Transportation Research Part D 25 (2013) 139–145

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

US residential charging potential for electric vehicles

Elizabeth J. Traut [a], TsuWei Charlie Cherng [a], Chris Hendrickson [b], Jeremy J. Michalek [c,*]

[a] Mechanical Engineering, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213, USA
[b] Civil and Environmental Engineering, Carnegie Mellon University, Porter Hall 123J, 5000 Forbes Avenue, Pittsburgh, PA 15213, USA
[c] Mechanical Engineering, Engineering and Public Policy, Carnegie Mellon University, Scaife Hall 324, 5000 Forbes Avenue, Pittsburgh, PA 15213, USA

ARTICLE INFO

Keywords:
Plug-in vehicles
Charging infrastructure
Parking

ABSTRACT

We assess existing and potential charging infrastructure for plug-in vehicles in US households using data from the American Housing Survey and the Residential Energy Consumption Survey. We estimate that less than half of US vehicles have reliable access to a dedicated off-street parking space at an owned residence where charging infrastructure could be installed. Specifically, while approximately 79% households have off-street parking for at least some of their vehicles, only an estimated 56% of vehicles have a dedicated off-street parking space – and only 47% at an owned residence. Approximately 22% vehicles currently have access to a dedicated home parking space within reach of an outlet sufficient to recharge a small plug-in vehicle battery pack overnight. Access to faster charging, required for vehicles with longer electric range, will usually require infrastructure investment ranging from several hundred to several thousand dollars, depending on panel and construction requirements. We discuss sensitivity of results to uncertain factors and implications for the potential of mainstream penetration of plug-in vehicles.

1. Introduction

In the current new light duty vehicle market, conventional vehicles (CV) make up the vast majority of market share, hybrid electric vehicles (HEVs) represent less than 4% share, and sales of plug-in electric vehicles (PEVs), including plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs), represent less than 0.6% (Electric Drive Transportation Association, 2012; HybridCars.com, 2012). One potentially significant limiting factor for any significant growth in PEV market penetration is the ability of US households to charge vehicles at home. Residential charging is likely to be important for adoption of both PHEVs and BEVs, not only because consumers without home charging may be less likely to purchase them, but also because off-peak electric load times take place overnight. Limited residential charging opportunities could be a significant barrier to PEV market penetration.

Level 1 charging is at 120 V and either 12 A or 16 A, while Level 2 charging, preferred for vehicles with larger battery capacity, uses a 240 V outlet at 16–80 A (National Petroleum Council, 2012; Society of Automotive Engineers, 2010). The Chevy Volt charges in about 10 h using Level 1 charging or 4 h using Level 2 (Chevrolet, 2010). The Nissan Leaf requires 4 h to charge completely using Level 2 (Nissan, 2013). Level 3 charging is the fastest charging method, but it requires high voltage and will not be an option for residential charging, so we address only Level 1 and Level 2 residential charging.

Prior analysis has identified residential parking availability per household as a factor influencing PEV market penetration. Fleet penetration of electric vehicles, however, is usually expressed as a percentage of vehicles, not households. Because a large percentage of US households have multiple vehicles (Fig. 1), we address residential parking and vehicle charging

* Corresponding author. Tel.: +1 412 268 3765; fax: +1 412 268 2908.
E-mail address: jmichalek@cmu.edu (J.J. Michalek).

