Electrified Vehicle Technology Trends, Infrastructure Implications and Cost Comparisons

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Alternatives to petroleum-based fuels for transportation are sought to address concerns over climate change and energy security. Key semiconductor, software, and battery technologies have sufficiently progressed over the past few decades to enable a mass-market-viable plug-in electric vehicle (PEV) alternative. In this paper, the various PEV architectures are described, including market availability, technologies and trends, practical ranges, battery replacement and power costs, implications for grid operations, and other developments. Manufacturers' recently announced prices and EPA standardized test data are used (where available) to increase the accuracy of cost comparisons for competing vehicles. Results indicate that in relatively low fuel-cost regions, like the U.S., PEVs enjoy a positive discounted net present value, thanks to tax credits and assuming that the original battery does not need replacement by the owner. Even without the tax credits, PEVs offer financial payback for those residing in higher fuel-cost regions, as long as their batteries last the vehicle's lifetime or are replaced by manufacturers (under warranty).

BACKGROUND

The motivations for developing alternative energy sources and associated vehicle powertrains[1] is to reduce a widespread dependence on oil (particularly foreign oil), imported oil-driven trade deficits (with oil imbalances constituting close to half of the U.S.'s trade deficit, [U.S. BEA 2008]), oil-related costs (Greene 2010), and environmental concerns (including climate change and oil spills) while improving energy security and air quality (Siosanshi and Denholm 2008, Thompson et al. 2009, EPRI and NRDC 2007).

Vehicle manufacturers have an interest in developing emerging technologies to demonstrate leadership (and improve brand image), while ensuring long-range capabilities in key alternative fuel/powertrain technologies critical for success in global vehicle markets. These alternative powertrains may, in the end, be more pervasively deployed in non-U.S. markets even after being pioneered and/or first sold in the U.S. Long-term average U.S. gasoline prices have generally stayed under $3 per gallon, and do not reflect external damages (Delucchi and McCubbin 2010). While oil prices are likely to rise over the long term (ECB 2008, Deffeyes 2002), low fuel prices (both in the past and currently) have not encouraged consumer demand for highly fuel efficient or alternative-fuel vehicles, which then would encourage active investment by manufacturers. In fact, hybrid-electric vehicles (HEVs) have enjoyed less than 3% of new U.S vehicle sales (Green Car Congress 2010).

During the last few decades, advanced technology was deployed to increase power, performance, and vehicle size instead of fuel economy. A combination of relatively recent events has contributed to new investments in alternative fuel and efficient powertrain technologies. These include spot fuel shortages in 2005 from Hurricane Katrina, substantial oil and gasoline price spikes in 2008, the passing of more stringent corporate average fuel economy (CAFE) and emissions regulations, and Tesla Motors' demonstration of a high-performance long-range full-function battery electric vehicle (BEV). Several new vehicle options are emerging in the U.S. market, as described below. Moreover, several foreign markets have substantially higher gasoline and diesel prices, and thereby offer strong near-term (and long-term) incentives for alternative vehicle technologies to reduce the near- and long-term private and social costs of personal mobility.

The following section describes new and emerging vehicle options. It is followed by a cost comparison for U.S. and non-U.S. consumer choice settings, to highlight differences in financial paybacks across competing vehicle pairs. Various vehicle designs' strengths and limitations and power grid impacts are also discussed, followed by the paper's conclusions.

NEW VEHICLE OPTIONS

In 2010, mass-market-viable PEVs became available from several global vehicle manufacturers. A variety of PEV models are emerging, and it is useful to define these, while assessing their strengths and weaknesses. Essentially, grid-enabled or plug-in electric vehicles (PEVs) can be categorized as BEVs, extended-range electric vehicles (eREVs), and plug-in hybrid electric vehicles (PHEVs).

BEVs incorporate a large on-board battery, charged while parked via a cord to the power grid. This battery then wholly provides the energy for the electric traction motor to propel the vehicle. eREVs are BEV-derived vehicles with an on-board internal combustion engine (ICE) generator that provides electrical energy to the motor once the initial battery charge is exhausted. This configuration solves the classic "range anxiety" problem of a BEV (Markel 2010) by providing an overall range on par with a traditional gas or diesel vehicle. Once its initial charge from the grid is depleted, or if the vehicle is never plugged into the grid, the eREV should operate like a conventional HEV. PHEVs effectively are HEVs with larger batteries and a charging cord to access grid power. PHEVs typically operate in a "blended" mode, using the gas engine and electric motor together, to substantially reduce gasoline consumption while operating in battery charge depletion (CD) mode (Vyas et al. 2009). PHEVs also solve the range anxiety problem and should operate similarly to a traditional HEV if never plugged into the grid.

Range-extended (eREV and PHEV) architectures leverage the energy density of petroleum to solve the problem of range anxiety at the cost of incorporating a hybrid electric-gasoline powertrain. Along with the energy density advantage of petroleum, a pervasive refueling infrastructure is available when longer trips are taken. Range-extension capabilities enable the eREVs and PHEVs to serve as a U.S. household's primary or sole vehicle. This petroleum-based backup allows downsizing of the most expensive PEV component, the battery (as compared to a BEV), while providing a range on par with those of conventional and hybrid-electric vehicles.

Since most models are still emerging, there is not yet full public disclosure (and third-party testing) of technical details to definitively compare their differences. Nevertheless, recent EPA test results for the Chevrolet Volt and Nissan Leaf (used for their respective window stickers) are now available and used in these comparisons. Meaningful differences in design and operation of eREV and PHEV powertrain technologies exist (Tate et al. 2008), even if, from a user's perspective, they appear to operate the same. For example, eREVs are fully functional in electric mode across the entire operating range — from being stationary at a stop light to operating at maximum speed without any dependence on gasoline. This architecture may provide a marketing advantage by creating a product which satisfies drivers who desire to drive "petroleum free," even with a modest all-electric range (AER) while still having a gasoline backup generator (which comes online after the initial charge is depleted). An eREV owner could conceivably never put gas in the tank and simply use the vehicle as a BEV.[2]

PHEVs operating in blended or mostly electric mode have the potential to achieve impressive liquid fuel economy (over 100 mpg) for some travel distances while the battery is in CD mode (Vyas et al. 2009). Since the gas engine and electric motor work cooperatively to propel the vehicle, the motor may be smaller than that of a comparable eREV design. Blended-mode designs also enjoy a wide array of design strategies, to optimize the balance of battery size, weight, and cost, engine size, and overall efficiency. Such design options may reduce vehicle price, thereby encouraging sales volumes and economies of scale in production.

