
1995	12,320	15,720	16,267	15,899	16,454	15,783	
1994	10,746	12,582	14,959	14,864	17,502	13,906	↑
1993	11,910	13,733	15,426	14,472	16,397	15,095	
1992	10,797	13,199	15,075	13,595	16,081	14,831	
1991	9,618	12,670	14,728	12,678	15,802	14,616	
1990	8,374	12,147	14,383	11,722	15,561	14,451	
1989	7,065	11,628	14,041	10,728	15,359	14,334	xtrapolate
1988	5,691	11,115	13,701	9,694	15,195	14,266	
1987	4,252	10,606	13,365	8,621	15,069	14,247	
1986	2,747	10,103	13,031	7,510	14,981	14,277	
1985	1,177	9,605	12,700	6,359	14,932	14,357	
1984	-	9,112	12,372	5,169	14,920	14,485	
1983	-	8,624	12,046	3,940	14,947	14,662	
1982	-	8,141	11,724	2,672	15,012	14,889	↓

Table 8. Estimated number of small vehicles suitable for BEVs on the road, and estimated VKT and gasoline consumption for those vehicles in US LDV fleet.

	No. of vehicles on the road (thousands)	Average fuel economy (Liters per 100 km)	total km traveled (VKT-million km per year)	ICV Gasoline Consumed (million liters/ year)	BEV gasoline (Million liters per year)	Net Oil Savings (million Liters per year)
Vehicles suitable for BEVs						
Small cars & wagons	64,525	9.7	511.6	49.5	0.77	(48.74)
Small vans	155	9.3	2.8	0.3	0.00	(0.25)
Small pickups	2,428	9.5	40.1	3.8	0.06	(3.76)
Small SUVs	3,643	9.9	68.4	6.8	0.10	(6.66)
50% of midsize sedans	20,125	10.6	356.7	37.7	0.58	(37.16)
Total or wgt. ave. "small cars"	90,876	9.9	979.6	96.7	1.50	(95.16)
"small cars+ 50% midsize" % of total	39.6%		27.2%	24.9%	0.39%	-24.5%
Larger cars and trucks:						
50% of midsize sedans	20,125	10.6	356.7	37.7	0.58	
Midsize wagons	2,775	10.9	48.3	5.3	0.08	
Midsize vans	16,418	10.1	322.7	32.5	0.50	
Midsize pickups	8,141	10.0	144.6	14.4	0.22	
Midsize SUVs	27,548	10.4	550.6	57.5	0.89	
Large cars	20,057	11.3	341.0	38.5	0.60	
Large vans	1,599	13.1	30.4	4.0	0.06	
large pickups	23,289	12.4	444.9	55.0	0.85	
large SUVs	18,391	11.9	388.8	46.2	0.72	
Total or wgt. Ave. large cars and LD Trucks	138,344	11.0	2,628.0	291.2	4.51	
% of total	60.4%			75.1%		

The resulting number of vehicles on the road in this "small" category suitable for BEVs, along with the estimated VKT and weighted average fuel economies and annual gasoline consumption are summarized in Table 8. We conclude that BEVs could replace up to 39.6% of all US cars on the road; However, since these smaller vehicles generally have higher fuel economy, they account for only 24.9% of all gasoline consumed by the US car fleet, and they account for 27.2% of all VKT. In addition, since petroleum is consumed in mining, processing and transporting coal and natural gas to the electrical generators to charge BEV batteries, the net reduction of petroleum consumption from replacing all small vehicles and 50% of all midsize vehicles with BEVs is equivalent to only a 24.5% reduction in oil consumption in the LDV fleet.