1361-9209/$ - see front matter
http://dx.doi.org/10.1016/j.trd.2013.10.001

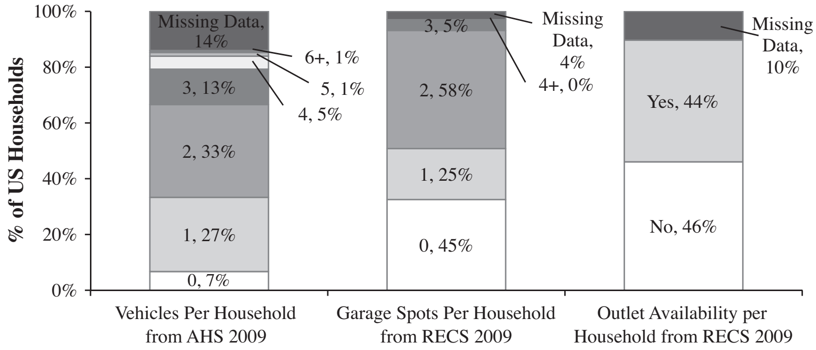

Fig. 1. Vehicles per household, garage spaces per household, and outlet availability from AHS 2009 and RECS 2009 data sets. *Note:* "Missing Data" indicates uncertainty from non-responses. Zero parking spaces indicate no garage.

availability both per household and per vehicle. By analyzing data from the American Housing Survey (AHS) and combining it with data from the Residential Energy Consumption Survey (RECS), we estimate the portion of US households and the portion of personal vehicles that currently have Level 1 charging access as well as the portion that have dedicated off-street parking where charging could be installed in the future. We examine the sensitivity of these results to assumptions, and we examine geographic and demographic variations. Finally we examine the implications of these results for future market penetration of electric vehicles.

2. Method

RECS (US Energy Information Administration, 2011a) is a US nationwide household energy consumption survey conducted every 4 years by the US Energy Information Administration. AHS (US Census Bureau, 2009) is a US nationwide housing stock survey conducted every 2 years by the US Census Bureau. The 2009 RECS survey was the most recent available at the time of the study, and the 2009 AHS data are used for consistency. Each data set has weighting factors to account for sampling bias and non-response bias.

Fig. 1 summarizes available data from AHS 2009 and RECS 2009 on the number of cars and light trucks per US household, the number of parking spaces available in garages at households, and the portion of households that have an outlet within 20 feet of vehicle parking. Since the maximum number of reported spaces per garage is three and each household has at most one garage reported, the maximum number of garage spaces per household is also three. The figure shows that more US households have vehicles than have garages, and most of those have multiple vehicles.

Where data were not available, we made educated assumptions and tested sensitivity of results to variation in these assumptions. Our assumptions for the base case, optimistic case, and pessimistic case are shown in Table 1. The major assumptions influencing charging opportunities are the size and presence of driveways (or other non-garage off-street parking), usability of outlets (e.g. whether the circuit would be overloaded by plugging in a vehicle), and the portion of parking spaces that are available for parking (i.e. not used for storage, boats, or other non-parking use). Some of these assumptions are based on the structure of the data available in RECS and AHS. For example, we lack data on whether any household has more than one garage or whether any household with a garage also has additional driveway space. Other assumptions are based on data that are entirely missing. The portion of outlets that will support vehicle charging is not asked, probably because respondents are unlikely to know the answer. Outlets need to be on a dedicated circuit to charge a vehicle. The portion of parking with access to outlets to charge multiple vehicles (meaning outlets on multiple dedicated circuits) is not known for the same reason. The portion of parking spaces that are available for parking is also not asked in these surveys.[1]

We initially combine RECS and AHS with our assumptions to create one data set that has no missing data and contains all the variables needed. These include those that will be used directly in the calculations and variables, such as demographic information, that will be used to match up the two data sets or to interpret the results. We use RECS as the base for this new data set, and we use multiple imputation with hot-deck imputation (Little and Rubin, 2008) both to fill in variables that are only available in AHS and to fill in individual values that are missing from the other variables. This method involves dividing the households into segments or bins and then using each bin as the "deck" from which to draw replacements for any missing variable values for households in that bin. By doing multiple imputations with different sets of random draws from the weighted distribution of households in the bins, we account for uncertainty in the values of the missing data using by a weighted probability distribution of the existing values. We use ten imputations.

Since we need to take draws from households in AHS to fill in the variables that are missing from RECS, the bin definitions need to be consistent in both data sets. Therefore we base the bins on 8 variables that both data sets have in common:

[1] According to Arnold and Lang (2006), the portion of garages that are used for storage and unavailable for parking cars may be as high as 75% in some regions. We use less pessimistic assumptions.