Without the gasoline engine running, the smaller PHEV motor size and reduced motor or battery-cooling capacity may limit top speeds below 62 mph and AER values to about 13 miles (Toyota 2010), depending on battery design and size, powertrain control algorithms, and other parameters. However, drivers with low-speed needs and short daily commutes may still find a PHEV can fulfill their desire to drive without consuming any petroleum and at a lower purchase price. Many will continue to refer to both eREVs and PHEVs simply as PHEVs, since the differences are likely to be subtle for many owners. Nevertheless, in an analysis of driving pattern data from a Southern California regional travel survey, Tate and Savagian (2009) concluded that PHEVs may rarely operate in EV mode over a full day's driving, while a majority of eREV drivers will experience a full day of driving without consuming gasoline.

BEVs have a relatively simple all-electric powertrain, which can reduce non-battery-related costs. Manufacturers also avoid the costs of emissions testing, certification, and warranties, since the vehicle has no tailpipe emissions. However, range limitations, greater battery weights, and longer charge times can be problematic in BEV vehicles. Without a range-extending back-up, BEVs also force a greater dependence upon public charging infrastructure, better trip planning by the driver, access to a conventional second car, or regular and modest-length commuting needs.

The advertised electric range for PEVs will be based upon a particular objective test cycle, such as the U.S. EPA's LA4/UDDS drive cycle (EPA 2010) for conventional vehicles. While these test cycles are useful for purchase comparisons, the effective ranges experienced in practice typically will differ from estimates stated on a new vehicle's required window sticker or on the U.S. government's official website (www.fueleconomy.gov). The actual electric range achieved by BEVs, in particular, will likely affect their adoption rate. The U.S. test procedures were updated in 2008 to reflect more realistic driving conditions, so official estimates have become more representative of owner-experienced fuel economies (EPA 2010). Over the short term it is expected that future advances in battery cost, capacity, and durability will result in the installation of smaller and, hence, less expensive batteries, to allow PEVs to reduce their initial cost disadvantage (as compared with conventional vehicles).

NEW VEHICLE DESIGNS

The Chevrolet Volt eREV, the Nissan Leaf BEV, and the $109,000 Tesla Roadster are the most popular PEVs available today. Tesla has created compelling performance BEVs with its Roadster and future Model S sports sedan. With the upcoming Ford Focus BEV, Ford CMAX Energi PHEV (a crossover utility vehicle), Mitsubishi iMIEV,and Toyota Prius PHEV, vehicle manufacturers appear to be targeting drivers seeking compact vehicles that dramatically improve fuel economy (while potentially permitting petrol-free travel). Plug-In America's evolving list of emerging (worldwide) vehicle models (http://www.pluginamerica.org/vehicles) notes whether a vehicle is available for purchase, under development, or a concept vehicle (with no committed production date).

A summary of the vehicles most likely to be available for near-term purchase in the U.S. — and with the greatest potential for market impact — can be divided into range-extended and non-range extended PEVs (i.e., BEVs). Table 1 describes key features of these various models (including estimates of the manufacturer's suggested retail price [MSRP] and state of charge [SOC] window, where SOC refers to the percentage of battery capacity that can be used to power the vehicle while maintaining long-term battery durability).

Table 1: PEV Details for Near-Term U.S. Sales

Make & Model	Release Date	Estimated Retail Price (after rebate)	Body Type	Battery Size (kWh)	Estimated State of Charge Window	All Electric Range (miles)
Range-Extended PEVs						
Chevy Volt eREV	2010	$33,500	4-door sedan	16	65%	25-50
Ford CMAX Energi PHEV	2012	TBA	4-door CUV	10	TBA	Est 30
Toyota Prius PHEV	2012	$29,500	4-door sedan	5.3	Est 70%	15 (at limited speeds)
Non-Range-Extended (BEVs)						
Tesla Roadster	2009	$101,500	2-door sports car	53	80%+	240
Nissan Leaf	2010	$25,250	4-door sedan	24	90%+	100
Ford Focus	2012	$31,700	4-door sedan	23	TBA	100
Tesla Model S	2012	$49,900 base	4-door sedan	42 (also 65 & 85kWh options)	80%+	160 (also 230 & 300 options)
Mitsubishi iMiEV	2011	$21,625	4-door sedan	16	TBA	100
Mercedes Smart Car ED	2012	TBA	2-door sedan	TBA	TBA	90

Note: All details shown here have been found at the manufacturer's websites: chevrolet.com, toyota.com, tesla.com, nissanusa.com, ford.com, mitsu-motors.com, and smartusa.com. Volt, Leaf, Focus, and iMiEV prices are after a federal $7,500 tax credit and the Prius-PHEV reflects a $2,500 tax credit (for the first 200,000 such vehicles sold in the U.S. by each manufacturer). All range-extended PEVs evaluated here are gasoline fueled (in order to meet strict U.S. particulate matter emissions standards).

THE MARKET FOR PEVS

An area of considerable debate is the projected PEV adoption rate (e.g., Vyas et al. 2009 and KEMA 2010). For example, KEMA's (2010) aggressive forecast meets the goal of one million U.S. PEV sales by 2015, and its slow case hits the one-million-units target in 2019. The KEMA penetration curves are based on the Prius experience, with an increase due to fleet introductions after initial market entry in 2012.

The PHEV adoption rate could be less than the HEV adoption rate over the past 10 years (dominated by the Toyota Prius), due to additional complexities involving grid charging, higher purchase costs (though lower operation costs), less certain technologies (e.g., battery life), and more uncertainty regarding long-term maintenance costs and support. Conversely, the adoption rate could be far greater than that of the Prius HEV, given gas price jumps, rising fuel economy requirements, climate change legislation, and other factors.

Since range-extended PEVs operate similarly to conventional HEVs — even if never plugged into the grid, they are a natural successor to advanced HEVs. Additionally, the potential of driving "petroleum free" is alluring to some, and perhaps many. Avoiding the risks of oil supply disruptions and price spikes, and helping mitigate concerns over oil-related environmental, security, and economic concerns, may outweigh the effort required for almost-daily charging for many potential owners. Some may also prefer the convenience or safety of home refueling instead of stopping at the gas station. Such factors may well lead to a U.S. PEV adoption rate that matches or exceeds that of the Prius HEV over the past decade. Concerns over the actual range achieved by drivers in different climates on different highway types, under different topographical conditions and speeds, may also impact adoption.

