Aggregated Impact of Plug-in Hybrid Electric Vehicles on Electricity Demand Profile

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***Abstract*—Greenhouse gas emissions, air pollution in urban areas, and dependence on fossil fuels are among the challenges threatening the sustainable development of the transportation sector. Plug-in hybrid electric vehicle (PHEV) technology is one of the most promising solutions to tackle the situation. While PHEVs partially rely on electricity from the power grid, they raise concerns about their negative impacts on power generation, transmission, and distribution installations. On the other hand, they have the potential to be used as a distributed energy storage system for the grid. Therefore, they can pave the way for a more sustainable power grid in which renewable resources are widely employed. Positive and negative impacts of PHEVs on the power grid cannot be thoroughly examined unless extensive data on the utilization of each individual PHEV are available. For instance, in order to estimate the aggregated impact of PHEVs on the electricity demand profile, one needs to know 1) when each PHEV would begin its charging process, 2) how much electrical energy it would require, and 3) how much power would be needed. This paper extracts and analyzes the data that are available through national household travel surveys (NHTS). Three charging scenarios are considered in order to obtain various PHEV charging load profiles (PCLPs). Further, the characteristics of each developed PCLP are studied. Finally, the effects of three suggested policies on the derived PCLPs are examined.**

***Index Terms*—Demand profile, load profile, national household travel survey (NHTS), plug-in hybrid electric vehicle (PHEV), transportation electrification, vehicle-to-grid.**

I. INTRODUCTION

AIR pollution, climate change, and fossil fuel resource depletion are all major public concerns of the recent century. These concerns are mainly raised by the transportation and electric power generation sectors as they are among the major consumers of fossil fuels. While most power plants are located in rural areas, personal automobiles are to be blamed for air pollution in urban areas. Moreover, most vehicles only consume petroleum-based fuels; whereas, there is more variety in the type of fuel that is used for electrical power generation. Therefore, the transportation sector faces more serious challenges on its sustainable growth path. All-electric, hybrid, and plug-in hybrid vehicles have been proven to benefit from more efficient power trains. Consequently, over the past few years, transportation electrification has been considered as an effective solution to combat the negative impacts of conventional vehicles.

A plug-in hybrid electric vehicle (PHEV) is essentially a hybrid vehicle with a larger battery pack [1], [2]. Therefore, it runs on electricity when its battery state-of-charge (SOC) is high. Otherwise, the internal combustion engine takes over and the vehicle consumes gasoline similar to a hybrid vehicle. The battery pack can be recharged through a plug which provides connection to and interaction with the electric power grid [3]–[6]. PHEVs are characterized by their all-electric range (AER). A PHEV which can be driven solely on electricity for the distance of x is referred to as PHEV-x. The electricity demanded by PHEVs raises concerns about their potential negative impacts on power grid generation, transmission, and distribution installations.

Hereinafter, the aggregated electricity demanded by PHEVs in a specific region at any given time is referred to as the PHEV charging load profile (PCLP). The prediction of PCLP is fundamental to any evaluation of how the power system will respond to PHEVs. PCLP impinges on numerous aspects of the power grid impact analysis such as transformers and cables, generation rate, overloading, under voltage, power losses, power system utilization, and the electricity market. Moreover, PCLP is useful for examining the impact of PHEVs on greenhouse gas emissions. PCLP makes it possible to study the emissions of marginal power plants, e.g., coal-fired, natural-gas-fired, based on the amount of extra load and its time distribution.

The number and types of PHEVs, their AER, driving patterns, and miles driven daily are the basic data required to obtain the PCLP. Other factors that affect the PCLP are charging start time and charging level. Therefore, the generation of the PCLP requires the knowledge of 1) when each vehicle begins to be charged, 2) how much energy is required to charge it, and 3) what level of charge is available. The miles driven and vehicle type determine the total energy required. In addition, the charging level determines the charging time duration. The information involved in building the PCLP can be represented as a prism, as shown in Fig. 1. The sides on the base are the driven mileage, vehicle type, and charging start time. These factors are mostly statistical or probabilistic. The height of the prism is the charging level, which is deterministic. In other words, the sides of the base are determined by the driver's behavior, and the height depends on the power grid distribution system.