Table 1
Assumptions defining the base case and bounding optimistic and pessimistic cases.

Base case	Optimistic case	Pessimistic case
Parking		
• Carport spaces: 1	• Carport spaces: 1–3, drawn from DGSSH	• Carport spaces: 1
• Off-street spaces: 1–3, drawn from distribution of garage sizes for similar households (DGSSH)	• Off-street spaces: 1–3, drawn from DGSSH	• Off-street spaces: 1–2, drawn from distribution of 1–2 car garages for similar households
• 10% of spaces unavailable for parking (other use)	• All spaces available for parking	• 50% of spaces unavailable for parking
• Each household has only 1 of: {garage, carport, other off-street parking area (OSPA), or no parking}	• Homes with garages also have other OSPA, in the same proportion as garage-less homes	• Each household has only 1 of: {garage, carport, OSPA, or no parking}
	• Each household has only 1 of: {garage, garage w/OSPA, carport, carport w/OSPA, OSPA, or no parking}	
Charging		
• Only 1 vehicle can access each outlet (capacity is limited since it has only one circuit)	• 50% of outlets could be shared by two vehicles (perhaps charging at different times) resulting in up to 1.5 vehicles per outlet on average	• Only 50% of outlets near parking can charge a vehicle (some circuits already in use and would be overloaded)

housing unit type, occupancy status, population density, year the home was built, household gross annual income, number of household members age 20 or older, presence of a garage or carport, and number of rooms in the home. Where possible we use all eight variables to segment, but where these bins result in no available data from which to take draws, we use a coarser set of bins. The coarser bins use a subset of the binning variables chosen based on their correlation with number of vehicles, since that is the variable most affected by bin definitions. Where there are still no data to draw from in these coarser bins (less than 6% of data) we drew missing values from all households with valid data for the variable with the missing value.

Two of our assumptions are defined as percentages or probabilities of availability: portion of parking spaces that are available for parking, and portion of outlets that are available to be used or shared. We implement these assumptions by creating two new variables: available parking spaces and available outlets. The number of available parking spaces for each household in the base case is determined by making each individual parking space available with a 90% probability, or unavailable with a 10% probability, and in the pessimistic case by making each space available with a 50% probability. The portion of outlets available is calculated similarly: each outlet is made available with a 50% probability in the pessimistic case and made available for up to two vehicles with a 50% probability in the optimistic case. These draws are taken separately for each imputation so that the multiple imputations capture uncertainty in which specific spaces and outlets are available or unavailable.

Once the data are prepared with missing values filled in, all variables combined into one data set, and probabilistic assumptions accounted for, we calculate several quantities of interest. To compute how many US households have dedicated parking for at least one vehicle, we assume that any household with a designated parking space for a vehicle has the potential to charge a BEV or PHEV in the future with some additional installation of charging infrastructure at that parking space. We assume that households without dedicated parking are not able to install charging infrastructure to which a PEV would have reliable access. The equation for portion of households with parking, P_{HP}, is

$$P_{\mathrm{HP}} = \frac{\sum_i \min(S_{\mathrm{A}i}, 1) W_i}{\sum_i W_i} \quad \forall i \tag{1}$$

where i is the index for each household, $S_{\mathrm{A}i}$ the number of parking spaces (garage, carport, and off-street parking area spaces) available at household i, and W_i is the weighting factor for household i.

To compute how many US households have Level 1 charging for at least one vehicle, we assume in the base case that a household that can park their vehicle daily at home within 20 feet of a 120 V outlet has the opportunity to plug in their vehicle immediately without additional installation required. The portion of households with charging access, P_{HC}, is

$$P_{\mathrm{HC}} = \frac{\sum_i \min(O_{\mathrm{A}i}, S_{\mathrm{A}i}, 1) W_i}{\sum_i W_i} \quad \forall i \tag{2}$$

where $O_{\mathrm{A}i}$ is the number of external outlets available at household i and is calculated as described in the Data Preparation section.

