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The Effects of Electricity Pricing on PHEV Competitiveness

By:

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Abstract

Plug-in Hybrid Electric Vehicles (PHEVs) will soon start to be introduced into the transportation sector, thereby raising a host of issues related to their use, adoption and effects on the electricity sector. Their introduction has the potential to significantly reduce carbon emissions from the transportation sector, which has led to government policies aimed at easing their introduction. If their wide-spread adoption is set as a target it is imperative to consider the effects of existing policies that may increase or decrease their adoption rate. In this study, we present a micro level electricity demand model that can gauge the effects of PHEVs on household electricity consumption and the subsequent economic attractiveness of the vehicles. We show that the electricity pricing policy available to the consumer is a very significant factor in the economic competitiveness of PHEVs. Further analysis shows that the increasing tier electricity pricing system used in California will substantially blunt adoption of PHEVs in the state; and time of use electricity pricing will render PHEVs more economically attractive in any state.

Keywords: PHEVs, Electricity Pricing, Electricity Demand Modeling

Introduction

The transportation sector is a major part of the United States economy which predominately operates using liquid fossil fuels and, as such, has a massive demand for those fuels. About 70% of oil consumed in the U.S. is used in the transportation sector (EIA, 2009b). Recent concerns about high oil prices, oil dependency, energy supply security, and climate change have led public and private entities to seek alternative fuels for this sector. Electricity is one promising alternative. In recent years, automotive companies have developed and refined technologies to produce more advanced vehicles that use electricity instead of gasoline as their main energy source. If these vehicles become commercially viable, they have the potential to significantly reduce oil consumption and provide enormous environment benefits. Several papers have evaluated economic and environmental impacts of using PHEVs (EIA, 2010; EPRI, 2007; Kintner-Meyer et al., 2007; Shiau et al., 2009; Smith, 2010; Vyas et al., 2007). However, they have not used a coherent modeling and simulation approach to evaluate impacts of adopting these vehicles on the household electricity usage at a micro level.

We argue that policy implications on the micro level will impact the economic competitiveness of PHEVs. Although California currently has electricity rates which cater to EVs and potentially PHEVs, we show that the current increasing tier electricity pricing system of the state of California, here represented by PG&E's plan, (Pacific Gas and Electric Company, 2009) which was designed to reduce electricity consumption, could harm the economic competitiveness of the PHEVs when compared with hybrid and standard vehicles. We examine the relative economic competitiveness of a plug-in electric hybrid vehicle (PHEV), a hybrid vehicle, and a standard gasoline vehicle. The state of California and its electricity pricing structure is used as the base case. California has among the highest electricity prices in the country with residential rates averaging 14.42 cents per kWh in 2007, 35% higher than the national average (EIA, 2009c), with an increasing tier pricing scheme put in place presumably to discourage higher electricity consumption and the environmental externalities associated with electricity production (Danner, 2010), mainly air pollution and greenhouse gas emissions.

The motivation for this research was to determine what impact this electricity pricing regime might have on the economics of PHEVs compared with other options. Many other states have flat rate electricity pricing or even declining rate systems. To conduct the comparison for this analysis, we compared the existing California system with an alternative flat rate system with the same average cost (and equivalent revenue to the utility) assuming no change in the quantity demanded for electricity, compared to the base California case. The equal demand assumption was used to enable direct comparison of the two rate structures with the addition of the PHEV to the household demand.

The consideration of California as an example is important for a number of reasons. The state is the most populous in the United States, with roughly 36 million residents and an estimated 20 million light-duty vehicles (BTS, 2008). California is a fairly large market by itself. California has also traditionally been an early adopter of environmental technologies. Additionally, the adoption rate of hybrid vehicles in California has typically been higher than the national average (HybridCars.com in partnership with Polk, 2009), meaning that a failure in this critical market could be a serious one for the technology.

Electricity Pricing

California has an increasing tiered pricing scheme for which the base level has the lowest price, and the price for a household increases in three additional tiers as household consumption increases. These higher tiers are activated at 130%, 200%, and 300% of the base level electricity usage. Additionally, the base level varies by region of the state and season of the year. California also has a time of use (TOU) pricing option under which the cost of electricity changes over the course of the day. For that option there are three price periods each day in summer and two in winter. The increasing tier pricing also applies to the TOU pricing regimes. Consumers can choose to opt in to TOU pricing or not, but either way, consumers face the increasing tier pricing system.

As a consequence of the push for electric vehicles in the 1990s, California also has electric pricing schedules available for consumers. PG&E provides two options for consumers, both found in rate schedule E-9 (Pacific Gas and Electric Company, 2009); a rate that adds the electricity used for charging the vehicle onto the existing household usage and another which meters the vehicle separately. These two scenarios provide different benefits to the consumers, a subject that will be addressed later in this study. An option that is offered to customers but not discussed in this study is the ability of the utility to limit the hours that the household can use electricity for PHEV charging. This option is not discussed since this involves primarily system wide benefits, which are not the focus of the paper.

PHEVs

Two major types of vehicles are emerging, pure Electric Vehicles (EVs) and Plug-in Hybrid Electric Vehicles (PHEVs). EVs rely only on electricity for propulsion while PHEVs use electricity stored in a battery as the primary means of propulsion, but can also contain a backup power source, typically gasoline. This study focuses only on PHEVs using one commercially available vehicle as the basis for parameter choices. The technical specifications of future commercially available PHEVs have been widely debated. The battery size, charging time, maximum discharge rate, weight, life and, especially, cost are all critical parameters that will affect the market penetration and ultimately the societal benefits of PHEVs. Argonne National Laboratory (Vyas et al., 2007) has examined a number of different PHEV and traditional hybrid vehicle configurations in order to perform a cost-benefit analysis on the potential fuel savings gained for a household using a PHEV. The Argonne results show that for a PHEV with an all-electric range of approximately 40 miles, the net present value of fuel savings is about $1,380. Another study (Shiau et al., 2009) focused on battery weight and charging patterns, and their effect on the economic and environmental benefits of PHEVs. It indicates that for small battery sizes, those allowing less than 20 miles of driving in all-electric mode, PHEVs could be both economically and environmentally superior to both hybrids and conventional vehicles. Bradley and Frank reviewed the design specifications for the vehicle architecture, energy management systems, drivetrain, and energy storage systems for a number of demonstration vehicles and concluded that CO_2 reductions are projected to be between 40% and 53% for a compact PHEV, depending on the all-electric range (Bradley and Frank, 2009) . A recent study on PHEV implementation in Ireland concluded that on a per km basis, PHEVs offer potential reductions in primary energy requirements and carbon dioxide intensity (Smith, 2010). However, in the 2009 Annual Energy Outlook (EIA, 2009a) , EIA concludes unless gasoline prices reach $6.00 a gallon, PHEVs would not be attractive to consumers. A study by the NRC concluded the figure to be somewhat less at $4.00 (NRC Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies, 2010).

Several studies have been conducted to estimate the impacts of adopting PHEVs on the United States electricity grid. For example, Kintner-Meyer et al. have estimated the maximum number of PHEVs that the existing electricity capacity could accommodate without additional generating capacity (Kintner-Meyer et al., 2007). They simply assume that all electricity generating capacity during non-peak hours will be used to charge PHEVs, in a "valley-filling" technique, resulting in up to 73% of the U.S light duty vehicle fleet supported. Another similar study that assumed that the utilities could control vehicle charging was performed by the National Renewable Energy Laboratory which indicated a 50% penetration of PHEVs would increase per capita electricity demand by around 5-10% (Denholm and Short, 2006) . While these studies provide boundaries for the maximum possible benefits gained from the widespread introduction of PHEVS, their simplistic charging assumptions dictate that their results cannot be used as credible forecasts of the type needed to make policy and infrastructure decisions.