Transportation surveys are the best source of information about vehicles and trip characteristics. However, extracting detailed information about each individual vehicle is practically impossible. For instance, existing surveys do not address the

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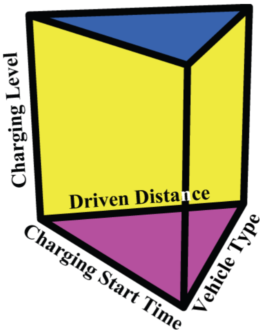

Fig. 1. Prism of the information involved in building the PCLP.

questions listed above. There are several reasons for this gap in the available information. First, the main purpose of the available transportation data is to study transportation concerns rather than electric energy issues. Second, in most cases, the data collected represents only a small sample of vehicles in a region. This lack of information would make the data-mining process complex. In order to answer the questions that underlie the PCLP, the raw data has to be manipulated.

In almost all of the previous PHEV studies, the charging profile is either added to the domestic load profile or treated as a percent increase in the electric load. Since the main objective of such studies has not been the extraction of the PCLP, they neither specifically focus on the PCLP nor provide such data in detail. For example, [7] compares total load profiles with and without PHEVs, but provides no detailed information about the data on which those profiles are based. Further, [8] provides a load demand schedule of PHEVs for each hour of the charging period, but it does not indicate the time of day at which vehicles are charged.

Another point that is worth noting is that previous studies have barely used transportation data to develop their PCLPs. A recent study in [9] used limited transportation data, treating last trip end time as charging start time and determining the number of PHEVs based on customer penetration probabilities. Miles driven and vehicles' SOC were not considered. Another study [10] developed a model predicting changes in load demand; however, it assumed that the number of vehicles was given or determined based on the number of customers in the circuit rather than on the transportation data for the region. The authors of [11] examined the impact of PHEVs on a distribution transformer. In their work, it is assumed that all vehicle owners, regardless of their vehicle type, start to charge close to 6 pm with an SOC of 30% based on Chevy Volt's battery pack. Although the peak arrival time is between 5 and 6 pm, a considerable number of the vehicles arrive at other times of the day, as shown in Section III.

Some studies have tried to find an optimal charging profile for a given number of vehicles based on the concept of valley filling [12], [13]. Another study [14] proposed probabilistic PHEV charging distribution weighted to reflect the time of day at which the power system load was lowest, i.e., early morning and late evening, but the authors provided no detailed information about input data.

The present work focuses primarily on the transportation data required to build a detailed PCLP. It obtains PCLP curves with three AERs of 20, 30, and 40 miles. Its objective is to present methods of extracting applicable information from transportation data which help the development of the PCLP. The most comprehensive reference for transportation data is the National Household Travel Survey (NHTS) [15], which is the basis of this study. Three characteristics that distinguish this work from other studies are 1) a large number of vehicle trips (around 40 000) is considered. This large pool of data is geographically distributed across the U.S. 2) The required charging energy of each vehicle is precisely calculated based on the distance driven and vehicle type. 3) The arrival time of each individual vehicle is taken into account.

The rest of the paper has been arranged as follows. Section II introduces NHTS and the data that is applicable to PHEVs. Section III presents the statistics relevant to the three sides forming the base of the PCLP prism (see Fig. 1). Section IV discusses other factors that are associated with the development of the PCLP. Section V represents the developed PCLP curves and their characteristics. These curves are compared based on the criteria defined during the data analysis process. Finally, Section VI presents three suggested policies which improve the PCLP.

II. 2001 National Household Travel Survey

The following section discusses the extraction of useful data from transportation data when the objective is to generate the PCLP. The NHTS website includes detailed transportation data from 1995 to 2009 [15]. Sponsored by the U.S. Department of Transportation, the 2001 NHTS provides comprehensive data about travel and transportation in the United States. Its objective is to assist transportation planners and policy makers.