The third quantity of interest is how many personal vehicles at US households have dedicated parking spaces. The portion of vehicles with parking, P_{VP}, is

$$P_{\mathrm{VP}} = \frac{\sum_i \min(S_{\mathrm{A}i}, V_i) W_i}{\sum_i V_i W_i} \quad \forall i \tag{3}$$

where V_i is the number of vehicles at household i (cars and light trucks).

Table 2
Results for each calculation in the base case and bounding optimistic and pessimistic cases, averaged across 10 imputations.

National, all households	Base case	Optimistic case	Pessimistic case
Households with dedicated parking	79% (0.3%)	92% (0.2%)	56% (0.3%)
Vehicles with dedicated parking	56% (0.4%)	84% (0.4%)	33% (0.5%)
Households with charging	38% (0.3%)	41% (0.2%)	14% (0.2%)
Vehicles with charging	22% (0.2%)	30% (0.4%)	8% (0.2%)

Note: Standard deviation shown in parentheses.

To compute how many personal vehicles have Level 1 charging access at home, the portion of vehicles with charging, P_{VC}, is

$$P_{VC} = \frac{\sum_i \min(O_{Ai}, S_{Ai}, V_i)W_i}{\sum_i V_i W_i} \quad \forall i \tag{4}$$

3. Results

Table 2 shows results from the four calculations for the base case, the optimistic case, and the pessimistic case. The results are averaged across 10 imputations, and as indicated by the standard deviations reported in parentheses, uncertainty from missing data and from randomness in matching up the data from AHS and RECS turned out to be very small, especially compared to the range of sensitivity analysis case results. As shown, in the base case 79% of households have some dedicated parking but only 56% of vehicles have dedicated parking at home. Although 38% of households have charging, it reaches only 22% of vehicles. In the optimistic case, in which we assume that households with garages also have driveways (where charging infrastructure can be installed in both locations and vehicles can routinely be shuffled into their dedicated spaces) and that all parking is available (none is unavailable due to being used for storage), at most 92% of households and 84% of vehicles have dedicated parking. In the pessimistic case where 50% of parking may be unavailable, as few as 56% of households and 33% of vehicles may have dedicated parking.

Fig. 2 displays the same base case results and further disaggregates them for urban and rural areas and by occupancy status, with error bars indicating the optimistic and pessimistic case results. As shown, all four measures of charging opportunities are lower in urban areas and higher in rural areas than the national average. If renters are ignored (due to the increased barriers to vehicle charging infrastructure installation and logistics in that situation), the lower portions of each bar in the figure can be read to show the results including only homeowners. In this case, only 61% of households and only 47% of vehicles have dedicated parking at an owned residence. Thus, if PEV owners require home charging, increasing PEV penetration beyond 47% of the fleet will require charging infrastructure at rental units, where the split incentive creates barriers to investment. Also, when renters are excluded the differences between urban and rural areas are exacerbated. In urban areas, only 44% of vehicles have home parking at an owned residence.

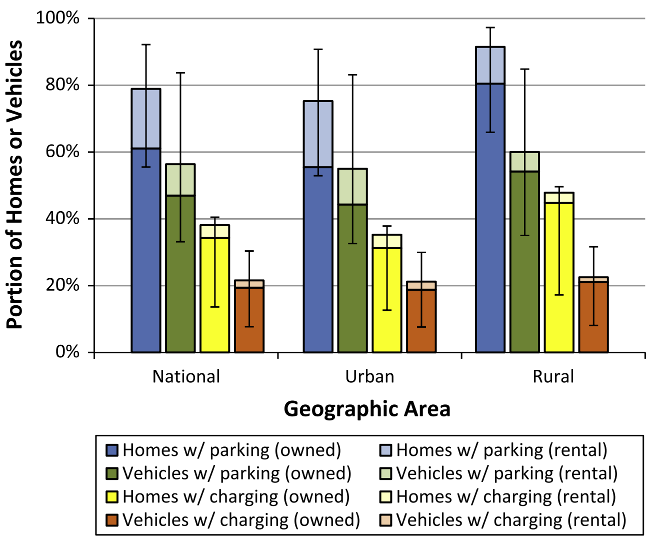

Fig. 2. Comparison of residential parking and charging availability nationally and in urban and rural areas, disaggregated by occupancy status of the home. *Note:* Error bars indicate range of estimates for optimistic and pessimistic scenarios.

