PHEVs: the Technical Side

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Abstract

Plug-in hybrid (PHEV) characteristics, fuel requirements, emissions (especially carbon), energy efficiency, and readiness for mass production are reviewed and compared against those of gasoline, Diesel, hybrid, electric, and hydrogen-powered vehicles. Only PHEVs, which can use bio-fuels as their liquid range-extension fuel, are capable of providing immediate and sufficient worldwide reductions in light-duty vehicle petroleum consumption and carbon emissions.

Diesel ICEs can reduce petroleum use and carbon emissions only around 20% below that of gasoline. Strong hybridization, including of Diesels, can save up to 50% over conventional gasoline – excellent but still insufficient. Plenty of off-peak electric capacity *is already* available, and electric propulsion can consume essentially no petroleum, reduce carbon emissions from by 60-100%, depending on the source of electricity, and facilitate the incorporation of renewable energy sources into the electric grid. However, BEV range is still limited, batteries for long-range BEVs are still very expensive, and the infrastructure for quick refueling is not readily available. The economics of hydrogen fuel-cell vehicles is far worse, the technology is far from ready, and they are at best 25-33% as energy efficient as BEVs. While new and even existing ICEs can be easily modified to run on bio-fuels, bio-fuels require large infrastructure investments, and only enough biomass can be reasonably expected to be available to meet 30% of current transportation energy requirements.

PHEVs have most of the advantages and none of the disadvantages of all of these other propulsion systems. On liquid fuels, they are as efficient as ordinary strong hybrids; 50-75% of their fuel consumption can be electricity, thereby reducing liquid fuel consumption to levels that bio-fuels can provide, even with rapid expansion of the worldwide fleet; and their technology – including good-enough batteries – is already in mass production, or ready for it.

Keywords: PHEV, alternative fuel, emissions, energy consumption, EV

1 US-centrism & vehicle sizes

The author wishes to apologize for presenting mainly US-centric – rather than European or worldwide – consumption, regulatory, and fuel availability information. Quantities are presented in metric units, but the decimal is shown as a point rather than a comma.

To keep comparisons simple, and since the technologies in question scale up and down fairly linearly, I will talk about Prius-sized passenger cars throughout.

2 Table of various propulsion system characteristics

Table 1: Various propulsion system characteristics vs. gasoline ICE

Propulsion system	• Advantages vs. gasoline	• Disadvantages vs. gasoline
Gasoline ICE	• Reference	• Reference
Diesel ICE	• ~20% lower consumption • ~15% lower carbon emissions • Already 50% penetration in Europe	• Heavier, more costly ICE • Sulfur and tiny particulate emissions difficult to remove • Emissions still far higher than PZEV • Noise, vibration, and drivability issues, now largely solved
Strong hybrid (HEV) (gasoline or Diesel)	• Up to 50% lower consumption • Gasoline HEV can meet PZEV (~10% of CA limits) emissions • Already in mass production • Payback from fuel savings in around 5 years • Increased production will bring better cost and performance	• Extra cost, weight, and space • Durability just beginning to be proven
Flex-fuel, burning alcohol (ethanol, methanol, or butanol) or Diesel	• Bio-fuels are generally renewable • Can be carbon-neutral, depending on crop • Potential to make fuel from urban, farm, and forest wastes • ICE modifications are minor – ~$150 new, more for retrofit • ICEs burn cleaner on bio-fuel	• Enough bio-mass available for only 30% of current vehicle fleet • Massive investment needed in fuel production facilities • Production from cellulose, needed for near-sufficient quantities and to avoid competition with food production, not yet proven commercially viable
Battery electric (BEV)	• Zero vehicle emissions • Can use carbon-neutral renewable electricity from sun, wind, geothermal, tides, etc. • Can help incorporate more wind-power into power grids • Can tap vast unused off-peak capacity of existing power grids • Very quiet, vibration-free, and low maintenance • US electricity is already cheap, domestic, non-petroleum, and lower carbon emissions	• Range limited by battery weight, space, and especially cost requirements • Rapid refueling infrastructure not yet available
Hydrogen fuel cell (FCV)	• Same as BEV, except H2 is not cheap	• Renewable electricity-H2-electricity efficiency is 1/3-1/4 that of a BEV • An FCV using H2 from natural gas requires more per mile than does an ICE • Fuel cells are still enormously expensive, hand-built, unreliable, and short lived • Onboard H2 storage requirements cause even shorter range than BEVs • H2 production and fueling facilities require unbelievably massive investments • Even accumulated small leaks – or liquid H2 boil-off – could add to climate change • Safety concerns, especially in garages
Hydrogen ICE	• Same as FCV	• Same as FCV, except half the efficiency instead of expense and unreliability
PHEV, gasoline or Diesel	• All HEV advantages, including possible 5-year payback, except not yet in mass production • As for BEV, except petroleum reductions of “only” 65-88% • Economically viable with existing batteries • Can be recharged overnight from an ordinary wall outlet • If not charged, the vehicle still runs as a clean, efficient HEV	• More extra cost, weight, and space than HEVs, but less than BEVs • Not yet in mass production, though no new technology is required • “Only” 65-88% reduction in petroleum consumption (30-50% from HEV, 50-75% from EV) • Many capable cell and battery pack designs are too new to have reliability/lifetime track records, especially in PHEVs
PHEV burning bio-fuel	• All advantages of PHEV • Bio-fuel consumption reductions of 65-88%, enough to match production ramp-ups and biomass limitations	• Same as PHEV, except reduction in petroleum consumption can be 95-100%