A more detailed study that takes into account more realistic charging scenarios was performed using Vermont as the study region (Letendre and Watts, 2008). Four charging scenarios are examined: uncontrolled evening charging, twice per day charging, delayed nighttime charging and optimal nighttime charging. Large increases in the state-wide peak load are predicted under the first two charging scenarios while the latter two tend to even the load over the course of the day. One notable drawback of the study is that the example PHEV used in the calculations had an all electric range of only 20 miles and was assumed to require a full charge every time that it was plugged in. This is a limitation shared by perhaps the most similar report (Lemoine et al., 2007) to the present study. The Lemoine et al. report, which examines the role of PHEVs in the California market, also makes the assumption that every trip is long enough to fully deplete the battery. This neglects the transportation aspect of the problem in which trip length and duration may play a role in the amount of electricity needed to return the battery to the fully charged state. Within the report three charging scenarios are examined: optimal charging, evening charging and twice per day charging. For each scenario a comparison of the annual fuel costs per vehicle is conducted for standard vehicles and PHEVs with varying electricity and gasoline prices. According to the report, a PHEV with an all electric range of 20 miles is expected to get about $400.00 in fuel savings per year when compared to a conventional vehicle. It is not clear, however, what assumptions the authors made about electricity pricing when calculating net present value of fuel savings. Parks et al. provides an alternative charging scenario based on a small dataset derived from GPS data in the St.Louis area (Parks et al., 2007). While suitable in the context of their study, a more representative dataset is needed for a statewide analysis as conducted in the present study.

Methodology

In this study, we used a combination of electricity load forecasting methods and economic analysis in order to determine the effect of a PHEV on a residential household. Electricity forecasting models in general can be divided into two groups: top-down and bottom-up approaches(Swan and Ugursal, 2009). The first approach forecasts future consumption of electricity based on historical data at high aggregation levels. The most common forecasting methods such as regression, time series, fuzzy logic, neural networks and expert systems fall in this category(Alfares and Nazeeruddin, 2002; Nowicka-Zagrajek and Weron, 2002; Tzafestas and Tzafestas, 2001). All of the methods described rely on huge amounts of historical data. Incremental changes in electricity consumption that occur slowly may be recognized by these top-down forecasting models, but forecasting radical changes in electricity usage patterns are confounding due to reliance of these models on past data.

The bottom-up approach forecasts consumption of electricity at the household level using engineering modules which break household electricity usage down to the appliance level (Larsen and Nesbakken, 2004; Paatero and Lund, 2006). The former model is an engineering model which forecasts electricity usage at the household level for Norway. The latter model is a more advanced bottom-up model which has been developed and applied to Finnish households. This model assigns appliances to a representative household based upon the country-level appliance saturation rates. Each appliance is assigned an hourly starting probability for both weekday and weekend use. A consumption cycle and standby load are specified for when the appliance is in or out of use. Each instance of an appliance in each instance of a household is then determined to be on or off for each hour of the day according the results of comparing a random number to the hourly starting probability. The daily household power usage can then be calculated by summing the demand of each of the individual appliances for each hour of the day based upon their usage status. In addition a seasonal load factor adjusts the results to correspond to the differences in daily demand over the course of the year. The results of a number of runs of the model can be combined in order to determine an average household use profile.

Since the bottom-up models break household electricity usage down to the appliance level, one can add PHEVs to the list of household appliances and examine impacts of adopting PHEVs on energy usage. In this paper we built and expanded a bottom-up framework based on the Paatero & Lund framework to investigate impacts of adopting PHEVs on electricity consumption at the household level. The framework for the model is built on two major components: a data set and a simulation engine. The first component includes a list of the appliances that may appear in a household, appliance saturation levels, daily frequency at which a particular appliance is used, usage profile of an individual appliance, standby power needed by a particular appliance and the consumption cycle of an appliance. The second component includes a set of stochastic simulation processes which generate temporal electricity consumption profiles for all appliances of each household separately on the hourly time scale and sums the individual appliances to generate an electricity load profile for an average household.

The present study differs from those found in the literature in a number of significant ways. First is the scope: to the best of the authors' knowledge there have not been any probabilistic engineering household electricity load models adapted to include PHEVs. Since the adoption of PHEVs at the household level will greatly change the electricity load profile of the home, it is important to consider the electricity usage patterns as a whole in order to gauge the true cost, especially when time of use electricity pricing is in effect. This bottom-up view will help to provide a more accurate picture of PHEV adoption, and hence benefits, than the macro view adopted in previous studies. Secondly the present study uses a number of assumptions that more closely reflect the anticipated future PHEV specifications and usage patterns. While the majority of previous studies have focused on PHEVs with an all-electric range of 20 miles, we have chosen to use 40 miles as the distance before charge sustaining mode is activated. This is done to reflect the anticipated range of the Chevrolet Volt PHEV (General Motors Corp.) scheduled to be commercially available in late 2010. Additionally, while previous studies have assumed that due to the short battery range every charge will be a full charge, this study allows for the possibility of the longer charge depleting mode considered, providing enough all electric range to fulfill a household's daily driving needs. Each household's daily driving distance is determined through a sampling of national daily distance driven distribution. This daily distance can then be converted to an amount of battery depletion or combination of full battery depletion and gasoline usage. The accuracy of the household load amount and timing due to PHEV use can only be improved by incorporating actual transportation usage data into the model. Lastly, the authors believe that underlying all factors, the way that electricity is priced would affect how attractive a PHEV would appear to a consumer, a point that has not been fully examined in the literature. It is through this combination of more realistic assumptions about commercial PHEV specifications and the integration of the PHEV usage patterns with a household electricity load profile model that the authors believe a more accurate picture of the costs and benefits associated with PHEV usage can be gained.

Baseline Appliances

Electricity demand for a household in the study is comprised of two portions: baseline household electricity demand and the PHEV electricity demand. Baseline electricity demand is determined from a set of common household appliances present in the household. Data on the availability of appliances in California households was gathered from the United States Energy Information Administration's Residential Energy Consumption Survey (EIA, 2008). Table A1 of Appendix A presents a full list of appliances and their corresponding saturation level are included. The presence of air conditioning as an appliance necessitates the use of summer and winter temperature distributions. For every day a maximum temperature is drawn from the distribution for the temperature, and if the temperature is above the baseline of 65^{o} F the air conditioning load is specified according to a correlation from the California Independent System Operator Corporation (CASIO) (CAISO, 2007). Additionally, for all appliances besides air conditioning, a load pre-factor distribution was created to match the CAISO historical data for both weekdays and weekends in both the summer and winter seasons using a regression tool. Household electricity usage for lighting was adopted from a survey of California households (Heschong Mahone Group, 1999). It is important to note that this data differs significantly from the Energy Information Administration (EIA) Residential Energy Consumption Survey data. The annual household energy use for lighting in the Heschong Mahone Group report is almost twice that of the EIA report. The Heschong Mahone Group data was chosen as it is California specific while the EIA data is an average for all US households. Washing machine and water heating data was adapted from a study by Lawrence Berkeley National Laboratory (Lutz et al., 1996). Standby power requirements for appliances such as televisions, DVD players, set-top boxes, computers and answering machines were taken from a study of standby power consumption in California homes (Ross and Meier, 2002). Other hourly usage probabilities for all other appliances were adapted from the Residential Energy Consumption Survey (EIA, 2008) and the 2008 Buildings Energy Data Book (D&R International, 2009). A list for the power consumption cycles for the appliances can be found in Table A2 of Appendix A, and a full list of the hourly usage probabilities used for both weekdays and weekends can be found in Tables A3 and A4 of Appendix A.

