




Transportation Electrification Load Development for a Renewable Future Analysis

Preprint

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Presented at the 25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition
Shenzhen, China
November 5 – 9, 2010

Conference Paper
NREL/CP-5400-49181
December 2010

Contract No. DE-AC36-08GO28308

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Transportation Electrification Load Development For a Renewable Future Analysis

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Abstract—Electrification of the transportation sector, which accounts for 70% of U.S. petroleum consumption, offers the opportunity to significantly reduce petroleum consumption. The transition to electricity as a transportation fuel will create a new load for electricity generation. In support of a recent U.S. Department of Energy-funded activity that analyzed a future generation scenario with high renewable energy technology contributions, a set of regional hourly load profiles for electrified vehicles was developed for the 2010 to 2050 timeframe. These load profiles with their underlying assumptions will be presented in this paper. The transportation electrical energy was determined using regional population forecast data, historical vehicle per capita data, and market penetration growth functions to determine the number of plug-in electric vehicles (PEVs) in each analysis region. Market saturation scenarios of 30% of sales and 50% of sales of PEVs consuming on average ~6 kWh per day were considered. Results were generated for 3109 counties and were consolidated to 134 Power Control Areas (PCA) for use in the National Renewable Energy Laboratory's (NREL's) electric generation and transmission capacity expansion model, ReEDS. PEV aggregate load profiles from previous work were combined with vehicle population data to generate hourly loads on a regional basis. A transition from consumer-controlled charging toward utility-controlled charging was assumed such that by 2050 approximately 45% of the transportation energy demands could be delivered across four daily time slices under optimal control from the utility's perspective. No other literature has addressed the potential flexibility in energy delivery to electric vehicles in connection with a regional power generation study. This electrified transportation analysis resulted in an estimate for both the flexible load and fixed load shapes on a regional basis that may evolve under two PEV market penetration scenarios.

Keywords—Electric vehicle, EV, PEV, plug-in hybrid, PHEV, load profile, electric power

1. INTRODUCTION

Plug-in electric vehicles (PEVs), including both plug-in hybrid (PHEVs) and battery-only electric vehicles (EVs), offer the opportunity for the transportation sector to significantly reduce petroleum consumption through electrification. PEVs may have a moderately sized energy storage system and a combustion engine to ensure most miles are electrified while retaining the range capability of today's vehicles. Other PEVs may be entirely battery dependent and provide complete petroleum displacement for certain vehicle sectors. As of 2010, the timeline for vehicle introduction will start in 2011 with several manufacturers adding to the options over a 2–3 year period toward market creation. Based on past technology markets, maturity would likely occur within 25–30 years from introduction.

Charging infrastructure for delivering electricity to these vehicles is also under development. For short-range vehicles, common 120V service outlets would generally suffice, while owners of vehicles with longer range will likely prefer moderate charge rates from 240V service. From a utility's perspective, 120V or Level I (typically 1.4 kW) charging has limited impact on infrastructure but has less value as a flexible load whereas vehicles and infrastructure delivering 240V or Level II charging (typically 6–7 kW) offers more opportunity for load shaping and management as individual vehicle needs can be delivered and scheduled optimally to match generation opportunities.

Many analyses have been conducted and papers published that include PEV market projections. Electric Power Research Institute and Natural Resources Defense Council collaborated on a foundational study highlighting the nationwide greenhouse gas and pollutant emissions impacts of plug-in hybrid electric vehicles on the US electricity grid on a regional basis [1]. The fleet makeup assumed ~40% PEVs by 2030 and 60% by 2050. An aggregate hourly load profile was assumed in which 74% of the energy was delivered during the off-peak period and 26% during daytime. Both Kintner-Meyer et al. of Pacific Northwest National Laboratory (PNNL) and Hadley et al. of Oak Ridge National Laboratory (ORNL) have assessed regional plug-in vehicle penetrations and future load characteristics. The PNNL study considers the situation in which all PEV loads could be managed and fit into the low points of the daily utility load curve [2]. The ORNL study considered a variety of charge levels and loading scenarios to understand the regional capacity and emissions impacts of the various scenarios [3].