3 Plug-in hybrids (PHEVs)

Because of their fuel flexibility, plug-in hybrids have most of the advantages, but few of the disadvantages, of both ordinary hybrids and battery electric vehicles. Daily use may be all electric, but without requiring a large, expensive battery for maximum range.

3.1 Flexibility from the ready availability of liquid fuels

Because the liquid fuel is always available, a PHEV's battery need only handle average daily driving – 48 km in the US [1]. As the ICE supplies the propulsion energy once the battery is depleted, a discharged PHEV effectively becomes an ordinary strong hybrid until it is once again charged, allowing, in the meantime, unlimited range (via rapid refueling as necessary) on its liquid fuel.

In fact, sizing the battery significantly larger than that yields diminishing returns, as additional range is used more rarely. EPRI's first PHEV study [1] shows an average of 40% propulsion supplied by electricity for a PHEV with 32 km EV range, 60% for 64 km, or 75% for 96 km. Actual figures are likely to be higher, as vehicles will first be sold to customers with PHEV-friendly use patterns.

3.2 PHEV battery size and power requirements

The sweet spot for PHEV battery capacity – where advantages most outweigh disadvantages -- is generally a little more than required to drive the vehicle's average daily distance electrically. Table 2 shows additional battery weight and cost over that of a Prius' existing pack.

Hybrid batteries are designed to supply high power rather than to store a lot of energy, and are consequently expensive per unit of energy storage (kWh). PHEV packs are larger to store more energy, so their power requirements are smaller relative to size, allowing use of lower cost technology. In fact, PHEV battery power and energy requirements are midway between those for HEVs and BEVs. Both intermittent and continuous power requirements are often stated in units of C, or multiples of a 1-hour discharge (or charge) rate.

3.2.1 Cost-effective batteries already exist

Table 2 shows PHEV battery characteristics. Toyota said several years ago that their cost for a Prius' HEV battery pack was around $1400. In contrast, for PHEV batteries in automotive volume production, a price of US$500 per useful kWh is reasonable. For longevity purposes, only a percentage – often 50-80% – of an EV battery's capacity is normally used. We call this reduced capacity its useful kWh. Other assumptions in the table are a conservative 35 useful-kWh/kg for NiMH and 85 useful-kWh/kg for Li-ion. C, in the table, is intermittent and based on useful-kWh rather than total capacity.