Total U.S. year 2020 PEV market share projections similar to HEV sales — with approximately 2.5% market share (Vyas et al. 2009) — may well be achieved if manufacturers avoid serious early technology safety and quality problems. Battery thermal management and durability are a clear risk, especially for the deep cycled and conductive-cooled battery packs that Nissan will be incorporating into its aggressively priced Leaf. PEV sales may increase more rapidly if manufacturers expand their product offerings over the next decade to include a greater diversity of PEV platforms, such as minivans and sport utility vehicles, or performance PEVs — ideally all with targeted marketing to highlight the positive social externalities (and personal benefits) or attractive driving experience of PEV ownership.

When PEVs use their electric motors to save petroleum consumption costs, they are obviously consuming electricity. The average retail residential price for electricity is \$0.1175 per kWh in the U.S. (EIA 2001). The cost of the electrically driven miles traveled will vary by vehicle, driver, location and season. To gain a rough estimate of the cost, the Chevrolet Volt will nominally consume 10.9 kWh to travel 30 miles, with a resulting electricity cost of \$0.0423 per mile (GM 2010). Assuming a comparable conventional vehicle achieves 28 mpg, a gasoline price of \$3.00 per gallon yields a cost of \$0.107 per mile (or two and a half times higher than electrically driven miles).

According to a recent Pacific Northwest National Laboratory study (Kintner-Meyer et al. 2007), with only modestly well-behaved charging (i.e., mostly off-peak times of day), the existing U.S. grid can support a 70% shift in light duty vehicle design, to PHEV status. Avoidance of extreme-peak charging of PEVs (during, for example, late afternoon on a hot summer day) can be met with relatively simple driver-programmed charge window settings and by lower night-time energy prices to encourage off-peak charging. Some local distribution transformers may need to be upgraded when stressed by PEV clustering (KEMA 2010), similar to upgrades following advances in home appliances 60 years ago, introduction of air conditioning systems 40 years ago, and rising electronics loads 20 years ago.

FINANCIAL ANALYSIS OF COMPETING PEVs AND COMPARABLE CONVENTIONAL VEHICLES

As U.S. and other consumers now enjoy the choice of a BEV and eREV, full-cost accounting becomes a factor in new-technology adoption rates. There are many factors to consider beyond base price and fuel costs. The durability of PEVs' advanced lithium batteries is a justifiable concern, given the technology's relative immaturity. A total-cost-of-ownership analysis should also include likely maintenance or repair costs and potential battery replacement costs.

A key assumption for asset payback comparisons is lifetime use, or vehicle miles traveled in the case of PEVs. A National Highway Traffic Safety Administration report (Lu 2006) finds average U.S. personal-vehicle lifetimes of 156,000 miles. This average lifetime is skewed high by pickups and SUVs, which tend to be used over more time and for greater distances (and thus average closer to 180,000 lifetime miles). Mid-size and compact cars, such as these PEVs and their conventional twins, typically are used less. To reconcile such statistics, the following calculations assume consumers evaluate range-extended PEVs (like the Volt eREV and the Prius PHEV) over a 15-year, 150,000-mile horizon (typical of the average U.S. light-duty vehicle). Given their shorter range and longer charge times, BEVs are likely to achieve higher adoption rate among households with lower-distance needs. The BEV analysis thus assumes a 15-year, 100,000-mile life. Included in the cash flow are estimates of expected maintenance costs from interviews with Chevrolet, Nissan, and Toyota service managers. While informal, such data provide insight and fairly accurate estimates on the differences in relevant costs. For example, HEV experience suggests that vehicles with regenerative braking exhibit substantially less brake wear than their conventional counterparts. Many Prius owners never experience the need for expensive brake service. This analysis assumes that the front and rear brakes are replaced at 40,000- and 60,000-mile intervals, respectively, on conventional vehicles. These assumptions imply that the comparable conventional vehicle will require three sets of front brakes and two sets of rear brakes over the 150,000-mile lifetime. For the BEV comparison, the Nissan Versa was assumed to have two front brake replacements and one rear brake replacement over its 100,000-mile lifetime.

Chevrolet and Nissan have both announced eight-year/100,000-mile battery warranties on their respective PEVs. For this analysis, if a battery is replaced, it is expected to occur during the ninth year, immediately after the warranty expires, which is a conservative assumption (in favor of conventional vehicles). Given the likelihood of second-use applications for such batteries (e.g., grid power and computer backup power storage devices) and falling battery costs (thanks to scale economies in production and accelerating competition), net replacement costs may lie close to Argonne National Laboratory's recent higher volume projection of \$150/kWh (Santini et al. 2010). Continued improvements in battery energy density are expected over time. These improvements can be applied to achieving greater range or reducing ownership costs. If customers indicate a satisfaction with 73 to 100 miles of AER, future battery packs may be smaller with fewer cells, and therefore less expensive.

This paper provides the net present values (NPVs) of the differences that will emerge in cash flows for a PEV relative to its conventionally fueled counterpart. A positive NPV should be interpreted as follows: the higher initial PEV purchase price is fully offset by the future savings from lower operating and maintenance costs. A negative NPV implies that the future savings do not offset the higher PEV purchase price. NPV calculations involve standard accounting equations to find the present-day value of a series of current and (discounted) future costs (and revenues or other benefits, when those exist). Since future gasoline and lithium battery prices are unknown, NPV values were computed for each PEV/conventional vehicle comparison over a wide range of price assumptions, as shown in Tables 2 through 5. Table values illuminate the impact of higher or lower fuel prices and battery replacement costs on the net, long-term monetary benefits of buying a PEV over a conventional vehicle. As one would expect, higher gasoline prices and lower battery replacement costs result in a higher NPV of a PEV over its conventional counterpart.

Table 2's values assume a 5% discount rate and 100,000-mile vehicle lifetime for the Nissan Leaf BEV over its comparably equipped conventional twin, the Nissan Versa. With the \$7,500 federal tax credit included and no battery replacement required, the NPV remains positive for gasoline priced as low as \$2.75/gallon. The BEV Leaf avoids not only brake replacement costs but also regular oil and filter changes, which should generate greater savings for its owners. By looking at NPV entries in Table 2 close to \$7,500 (the assumed tax credit), it can be deduced that without a tax credit, the Leaf is estimated to offer cost savings (i.e., have a positive NPV) at gasoline prices between \$5.50 and \$6/gallon (again assuming no battery replacement). If battery replacement is required post warranty, the break-even gasoline price (where the Leaf offers no long-term owner savings or cost over the Versa) is estimated to increase by approximately \$0.66/gallon for each \$100/kWh increase in battery replacement cost, as implied by pairs of similar values in Table 2, including the two values that are underlined. For example, the paired values of \$1,969 and \$1,927 suggest that for a \$100/kWh increase in battery replacement cost, the gasoline price must rise approximately \$0.66/gallon (\$3/4.5) to maintain the same NPV.