2.2 Fuel Cell Electric Vehicle Market Potential

FCEVs are able to provide the range and refueling times comparable to conventional gasoline cars. Five major automobile companies have already demonstrated SUV-size vehicles powered by fuel cells:

- Toyota has road-tested a FCEV version of their Highlander SUV. This FCEV has been certified by DOE National laboratory engineers with a 693-km (431-mile) on-the-road range in California [10].
- GM has built and provided 100 of their Equinox cross-over utility vehicles to ordinary drivers in their "Project Driveway" road-test program. The Equinox FCEV has an estimated range between 257 and 322 km (160 to 200 miles).
- Nissan has developed a FCEV version of their X-Trail SUV. This FCEV has an estimated range of 500km (310 miles) using 70-MPa hydrogen storage tanks.

- Hyundai has developed a FCEV version of their Tucson ix SUV. This FCEV has an estimated range of 648km (403 miles) using 70-MPa hydrogen storage tanks.
- Kia has demonstrated a FCEV version of their Borrego SUV, with an estimated range of 750 km (466 miles) using 70-MPa hydrogen storage tanks

We conclude that FCEVs could replace all LDVs, large and small.

3 Greenhouse Gas Emissions

To determine the impact of replacing all small vehicles with BEVs, we calculated the annual greenhouse gas (GHG) emissions for these vehicles using the Argonne National Laboratory GREET model [11]. One important input to the GREET model for electric vehicles is the electrical generation grid mix used to charge BEV and PHEV batteries, which is currently dominated by burning fossil fuels in the US. For example, the DOE's Energy Information Agency (EIA) in their 2011 Annual Energy Outlook (AEO) [12] estimates that 70.3% of all US electricity is generated by fossil fuels (46.2% coal and 23.1% natural gas and 1.0% oil) in 2010. Furthermore, given the number of "climate change deniers" elected in 2010, it is unlikely that the US Congress will pass any climate change legislation in the foreseeable future that might provide incentives for utilities to switch to cleaner fuel sources. As shown in Table 9, the 2011 AEO reference case projects very small declines in fossil fuel generation out to 2035, decreasing from 70.3% to 68.6% of all US electricity [12]. With these average US grid mixes, the estimated GHGs for various alternative vehicles calculated by the Argonne GREET model is summarized in Table 10 for various alternative vehicles; we used the EIA's 2011 Annual Energy Outlook data [12] for the average on-the-road projected fuel economy[6] of stock gasoline ICVs (second row of Table 10)

Table 9. Percentage of US electricity projected by the EIA's 2011 Annual Energy Outlook reference case

	2010	2015	2020	2035
Residual Oil	1.0%	0.9%	1.0%	0.9%
Natural Gas	23.1%	20.9%	19.9%	21.9%
Coal	46.2%	44.6%	45.2%	45.8%
Total Fossil Fuels:	70.3%	66.4%	66.1%	68.6%
Nuclear	20.3%	21.0%	21.3%	19.0%
Renewables & other	9.4%	12.5%	12.7%	12.3%

Table 10. Fuel economy of conventional gasoline ICVs and greenhouse gas emissions for various vehicles in four time periods

	2010	2015	2020	2035
Fuel Economy (Liters/100km)=>	11.3	10.2	9.9	8.7
	GHGs (grams/km):			
Gasoline ICV	331	298	288	255
Gasoline HEV	237	214	207	183
Gasoline PHEV-40	241	225	222	209
NGV	259	234	226	200
NG PHEV-40	213	200	198	187
BEV (average US grid)	223	197	193	173
FCEV (H2 from NG)	161	146	141	124

For BEVs with batteries charged by the average US grid mix, BEVs through 2035 will generate from 35% to 39% more GHGs than FCEVs running on hydrogen made from natural gas according to the GREET model and AEO 2011 projections. Notice also that plugging in gasoline powered PHEVs increases GHGs in all time periods by 1 to 7% compared to

[6] Fuel economy in Liters of gasoline per 100 km, which is inversely proportional to the fuel economy numbers in miles per gallon used in the U.S.

HEVs running exclusively on gasoline. Therefore in most parts of the US, drivers purchasing PHEV-40's like the Chevy Volt will minimize GHGs if they never plug in these PHEVs but run them exclusively on gasoline at all times!