PHEVs

PHEVs are assumed to discharge linearly with respect to the distance travelled. Electricity stored within the battery would be discharged first for mobility in the first 40 miles of usage and subsequent travel assumes a charge sustaining mode where gasoline is consumed. Although the battery capacity of the PHEV is 16 kWh, the effective capacity is assumed to be 8.8 kWh. This corresponds to approximately 0.22kWh per electric mile. The PHEVs are also assumed to be charged from a conventional 110V power outlet and a full charge of 8.8 kWh would require approximately 8 hours of charging time after taking into account battery and charger inefficiencies whose values are taken to be 0.85 and 0.82 respectively (Duvall, 2002).

The PHEV in this study is compared with two comparable alternate vehicles, a regular internal combustion engine vehicle (ICE) and a conventional hybrid vehicle. The Chevrolet Cobalt represents the former while the Toyota Prius the latter. Both vehicles are viewed to be comparable in performance and size. Although the Prius also contains a battery pack that can supplement propulsion, it differs from the PHEV such that it cannot rely solely on electricity for mobility. Hence it is still highly dependent on gasoline as an energy source. The parameters used in modeling the vehicles will be presented in a later section.

Charging Scenarios

An important aspect of PHEV use is the charging pattern chosen. Two charging pattern scenarios have been examined: off-peak charging and uncontrolled charging. The charging scenarios are important because they affect the timing of the additional electricity usage due to PHEVs. This is especially important when considering electricity demand at the utility level and can also play a significant role in the operating costs of PHEVs when time of use pricing schemes are in effect.

The off-peak charging scenario is similar to many of the charging scenarios thus far reported in the literature. For this scenario it is assumed that there is some form of utility regulation, or consumer self-governance due to higher peak prices, that allows charging of a PHEV to only occur during off-peak electricity hours. Hourly starting probabilities are then assigned under the condition that the charging must be completed before the next partial-peak period begins. The hourly starting probabilities that make up the two charging scenarios can be found in Figure 1.

For the uncontrolled case charging, data on hourly vehicle usage (FHWA, 2009) has been used in order to assign hourly starting probabilities for a household PHEV. In order to obtain this data, a custom table was built from the NHTS online analysis tool with an output of annualized vehicle trips against trip start time. This data gives the time periods when the vehicle is most likely on the road away from home, the inverse being that the vehicle is not on the road and thus has a greater likelihood of being at the household residence. A vehicle determined to be at home is thus able to begin a charging cycle if selected. The uncontrolled charging scenario is seen as a more accurate representation of possible PHEV charging patterns than typical assumptions such as utility controlled “optimal” charging patterns or evening only charging, in environments without consumer incentives to adopt such policies. By using the uncontrolled charging pattern we may gain a better understanding of how consumer availability driven charging may affect the electricity system and the vehicle charging costs associated with non-optimal charging.

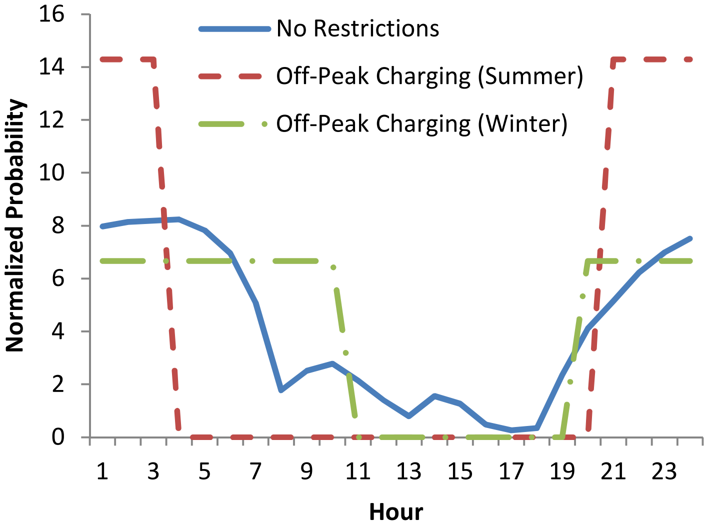

Figure 1: Charging Schedules for PHEV – Hourly Starting Probabilities

Economic Analysis Assumptions

The economic parameters used for the three vehicles are included in the Table 1. For all three vehicles, a nominal loan interest rate of 6% over 5 years was assumed. The vehicle life was assumed to be 10 years, with a 15% resale value at the end of 10 years (in real terms). Maintenance and insurance were assumed to be the same for all three vehicles and battery lifespan is assumed to be 100,000 miles. Vehicle use per day was determined from data from the Bureau of Transportation Statistics, where both a daily frequency of 2.53 for vehicle trips and a distribution of trip distances were utilized to determine the daily distance travelled per vehicle (BTS, 2004). The fitted distribution for trip distances can be found in Figure A5 in Appendix A.

Petroleum price projections were taken from the DOE Energy Information Agency 2010 reference and high price scenarios (EIA, 2010). In the reference case, real oil prices increase 2.6% per year and in the high price case, 7.2% per year. Both cases are for the time period of 2010 to 2020. The prices range from $67 to $98 in the reference case, and $67 to

$176 in the high crude oil projection. To convert the DOE crude oil price projection to California retail gasoline price, we used DOE historic monthly data on the California gasoline price and U.S. composite refiner acquisition cost of crude oil (EIA, 2009d). The R^2 for this regression was 0.925. The starting gasoline price for both the reference case and high oil price case was $2.95. It is important to note that California gasoline prices are higher than the national average. The assumed general inflation rate is 3%. Battery replacement costs are assumed to decline 7% in real terms per year (EIA, 2009a). The Volt and Prius batteries are replaced at the end of year 7. A real interest rate of 6% was used for the net present value calculations. Tariff rates for Californian households were obtained from the tariff book of the Pacific Gas and Electric Company. A summary of the rates can be found in Table 2. Sensitivity analysis also showed that the direction of the results was not very sensitive to the interest rate.

Table 1: Summary of economic data and key parameters for the various vehicles.

Item	**GM Volt**	**Chevrolet Cobalt**	**Toyota Prius**
Purchase price	41,000	16,000	24,000
Federal tax credit	7,500		
Net purchase price	33,500	16,000	24,000
MPG	50*	27.5	50
Battery replacement cost	12,000		3,000
Charging time	8 hr		

*For travel beyond 40 miles/charge.

Table 2: Summary of electricity tariff rates for a California household. The tariff rates were obtained from the Pacific Gas and Electric Company Tariff Book rate E-9 and E-6 (22). The alternative flat rate tariff was calculated at an average cost to the customer but with the same revenue to the utility.