Similar calculations (not shown here, due to space limitations) with a discount rate of 10% (common among relatively myopic consumers) reduces the benefit of the BEV's future fuel and maintenance savings (but also battery replacement cost implications) such that the NPV becomes slightly negative (-\$932) with the tax credit in place and gasoline at \$3.00/gallon. When discounting at 10%, a gas price of about \$8 per gallon (still below that in many EU countries) is required for the Leaf to break even with the Versa (i.e., zero NPV) without any tax credit and with a relatively low lifetime VMT (100,000 miles, as stated earlier and noted in the table).

Given its lower travel-distance assumptions, the Leaf's fuel and maintenance cost savings are reduced; 100,000 miles over 15 years averages to less than 19 miles per day, well below the 100-mile nominal range (and below its worst-case harsh-weather range). If this short range does represent the typical driving pattern, then this very low reliance on the battery's capacity could lead to far lower stresses and failures and contribute to greater durability and battery life. If the miles driven are increased, the fuel and maintenance costs savings over the conventional Versa also increase, improving the NPV for the Leaf (Table 3). A lowest-cost scenario would maximize miles driven while avoiding battery replacement. Noting that the eight-year/100,000-mile battery warranty expired from age (not mileage) after eight years, one may expect the battery to last the 15-year/100,000-mile life of the vehicle (since the battery is lightly stressed).

Table 2: Net Present Values of Nissan Leaf Over Nissan Versa (100,000-mile lifetime)

	Replacement Battery Price (per kWh)				
Gasoline Price ($/Gallon)	$0 No Battery Replacement	$150	$250	$350	$450
$7.00	$10,042	$7,721	$6,174	$4,627	$3,080
$6.50	$8,889	$6,568	$5,021	$3,474	<u>$1,927</u>
$6.00	$7,735	$5,415	$3,868	$2,321	$774
$5.50	$6,582	$4,262	$2,715	$1,167	($380)
$5.00	$5,429	$3,108	$1,561	$14	($1,533)
$4.50	$4,276	$1,955	$408	($1,139)	($2,686)
$4.00	$3,122	$802	($745)	($2,292)	($3,840)
$3.50	<u>$1,969</u>	($352)	($1,899)	($3,446)	($4,993)
$3.00	$816	($1,505)	($3,052)	($4,599)	($6,146)
$2.50	($338)	($2,658)	($4,205)	($5,752)	($7,299)

Note: The underlined, similar values of $1,927 and $1,969 are used to estimate a value for the increase (or decrease) in gas prices needed to maintain a similar NPV given a higher (or lower) battery replacement cost. Assumptions: 5-% (real) discount rate; 100,000 miles over 15 years; Versa: 30 miles/gallon; Leaf: 73-100 miles AER, 2.94 miles/kWh (electric); 6,667 miles/year; electricity cost: $0.1175/kWh; battery replacement in year nine (after eight year warranty's expiration); 2011 Leaf price of $25,280 (after $7,500 U.S. federal tax credit); 2011 Versa at $19,840 (comparably equipped to Leaf); Terminal values of both vehicles assumed equal.

Table 3: Net Present Values of Nissan Leaf Over Nissan Versa (150,000-mile lifetime)

	Replacement Battery Price (per kWh)				
Gasoline Price ($/Gallon)	$0 No Battery Replacement	$150	$250	$350	$450
$7.00	$18,128	$15,807	$14260	$12,713	$11,166
$6.50	$16,398	$14,077	$12,530	$10,983	$9,436
$6.00	$14,668	$12,347	$10,800	$9.253	$7,706
$5.50	$12,938	$10.617	$9,070	$7,523	$5,976
$5.00	$11,208	$8,888	$7,340	$5,793	$4,246
$4.50	$9,478	$7,158	$5,611	$4,063	$2,516
$4.00	$7,748	$5.428	$3,881	$2,333	$786
$3.50	$6,018	$3,698	$2,151	$604	($944)
$3.00	$4,288	$1,968	$421	($1,126)	($2,673)
$2.50	$2,558	$238	($1,309)	($2,856)	($4,403)

Note: The underlined, similar values of $4,246 and $4,288 are used to estimate a value for the increase (or decrease) in gas prices needed to maintain a similar NPV given a higher (or lower) battery replacement cost. Assumptions: 5% (real) discount rate; 150,000 miles over 15 years; Versa: 30 miles/gallon; Leaf: 73-100 miles AER, 2.94 miles/kWh (electric); 6,667 miles/year; electricity cost: $0.1175/kWh; battery replacement in year nine (after eight year warranty's expiration); 2011 Leaf price of $25,280 (after $7,500 U.S. federal tax credit); 2011 Versa at $19,840 (comparably equipped to Leaf); Terminal values of both vehicles assumed equal.

Table 4 contains the NPVs calculated using a 5% discount factor for the Chevrolet Volt over its comparably equipped conventional twin, the Chevrolet Cruze. With the $7,500 tax credit included and no battery replacement required, its NPV becomes positive when gas costs $3.00/gallon or more and reaches a maximum at $7.00/gallon (the highest gas price assumed here, and relatively common abroad). As with other PEVs and hybrids, the Volt should avoid brake replacement costs but will still require oil and filter changes at least every two years, according to the Volt owner's manual (compared to the Cruze's twice-a-year or every 5,000-8,000 miles recommendation). The table's NPV entries will hit $7,500 at slightly more than $5.00/gallon (without battery replacement), suggesting that, without the tax credit, the Volt enjoys a positive NPV advantage at gas prices below that. Interpolating from Table 4's underlined values, if battery replacement is required post warranty, the gasoline price must increase approximately $0.29/gallon ($1/3.5) for each $100/kWh increase in battery replacement cost to maintain the same NPV difference between the two competing vehicles. The implied break-even ratio of gas price to battery storage price is less than half that computed for the Leaf-Versa comparison, because the Volt's battery is 33% smaller than the Leaf's and fewer annual miles were assumed for the range-limited Leaf. As discussed earlier, discounting at 10%[3] reduces the benefit of future fuel and maintenance savings (but also the cost of the battery replacement in the outyears) such that the NPV is a negative $928 with the federal tax credit, no battery replacement, and gasoline at $3.50/gallon. A gas price of about $6.60/gallon is required for zero NPV (where the Volt and Cruze have equal long-term costs) without any tax credit.