3.1 California GHGs and Marginal Grid Mix

GHGs are less in some parts of the country with a lower proportion of coal-generated electricity. For example, many analysts point to California that has a lower fraction of coal-generated electricity and more zero-carbon sources (nuclear and renewables, primarily hydroelectric) than the rest of the country as shown in Table 11 for 2010.

Table 11. Percentage of electricity generated in 2010 by fuel source in California compared to the entire US

	Cal	US
Coal	8.1%	46.2%
Oil	0.0%	1.0%
Natural Gas	41.0%	20.3%
Total Fossil fuels	49.1%	67.5%
Nuclear	23.1%	20.3%
Renewables	28.0%	9.4%

However, McCarthy and Yang at the University of California at Davis have pointed out that the *average* utility grid mix is not the appropriate metric for determining GHG emissions for electric vehicles [13]. GHG emissions from adding BEVs and PHEVs to the vehicle fleet are determined by the *marginal* grid mix. For example, the zero-carbon electrical generators, renewables and nuclear also have the lowest operating cost. With economic dispatch, utilities run their lowest cost generators first, and only turn on the more expensive generators when demand rises. As a result, nuclear and renewable power plants are run at full capacity whenever possible. Adding a new load such as a BEV or a PHEV then requires the utility to ramp up other generators, primarily natural gas fired combustion turbines in California, which do generate significant GHGs. McCarthy and Yang determined that up to 40% of the electricity to charge BEV and PHEV batteries would come from natural gas fired combustion turbines. As a result, the large fraction of nuclear and renewable energy in California has little or no impact of the GHGs from charging batteries. The results of their analysis are shown in Figure 3.

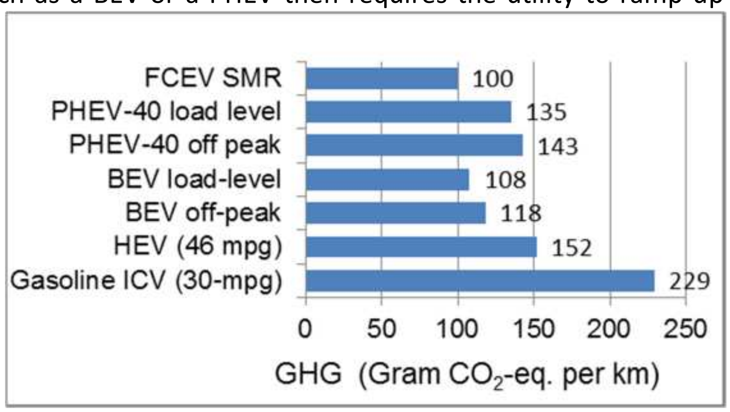

Figure 3. Estimated GHG emissions in California using the marginal grid mix calculated by McCarthy and Yang at UC-Davis

They conclude that even in California with higher zero-carbon electricity[7], FCEVs using hydrogen made from natural gas will generate lower GHGs than either BEVs or PHEVs. All the other GHG data in this report use the average electricity grid as utilized by the GREET model.[8] As a result, all the GHG emissions estimated for BEVs and PHEVs in this report except Figure 3 are conservative: actual BEV and PHEV GHG emissions will be greater than estimated here since marginal grid mixes emit more carbon than the average grid mixes, while GHG emissions for FCEVs are accurate, since the FCEV does not use much grid electricity[9]

[7] "SMR" in Figure 3 refers to "steam methane reforming," the process of converting natural gas to hydrogen.
[8] Estimating the marginal electricity grid mix is very complex, which is why average grid mix is often used instead.
[9] A small amount of electricity is required to compress the hydrogen for storage onboard the vehicle.

Table 12. Estimated greenhouse gas reductions by replacing all small vehicles (and 50% of all midsize sedans) with BEVs powered by the average US grid mix in 2015.