	Summer Tariff Rates				**Winter Tariff Rates**		
	Time of Use Service				Time of Use Service		
	Off Peak	Part Peak	Peak	Standard	Off Peak	Part Peak	Standard
Tier 1	$0.05	$0.11	$0.31	$0.12	$0.06	$0.11	$0.12
Tier 2	$0.05	$0.11	$0.31	$0.13	$0.06	$0.11	$0.13
Tier 3	$0.11	$0.17	$0.37	$0.26	$0.11	$0.17	$0.26
Tier 4	$0.15	$0.21	$0.41	$0.38	$0.16	$0.21	$0.38
Tier 5	$0.17	$0.23	$0.43	$0.44	$0.18	$0.23	$0.44
Flat Rate	$0.05	$0.11	$0.31	$0.12	$0.07	$0.12	$0.13

Model Results

California Validation

Before we may consider the effects of PHEV use on the electricity load profile of California we must first confirm that our household load profile reflects that of a typical California household before the introduction of a PHEV. Data for this comparison is taken from the recent California Statewide Pricing Pilot (SPP) which studied residential response to peak pricing of electricity (Herter et al., 2007). Average household summer daily electricity consumption from the reference data is 15.9 kWh day^{-1} while the corresponding value from the current model is 15.17 kWh day^{-1}. As may be seen in Figure 2, the California demand model tracks the summer average household demand from the literature quite well, with only a brief period of underestimation during the morning hours.

Average household winter daily electricity consumption from the reference data is 18.81 kWh day^{-1} while the corresponding value from the current model is 18.06 kWh day^{-1}. As from Figure 3 the model shows a slightly earlier and lower peak period than the literature data, but overall the model tracks well with the reference load profile.

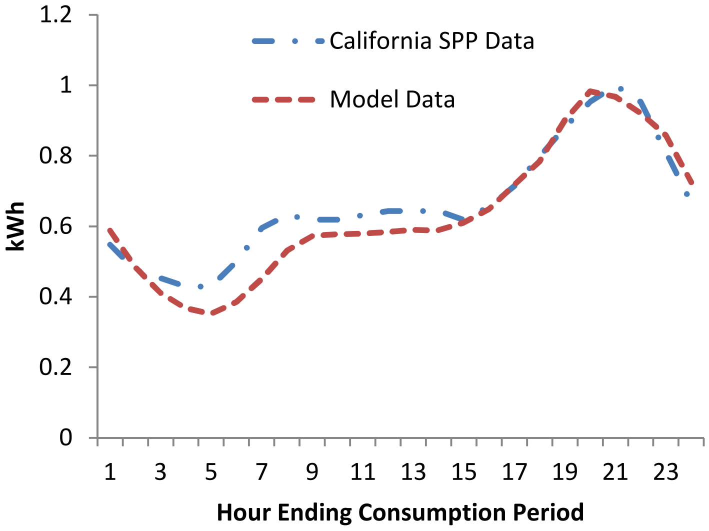

Figure 2: Average Californian Household Demand for Summer without PHEVs

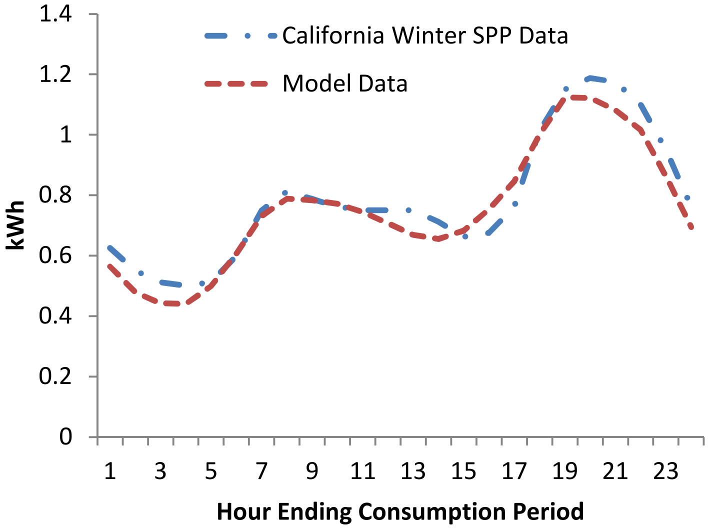

Figure 3: Average Californian Household Demand for Winter without PHEVs

PHEV Addition

Having established that the model can produce household load profiles that resemble residential load profiles available in the literature we may add the PHEV component to the model. As mentioned previously the specifications of the Chevrolet Volt were used as the basis for a PHEV in the model. Comparing the breakdown of household electricity use with and without a PHEV, we see that the PHEV requires 37% of the household daily electricity usage, (Figure 4).

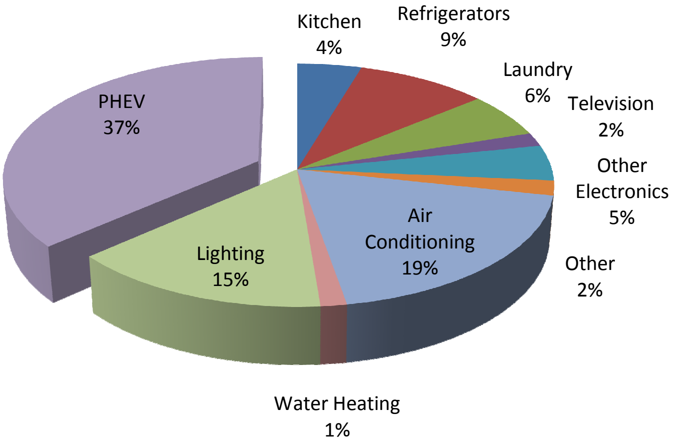

Figure 4: Breakdown of electricity consumption of an average Californian household in summer with the addition of PHEVs

This increases the average summer household usage rate from 15.17 kWh day^{-1} to 24.23 kWh day^{-1}. The 9.06 kWh day^{-1} includes the electricity consumed by the PHEV and that lost due to charging and battery inefficiencies and corresponds to an average daily commute of roughly 31 miles. Two different charging scenarios were included in the analysis: no restrictions and off-peak only charging. The charging scenario used plays a large role in the shape of the average household electricity usage profile, and large-scale adoption of PHEVs could lead to a very different electricity load profile at the utility level. For the summer no restriction case (Figure 5) the additional load is spread fairly evenly over the course of the day with a roughly 30% increase during the evening peak period. This is due to the long charging times examined in the scenario which dictate that even though there is a low probability of starting a charge during the day many charging sessions will continue into the peak periods. The summer off-peak only charging scenario shown in Figure 6 produces a more drastic increase almost doubling the peak load but shifting the peak by three hours. The same scenario performed for the winter, and shown in Figure 7, also produces an increased off-set evening peak but also creates a new morning peak of almost equal magnitude as the evening peak.