The fuel and maintenance costs savings for the Volt extend to 150,000 miles. This total vehicle life yields an average daily usage of less than 29 miles per day — and thereby well within the Volt's 40-mile all-electric range. Hence, all 10,000 yearly miles traveled are assumed to be electrically driven. GM has indicated that the battery failure mode may be a degradation of storage capacity instead of a sudden total failure. If all 10,000 miles traveled are electrically driven, the battery may last the entire 15-year/150,000-mile life of the vehicle and still meet the 29-mile average daily driving need.

Table 4: Net Present Values of Chevrolet Volt (eREV) Over Chevrolet Cruze

	Replacement Battery Price (per kWh)				
Gasoline Price ($/Gallon)	$0 No Battery Replacement	$150	$250	$350	$450
$7.00	$14,869	$13,322	$12,291	$11,259	$10,228
$6.50	$13,205	$11,468	$10,437	$9,406	$8,374
$6.00	$11,162	$9,615	$8,584	$7,552	$6,521
$5.50	$9,308	$7,761	$6,730	$5,699	$4,667
$5.00	$7,455	$5,908	$4,877	$3,845	$2,814
$4.50	$5,601	$4,054	$3,023	$1,992	$960
$4.00	$3,748	$2,201	$1,170	$138	($893)
$3.50	$1,894	$347	($684)	($1,715)	($2,747)
$3.00	$41	($1,506)	($2,538)	($3,569)	($4,600)
$2.50	($1,813)	($3,360)	($4,391)	($5,422)	($6,454)

Note: The underlined, similar values of $5,601 and $5,699 are used to estimate a value for the increase (or decrease) in gas prices needed to maintain a similar NPV given a higher (or lower) battery replacement cost. Assumptions: 5% (real) discount rate; 150,000 miles over 15 years; Cruze: 28 miles/gallon; Volt: 40 miles AER, 2.78 miles/kWh (electric); cost of electricity: $0.1175/kWh; Battery replacement in ninth year (after eight-year warranty's expiration); 2011 Volt price of $33,500 (after $7,500 Federal Tax Credit) vs. 2011 Cruze at $25,100 (comparably equipped to Volt); Terminal values of both vehicles assumed equal.

Table 5 contains the net present values calculated using a 5% discount factor for the Toyota Prius-PHEV over its comparably equipped conventional twin, the Toyota Corolla. With the $2,500 tax credit included and no battery replacement required, the NPV is positive for gasoline values nearing $3.75/gallon. As with other PEVs and HEVs, the Prius-PHEV should avoid brake replacement costs but will likely still require yearly oil and filter changes (compared to the Corolla's recommended twice yearly per 5,000-8,000 mile interval). The lower-cost benefit of the relatively small 5.3kWh battery is apparent, since NPVs become positive — even without this PHEV's $2,500 tax credit — at gas prices of slightly less than $3.75/gallon (again assuming no battery replacement). From Table 5, given lower battery replacement costs overall (due to smaller battery size) and the difficulty in determining the exact price decline rate over time for batteries, for each $100 higher price in potential Prius PHEV replacement battery costs, the gasoline price must increase by only $0.14/gallon ($0.50/3.5) to maintain the same NPV (versus $0.66/gallon for the Leaf and $0.29/gallon for the Volt). As before, annual discounting at 10% (for more risk-averse or myopic buyers) will reduce the benefit of future fuel and maintenance savings (but also the present value of battery replacement) such that the NPV of the Prius PHEV (over a Corolla) begins being positive at about $3.10 per gallon, with a tax credit and assuming no battery replacement. A gas price of about $5.90/gallon is required for a break-even condition, without any tax credit (and no battery replacement).

The fuel and maintenance costs savings for the Prius-PHEV extend to 150,000 miles. As noted earlier, this assumption implies an average daily usage of 29 miles per day. Given Toyota's AER intent of 15 miles, just 15 miles are assumed to be driven electrically, and the remainder uses gasoline to provide a reasonable approximation of fuel consumption. It is interesting to note the lower gasoline-price break-even points without tax credits given the Prius-PHEV's smaller battery and modest AER, but lower purchase price premium. These results are consistent with prior PEV architecture cost studies (Vyas, et al. 2009). In addition, if a replacement battery is required, it should be considerably less expensive, given the smaller size.

Table 5: Net Present Value of Toyota Prius-PHEV Over Toyota Corolla

	Replacement Battery Price (per kWh)				
Gasoline Price ($/Gallon)	$0 No Battery Replacement	$150	$250	$350	$450
$7.00	$8,548	$8,035	$7,693	$7,352	$7,010
$6.50	$7,237	$6,725	$6,383	$6,041	$5,700
$6.00	$5,927	$5,414	$5,073	$4,731	$4,390
$5.50	$4,617	$4,104	$3,762	$3,421	$3,079
$5.00	$3,306	$2,794	$2,452	$2,110	$1,769
$4.50	$1,996	$1,483	$1,142	$800	$459
$4.00	$686	$173	($169)	($510)	($852)
$3.50	($625)	($1,137)	($1,479)	($1,820)	($2,162)
$3.00	($1,935)	($2,448)	(2,789)	($3,131)	($3,472)
$2.50	($3,245)	($3,758)	($4,100)	($4,441)	($4,783)

Note: The underlined, similar values of $3,421 and $3,306 are used to estimate a value for the increase (or decrease) in gas prices needed to maintain a similar NPV given a higher (or lower) battery replacement cost. Assumptions: 5% (real) discount rate; 150,000 miles over 15 years; Corolla: 29 miles/gallon; Prius-PHEV: 15 miles AER, 49 mpg (gas), 3.8miles/kWh (estimated electric); 5,475miles/year (electric) + 4,525miles/year (gas); cost of electricity: $0.1175/kWh; Battery replacement in ninth year (after eight-year warranty expiration); 2012 Prius-PHEV announced price at $29,500 ($32,000 MSRP - $2,500 federal tax credit), vs. 2011 Corolla: $19,244 (comparably equipped but Navigation not available on Corolla); Terminal values of both vehicles assumed equal.

Interestingly (but perhaps not by accident, given manufacturer and government sales aspirations), for all three vehicles, the U.S. battery-size-based tax credit results in positive (though slight) NPVs at fuel costs of under $3.75, if the owner does not face battery replacement costs. Of course, as driving distances, future-cost discounting, recharge frequencies, gasoline prices, battery prices, power prices, and other attributes or assumptions change, the NPVs can go either way. A sensitivity analysis was performed to estimate the price of fuel required for breaking even between each PEV and its comparable conventional vehicle. Assuming no battery replacement and no credits, the NPV would also be positive with gas prices above approximately $5.90, $5.00, and $4.70 per gallon for the Leaf (assuming a 100,000-mile life), Volt (150,000 lifetime), and Prius-PHEV (150,000 lifetime), respectively.