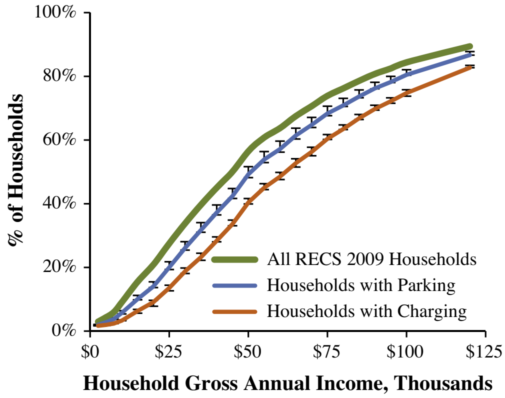

Fig. 3. Cumulative distributions of households gross annual income for all RECS 2009 households, households with parking, and households with charging. *Note:* Error bars indicate the range of income in the optimistic and pessimistic cases.

The percentage of parking spaces assumed unavailable contributes substantially to variation observed in the optimistic and pessimistic cases. Relative to the base case, if all spaces are assumed available, the portion of vehicles with dedicated home parking rises to 61%, and if 50% of spaces are assumed unavailable, the portion of vehicles with dedicated home parking drops to 34%.

The income distribution of households with parking, households with charging, and all RECS 2009 households are shown for comparison in Fig. 3. Households with parking have a higher income profile than the sample in general, and households with charging have higher incomes still. The median income of all households is about $42,500, of households with parking is about $50,000, and of households with charging is about $60,000.

Few data points exist for comparison to our results, and all of them quantify residential charging opportunities for households, not per vehicle. A study by the Electrification Coalition (2009) estimates availability of residential charging based on the AHS data for how many US households have a garage, finding that the portion of US households with a garage is 54% in central cities, 69% in suburbs, and 60% in rural areas. A US Energy Information Administration study, based on RECS 2009 data, estimates that 49% of households that own a vehicle can park within 20 feet of an outlet and that access is higher in rural areas and lower in urban areas (US Energy Information Administration, 2012). Since RECS does not contain vehicle ownership information and since about 7–21% of US households do not own a vehicle (based on AHS 2009 data and including

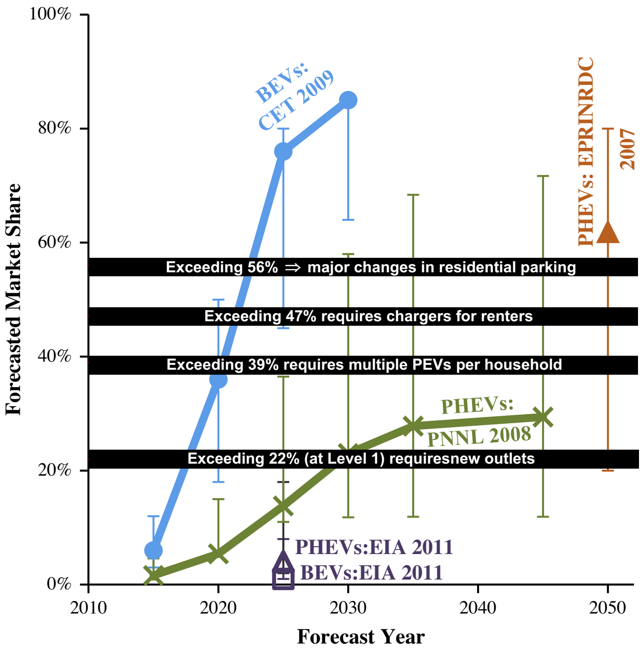

Fig. 4. US PEV sales forecasts with barriers to fleet penetration from limited residential charging infrastructure. *Source:* adapted from Heckmann et al. (2013).