Table 2: PHEV battery packs

Use	Chemistry	Range, km	Useful-kWh	C	Wt, kg	Cost, US$
Prius HEV	NiMH	1.6	0.5	50	31	$1400
PHEV-20	NiMH	32	4	6	114	$2000
PHEV-20	Li-ion	32	4	6	45	$2000
PHEV-40	Li-ion	64	8	3	90	$4000
PHEV-60	Li-ion	96	12	2	135	$6000

Table 3: Some existing Li-ion cells

Manuf.	Safety	total kWh/kg	Int C	Cycle life	Volume	Cost, US$/kWh
Generic Laptop (18650)	Via pack design	180	1-3	1000?, 3-5 yr	High	<$250 wholesale
A123	No runaway	108	52	1K+	Medium	~$1k retail
Altairnano	No runaway	~90	60	10k+, 20 yr	Low	Unknown
Valence	No runaway	118	4	1k+	Medium	~$1k retail
Worley	AABC tested	130	10	Unknown	Low	~$500 wholesale

3.2.2 Further liquid fuel efficiencies are possible

Once one has enough battery energy available to provide climbing power up the tallest expected slope, the ICE can be downsized even further that for a strong hybrid, down to the maximum continuous output required to sustain top cruise speed with a maximum expected headwind – about half the size of the Prius' engine. This will in turn provide liquid fuel consumption and some weight savings.

On one hand, if a PHEV is designed, like a Prius conversion, so that its ICE is used at high speeds and when more than moderate acceleration is requested, then the electric propulsion system, including the battery's power capabilities, can be sized for only moderate loads, making it less expensive.

At the other extreme, a PHEV designed as a serial hybrid like GM's upcoming Volt can also be efficient and effective. An ordinary serial hybrid is somewhat inefficient due to the weight and inefficiency of ICE energy conversion from mechanical to electrical back to mechanical – though this can be as low as 10-20%. However, turn the same drivetrain into an electric-centric PHEV and the efficiency of the electric drivetrain dominates. The complexity and losses involved in transferring ICE power to the wheels, estimated to be 20% for a Prius, can be eliminated in favor of a much simpler, more efficient drivetrain; and an oversized electric motor and electronics can actually be more efficient, unlike an ICE.

A serial PHEV's ICE can be small and run only at full power and optimum speed, as it is only needed to sustain or slightly recharge the battery once depleted. The added efficiency of an ICE designed for such a narrow task can more than make up for the serial system's added conversion inefficiencies. Even more importantly, the ICE need never be started except once the EV range is exceeded. If this range is greater than the average daily use, many, many cold starts can be eliminated. Since a huge amount of extra fuel is consumed, and pollutants emitted, during each cold start, this can dramatically improve the vehicle's real-world efficiency and cleanliness, especially in cold weather. These improvements will help the customer and planet even if it doesn't show up in current government testing.

3.3 V2G

Given smart power meters and outlets that power companies and some rapid-transit organizations are excited to build, PHEV batteries can do double duty while plugged in. The charger can be designed to be bi-directional, to optionally dump energy back into the grid. This energy can be used for grid regulation and/or peaking services that would otherwise require expensive, inefficient spinning reserves. Power companies estimate that they may be willing to pay each PHEV owner up to US$2000 annually for such services, making PHEVs that much more economically attractive. Of course, the battery must have enough cycle life to not wear out from the extra cycling. In contrast to a BEV, a PHEV owner need not ever worry about getting stranded from losing too much charge to V2G; he may end up using more liquid fuel, but only after earning more by selling the energy at high peak rates.

An additional option a PHEV has is to use the ICE as a clean-burning emergency generator. The 25kW+ capacity is sufficient to fully supply one or more homes or, e.g. a neighborhood clinic during a disaster.