This work expands upon past activities to uniquely define both a transitioning fixed load for the transportation sector and a load portion that can be dynamically managed by utilities for integration with high renewable energy integration analyses.

2. APPROACH

In 2009, the U.S. Department of Energy funded a multi-laboratory analysis referred to as Renewable Electricity Futures study to explore the electric generation mix over the next 40 years under a very high renewable portfolio constraint. As input to the Renewable Electricity Futures study [4], an hourly PEV load profile and the energy demand for the fleet of PEVs by region over time (2010 through 2050) were developed. The approach was as follows:

1. Use population growth forecasts and historical vehicle ownership trends to estimate vehicle population by region.
2. Use a market penetration model to estimate the fraction of vehicles that will be PEVs throughout the study period.
3. Develop the vehicle fleet electrical energy demand profile varying over time as the fleet transitions its charging strategy from a fully customer-controlled to a partially price-based or utility-controlled charging scheme.

The customer-controlled charging profiles were based on past fleet studies. The price-based or utility-controlled profiles were based on optimal electric generation dispatch decision by the utility or grid operator. In developing the electrified transportation loads and energy requirements, the following simplifying assumptions were made:

1. There will be no significant change in transportation mode selection and miles driven. Personal vehicles will continue to be the mode of choice. As a result, loads due to mass transit are neglected.
2. Transportation electrical energy demands will not vary significantly in amount or timing between seasons of the year.
3. PHEVs are expected to make up the majority of the stock, meaning that electrical energy is likely to provide the majority, but not all, of the energy needed. The hybrid combustion engine would likely make up any limitations of the electric drive system and thus take up any variability.
4. The PHEV fleet load shapes are based on historical consumer travel survey data and assume 120V, 1.4kW charge rates from widespread infrastructure. Level II, 240V charging was only considered if the charging was under utility control. The following three charging profiles were considered:
   a. No-control charging (Level I): primarily home charging
   b. Opportunity charging (Level I): assuming ubiquitous charging stations and charging whenever vehicle is parked
   c. Utility-controlled charging (Level II): based on optimal dispatch generation/load dispatch by the grid operator.
5. PEV load curves are based on PHEVs with 20 mi. of electric range (PHEV20) and urban power capability. On average, this results in ~6 kWh of energy per PEV per day. Some vehicle designs and some vehicle usage profiles may use more or less energy.
6. No differentiation between car and truck vehicle energy needs was included.
7. It has been assumed that there are no differences in regional penetration rates.
8. There is no differentiation in the growth rate among counties in the same state.
9. No vehicle-to-grid or grid service functions are considered.
10. The utility-controlled charging strategy was defined by NREL's ReEDS (Regional Energy Deployment Systems) model. The model dispatches loads and generators in certain time slices (blocks of time) to minimize the cost. Based on the ReEDS time slice definition, charging would be selected at a constant rate during a time slices. It should be noted that utility-controlled charging would be very similar if not identical with price-based charging where the customer would charge his/her vehicle based on time-varying electricity prices to minimize cost.

3. RESULTS ANALYSIS

Data on population growth projections to 2030 by state available from the U.S. Census Bureau provides the starting point for projecting the energy demands of electrified vehicles. Figure 1 shows the consolidated growth rates for the nine census regions [5]. The projections for each state were fit with either a linear or quadratic function, whichever provided the best fit, and extended to 2050. Table 1 highlights the states with the least and greatest calculated rates of change in population growth between 2010 and 2050.