uncertainty due to non-responses), the EIA estimates are reasonably consistent with our results that 38% of households, including those without vehicles, have parking within 20 feet of an outlet, although the EIA estimates are in the optimistic end of the uncertainty range. A survey by Axsen and Kurani (2012) indicated that 36% of US households have a Level 1 outlet within 10 feet of parking, 52% within 25 feet, and 61% within 50 feet. This is comparable to RECS, which reports that 44% of households have an outlet within 20 feet of parking. When accounting for our base case, where 10% of parking spaces are unavailable for vehicle parking, we estimate only 38% of households have an outlet within 20 feet of an available parking space. Also, the Axsen and Kurani data include not only households with dedicated off-street parking but also a few households with street parking, so it is not clear whether the presence of an outlet indicates that the outlet (or the parking) would be consistently available for a PEV belonging to that household.

4. Conclusions

Our results suggest that the potential for future residential charging infrastructure is limited by the availability of dedicated parking locations where chargers could be installed, suggesting significant barriers to mainstream EV penetration. Several recent PEV adoption forecasts suggest adoption rates that would require these parking limitations to be resolved. For example, the Pacific Northwest National Laboratory estimates that PHEVs could achieve as high as 70% market share by 2045 (Balducci, 2008), the Electric Power Research Institute (EPRI) suggests that PHEVs could achieve a market share as high as 80% by 2050 (Duvall and Knipping, 2007), and the Center for Entrepreneurship & Technology (CET) forecasts BEV market share of 80% by 2030 (Becker et al., 2009). These and other PEV penetration forecasts are summarized in Fig. 4 (Heckmann et al., 2013; US Energy Information Administration, 2011b). Our estimates suggest that fleet penetration of PEVs beyond 22% will require residential infrastructure investment to increase access to outlets near home parking, and fleet penetration beyond 39% may require significant residential infrastructure investment because many households will need to upgrade their electrical infrastructure to charge multiple vehicles. Fleet penetration beyond 47% will require residential charging to be available for renters, and fleet penetration beyond 56% may require not only new chargers but also additional residential parking, with associated logistics, space implications, and environmental impacts (Chester et al., 2010). All of these challenges to PEV penetration will be more severe in urban areas, where there are fewer charging and parking opportunities. Shared street parking and charging may be an option for PHEVs in residential areas, since it is not necessary to charge every night, but dedicated parking with guaranteed access to charging is necessary for BEVs and likely expected by customers who purchase PHEVs. Public charging infrastructure for street parking is likely only realistic for dense urban areas, although competing parking needs and charging needs will create logistical challenges. There are significant economic, logistical, and consumer convenience barriers to market penetration beyond households capable of charging at home.

The bounding sensitivity case results show that the uncertainty from assumptions could be significant. For example, the portion of vehicles with parking is 56% in our base case but could range from 33% to 84% under pessimistic and optimistic assumptions, respectively. The parameter with the greatest influence on the optimistic case is the prevalence of driveways at households that also have garages. If many households have driveway space that could be used for dedicated charging without blocking garage access, the potential for residential charging may be higher than our base case estimate. The parameter with the greatest influence on the pessimistic case is the portion of parking spaces that are unavailable for parking vehicles. Unavailability may be substantial in some regions, although some of this parking could potentially be reclaimed, and in some cases these unavailable parking spaces, especially in garages, may be offset by other available parking spaces, such as a driveway space in front of the unavailable garage space.

We recommend that PEV penetration forecasts and other studies that pose PEV penetration scenarios consider the effect of limited residential parking availability on the potential for PEV market penetration.