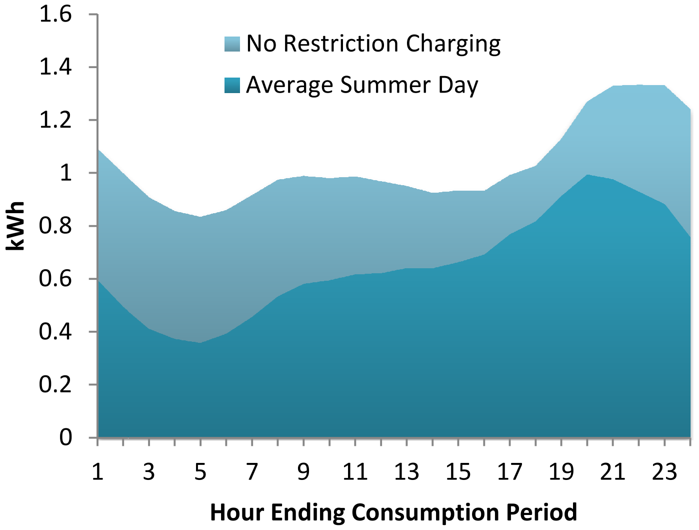

Figure 5: Load profile of a Californian household on an average summer day with no restrictions on PHEV charging

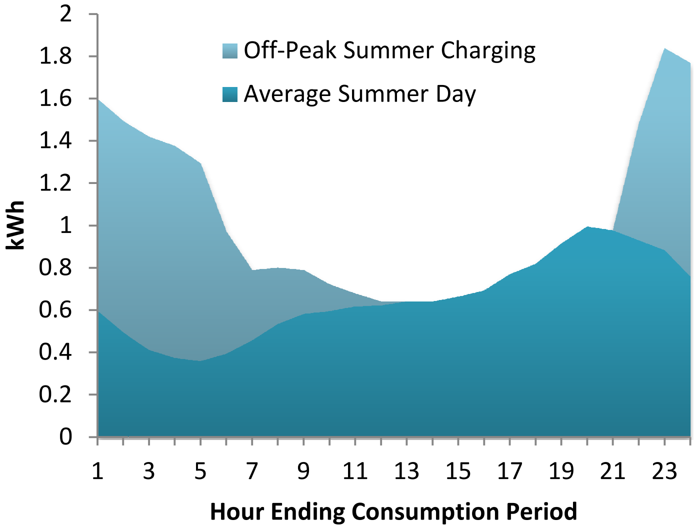

Figure 6: Load profile of a Californian household on an average summer day following summer off-peak PHEV charging

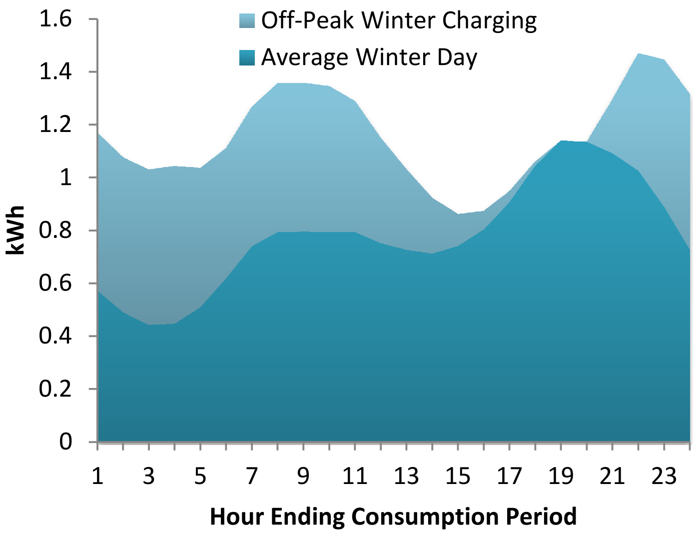

Figure 7: Load profile of a Californian household on an average winter day following winter off-peak PHEV charging

Economic Analysis and Discussion

Results are presented for the California base case (non TOU), a California TOU pricing base case that corresponds to a household with a single meter for both the household and PHEV (TOU), California TOU pricing with a separate meter for PHEVs (TOU separate meter) and for alternative flat rate pricing plans with and without TOU pricing. The alternative flat rate pricing schemes proposed are schemes that are non-tiered that would confer approximately the same revenue to the utility for a base case scenario. It can be argued that the main factor that makes PHEVs unattractive in the current California tariff system is the tiered breakdown of pricing. A flat rate pricing that confers the same revenue to the utility at base case could increase the attractiveness of PHEVs with respect to the other vehicle options. A significant component in the difference between a single meter and a separate meter for the PHEV is the cost of the additional meter. At about $0.41 a day, it represents a significant cost to the household. Since it is such a significant cost, an alternate scenario in which the separate meter is subsidized by the relevant authority is also examined.

PHEVs are assumed to charge only during off-peak and shoulder peak periods for TOU pricing. Results are also provided for the DOE reference and high oil price cases. Table 3 contains the key results. The values in Table 3 are the difference in net present value (NPV) between the Volt and the other options. A negative value indicates that the Volt is less attractive than the alternative. The alternative pricing schemes suggested here represent schemes that would make the PHEVs more attractive to potential consumers. Alternate schemes to non TOU and TOU consumers represent non-tiered rates while the alternative pricing scheme for TOU separate meter customers represent a scenario where the daily meter charge is subsidized by a third party.

Table 3: Differences between the net present value of PHEV and other vehicle options under alternative electricity pricing systems (figures are in US$)

		Non TOU		TOU		TOU Separate Meter	
Case	Oil Price	Prius	Cobalt	Prius	Cobalt	Prius	Cobalt
Tiered	*Reference*	-11068	-12988	-7499	-9419	-7567	-9487
Tiered	*High Price*	-9594	-9867	-6025	-6298	-6093	-6366
Alternate	*Reference*	-7859	-9780	-6346	-8267	-6472	-8393
Alternate	*High Price*	-6386	-6658	-4873	-5145	-4999	-5271

The bottom line is that with the current California pricing system, the PHEV is a much less attractive option than either the Prius or the Cobalt under either reference or high oil price assumptions. Another clear conclusion is that the PHEV option is considerably more attractive under TOU pricing than standard pricing options. This result makes sense because with TOU pricing the PHEV can be charged during off-peak times when electricity is less expensive. The two TOU options available to Californians present very similar benefits to consumers with NPV values differing only by a small margin, with the normal TOU plan being slightly more attractive. The other major conclusion is that the PHEV option becomes much more attractive with flat rate pricing with or without TOU pricing. For the reference case, the PHEV is still less attractive than the other options, hampered by the high price of the PHEV. For example, for the reference case comparison with the Prius with no TOU pricing, the California rate structure yields a NPV advantage for the Prius of $11,068 whereas the flat rate pricing reduces the advantage of the Prius to $7,859, a difference of $3,209. With TOU pricing and the flat rate pricing, the Prius advantage drops further to $6,346, still significantly less competitive than its peers. Under the high oil price scenario, a flat rate TOU pricing scheme provides the most competitive circumstance for the PHEV when compared to its rivals. If the household opts for a separate meter for the PHEV charger, the daily meter charge needs to be waived or heavily subsidized for the vehicle to be economically competitive.

Another way to characterize the differences caused by the pricing policy is to calculate the breakeven crude oil price between the PHEV and the other vehicle options under California and flat rate pricing (Figure 8). The breakeven crude oil price is the point at or above which the consumer would prefer the PHEV on purely economic grounds. Compared with the Prius, $254 crude oil would be required under the current California pricing scheme and $227 under flat rate (and TOU) pricing to make the PHEV an economic winner, a difference of 11%. These crude oil prices reflect California gasoline prices of $8.24 and $7.29 per gallon respectively. Similarly, against the Cobalt, the breakeven falls from $184 under California pricing to $171 under flat rate pricing. This corresponds to gasoline prices of $6.26 and $5.91 per gallon. Interestingly, these values are much higher than the around $120 per barrel crude oil breakeven values for other alternative energy sources (Tyner, 2008), such as cellulosic biofuels. In California, this means that PHEVs are significantly less more competitive than these alternate fuels even if electricity prices policies are structured to provide maximum advantage for PHEVs.