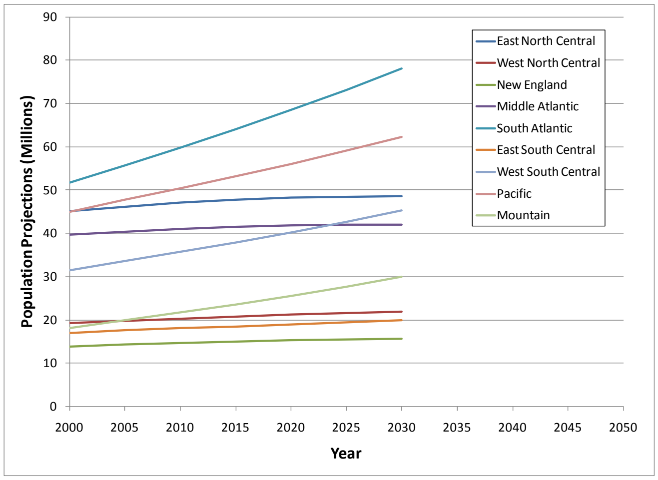

Figure 1: U.S. Census regional population projections to 2030

Table 1: Ten States with Least and Greatest Percent Change in Population between 2010 and 2050

State Name	Population Percent Change 2050 Relative to 2010
District of Columbia	65
West Virginia	77
Iowa	87
Wyoming	88
North Dakota	94
Ohio	94
New York	95
Pennsylvania	105
South Dakota	108
Nebraska	108

State Name	Population Percent Change 2050 Relative to 2010
Nevada	211
Arizona	209
Florida	185
Texas	166
Utah	163
Idaho	159
North Carolina	159
Washington	154
Georgia	153
Oregon	149

Using data from an RL Polk database query, 2005 county population measurements were extended to estimate county population between 2010 and 2050 using the state-level population growth trends [6]. It was assumed that all counties within a state grow at the state rate.

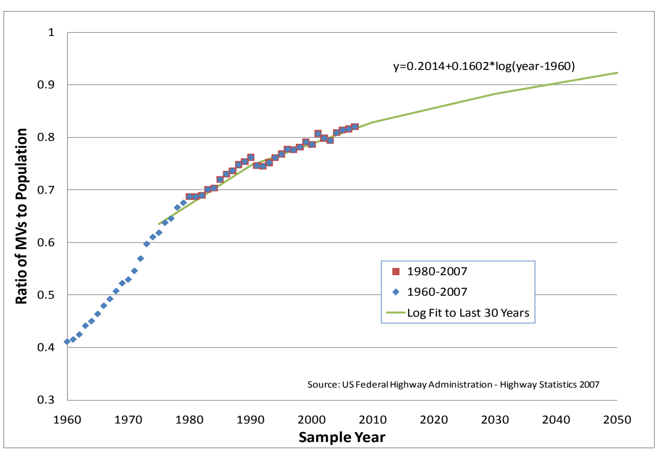

Figure 2: Historical and projected motor vehicles per capita

The population estimates on a county basis were then scaled to estimate the number of motor vehicles on a county basis. Historical data from the Federal Highway Administration presents the number of motor vehicles per capita between 1960 and 2007 [7]. The last 20–30 years of data fit well to a logarithmic function. This trend suggests that between 2010 and 2050 the number of motor vehicles per capita is likely to grow from just over .8 to a little over .9 motor vehicles per person. These analyses are summarized in Figure 2.

PEV market penetration model based on a logit function was used with the motor vehicle estimates to determine the number of PEVs likely to be in use on a county level over the time period of the study [8]. The penetration model represents a slow ramp toward consistent market growth and a final tapering of growth to saturation. The model used is represented by Equation 1.

$$N(t) = \frac{\kappa}{1 + \exp(-\frac{\ln(81)}{\Delta t}(t - t_m))} \quad (1)$$

Where,

κ = the maximum market share potential

Δt = the time to grow from 10% to 90% of potential (years)

t_m = the year in which 50% of potential is reached

Two scenarios, default and aggressive, were defined. In the default scenario, the sales of PEVs saturate at a level of 30% penetration over a ~35 year period. In the aggressive scenario, sales saturate at 50% market share after ~50 years. The parameter values for each scenario are shown in Table 3. A comparison of the sales rates, vehicle stock, and historical HEV sales shifted by introduction year are shown in Figure 3. The rates in the aggressive scenario are consistent with results recently developed by Greene and Lin in 2010 [9].