The relative cost analysis was repeated to observe the effect of increasing the Leaf's lifetime miles to that of the other PEVs (150,000 miles). If the Leaf is driven an average of 29 miles per day (150,000 over its 15-year vehicle life, instead of 100,000 miles), the break-even fuel price (without tax credit and without battery replacement) drops to less than $4.00 per gallon. This 29 miles-per-day distance lies well within the range of a BEV, such as the Leaf (and well within the round-trip commute of most workers), even in harsh weather conditions with reduced range. If vehicle manufacturers succeed in engineering and manufacturing PEVs with batteries to last the vehicle's lifetime, their financial attractiveness, particularly in higher fuel cost regions (including China), seems very solid, especially at moderate discount rates. If one were to price the social costs of the various vehicles, the comparisons should land more heavily in favor of PEVs (Lemp and Kockelman 2008).

Analysis was also performed to compare the payback for the 2010 Prius HEV to the 2010 Toyota Corolla, and then to the Prius PHEV described earlier. Given its higher purchase price, but slightly lower maintenance costs and much lower fuel costs, the NPV of a Prius HEV over a Corolla is positive at gas prices below $2.50 per gallon (assuming no battery replacement, 150,000-mile life, 5% real discount rate and no tax credits). Using a 10% discount rate, the HEV Prius enjoys a positive payback over a Corolla at gas prices below $3.10 per gallon. Given the recently announced pricing of the Prius PHEV at only $2,205 over a comparably equipped Prius III HEV, gas price estimates must reach only $3.50/gallon to generate a positive return on the Prius PHEV, over the Prius III HEV, but nearly $4.75 per gallon without its $2,500 federal tax credit.

These results rely on actual retail prices and EPA efficiency data. Some observations can be made that are consistent with previous studies that used bottom-up component cost and efficiency estimates (Kromer and Heywood 2007, Vyas 2009, and Shaiu et al. 2009) in that the most attractive purchase conditions without tax credits are typically achieved when the expensive battery's size is as small as possible to provide no spare electric drive range capacity and the electric driving range is somewhat less than the driver's average driving needs.

KEY TRENDS

The rate of PEV adoption and use, as well as their environmental and other implications, will depend on a variety of trends that are expected, but with uncertain rates. These include grid management and feedstock use, battery technology advances, charging infrastructure, and energy pricing, and they are discussed briefly in turn here.

Evolution of Grid Power Generation

Emissions levels from electricity generation are specific to the region, technologies, and feed stocks used. Some sources, including wind, solar, nuclear, and hydro, create little or no emissions (though their construction and maintenance certainly imply some embodied energy). Other sources, such as coal and natural gas have become less polluting as environmental regulations have tightened over time and newer technologies have improved efficiencies. It is reasonable to expect further improvement is possible given the eventual retirement of older, less efficient coal plants with less effective grandfathered emissions control systems. The technology exists today to make grid generation emissions-free; however, doing so would substantially raise electricity prices. The issue is economic deployment of zero/low emitting generation resources.

Given that the grid has no electron-based energy storage, to maintain system stability grid operators must fine-tune total output to precisely match real-time loads every second of every day. The unique nature of PEV charging offers the new opportunity for grid operators to fine-tune the charging load to match intermittent renewable generation sources such as wind and solar. PEV owners do not care about the precise power charging levels of their vehicles at any particular time. Drivers simply care that the vehicle is charged sufficiently by the time of their next departure, such as leaving for work in the morning. Hence, while the electric industry has lowered relative emissions in the U.S. to meet progressively more stringent regulatory standards over time, the mass deployment of intelligently charging PEVs presents the opportunity to further improve overall emissions by improving the economics and hence deployment of renewable zero-emissions generation.

Automotive-Grade Battery Trends

A number of factors lead to the expectation that battery costs will decline over time. Automotive-grade lithium batteries have no meaningful global sales at this time. Increased volumes typically introduce manufacturing or scale efficiencies and encourage new manufacturers to enter the market, increasing competition and reducing prices.

Engineers are expected to enhance control algorithms, which will improve efficiency and enable downsizing as more is learned about battery wear mechanisms from field experience. Electrical energy required for cabin heating and cooling directly reduces PEV range, so weather conditions become relevant. It is reasonable to expect efficiency improvements in electrically driven PEV heating and air conditioning systems and cabin insulation to further reduce demands on the battery.

Also, increased energy recapture through advances in regenerative braking are likely, through innovations like ultracapacitor/battery combinations. PEV batteries appear to have substantial potential for cost reductions as production volumes increase (Santini et al. 2010), perhaps to $150/kWh with large volumes. The overall incremental price of a PEV driven by the battery cost is likely to decline from a combination of lower battery prices and an ability to use smaller batteries while maintaining range and other capabilities through design innovations.

Public and Multifamily Charging Infrastructure

Homes are expected to be the predominant charging location (PUCT 2010). More charging points (and smart plugs) are expected to be installed over time to support potential PEV buyers who do not have a home garage. Work, apartment building, and public charging options are far more important for BEVs than for eREVs and PHEVs. It is likely that PEV drivers without garages will favor eREVs/PHEVs, have reasonable charging options at work, and/or live in a community with strong commitment to (and investment in) public charging. With more pervasive deployment, shorter daily commuting distances, and better mass-transit systems, European and Japanese markets may experience much greater shares of BEVs (as compared to eREVs/PHEVs) than in the U.S. and much greater PEV adoption rates overall.

Residential Energy Pricing

Electricity is an essential good and, hence, typically served by utilities with oversight from public utility commissions, self-owned co-operatives, and/or other forms of democratically elected oversight bodies (in the case of municipally owned utilities). For the foreseeable future, retail energy prices (and customers) are unlikely to be subjected to real-time price fluctuations (with a market clearing price determined every five to 15 minutes, for example) as wholesale power prices are today. Time-of-use (TOU) rates presently differ from real-time rates in that they typically offer just two rates per day: peak and off-peak. TOU rates also may have different peak/off-peak rates for summer and winter seasons, to provide incentives for efficiency during the most stressful, seasonal peaks, and to encourage loadshifting (to off-peak periods).

It is important to note that a significant portion of the grid's value to customers for the past century has been providing as much energy as a homeowner desires, whenever they want it, at an attractively low cost (relative to other energy options) and delivered with great simplicity. Customers simply plug their devices into the wall. The ability to improve incentives for energy efficiency has been moderated in the past by the relatively low price of energy, and an inability to precisely estimate the benefits of energy-saving behaviors and investments given that the only data available are monthly total-energy bills. TOU rates are expected to continue to provide attractive energy costs during the expected dominant nighttime PEV's charging period. Regulating entities are highly unlikely to support substantially raising off-peak retail rates as a policy as they are typically resistant to allowing any rate increase. Experience has shown that even in the highest electricity cost regions, nighttime rates are still relatively low.