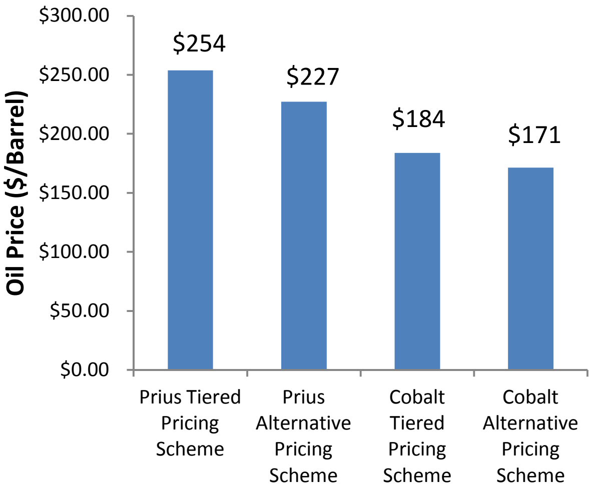

Figure 8: Breakeven crude oil price between the PHEV and other vehicle options

A crucial component which greatly affects the competitiveness of the PHEV is the cost of the battery, which represents a significant contribution to the premium of the PHEV over its competitors. The battery represents two costs, the upfront premium for the initial purchase of the vehicle and the replacement for a new battery once the expected lifetime is reached. It is therefore interesting to determine the cost of the battery at which the PHEV would become economically competitive (Figure 9). Under the California tiered pricing schedules, the PHEV would start to become competitive once the 16 kWh battery drops below $5,500, which corresponds to about $344/kWh. To compete with a conventional ICE vehicle, it needs to drop even further to about $234/kWh. With an alternative pricing schedule, the PHEV becomes slightly more competitive at $402/kWh versus a Prius but it still requires a significant drop in cost since current estimates peg battery costs at $800 - $1000 / kWh (Pesaran et al., 2007). It is also worth noting that these estimates include the $7500 tax credit that initial adopters of PHEVs receive. Once those credits expire, the battery costs would have to drop even lower to remain competitive.

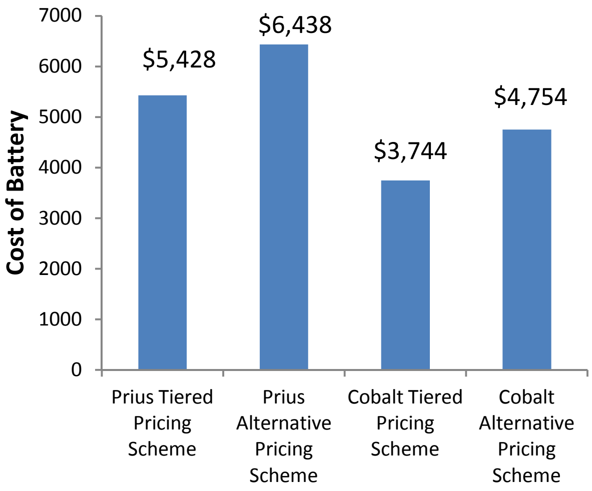

Figure 9: Battery costs switching values assuming reference case parameters

Concluding Remarks

The combined simulation/economic modeling exercise was used to conduct a cost effectiveness analysis for owning a PHEV in the California market. A coherent load generating model capable of micro-scale prediction has been adapted and used in this analysis. Such a model has the potential to be used in more detailed studies with regards to polices affecting PHEVs or any other devices that can be characterized as an appliance in the household. From this study it appears that the anticipated first generation PHEVs will not be economically competitive with conventional and hybrid vehicles, even with a $7,500 tax incentive. Its competitiveness is further hampered by the current structure of the electricity pricing structure in California. The high costs of electricity in California when compared to the nation at large deal another blow to the PHEVs ability to replace gasoline with electricity in a cost-efficient manner.

The tiered electricity pricing regime in use plays an important role. California adopted the increasing tier pricing system to discourage electricity consumption for environmental reasons. That is, less electricity consumption results in lower adverse environmental consequences including lower greenhouse gas emissions. However, here the law of unintended consequences comes into play. Namely, the same pricing structure, while achieving environmental gains under normal circumstances, now discourages PHEV adoption and use and thus leads to adverse environmental outcomes. Clearly, California will want to reconsider its current rate structure if it wants to be able to achieve the clean air and GHG benefits possible from PHEV adoption in the state.

The second major conclusion is that PHEVs are economically more attractive under TOU pricing than under standard electricity pricing. That stands to reason because most of the vehicle charging would be in the evening during off-peak times. Although California already has prior plans that provide TOU pricing for EVs, this insight is still valuable for other states that provide only flat rate pricing schedules. Hence other states that want to encourage PHEV adoption should consider TOU pricing.

Separate metering provides a cheaper alternative for households electricity cost-wise but with the added burden of additional meter charges. If there could be options to subsidize this cost or if cheaper metering technology were available, separate metering could provide economic benefits on par with removing tiered electricity pricing. No matter what options California uses to resolve the contradiction of its standard “green” electricity pricing and aim to promote PHEVs at the same time, it is certainly probable that: if nothing is done, the current rate structure will have the unintended consequence of discouraging PHEV adoption in California.

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Appendix A

Major data items used in this paper

TableA1: Full list of appliances included in the model for an average Californian household

Appliance	**California Saturation Level**
Electric Stove	0.35
Electric Oven	0.4
Microwave Oven	0.85
Coffee Maker	0.52
Refrigerator	1
2nd Refrigerator	0.21
Freezer	0.18
Dishwasher	0.55
Clothes Washer	0.76
Tumble Dryer	0.35
Television	0.99
2nd Television	0.35
3rd Television	0.21
Set Top Box	0.78
Video Recorder	0.79
DVD	0.84
Radio/Player	0.81
Personal Computer	0.74
Printer	0.65
Lighting	1
Central Air Conditioning	0.45
Room Air Conditioning	0.16
Water Heating	0.11
Cordless Phone	0.8
Answering Machine	0.66
Electric Space Heating	0.28
Pool Pumps	0.12
Other Occasional Loads	1

TableA2: Data for power consumption cycles for appliances

Appliance	Power	Time	Power	Time	Power	Time	Power	Time	Standby Power	Weekday Daily Frequency	Weekend Daily Frequency
Stove and Oven	1050	12	525	18	220	12			0	0.7	0.72
	1100	12	550	6						1	1.1
	2100	24	700	6	1400	6	0	6		0.5	0.5
Microwave Oven	1500	20							3	0.98	1
Coffee Maker	1000	6	105	20					0	0.98	1
Refrigerator	245	14	0	22					0	45	45
Freezer	165	14	0	22					0	45	45
Dishwasher	1800	18	220	18	1800	6	220	12	0	0.62	0.63
Clothes Washer	2150	12	210	24	450	6			0	0.88	0.9
	2150	18	210	24	450	6				0.45	0.45
Tumble Dryer	3250	80							0	0.78	0.8
Television	113	93							4	1.95	2.12
	195	150								0.65	0.71
2nd/3rd Television	86	60							4	0.28	0.3
Video Recorder / DVD /Set Top Box	0	0							9/9/20	0	0
Radio/Player	30	60							6	4.18	4.54
Personal Computer	212	60							3	3	3.5
Printer	600	5							4	0.78	0.83
Lighting	62	140							0	25	25
	72	530								1	1
Other Occasional Loads	1000	30							3	0.14	0.15
Central Air Conditioning	4000	220							0	0.7	0.85
Room Airconditioning	1500	220							0	0.7	0.85
Water Heater	1175	30							0	10	10.5
Telephone/Answering Machine	0	0							2.1/2.2	0	0
Electric Space Heating	2000	120							0	2.5	2.6
Pool Pump	1000	15							0	10	11