4 CalCars' goals, efforts, and data

4.1 Petroleum dependency must be quickly reduced

4.1.1 Climate change threatens

The author believes, along with many scientists, that minimizing and dealing with climate change will be the greatest, most imperative challenge the human race has ever met, and that immediate, definitive action is necessary to stave off the worst effects. An order-of-magnitude projection is that greenhouse gas emissions must be reduced by 80% by 2050, even as (barring a depression) world energy use keeps increasing and fossil fuels run out.

4.1.2 World oil supply will soon fall short

Not only is the supply of fossil fuels finite, but petroleum, and possibly other fossil fuel, production peaks when half of the supply is still in the ground. World oil supply appears to already be flat, and either has or will soon peak, just as China and India's economies are taking off, fueled, as was the US's and Europe's, by constantly increasing use of oil and other fossil fuels.

4.2 Only PHEVs can do it

Light surface transportation vehicles (cars and light trucks) contribute over 20% of worldwide, 30% of US, and 40% of California greenhouse gas emissions. While we can work on replacing private autonomous vehicles with mass transit where effective, efficiently moving people and goods from any point to any point is not a trivial problem, and cars and trucks will no doubt dominate surface transportation for some time.

As can be seen from Table 1 and Tables 4-7 below, all propulsion systems other than PHEVs have one or more serious in-use, economic, or technical limitations that prevent rapid large-scale deployment. Additionally, PHEVs, via their inherent energy storage, oportunistic night-time charging, and V2G option, can help power companies deploy intermittent renewable energy sources like windpower.

The social value of PHEVs does not depend upon, but can be greatly enhanced, if their liquid range-extension fuel is a renewable bio-fuel. It can also be greatly enhanced by serious incremental governmental power generation renewable energy portfolio requirements.

4.3 CalCars' goal

CalCars' goal, therefore, is to first get auto manufacturers to begin building PHEVs, then for

PHEVs to become the predominant propulsion system of all new vehicles.

4.4 How to get auto manufacturers to switch to PHEVs?

4.4.1 Auto manufacturers hate change

Partially because auto manufacturers produce very large quantities of devices the reliability of which both their profits and people's lives depend upon, automakers do not like to risk change. In fact, US manufacturers have over and over chosen the risks of lack of change over those of change. Seat belts, air bags, and several levels of pollution controls could each have given the first implementer a competitive edge, but all were fought tooth and nail until people demanded the governmental mandates that were finally put in place.

4.4.2 Grass-roots enthusiasm

CalCars believes that grass-roots enthusiasm provides the fastest route to getting automakers to make this change. This enthusiasm can indicate to the manufacturers that there is a market, and to governments that there is a practical, popular option.

To this end, CalCars converted the author's Prius into the world's first plug-in PRIUS+. By doing so, we were able to demonstrate that an existing mass-produced hybrid could, with minor modifications, become even more fuel-efficient as a PHEV. We also generated large amounts of publicity for PHEVs because we had a proof-of-concept that reporters and leaders could touch and feel.

Since we did that first conversion in the fall of 2004:

- Many organizations have jumped on the bandwagon, including Plug-in Austin, Plug-in Partners, Plug-in America, Set America Free, the Apollo Alliance, and many others
- Many constituencies have joined in, including environmentalists, hawks (for energy security), and evangelicals (to protect God's creation)
- Several companies have sprung up to commercialize conversions of Prii and Ford Escapes, though none has yet converted more than a handful of vehicles
- Toyota has gone from saying "No one will want to plug their car in" to saying that they are working on a PHEV and want to be first to produce one (they still say the batteries aren't ready; we disagree)
- GM has announced both a PHEV Saturn Vue (as early as 2008-9) and the ad-vanced Chevy Volt serial PHEV (they too say the batteries aren't ready yet; again we disagree)
- Anti-environmental President Bush has begun touting PHEVs, showed one off at the White House, and has had a picture of the author's PRIUS+ on the White House website.

CalCars is now documenting Prius conversion plans for do-it-yourself experimenters (the first experimenter-built conversion is almost complete) and working with Valence Battery company to production engineer Prius, then Escape, conversion kits to quickly get hundreds to thousands of PHEVs on the road.