Utilities face an inherent dilemma: lower CO_2 emissions imply lower energy sales and hence lower revenues. PEV energy sales provide a means for utilities to offset their residential energy sales lost to structure energy efficiency improvements while improving overall (vehicle plus generation) CO_2 emissions.

Potential Implications for Travel Patterns

While both PHEVs and BEVs are grid connected, BEVs will likely foster a greater variety of behavioral changes. Even with a 100-mile claimed AER, more planning for the day's travel will be required. This overhead will be driver specific and may not be meaningful if daily travel distances (e.g., the work commute) do not vary greatly. When the daily drive is less predictable, rental or ownership (and use) of a second conventional vehicle may be needed, and/or searching for available public charging stations. BEV owners may be much more "interconnected" through the use of their vehicle telematics (communications plus navigation) systems, which can guide them to pre-reserved public charging stations. It is possible that this overhead may decrease (or vacillate) over time, with improvements in the availability of public charging stations but then worsen with more PEVs on the road competing for these stations.

The range anxiety of a BEV might also be solved via non-technological solutions. For example, manufacturers may sell BEVs with attractive car rental arrangements at their dealerships for longer range and/or less conventional vehicle types. Rental options are very likely to include SUVs, pickup trucks and minivans, for example, to accommodate less regular — but important — tripmaking, including weekend camping trips or furniture moving days. Such strategies can help a variety of U.S. households — and others around the globe — "downsize," offering a potentially dramatic long-term gasoline savings, by moving household ownership trends away from the light-duty-truck fleet. This strategy may also provide less risk of remote repair (if an accident or breakdown occurs, the renter simply and quickly gets another vehicle to continue the trip without the need to search for a reputable repair shop or wait for the repair) and the advantage of bringing the PEV owner into the dealer for service, enhancing the dealer- and manufacturer-consumer relationships.

SUMMARY AND CONCLUSIONS

PEV-related technologies have progressed sufficiently to enable the introduction of mass-market-viable vehicles by mainstream global manufacturers. With the advent of the Chevrolet Volt and Nissan Leaf PEVs, the industry has been set in motion and consumers have some serious choices to make.

Assuming a discount rate of 5%, the estimated net gains for owners of these early PEV models (compared to comparably-equipped conventional vehicles) is small in low-gas-price regions like the U.S., but still positive, when U.S. tax credits are included, assuming no battery replacement is required by owners. Without such credits, the relative NPVs are negative at current U.S. gas prices. Nevertheless, cost savings may be substantial for longer-distance drivers who electrify their miles and is estimated to be strongly positive for those in higher-fuel-cost regions (e.g., Germany at $7 to $8 per gallon). Gas prices above approximately $5.90, $5.00, and $4.70 per gallon are estimated to make the Leaf, Volt, and Prius-PHEV attractive from a purely financial standpoint, respectively, than their conventional counterparts, without any credits and with today's PEV component and retail prices, using a 5% discount rate. Gas prices above approximately $8.00, $6.60, and $6.50 per gallon are required when using a discount rate of 10% for a positive NPV without tax credits.

PEVs are expected to sell well to innovators and early adopters despite potentially higher overall costs in low-fuel-cost regions, just as HEVs have enjoyed some niche-market success. Early purchase opportunities, greater personal wealth, and pent-up demand for such innovative vehicles may trigger the greatest markets for PEVs initially in the U.S., with long-term total sales highest abroad, thanks to higher fuel prices settings elsewhere, higher base-level charging voltages, shorter commutes, and/or a greater focus on transportation environmental impacts (and potentially stronger government incentive programs relative to the U.S.).

The higher component costs (such as lithium batteries), which lead to higher purchase prices for PEVs, are likely to decline over time, as they have for HEV-related components and past automotive innovations (such as fuel injection, electronic engine management, and air bags). Continued component price declines and fuel cost increases will lead to higher NPVs for PEVs, relative to comparable conventional vehicles. Even in relatively low-fuel-cost countries, such as the U.S., the HEV Prius has a positive NPV over a similar conventional vehicle. The experience with the HEV

Prius over the past decade demonstrates the trends and factors that may lead to PEV cost parity with conventional vehicles over the coming decade.

Charging infrastructure build-out also may also proceed more rapidly in the U.S. over the short term, but then accelerate relatively rapidly in regions with higher fuel prices (such as Europe and Japan). Over time, the share of BEVs in European and Japanese markets may become much greater than in the U.S., due to shorter daily commuting distances, the presence of better mass-transit systems, and potentially more pervasive charging infrastructure deployment.

The U.S. grid is expected to continue to become more "green" over time (EIA 2001), and the deployment of larger numbers of PEVs has the potential to accelerate grid-emissions reductions, through the synergistic coordination of PEV charging with renewable generation sources (such as wind and solar). More meaningful PEV architectures and battery-technology competition are expected, with many viable combinations that offer a variety of optimization opportunities, reducing battery costs and PEV prices over time.

Interestingly, the introduction of PEVs may stimulate a competitive response which may accelerate advances in conventional powertrain efficiency, biofuels, or hydrogen fuel-cell vehicles as well. As long as issues like energy security, air quality, trade deficits, and other concerns continue, all such innovations bode well for the world at large.

Endnotes

1. A vehicle powertrain includes the components associated with the source of propulsion (such as a gasoline engine or electric motor), transmission, driveshaft(s), differential(s), and axles.

2. While eREV/PHEV owners can drive in a fashion to avoid gasoline use and maximize electric drive, manufacturers will likely advise that owners need to keep a few gallons of gasoline in the tank to let the engine occasionally operate to lubricate the ICE's bearings and seals. Blended-mode-PHEV manufacturers will likely require that drivers have gas in the tank to ensure full functionality for safe operation (e.g., over 15 miles range, above 60 mph, or freeway merging acceleration). While the ability to replace liquid fuel consumption with electric drive substantially depends on the nature of the driver's commuting pattern, it is reasonable to assume that PEVs with a wider range of electric operation (either distance, load, and/or speed) have the potential for greater degrees of reduction in the amount of liquid fuel consumed.

3. The break-even gas prices and 10% discounting calculations are not shown here, due to paper length limitations.

References

Deffeyes, Kenneth. *Hubbert's Peak: The Impending World Oil Shortage*. Princeton University Press, Princeton, NJ, 2002.