	ICV GHG (grams per km)	ICV GHGs (Tonnes per yr CO_2-eq.)	BEV GHGs (gram per km)	BEV GHGs (Tonnes per yr CO_2-eq.)	Net GHG Savings
Vehicles suitable for BEVs					
Small cars & wagons	455	144,758	189	96,505	(48,253)
Small vans	439	753	182	502	(251)
Small pickups	449	11,177	186	7,451	(3,726)
Small SUVs	465	19,784	193	13,189	(6,595)
50% of midsize sedans	498	110,364	206	73,576	(36,788)
Total or wgt. ave. "small cars"		286,835		191,224	(95,612)
"small cars+ 50% midsize" % of total		25.2%		16.8%	-8.40%

As shown in Table 12, the gasoline-powered ICVs that are replaced by the BEVs account for 25.2% of all LDV GHG emissions. But the average US grid used to charge the BEVs would emit 16.8% of the total GHGs, so the net savings in GHGs is only 8.4%, far short of the goal of reducing GHGs by 80% below 1990 levels or 83% below 2009 levels by 2050.

3.2 Future GHG Reductions

In the future, both hydrogen and electricity can be made from lower carbon sources to further reduce GHGs. However, as discussed above, the low carbon electricity sources such as nuclear and renewables will most likely be used to displace fossil fuel electricity directly to maximize GHG reductions, and will not be on the margin for charging EV batteries.

Zero-carbon Hydrogen, on the other hand, is already being economically generated from renewable sources. For example, the Orange County Sanitation District in Fountain Valley, California has installed a 250-kW molten carbonate fuel cell system to produce electricity to run their waste water treatment plant, displacing grid electricity and cutting GHGs. This stationary fuel cell runs on the anaerobic digester gas from the treatment plant. Excess thermal energy from the fuel cell is used to heat the digester tanks, displacing natural gas previously used to heat the tanks, which further reduces GHGs. Excess hydrogen produced by the stationary fuel cell is cleaned up and used to power FCEVs. The electricity and heat produced by the stationary fuel cell can pay for the equipment in a few years, meaning that the hydrogen price can be cost competitive with gasoline per mile driven. Since hydrogen would only be used to fuel FCEVs (as opposed to low-carbon electricity being fed to the grid), substantial GHG reductions would be immediately realized with this renewable hydrogen pathway.

Another renewable hydrogen pathway would convert the methane from landfill gas to hydrogen. Methane escaping from landfills accounted for approximately 7% of all US GHGs and waste water treatment plant digester gas emissions accounted for just under 2% in 2009. Replacing all US cars with

FCEVs running on hydrogen from waste water or landfills could result in a 109% reduction in the transportation GHG level.

4.0 Petroleum Consumption

The GREET model also calculates petroleum consumption for various vehicles as summarized in Table 13.

Table 13 Projected average vehicle fuel economy and petroleum consumption in kJ-km^{-1} for various vehicle types in four time periods

	2010	2015	2020	2035
AEO Fuel Economy (Liters/100km)=>	11.3	10.2	9.9	8.7
	Petroleum Consumption (kJ-km^{-1}):			
Gasoline ICV	3,808	3,435	3,317	2,935
Gasoline HEV	2,720	2,453	2,369	2,096
Gasoline PHEV-40	1,761	1,596	1,546	1,377
NGV	21	19	18	16
NG PHEV-40	36	33	35	32
BEV (average US grid)	63	53	55	46
FCEV (H2 from NG)	16	15	14	13

Some readers might be surprised to see that BEVs “consume” petroleum. The GREET model analyzes the complete “well-to-wheels” GHG emissions and oil consumption. Thus petroleum is required to mine and process coal and natural gas and particularly to transport coal to electrical generation plants. So charging vehicle batteries with electricity produced by burning fossil fuels will require the consumption of petroleum to process and deliver those fuels. Similarly, compressing hydrogen for FCEVs consumes electricity, so some petroleum is required to power FCEVs, although BEVs “consume” approximately four times more petroleum than FCEVs, although both consume less than 4% of regular gasoline cars.