Table 2: PEV Market Penetration Model Parameter Values

Parameter	Value–Default	Value–Aggressive
κ	30%	50%
Δt	20	30
t_m	17	25

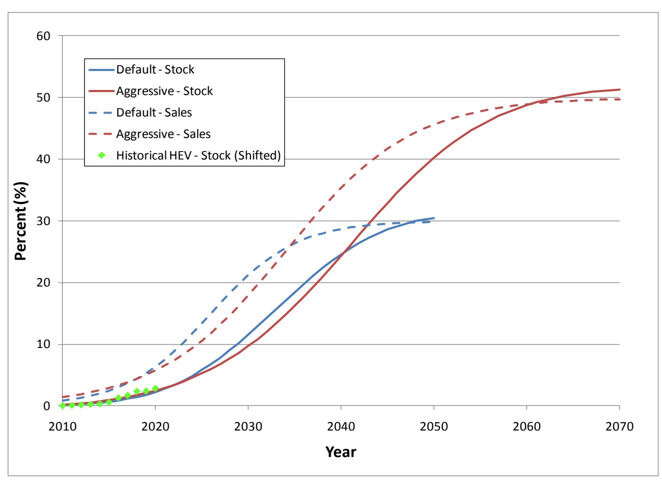

Figure 3: PEV market penetration model comparison showing both annual sales and vehicle stock data.

Using the PEV market models, the number of vehicles per capita, and county population estimates, it is possible to calculate the number of PEVs on a county and state basis. Table 3 summarizes the PEV population estimates for the largest growing vehicle sales markets in the United States. The vehicles in these 14 states highlighted compose nearly 70% of the total U.S. PEV population. The PEV population growth trend for these 14 states is shown in Figure 4. The resulting shape is a function of both population growth and PEV market growth and saturation.

Table 3: PEV Stock Distribution by State – Top 14 (millions)

	2010	2030	2050	2050 Percent of U.S.	2050 Cumulative Percent
United States	0.283	31.07	154.43	100	
California	0.035	4.01	20.58	13.32	13.32
Texas	0.023	2.85	15.49	10.03	23.36
Florida	0.018	2.45	13.83	8.96	32.32
New York	0.018	1.67	6.88	4.45	36.77
North Carolina	0.009	1.04	5.55	3.59	40.36
Georgia	0.009	1.05	5.55	3.59	43.95
Illinois	0.012	1.17	5.33	3.45	47.41
Arizona	0.006	0.89	5.26	3.41	50.81
Pennsylvania	0.011	1.10	4.93	3.19	54.01
Virginia	0.007	0.85	4.36	2.83	56.83
Michigan	0.010	0.93	4.26	2.76	59.59
Ohio	0.011	0.99	4.08	2.64	62.23
New Jersey	0.008	0.84	4.01	2.60	64.83
Washington	0.006	0.73	3.87	2.51	67.33