4.4.3 Carrots

The Austin, Texas', Plug-in Partners campaign is getting governments, commercial entities, and even individuals to create soft orders for PHEVs that don't yet exist.

At the same time, legislation is in progress to provide additional hybrid-like tax incentives for PHEV purchases, a California feebate bill has been introduced to create an add-on fee for high carbon-emitting vehicles, to fund rebates for the lowest-emitting ones, and some corporations are beginning to offer their employees rebates for PHEV purchases.

4.4.4 Sticks

CalCars has, and is continuing to, help promote legislation such as California's precedent-setting auto greenhouse gas and general global warming bills, add-on bills to these, and similar federal legislation that is now pending.

4.4.5 Data from CalCars' first plug-in Prius conversion, the author's PRIUS+

CalCars' first Prius conversion was limited by both the vehicle's hybrid system, which was not optimized for PHEV operation, and by the battery we used.

To learn how to make the conversion work, and the specifications a high-tech battery would need to meet, our first conversion used a lead-acid battery pack consisting of 18-20 12V, 20Ah sealed electric bicycle modules. This, we found, provided a pure electric range of around 16 km at around 130 Watt-hr/km from the battery or 165 Watt-hr/km from the grid.

Though, due to the reverse-engineering efforts of a Texan, we were able to take advantage of the EV mode available on European and Asian, but not North American, Prii, there were (and still are) many limitations to the Prius' ability to be driven purely electrically: 55 kph, 25 kW of electric power, half the motor/generator's rating, etc. We did find, however, that we could keep the hybrid battery charged to the point where the system would use some electricity and less gasoline at any speed.

On the average, we could get half the normal Prius' gasoline consumption in mixed driving, until the PHEV battery was depleted, which occurred after double the pure EV mileage, or around 32 km. In mostly-low-speed driving, we could easily get over 100 miles per gallon (0.0237 liters/km), which we began using as an easy-to-remember slogan.

We went on, after a long battery search, to work with Electro Energy, Inc. (EEI), in Connecticut, on a second Prius conversion, this time with a pack made of EEI's NiMH cells. This conversion got 20-25 miles of pure electric range.

Though the lead-acid battery pack had such a short range and short life of only a year, it generated enthusiasm among environmentalists and engineers who wanted to convert their own Prius. We therefore did an on-site conversion during a weekend Fair put on by the new do-it-yourself (DIY) Make magazine. That event kicked off our effort to document in the public domain a conversion that anyone with sufficient skills and several thousand dollars for parts can do. The expanding documentation is at http://www.eaa-phev.org/wiki/PriusPlus.

CalCars latest project is a joint venture with Valence Technology, Inc, who makes safe Li-ion cells, to production engineer Prius and Ford Escape hybrid PHEV conversion kits for mass production. The Prius kit is expected to come out this summer, possibly by the time of this conference. We plan to quickly get hundreds to thousands of Li-ion PHEVs on the road, both to gather data and publicize PHEV capabilities.

5 More detail

CalCars has much more detail available that would require a much longer talk to present. As much as possible is in tables 4-7 below. Please visit the author's slides [2] and notes [3] from a standing-room-only talk at Pacific Gas and Electric's Pacific Energy Center on April 29, 2006. The notes also provide many further references.