5 Four Market Penetration Scenarios

Given these data, we can now calculate the reductions in GHGs and oil consumption under four scenarios:

- BEVs-only (BEV market penetration limited according to Table 8)
- PHEVs-only (All cars replaced by PHEVs)
- BEVs and PHEVs (BEVs limited according to Table 8, with PHEVs replacing all other vehicles so all cars are “electric vehicles” as proposed by the Obama administration)
- FCEVs-only (All vehicles replaced by FCEVs)

The results are shown in Figure 4 for GHG reductions for three time periods: 2015, 2020, & 2035. FCEVs can reduce GHGs in the near-term by over 51% with hydrogen made from natural gas, while the next best option, BEVs and PHEVs could at best reduce GHGs by only 27%.

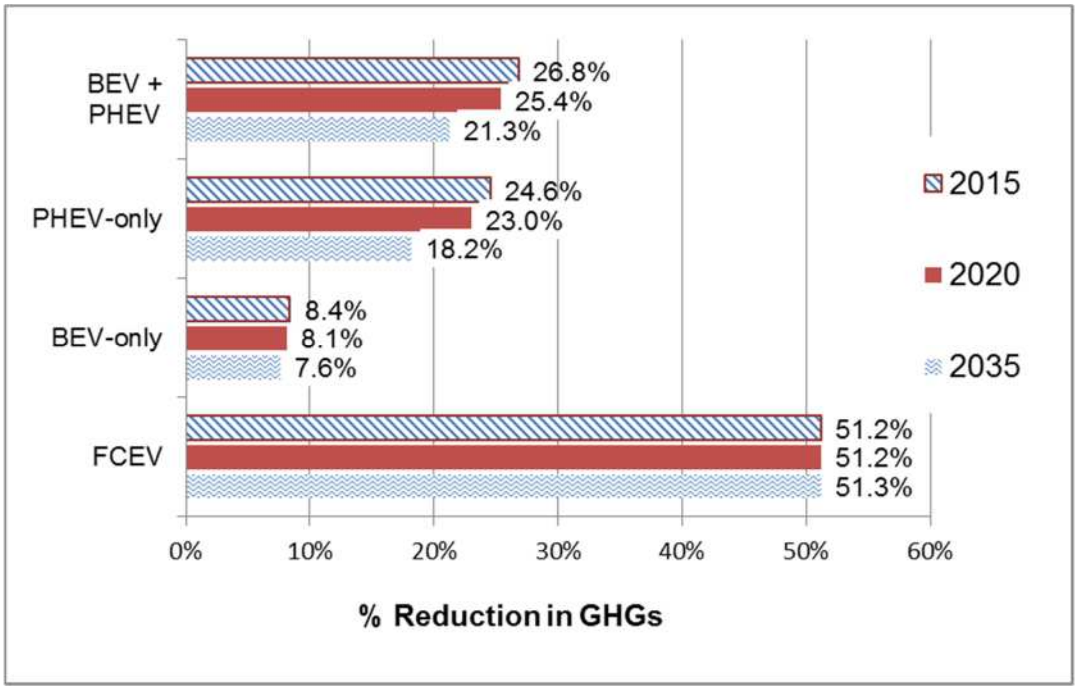

Figure 4. Maximum possible reduction in greenhouse gas (GHG) emissions for the four scenarios (Large reductions are good!)

Finally, Figure 5 shows the percentage reduction in petroleum consumption for the same four scenarios as Figure 4. Again, the best option is the FCEV case, which eliminates almost all petroleum use, while the second-best option is BEVs for all small vehicles and PHEVs for all other vehicles, which could only reduce petroleum consumption by less than 67%.