Delucchi, M. and D. McCubbin. "External Costs of Transport in the U.S." A. de Palma, R. Lindsey, E. Quinet, and R. Vickerman (eds.). Forthcoming in *Handbook of Transport Economics*. Cheltenham,UK: Edward Elgar Publishing Ltd. (2010).

ECB. "Will Oil Prices Decline Over the Long Term?" European Central Bank Occasional Paper Series No. 98, October, 2008. Available at http://www.ecb.de/pub/pdf/scpops/ecbocp98.pdf.

EIA." *Reducing Emissions of Sulfur Dioxide, Nitrogen Oxides, and Mercury from Electric Power Plants*." Energy Information Agency Report Number SR-OIAF/2001-04, 2001. Available at: http://www.eia.doe.gov/oiaf/servicerpt/mepp/chap2.html.

EPA. *Dynamometer Drive Schedule Quick View*. U.S. Environmental Protection Agency, 2010. Available at http://www.epa.gov/nvfel/methods/quickdds.htm.

EPRI and NRDC. *Environmental Assessment of Plug-In Hybrid Electric Vehicles; Volume 2: United States Air Quality Analysis Based on AEO-2006 Assumptions for 2030*. Final report by the Electric Power Research Institute (EPRI) and National Resources Defense Council. Washington, D.C., 2007. Available at http://my.epri.com/portal/server.pt?open=514&objID=223132&mode=2.

GM. "Chevrolet Volt Receives New Fuel Economy Label from EPA," 2010. Available at http://www.chevroletvoltage.com/index.php/Volt/2011-chevrolet-volt-receives-new-fuel-economy-label-from-epa.html.

Green Car Congress. "Reported US Hybrid Sales Up 42% in December, Down 7.5% for CY 2009; New Vehicle Market Share of 2.8% for CY 2009." January, 2010. Available at http://www.greencarcongress.com/2010/01/hybsales-20100107.html.

Greene, D.L. "Measuring Energy Security: Can the United States Achieve Oil Independence?" *Energy Policy* 38 (4), (2010): 1614-1621.

KEMA. *Assessment of Plug-in Electric Vehicle Integration with ISO/RTO Systems*. Produced by KEMA Inc. for the ISO/RTO Council, 2010. Available at http://www.isorto.org/atf/cf/%7B5B4E85C6-7EAC-40A0-8DC3-003829518EBD%7D/IRC_Report_Assessment_of_Plug-in_Electric_Vehicle_Integration_with_ISO-RTO_Systems_03232010.pdf.

Kintner-Meyer M., K. Schneider, and R. Pratt. *Impact Assessment of Plug-in Hybrid Vehicles on Electric Utilities and Regional US Power Grids. Part I: Technical Analysis*. Pacific Northwest National Laboratory paper, 2007. Available at http://www.pnl.gov/energy/eed/etd/pdfs/phev_feasibility_analysis_combined.pdf.

Kromer, M. and J.B. Heywood. "Electric Powertrains: Opportunities and Challenges in the U.S. Light-duty Vehicle Fleet." (Report No. LFEE 2007-02-RP 2007). MIT Laboratory for Energy and the Environment, Cambridge, MA, 2007.

Lemp, J. and K. Kockelman. "Quantifying the External Costs of Vehicle Use: Evidence from America's Top-Selling Light-Duty Models." *Transportation Research Part D* 13 (8), (2008): 491-504.

Lu, S. *Vehicle Survivability and Travel Mileage Schedules*. National Highway Traffic Safety Administration (NHTSA). U.S. DOT HS 809 952, 2006. Washington, D.C. Available at http://www-nrd.nhtsa.dot.gov/Pubs/809952.PDF.

Markel, Tony. "Plug-in Electric Vehicle Infrastructure: A Foundation for Electrified Transportation." National Renewable Energy Laboratory Conference Paper 540-47951. Presented at the MIT Energy Initiative Transportation Electrification Symposium in Cambridge, Massachusetts, 2010. Available at http://www.nrel.gov/docs/fy10osti/47951.pdf.

Public Utilities Commission of Texas (PUCT). "Electric Vehicle Utility Stakeholder Group Workshop," Austin, Texas. May 12, 2010. Presentations by representatives of GM, Ford, and Nissan.

Santini, D., K. Gallagher, and P. Nelson. "Modeling of Manufacturing Costs of Lithium-Ion Batteries for HEVs, PHEVs, and EVs." Argonne National Laboratory. Paper presented at the World Electric Vehicle Symposium and Exposition (EVS25), in Shenzhen, China, 2010. http://www.evs25.org/event/2009ddc-en/index.html

Sioshanshi, R. and P. Denholm. "Emissions Impacts and Benefits of Plug-in Hybrid Electric Vehicles and Vehicle to Grid Services." National Renewable Energy Laboratory, 2008. Available at http://www.iwse.osu.edu/ISEFaculty/sioshansi/papers/PHEV_emissions.pdf.

Shiau, C.N., C. Samaras, R. Hauffe, and J. Michalek. "Impact of Battery Weight and Charging Patterns on the Economic and Environmental Benefits of Plug-in Hybrid Vehicles." *Energy Policy* 37, (2009): 2653-2663.

Tate, E.D., M.O. Harpster, and P.J. Savagian "The Electrification of the Automobile: From Conventional Hybrid, to Plug-in Hybrids, to Extended-Range Electric Vehicles." SAE International World Congress. SAE Technical Paper 2008-01-0458, 2008.

Tate, E.D. and P. Savagian. "The CO2 Benefits of Electrification E-REVs, PHEVs and Charging Scenarios." SAE Technical paper 2009-01-1311, 2009.

Thompson, T., M. Webber, and D. Allen. "Air Quality Impacts of Using Overnight Electricity Generation to Charge Plug-in Hybrid Electric Vehicles for Daytime Use." *Environmental Research Letters* 4 (1), (2009): pp. 1-12.

Toyota. 2010 Toyota Prius Plug-In Hybrid Vehicle, 2010. Available at http://www.toyota.com/esq/articles/2010/Prius_Plgin_In_Hybrid.html.

U.S. BEA. *U.S. International Trade in Goods and Services*. U.S. Census Bureau of Economic Analysis, March 11, 2008.

Vyas, A., D. Santini, and L. Johnson. "Plug-In Hybrid Electric Vehicles' Potential for Petroleum Use Reduction: Issues Involved in Developing Reliable Estimates." Proceedings of the 89th Annual Meeting of the Transportation Research Board, Washington, D.C., (2009). Available at http://www.transportation.anl.gov/pdfs/TA/621.PDF.

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