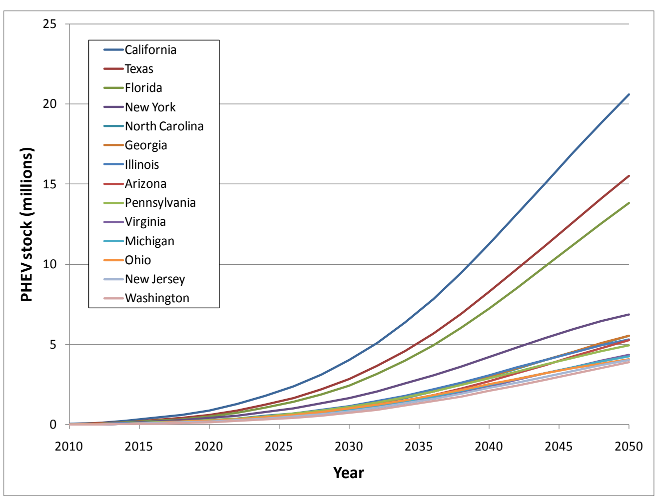

Figure 4: Growth Trends of PEV Stock for the States with the Greatest 2050 PEV Population

Hourly load shapes for PEVs have been presented in several locations [1, 2, 3]. For this study, three profiles from previous work based on detailed vehicle system simulations using second-by-second vehicle speed and trip profile characteristics collected using GPS units on-board a vehicle were used. This data was collected under a periodic household travel survey from the St. Louis metropolitan area and is based on 227 24-hr driving profiles for unique vehicles. Three scenarios defined in previous work [10, 11] were used in this study and are shown in Figure 5.

In the first case, the consumer is allowed to plug in and charge as soon as the vehicle ends the last trip for the day. This case is called "No Utility Control" because the vehicle load occurs on consumer demand and charges until complete or the consumer starts another trip. A second scenario is labeled "Opportunity": under this case, it is assumed that charging infrastructure is ubiquitous and the consumer will choose to plug-in any time the vehicle is parked regardless of stop duration. This scenario leads to significantly more fuel savings but also increases the daytime electric vehicle loads, total energy demands, and potential battery wear. The total electric energy consumed is limited by the size of the battery and travel behavior. "Opportunity" charging demands more electric energy (kWh) indicating that PEVs typically exceeded the range of the moderate battery assumed and gained value from ubiquitous infrastructure. Finally, a "Valley Fill/Managed" scenario is used. Although this scenario is shown in Figure 5 to optimally fill the lowest load point of a traditional hourly utility load curve, in this study, with high penetration of renewables the optimal dispatch time for this total energy is allowed to shift between several defined daily time periods as needed to support the renewables integration. Both the "No Utility Control" and "Opportunity" scenarios assume 120V 1.4kW charge rates (Level I) while the "Valley Fill/Managed" curve allowed 3kW (Level II) charging to best match the energy demands with the utility valley shape.

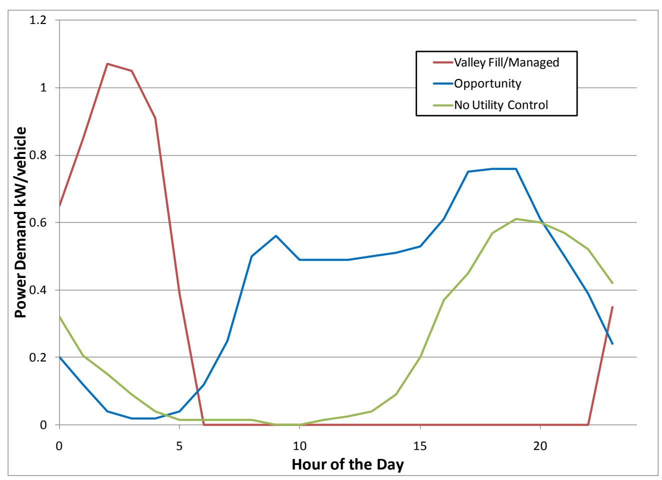

Figure 5: Three PEV fleet charging profiles based on 227 driving profile vehicle simulation results

It was assumed that initially, all consumers would charge at home without utility controls and as public charging infrastructure is created and consumers learn to optimize value of their investment in vehicle technology, the growth of opportunity charging would occur. Furthermore, we assumed that over the duration of this study, PEV owners would migrate toward the price-based or utility-controlled charging strategies primarily induced by lower electricity cost and technology advancements that support seamless communications to the vehicles and automating the load management and advanced charging strategies. The rate at which opportunity charging and price-based/utility-controlled charging would displace home charging was based on our judgment. The transition between the three scenarios over time is summarized in Figure 6.