Table 4: Propulsion system characteristics

	Range, km			**Electric propulsion (BEV)**				
Prius-size auto, propulsion type	**Typical**	**Ave. daily use**	**EV**	**Est. %**	**Grid kWh/ charge**	**Batt. wt, kg**	**% of unused grid capacity*****	**Rapid refill avail.**
Gasoline (ref.)	**640**	**1333%**	**0**	**0%**	**0**	**0**	**0%**	**yes**
Diesel	640	1333%	0	0%	0	0	0%	yes
Strong HEV (Prius)	640	1333%	0	0%	0	0	0%	yes
Strong Diesel HEV	640	1333%	0	0%	0	0	0%	yes
Highway EV, limited	100	208%	100	100%	12.0	141	44%	no
Highway EV, limited	100	208%	100	100%	12.0	141	44%	no
Highway EV, limited	100	208%	100	100%	12.0	141	44%	no
Highway EV, max.	400	833%	400	100%	48.0	565	175%	no
Highway EV, max.	400	833%	400	100%	48.0	565	175%	no
Highway EV, max.	400	833%	400	100%	48.0	565	175%	no
LNG, LPG, propane	200	417%	200	0	0	0	0%	yes
Hydrogen fuel cell	150	313%	150	0%	0	0	0%	few
Hydrogen fuel cell	150	313%	150	0%	0	0	0%	few
Hydrogen fuel cell	150	313%	150	0%	0	0	0%	few
Hydrogen ICE	100	208%	100	0%	0	0	0%	few
Hydrogen ICE	100	208%	100	0%	0	0	0%	few
Hydrogen ICE	100	208%	100	0%	0	0	0%	few
PHEV, ICE only	640	1333%	0	0%	0	0	0%	yes
PHEV-20, EV only	32	67%	32	100%	3.8	45	14%	no
PHEV-20, EV only	32	67%	32	100%	3.8	45	14%	no
PHEV-20, EV only	32	67%	32	100%	3.8	45	14%	no
PHEV-20, total *****	672	1400%	32	50%	3.8	45	14%	yes
PHEV-20, total *****	672	1400%	32	50%	3.8	45	14%	yes
PHEV-20, total *****	672	1400%	32	50%	3.8	45	14%	yes
PHEV-40, EV only	64	133%	64	100%	7.7	90	28%	no
PHEV-40, total *****	704	1467%	96	67%	7.7	90	28%	yes
PHEV-40, total *****	704	1467%	96	67%	7.7	90	28%	yes
PHEV-40, total *****	704	1467%	96	67%	7.7	90	28%	yes
PHEV-60, EV only	96	200%	96	100%	11.5	136	42%	no
PHEV-60, total *****	736	1533%	96	75%	11.5	136	42%	yes
PHEV-60, total *****	736	1533%	96	75%	11.5	136	42%	yes
PHEV-60, total *****	736	1533%	96	75%	11.5	136	42%	yes

Table 5: Propulsion system characteristics, con't

	Est. real-world consumption****			"Well", est.		Liquid fuel	
Prius-size auto, propulsion type	**Per km**	**Fuel units**	**Fuel source**	**Wh/km**	**Eff. to wheels**	**Req'd**	**Req'd % of possible biomass*** **
Gasoline (ref.)	**0.09**	**liters**	**oil (or ethanol**)**	**1025**	**12%**	**100%**	**303%**
Diesel	0.065	liters	oil (or biodiesel)	821	15%	80%	243%
Strong HEV (Prius)	0.05	liters	oil (or ethanol**)	569	21%	56%	168%
Strong Diesel HEV	0.04	liters	oil (or biodiesel)	505	24%	49%	149%
Highway EV, limited	156	Wh	renewables*	156	77%	0%	0%
Highway EV, limited	156	Wh	Calif. grid*	363	33%	0%	0%
Highway EV, limited	156	Wh	2004 US grid*	363	33%	0%	0%
Highway EV, max.	156	Wh	renewables*	156	77%	0%	0%
Highway EV, max.	156	Wh	Calif. grid*	363	33%	0%	0%
Highway EV, max.	156	Wh	2004 US grid*	363	33%	0%	0%
LNG, LPG, propane	0.122	liters	LNG	1025	12%	100%	303%
Hydrogen fuel cell	600	Wh	renewables*	600	20%	0%	0%
Hydrogen fuel cell	600	Wh	Calif. grid*	1395	9%	0%	0%
Hydrogen fuel cell	600	Wh	2004 US grid*	1395	9%	0%	0%
Hydrogen ICE	1643	Wh	renewables*	1643	7%	0%	0%
Hydrogen ICE	1643	Wh	Calif. grid*	3820	3%	0%	0%
Hydrogen ICE	1643	Wh	2004 US grid*	3820	3%	0%	0%
PHEV, ICE only	0.05	liters	oil	569	21%	56%	168%
PHEV-20, EV only	156	Wh	renewables*	156	77%	0%	0%
PHEV-20, EV only	156	Wh	Calif. grid*	363	33%	0%	0%
PHEV-20, EV only	156	Wh	2004 US grid*	363	33%	0%	0%
PHEV-20, total *****	0.025	liters	50% renewables*	363	33%	28%	84%
PHEV-20, total *****	0.025	liters	50% Calif. grid*	466	26%	28%	84%
PHEV-20, total *****	0.025	liters	50% '04 US grid*	466	26%	28%	84%
PHEV-40, EV only	156	Wh	renewables*	156	77%	0%	0%
PHEV-40, total *****	0.0165	liters	67% renewables*	293	41%	18%	56%
PHEV-40, total *****	0.0165	liters	67% Calif. grid*	431	28%	18%	56%
PHEV-40, total *****	0.0165	liters	67% '04 US grid*	431	28%	18%	56%
PHEV-60, EV only	156	Wh	renewables*	156	77%	0%	0%
PHEV-60, total *****	0.0125	liters	75% renewables*	260	46%	14%	42%
PHEV-60, total *****	0.0125	liters	75% Calif. grid*	415	29%	14%	42%
PHEV-60, total *****	0.0125	liters	75% '04 US grid*	415	29%	14%	42%