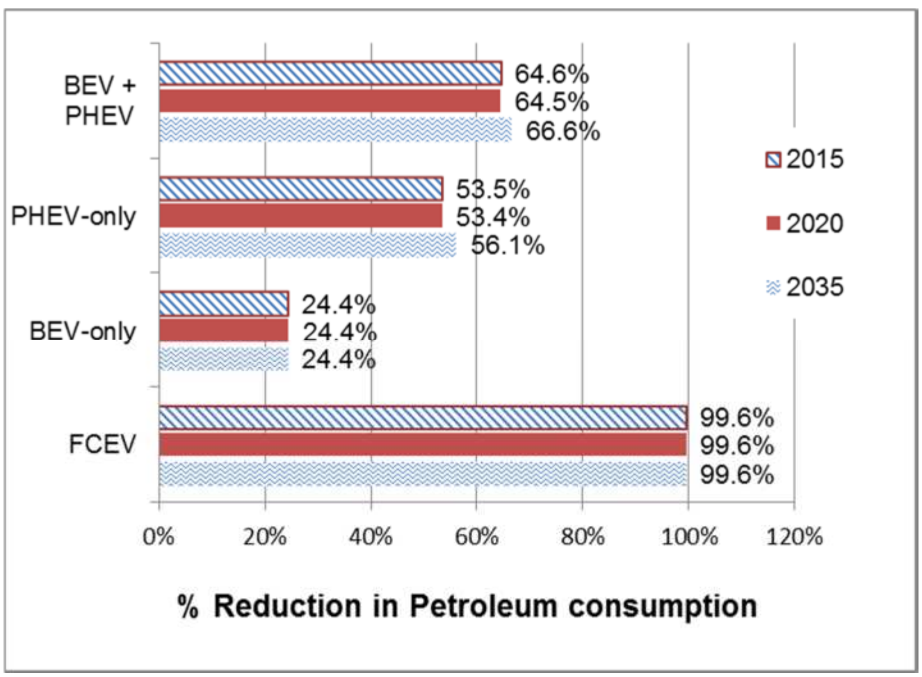

Figure 5. Maximum possible reduction in oil consumption for the four scenarios (large is good!)

6.0 Conclusions

Based on the detailed "well-to-wheels" analysis using the Argonne National Laboratory GREET model, we conclude that:

"How Green are Electric Vehicles?"

To substantially cut greenhouse gas emissions and oil dependence, society must curb gasoline and diesel fuel in the operation of conventional vehicles. These reductions in transportation GHGs and oil consumption will require a portfolio of alternative vehicles. No single alternative will suffice. The Obama administration's selection of battery electric vehicles and plug-in hybrids as the only options for their alternative vehicle strategy is particularly short-sighted and ill-advised since:

Battery electric vehicles alone, even if they replaced *all* small cars, *all* small vans, *all* small pickup trucks and *all* small SUVs plus *50% of all midsize passenger* cars in the U.S. would only reduce LDV GHGs by 8.4%, far less than the 83% reduction below 2009 levels required to achieve an overall reduction of 80% below 1990 GHG levels, and they would only cut petroleum consumption by less than 25%.

Therefore BEVs alone will not be able to make substantial reductions in GHGs or oil consumption until a) higher specific power batteries are developed so that BEVs can replace larger cars with longer driving capacity, and b) almost all carbon is eliminated from electricity generation.

If, in addition to the small BEVs mentioned above, plug-in hybrids replace all other vehicles, (all gasoline vehicles would be replaced by either BEVs or PHEVs) then GHGs would be reduced by less than 27% and oil consumption by less than 67%.

If, on the other hand, fuel cell electric vehicles replaced all vehicles in the U.S., then GHGs would immediately be reduced by more than 50% and oil consumption would be cut by nearly 100%, even if all hydrogen was still made from natural gas. Greater GHG reductions would be achieved as hydrogen is made from low-carbon sources such as from landfill gas or from waste water treatment plant anaerobic digester gas, or, eventually, from water electrolysis using renewable electricity or nuclear power.
The need to reduce GHGs and oil consumption from the transportation sector is too urgent to limit our options at this time. We need to develop all of the above.

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