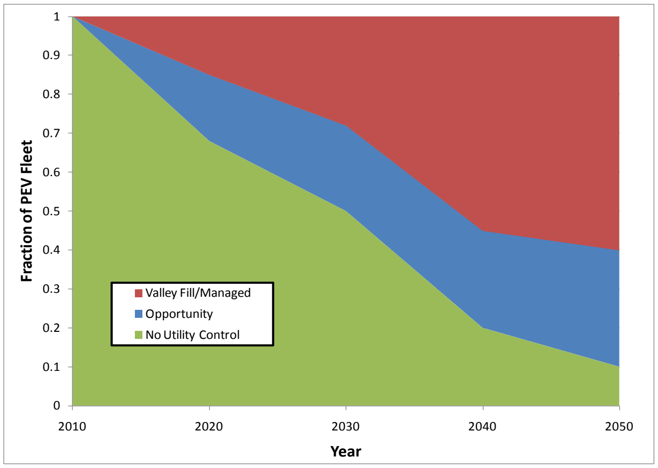

Figure 6: Transition assumptions from no utility control to opportunity and managed scenarios

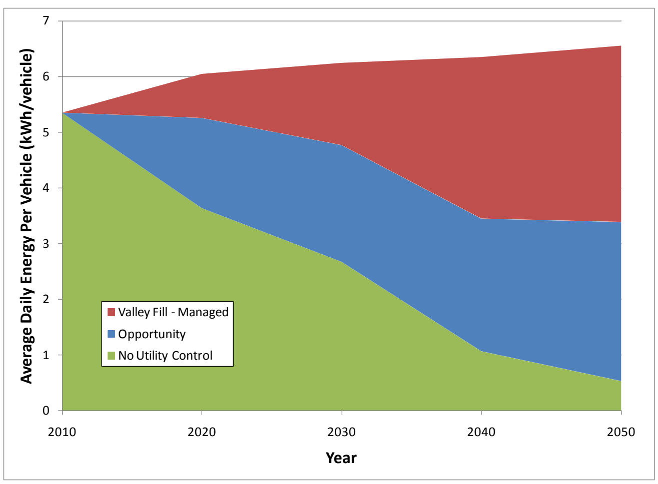

Figure 7: Average daily per-vehicle energy demands by charging scenario

Figure 7 shows how the average per-vehicle energy demand grows slightly over time due to the increasing portion of the vehicles that are being opportunity charged. It also shows that the "Valley Fill/Managed" portion of the total vehicle energy demands grows to ~45% of the total PEV energy demands by 2050.

The ReEDS model assesses energy delivery by 134 PCAs. Load profiles were generated on a county basis. A total of 3,109 counties in the contiguous United States were consolidated into 134 PCAs.

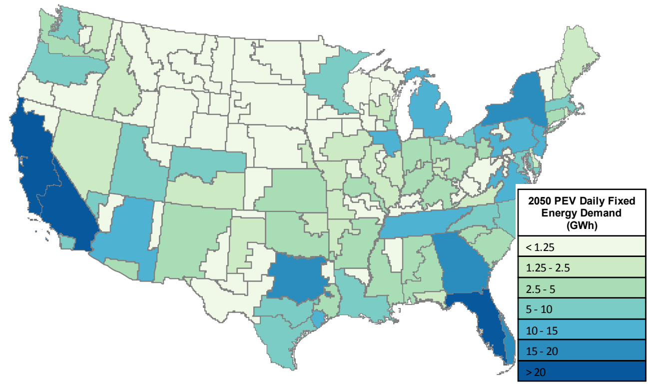

Figure 8: 2050 PEV daily fixed energy demand by PCA region

Figure 8 shows a map of the regional distribution of the fixed portion of the daily energy demands for PEVs (no utility control and opportunity charging) by PCA region in 2050. The energy shown is ~55% of the total PEV load in 2050. PEV population growth follows general population growth in this analysis; therefore, highly populated areas are highlighted as PEV load centers.