Table 6: Propulsion system characteristics, con’t

	Est. real-world consumption****			"Well", est.		Liquid fuel	
Prius-size auto, propulsion type	gm/km	vs. 130 gm/km	Est. reduction	Est. extra US$	Fuel, US$/ year	Fuel savings, US$/yr	Years to payback*
Gasoline (ref.)	212	163%	0%	$0	$1,250	$0	0.0
Diesel	175	135%	17%	$1,000	$963	$287	3.5
Strong HEV (Prius)	118	90%	44%	$3,000	$694	$555	5.4
Strong Diesel HEV	108	83%	49%	$4,000	$592	$657	6.1
Highway EV, limited	0	0%	100%	$6,000	$246	$1,003	6.0
Highway EV, limited	37	28%	83%	$6,000	$246	$1,003	6.0
Highway EV, limited	96	74%	55%	$6,000	$246	$1,003	6.0
Highway EV, max.	0	0%	100%	$24,000	$246	$1,003	23.9
Highway EV, max.	37	28%	83%	$24,000	$246	$1,003	23.9
Highway EV, max.	96	74%	55%	$24,000	$246	$1,003	23.9
LNG, LPG, propane	188	145%	11%	$1,000	UNK	UNK	UNK
Hydrogen fuel cell	0	0%	100%	huge	$1,472	-$222	No paybk
Hydrogen fuel cell	142	109%	33%	huge	$1,472	-$222	No paybk
Hydrogen fuel cell	369	284%	-74%	huge	$1,472	-$222	No paybk
Hydrogen ICE	0	0%	100%	$5,000	$4,029	-$2,779	No paybk
Hydrogen ICE	388	298%	-83%	$5,000	$4,029	-$2,779	No paybk
Hydrogen ICE	1010	777%	-378%	$5,000	$4,029	-$2,779	No paybk
PHEV, ICE only	118	90%	44%	$1,600	$694	$555	2.9
PHEV-20, EV only	0	0%	100%	$1,920	$246	$1,003	1.9
PHEV-20, EV only	37	28%	83%	$1,920	$246	$1,003	1.9
PHEV-20, EV only	96	74%	55%	$1,920	$246	$1,003	1.9
PHEV-20, total *****	59	45%	72%	$3,520	$470	$779	4.5
PHEV-20, total *****	77	59%	64%	$3,520	$470	$779	4.5
PHEV-20, total *****	107	82%	50%	$3,520	$470	$779	4.5
PHEV-40, EV only	0	0%	100%	$3,840	$246	$1,003	3.8
PHEV-40, total *****	39	30%	82%	$5,440	$394	$856	6.4
PHEV-40, total *****	63	49%	70%	$5,440	$394	$856	6.4
PHEV-40, total *****	103	79%	51%	$5,440	$394	$856	6.4
PHEV-60, EV only	0	0%	100%	$5,760	$246	$1,003	5.7
PHEV-60, total *****	29	23%	86%	$7,360	$394	$856	8.6
PHEV-60, total *****	57	44%	73%	$7,360	$394	$856	8.6
PHEV-60, total *****	101	78%	52%	$7,360	$394	$856	8.6