TableA3: Hourly usage probabilities for weekdays

Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Stove and Oven	0.20	0.20	0.40	0.40	1.78	2.59	3.19	3.83	3.70	4.13	4.29	4.15	3.89	4.46	5.79	8.76	10.00	10.30	9.24	8.15	5.82	2.79	1.51	0.36
Microwave Oven	0.20	0.20	0.40	0.40	1.78	2.59	3.19	3.83	3.70	4.13	4.29	4.15	3.89	4.46	5.79	8.76	10.00	10.30	9.24	8.15	5.82	2.79	1.51	0.36
Coffee Maker	0.20	0.20	0.40	0.40	1.78	2.59	3.19	3.83	3.70	4.13	4.29	4.15	3.89	4.46	5.79	8.76	10.00	10.30	9.24	8.15	5.82	2.79	1.51	0.36
Refrigerator	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17
Freezer	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17
Dishwasher	2.33	2.33	2.33	2.42	2.59	3.46	4.06	4.32	4.32	4.15	3.98	3.89	4.15	4.67	4.93	5.19	5.62	6.40	7.09	7.52	5.62	3.46	2.85	2.33
Clothes Washer	2.60	1.80	1.60	1.60	1.60	2.08	3.20	4.40	5.60	5.64	5.20	4.80	4.40	4.40	4.80	5.00	5.32	5.40	5.48	5.60	5.72	5.80	4.80	3.20
Tumble Dryer	2.60	1.80	1.60	1.60	1.60	2.08	3.20	4.40	5.60	5.64	5.20	4.80	4.40	4.40	4.80	5.00	5.32	5.40	5.48	5.60	5.72	5.80	4.80	3.20
Television	2.40	1.20	0.70	0.60	0.70	1.30	2.10	2.45	3.35	3.20	3.20	3.84	3.84	4.00	4.80	6.39	7.99	7.99	7.99	9.59	7.99	6.39	4.80	3.20
Set Top Box	2.40	1.20	0.70	0.60	0.70	1.30	2.10	2.45	3.35	3.20	3.20	3.84	3.84	4.00	4.80	6.39	7.99	7.99	7.99	9.59	7.99	6.39	4.80	3.20
Video Recorder	2.40	1.20	0.70	0.60	0.70	1.30	2.10	2.45	3.35	3.20	3.20	3.84	3.84	4.00	4.80	6.39	7.99	7.99	7.99	9.59	7.99	6.39	4.80	3.20
DVD	2.40	1.20	0.70	0.60	0.70	1.30	2.10	2.45	3.35	3.20	3.20	3.84	3.84	4.00	4.80	6.39	7.99	7.99	7.99	9.59	7.99	6.39	4.80	3.20
Radio/Player	2.40	1.20	0.70	0.60	0.70	1.30	2.10	2.45	3.35	3.20	3.20	3.84	3.84	4.00	4.80	6.39	7.99	7.99	7.99	9.59	7.99	6.39	4.80	3.20
Personal Computer	2.40	1.20	0.70	0.60	0.70	1.30	2.10	2.45	3.35	3.20	3.20	3.84	3.84	4.00	4.80	6.39	7.99	7.99	7.99	9.59	7.99	6.39	4.80	3.20
Printer	2.40	1.20	0.70	0.60	0.70	1.30	2.10	2.45	3.35	3.20	3.20	3.84	3.84	4.00	4.80	6.39	7.99	7.99	7.99	9.59	7.99	6.39	4.80	3.20
Lighting	1.89	1.68	1.89	2.10	3.15	4.20	3.99	3.36	3.15	2.94	2.73	2.10	2.10	2.10	2.31	3.15	4.20	8.40	11.55	11.55	9.45	6.30	3.36	2.31
Other Occasional Loads	1.03	0.83	0.83	0.83	1.03	2.04	3.06	3.24	3.44	3.54	3.64	3.74	3.94	4.14	4.55	4.96	5.79	6.70	7.71	8.51	9.01	8.10	5.67	3.66
Central Air Conditioning	1.49	1.22	1.02	0.68	0.54	0.50	0.45	1.04	1.22	1.63	2.85	3.73	5.15	7.18	9.19	10.57	11.25	10.98	9.08	6.50	5.15	3.73	2.85	2.03
Room Air Conditioning	1.49	1.22	1.02	0.68	0.54	0.50	0.45	1.04	1.22	1.63	2.85	3.73	5.15	7.18	9.19	10.57	11.25	10.98	9.08	6.50	5.15	3.73	2.85	2.03
Water Heating	1.40	0.80	0.90	1.10	2.00	4.40	8.90	10.70	8.90	6.60	5.20	3.80	3.60	3.30	3.20	2.60	4.20	4.80	5.20	4.70	4.20	3.90	3.60	2.20
Telephone	3.40	1.94	0.87	0.77	0.87	0.97	0.97	1.46	2.43	3.40	3.88	4.85	4.85	5.93	6.13	6.80	6.80	6.80	7.77	8.25	6.80	5.34	4.85	3.88
Answering Machine	3.40	1.94	0.87	0.77	0.87	0.97	0.97	1.46	2.43	3.40	3.88	4.85	4.85	5.93	6.13	6.80	6.80	6.80	7.77	8.25	6.80	5.34	4.85	3.88
Electric Space Heating	3.44	2.99	3.01	3.14	3.31	4.12	5.37	5.59	5.54	5.05	4.64	4.43	4.17	3.69	3.57	3.48	3.93	4.73	4.85	4.81	4.64	4.17	3.95	3.39
Pool Pump	3.10	3.10	3.10	3.10	3.10	3.10	3.10	3.17	4.33	4.53	4.53	4.53	4.53	4.53	5.17	5.17	5.82	7.12	6.47	5.17	3.88	3.10	3.10	3.10