By combining the hourly load profile results from previous work and the transition assumptions over the period from 2010 to 2050, an aggregate per vehicle load profile that changes shape over time was generated (Figure 9). Figure 9 only shows the fixed portion that is not under the control of the utility. This includes the "No Utility Control" profile and the "Opportunity" profile. The transition from a large fraction of the vehicles in the "No Utility Control" scheme in 2010 to more in the "Opportunity" scheme by 2050 is observed in Figure 9 by comparing the shape of the 2010 and 2050 curves to those in Figure 5. Figure 9 only shows the fixed hourly load as the flexible portion is allowed to be different for each of the 134 PCAs.

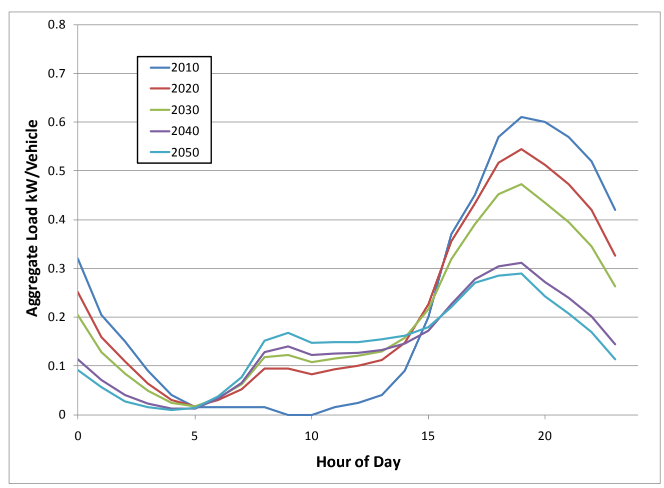

Figure 9: Shape and transition of the fixed hourly aggregate load profile for PEVs

The aggregate load shape in Figure 9 only represents the fixed load profile. From Figure 7, the dynamic portion under utility control (Valley Fill/Managed) grows from 0% of the load in 2010 to ~45% of the total load in 2050.

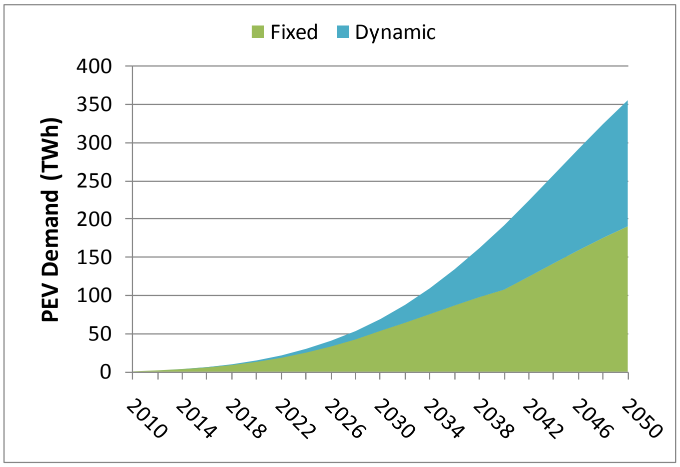

Figure 10: Projected PEV fixed and dynamic annual electricity consumption for aggressive scenario

In Figure 10, the total annual energy demand for PEVs is shown. Both the fixed and dynamic portions are highlighted. In 2030, the fixed demand is ~50 TWh, accounting for ~80% of the total load. By 2050, the total load grows to 350 TWh, and the fixed portion is ~180 TWh, or 55% of the total load. Greene and Lin predict the total annual PEV energy demand as ~100 TWh in 2050 in a PEV Success scenario.[9] Several assumptions contribute to these differences.