Table 7: Conversion factors, estimates, and notes

Conversion factors:					
Gasoline energy content	9.68	kWh/liter	36.64	kWh/gallon	[4]
Diesel energy content	10.74	kWh/liter	40.65	kWh/gallon	[4]
Liquified gas energy content	7.13	kWh/liter	26.99	kWh/gallon	[4]
Gasoline CO2 emissions	2.35	kg/liter	8.89	kg/gallon	[4]
Diesel CO2 emissions	2.69	kg/liter	10.18	kg/gallon	[4]
Liquified gas CO2 emissions	1.538	kg/liter	5.82	kg/gallon	[4]
Grid CO2 emissions from renewables			0	gm/kWh	
Grid CO2 emissions, California, 2004			236	gm/kWh	
Grid CO2 emissions, EPRI US projection for 2010			500	gm/kWh	
Grid CO2 emissions, 2004 US, approx. equal to combined-cycle coal			615	gm/kWh	
	1.6	km/mile	0.625	mile/km	
	3.785	liter/gallon	0.2642	gallon/liter	
	3.412	BTU/Whr	0.2931	Whr/BTU	
	31858	therms/Whr	0.00003139	Whr/therm	
	0.4227	km/liter per mpg	2.3656	mpg per km/liter	
Estimates:					
Estimated travel per vehicle	17520	km/year	10950	mi/year	
Estimated travel per vehicle	48	km/day	30	mi/day	
Est. petroleum well-to-tank	85%	efficiency			
Est. H2 fuel consumption	50%	grid-kWh to H2-in-vehicle eff.	85%	LNG to H2-in-vehicle efficiency	
Est. H2 fuel consumption	40%	fuel cell efficiency	15%	H2 ICE efficiency (same as gasoline)	
Est. EV fuel consumption	156.3	grid-kWh/km	250	grid-kWh/mi	
Est. Prius-equiv. energy use	120	wheel-Wh/km	192	wheel-kWh/mi	
Est. volume battery usable input kWh vs. cost & weight (at ~US$300-400/kWh)	500	US$/usable-kWh	85	usable-Wh/kg	
Est. volume battery costs	60	US$/km range	96	US$/mi range	
Est. average 2010 US fossil fuel supply efficiency, based on CO2 output vs. fuel content			43%		
Est. US gasoline cost	0.79	US$/liter	3.00	US$/gallon	
Est. US Diesel cost	0.85	US$/liter	3.20	US$/gallon	
Est. US nighttime electricity cost	0.09	US$/kWh	0.05	US$/kWh from grid to H2-in-vehicle	
Est. future total US biomass availability (incl. cellulose) vs. current light vehicle energy			33%		
Ave. unused 2004 US electric capacity (54%)	5499	gWh/day	27	kWh per vehicle for	
* Without incentives or increasing fuel costs					
** Changes fuel consumption and well-to-wheel figures and can greatly reduce CO2, depending on source, but little immediately available & future limit					
*** If all light vehicles were this type (see est. future total biomass and off-peak power availability, above); EVs can facilitate addition of nighttime windpower					
**** Average real-world consumption is at least 15% higher than US EPA estimates					
***** Extra PHEV HEV cost is less $1400 hybrid battery PHEV one replaces; only liquid consumption is shown, but efficiency and CO2 are based on total consumption					

References

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Author

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