Acknowledgements

We would like to thank Grace Heckmann for her help in compiling PEV market share forecasts and Costa Samaras for feedback on an early version of this work. This research was supported in part by grants from the National Science Foundation (CAREER Grant 0747911, GRF Grant 0750271, and CBET Grant 1032722), by the General Motors Foundation Fellowship, by the Steinbrenner Graduate Fellowship, and by grants from Ford Motor Company and Toyota Motor Corporation. The views expressed are those of the authors and not necessarily those of the sponsors.

References

Arnold, J.E., Lang, U.A., 2006. Changing American home life: trends in domestic leisure and storage among middle-class families. Journal of Family and Economic Issues 28, 23–48.

Axsen, J., Kurani, K.S., 2012. Who can recharge a plug-in electric vehicle at home? Transportation Research Part D: Transport and Environment 17, 349–353.

Balducci, P.J., 2008. Plug-in Hybrid Electric Vehicle Market Penetration Scenarios (No. PNNL-17441). US Department of Energy Pacific Northwest National Laboratory, Richland, Washington.

Becker, T.A., Sidhu, I., Tenderich, B., 2009. Electric Vehicles in the United States: A New Model with Forecasts to 2030 (Technical Brief No. 2009.1.v.2.0). Center for Entrepreneurship & Technology, University of California, Berkeley, Berkeley, California.

Chester, M., Horvath, A., Madanat, S., 2010. Parking infrastructure: energy, emissions, and automobile life-cycle environmental accounting. Environmental Research Letters 5, 034001.

Chevrolet, 2010. Have Questions about Volt? Get Plugged into the Facts Here [WWW Document]. Chevrolet. <http://www.chevrolet.com/tools/volt-faq/volt-faq.html> (accessed 04.12.12).

Duvall, M., Knipping, E., 2007. Environmental Assessment of Plug-in Hybrid Electric Vehicles. Volume 1: Nationwide Greenhouse Gas Emissions (No. 1015325). Electric Power Research Institute, Palo Alto, CA.

Electric Drive Transportation Association, 2012. Electric Drive Vehicle Sales Figures (US Market) [WWW Document]. Electric Drive Transportation Association. <http://electricdrive.org/index.php?ht=d/sp/i/20952/pid/20952> (accessed 11.15.12).

Electrification Coalition, 2009. Electrification Roadmap: Revolutionizing Transportation and Achieving Energy Security. Electrification Coalition, Washington, DC.

Heckmann, C.G., Michalek, J.J., Morrow, W.R., Liu, Y., 2013. Sensitivity of vehicle market share predictions to alternative utility form specifications in multinomial logit demand models. In: Submitted to Proceedings of the ASME 2013 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2013, Portland.

HybridCars.com, 2012. Hybrid Cars Hybrid Market Dashboard [WWW Document]. Hybrid Cars. <http://www.hybridcars.com/market-dashboard.html> (accessed 11.15.12).

Little, R.J.A., Rubin, D.B., 2008. Statistical Analysis with Missing Data. Wiley, Hoboken, NJ.

National Petroleum Council, 2012. NPC Future Transportation Fuels Study: Advancing Technology for America's Transportation Future. NPC, Washington, DC.

Nissan, 2013. Nissan LEAF® Electric Car Charging [WWW Document]. Nissan USA. <http://www.nissanusa.com/electric-cars/leaf/charging-range/charging> (accessed 07.25.13).

Society of Automotive Engineers, 2010. J1772: SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler (Surface Vehicle Recommended Practice No. SAE J1772 JAN2010). Society of Automotive Engineers.

US Census Bureau, 2009. The 2009 American Housing Survey (AHS). US Census Bureau, Washington, DC.

US Energy Information Administration, 2011a. Residential Energy Consumption Survey (RECS). US EIA, Washington, DC.

US Energy Information Administration, 2011b. Annual Energy Outlook 2011 (No. DOE/EIA-0383(2011)). US EIA, Washington, DC.

US Energy Information Administration, 2012. Significant Potential for Plug-in Vehicles exists in US Housing Stock [WWW Document]. Today in Energy, US EIA. <http://www.eia.gov/todayinenergy/detail.cfm?id=6810> (accessed 07.09.12).