- Greene and Lin assumed mostly PHEV10 with a few PHEV40 vehicles while this study bases the energy demands and load curves on a PHEV20 design.
- Greene and Lin assumed a single daily charge per day while this study includes opportunity charging, which increases daily electrical energy consumption per vehicle.

As a result, the total annual energy for PEVs is about 3 times greater than suggested by Greene and Lin's work. However, the estimated annual electric energy demand for PEVs in 2050 is only about 9% of the total electricity consumption in the base case of the Renewable Electricity Futures study scenario.

4. CONCLUSION

The introduction of PEVs creates opportunities for the reduction of petroleum and the creation of new flexible load that can be integrated in utility operations with a high penetration of renewables to achieve a long-term strategy of creating a more sustainable transportation system. This work developed energy system load characteristic forecasts on a regional basis from 2010 to 2050 for two PEV market penetration scenarios to be used in a Renewable Electricity Futures study. The work builds upon past travel survey data analysis, regional population forecasts, and assumptions regarding incentives of charge management scenarios. An aggressive market scenario achieving a vehicle stock of ~40% PEVs by 2050 (or 50% in 2060) and a default scenario achieving ~30% PEVs in the fleet by 2050 were used. Both trends mirror historical HEV market stock thus far.

Three PEV charge scenarios were considered, including "No Utility Control," "Opportunity," and "Valley Fill/Managed." The energy needed in the "Valley Fill/Managed" scenario was assumed to be flexible in terms of when it needed to be delivered throughout the day and thus provides the utility with an interesting flexible load that can be managed to improve renewable generation asset utilization. By 2050, 45% of the total vehicle energy demand of 350 TWh was under managed control while the remaining 55% was a fixed load to be planned for and met by utility assets. The hourly load profile of the fixed transportation energy demand also shifted over the time period from mainly "No Utility Control" towards "Opportunity" charging. This is the first study to assume that a variety of vehicle load shapes will exist and may transition overtime resulting in a unique fixed load and flexible load for integration into utility operational planning tools.

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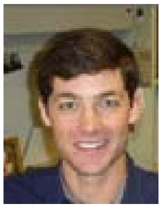

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December 2010	Conference Paper	

4. TITLE AND SUBTITLE
Transportation Electrification Load Development For a Renewable Future Analysis: Preprint

5a. CONTRACT NUMBER
DE-AC36-08GO28308

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
T. Markel, T. Mai, and M. Kintner-Meyer

5d. PROJECT NUMBER
NREL/CP-5400-49181

5e. TASK NUMBER
FC10.2400

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-5400-49181

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
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13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
The transition to electricity as a transportation fuel will create a new load for electricity generation. A set of regional hourly load profiles for electrified vehicles was developed for the 2010 to 2050 timeframe. The transportation electrical energy was determined using regional population forecast data, historical vehicle per capita data, and market penetration growth functions to determine the number of plug-in electric vehicles (PEVs) in each analysis region. Market saturation scenarios of 30% and 50% of sales of PEVs consuming on average ~6 kWh per day were considered. PEV aggregate load profiles from previous work were combined with vehicle population data to generate hourly loads on a regional basis. A transition from consumer-controlled charging toward utility-controlled charging was assumed such that by 2050 approximately 45% of the transportation energy demands could be delivered across four daily time slices under optimal control from the utility's perspective. This electrified transportation analysis resulted in an estimate for both the flexible load and fixed load shapes on a regional basis that may evolve under two PEV market penetration scenarios.

15. SUBJECT TERMS
Electric vehicle; EV; PEV; plug-in hybrid; PHEV; load profile; electric power

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			
Unclassified	Unclassified	Unclassified	UL		**19b. TELEPHONE NUMBER** *(Include area code)*

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

F1147-E(10/2008)