TableA4: Hourly usage probabilities for weekends

Hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Stove and Oven	0.37	0.05	0.00	0.00	0.00	0.17	1.72	2.65	4.37	5.94	6.97	7.86	7.92	7.15	6.39	5.89	6.78	7.41	7.32	7.23	6.93	4.09	2.30	1.02
Microwave Oven	0.37	0.05	0.00	0.00	0.00	0.17	1.72	2.65	4.37	5.94	6.97	7.86	7.92	7.15	6.39	5.89	6.78	7.41	7.32	7.23	6.93	4.09	2.30	1.02
Coffee Maker	0.37	0.05	0.00	0.00	0.00	0.17	1.72	2.65	4.37	5.94	6.97	7.86	7.92	7.15	6.39	5.89	6.78	7.41	7.32	7.23	6.93	4.09	2.30	1.02
Refrigerator	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17
Freezer	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17
Dishwasher	1.73	0.96	0.40	0.40	0.40	0.96	1.73	2.93	3.75	4.58	4.68	4.68	4.68	4.68	4.68	6.11	6.83	7.16	7.80	8.60	8.16	7.01	5.05	2.03
Clothes Washer	1.73	0.96	0.40	0.40	0.40	0.96	1.73	2.93	3.75	4.58	4.68	4.68	4.68	4.68	4.68	6.11	6.83	7.16	7.80	8.60	8.16	7.01	5.05	2.03
Tumble Dryer	1.73	0.96	0.40	0.40	0.40	0.96	1.73	2.93	3.75	4.58	4.68	4.68	4.68	4.68	4.68	6.11	6.83	7.16	7.80	8.60	8.16	7.01	5.05	2.03
Television	3.40	1.94	0.87	0.77	0.87	0.97	0.97	1.46	2.43	3.40	3.88	4.85	4.85	5.93	6.13	6.80	6.80	6.80	7.77	8.25	6.80	5.34	4.85	3.88
Set Top Box	3.40	1.94	0.87	0.77	0.87	0.97	0.97	1.46	2.43	3.40	3.88	4.85	4.85	5.93	6.13	6.80	6.80	6.80	7.77	8.25	6.80	5.34	4.85	3.88
Video Recorder	3.40	1.94	0.87	0.77	0.87	0.97	0.97	1.46	2.43	3.40	3.88	4.85	4.85	5.93	6.13	6.80	6.80	6.80	7.77	8.25	6.80	5.34	4.85	3.88
DVD	3.40	1.94	0.87	0.77	0.87	0.97	0.97	1.46	2.43	3.40	3.88	4.85	4.85	5.93	6.13	6.80	6.80	6.80	7.77	8.25	6.80	5.34	4.85	3.88
Radio/Player	3.40	1.94	0.87	0.77	0.87	0.97	0.97	1.46	2.43	3.40	3.88	4.85	4.85	5.93	6.13	6.80	6.80	6.80	7.77	8.25	6.80	5.34	4.85	3.88
Personal Computer	3.40	1.94	0.87	0.77	0.87	0.97	0.97	1.46	2.43	3.40	3.88	4.85	4.85	5.93	6.13	6.80	6.80	6.80	7.77	8.25	6.80	5.34	4.85	3.88
Printer	3.40	1.94	0.87	0.77	0.87	0.97	0.97	1.46	2.43	3.40	3.88	4.85	4.85	5.93	6.13	6.80	6.80	6.80	7.77	8.25	6.80	5.34	4.85	3.88
Lighting	1.03	0.33	0.33	0.83	1.78	2.64	3.56	3.74	3.44	3.04	3.04	3.24	3.94	4.14	4.55	4.96	5.79	6.70	8.21	9.11	9.81	8.50	4.32	2.96
Other Occasional Loads	2.55	1.33	1.23	1.23	1.33	1.73	2.13	3.55	4.07	3.99	3.77	3.97	4.07	4.47	4.97	6.00	6.32	6.84	7.34	7.56	6.79	6.67	4.84	3.22
Central Air Conditioning	1.49	1.22	1.02	0.68	0.54	0.50	0.45	1.04	1.22	1.63	2.85	3.73	5.15	7.18	9.19	10.57	11.25	10.98	9.08	6.50	5.15	3.73	2.85	2.03
Room Air Conditioning	1.49	1.22	1.02	0.68	0.54	0.50	0.45	1.04	1.22	1.63	2.85	3.73	5.15	7.18	9.19	10.57	11.25	10.98	9.08	6.50	5.15	3.73	2.85	2.03
Water Heating	1.80	1.00	0.90	0.80	1.50	2.30	2.60	4.70	7.70	8.30	7.40	6.10	5.10	4.30	3.90	3.90	5.20	5.80	5.60	5.20	4.70	4.40	4.00	2.80
Telephone	2.40	1.20	0.70	0.60	0.70	1.30	2.10	2.45	3.35	3.20	3.20	3.84	3.84	4.00	4.80	6.39	7.99	7.99	7.99	9.59	7.99	6.39	4.80	3.20
Answering Machine	2.40	1.20	0.70	0.60	0.70	1.30	2.10	2.45	3.35	3.20	3.20	3.84	3.84	4.00	4.80	6.39	7.99	7.99	7.99	9.59	7.99	6.39	4.80	3.20
Electric Space Heater	3.44	2.99	3.01	3.14	3.31	4.12	5.37	5.59	5.54	5.05	4.64	4.43	4.17	3.69	3.57	3.48	3.93	4.73	4.85	4.81	4.64	4.17	3.95	3.39
Pool Pump	2.64	2.64	2.64	2.64	2.64	2.64	2.64	2.70	3.69	5.51	6.06	6.06	6.06	6.06	6.06	6.06	6.06	6.06	5.51	4.41	3.30	2.64	2.64	2.64

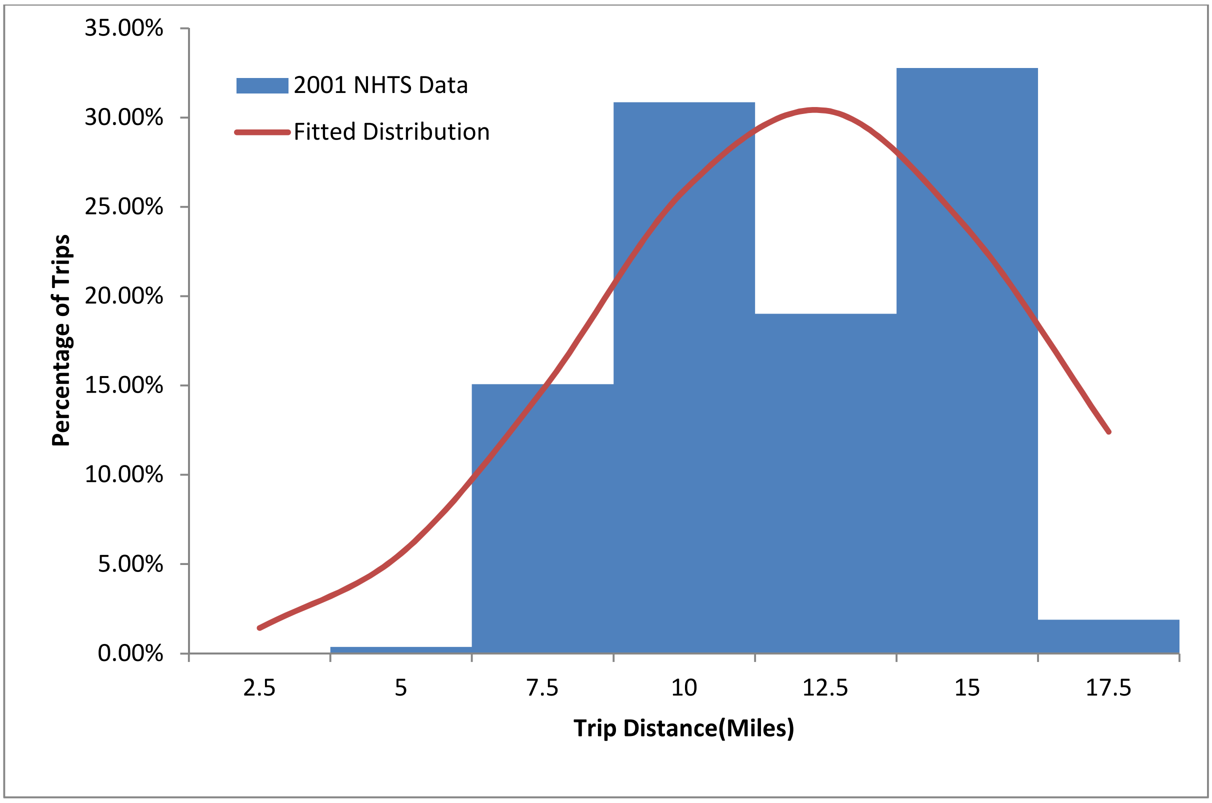

Figure A1: Distribution of trip distances with a fitted normal mean of 12.2329 and standard deviation of 2.92