The 2001 NHTS was carried out by telephone interviews, and sampling was based on random digit dialing list of telephone numbers. This list excluded motels, hotels, and group quarters. The sample size was 69 817 usable households, that is, households in which at least 50% of the adults (age 18+) were interviewed [16]. The data reflect daily trips in a 24-hour period, and they were collected for all trips, all purposes, all trip lengths, and all areas of the country, both urban and rural. Each household, person, and vehicle in the 2001 NHTS has a unique ID number. These IDs are appropriate tools for linking any two data files.

The 2001 NHTS data consist of five large databases. Since the extraction of the PCLP concerns vehicles, not people, this paper primarily considers data related to vehicle trips, rather than those related to person trips. However, the extraction of viable data demands the consideration of person trips as well. Therefore, two Microsoft Excel files of the 2001 NHTS, 1) DAYPUB.csv and 2) VEHPUB.csv, are applicable to the research presented here.

1) DAYPUB.csv: This file consists of information associated with 642 293 person trips, each of which has 150 attributes. Our study focuses on four attributes: household ID number (HOUSEID), vehicle ID number (VEHID), travel day trip end time (ENDTIME), and type of vehicle (VEHTYPE). Appendix B of the 2001 user's guide, titled 2001 NHTS Codebook, defines

TABLE I
DEFINITION OF VEHTYPE VALUES

VEHTYPE:	**Type of vehicle**
01	Automobile/car/station wagon
02	Van (mini, cargo, passenger)
03	Sports utility vehicle
04	Pickup truck

these attributes and their assigned values. The four vehicle types that are considered in this study are listed in Table I [16].

2) VEHPUB.csv: This file tabulates the information regarding 139 383 vehicles and each vehicle has 92 attributes. Those of particular concern here are HOUSEID, VEHID, VEHTYPE, and VEHMILES. VEHMILES represents the vehicle miles driven within the last 12 months.

As mentioned above, VEHMILES addresses the annual vehicle mileage. According to [16], the annual mileage is obtained by multiplying daily mileage by 365, and the daily mileage is obtained during the survey based on weekday, weekend, and seasonal factors. Our study calculates daily mileage by dividing VEHMILES by 365.

The comparison of these two files shows, first, that DAYPUB addresses trips whereas VEHPUB refers to vehicles. Second, attributes HOUSEID, VEHID, and VEHTYPE are common to both files and can be used to connect the two. For example, to determine the arrival time of a vehicle specified in VEHPUB, we need to lookup the vehicle in DAYPUB, then find the ENDTIME in the related row and column of the DAYPUB spreadsheet. Similarly, in order to find out the mileage of a specified vehicle in DAYPUB, we need to lookup the vehicle in VEHPUB, and then find the VEHMILES in the related row and column of the VEHPUB spreadsheet.

The objective is to create a single file, each row of which is dedicated to a vehicle trip. This file includes attributes such as vehicle type, daily miles driven, and last arrival time. The two files are connected based on their common attributes. The resulting file includes about 40 000 vehicle trips with the attributes of VEHTYPE, VEHMILES, and ENDTIME. The following results are based on the information associated with these 40 000 vehicle trips.

III. STATISTICAL STUDY OF THE SIDES WHICH FORM THE BASE OF THE PCLP PRISM

This section sets forth data analyses associated with the three sides which form the base of the PCLP prism. The required data for developing the PCLP is obtained during these analyses.

A. *Vehicle Daily Mileage Analysis*

One of the factors forming the PCLP is daily miles driven by each vehicle (see Fig. 1). Based on the VEHMILES of vehicle trips, the bar chart in Fig. 2 indicates what percentage of vehicles are driven a specified range of miles daily. The most common distance is in the range of 25–30 miles. This figure also shows the percentage of vehicles that drive less than a certain daily mileage (the cumulative curve). For instance, it shows that about 55% of vehicles drive 30 miles a day or less. This closely agrees with the data presented in [17] where it is reported that 61% of trips in the United States are 50 km (30 miles) or less. In addition, the study in [18] estimates that about 63% of vehicles are driven less than 50 km per day. Based on the vehicle daily mileage analysis, the following factors (or indicators) can be defined:

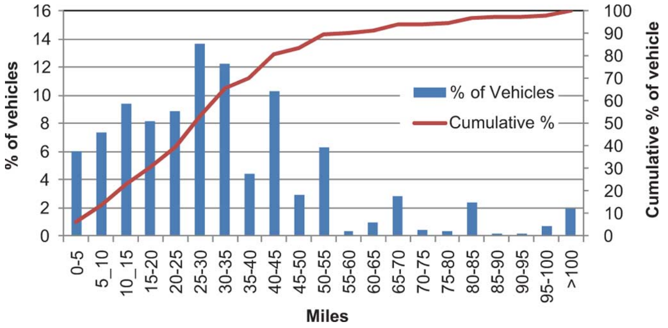

Fig. 2. Percentage of vehicles versus daily miles driven.

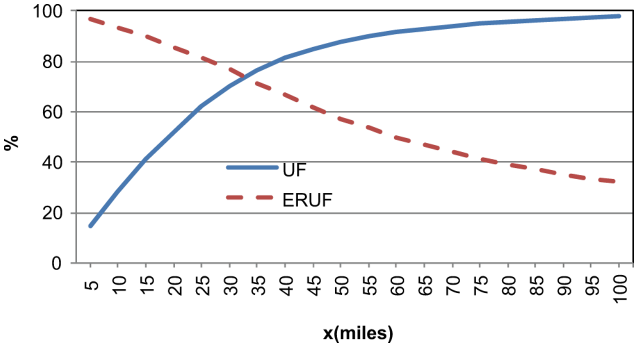

Fig. 3. Comparison of UF and ERUF.

1) Utility Factor (UF): UF is defined as "the fraction of the total daily vehicle miles traveled that are less than or equal to the said distance" [19]. This factor expresses if all vehicles were to be converted to PHEV-x, what percentage of petroleum-fueled miles would be displaced by electricity driven miles. Therefore, one can write

$$\mathrm{UF} = \frac{\sum_{i=l}^{N} d_{ei}}{\sum_{i=l}^{N} d_i} \tag{1}$$

where d_{ei} is the distance driven by electricity by vehicle i, d_i is the total distance driven by vehicle i, and N is the total number of vehicles. Assuming all vehicles are PHEV-x, the curve of UF versus the AER of the PHEVs is shown in Fig. 3. Clearly, the higher the AER, the more miles driven are powered by electricity. Therefore, a UF of 1 implies that all miles driven are fueled by electricity.

2) Electric Range Utility Factor (ERUF): The electric range utility factor (ERUF) is defined as the ratio of actual miles driven by electricity to the total number of miles that could be driven by electricity. Assuming the AER of all vehicles is x

$$\mathrm{ERUF} = \frac{\sum_{i=l}^{N} d_{ei}}{N \cdot x} \tag{2}$$

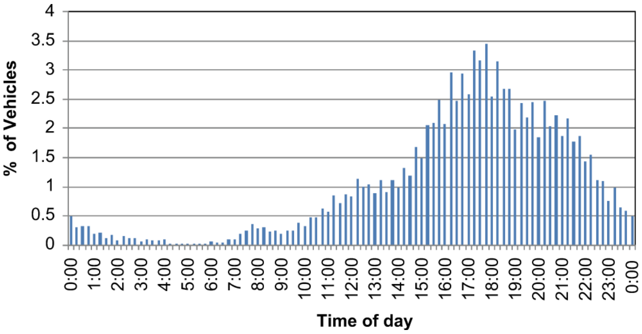

Fig. 4. Percentage of vehicles versus their final arriving time.

where d_{ei} is the distance driven by electricity by vehicle i, N is the total number of vehicles, and x is the AER of the PHEVs. This factor evaluates how effectively the PHEVs would utilize their AER. The curve of ERUF versus AER is also shown in Fig. 3. It is clear that the lower the value of x, the higher the ERUF.

Fig. 3 also demonstrates that UF and ERUF are in contrast. For example, for PHEV-60, 90% of the miles are driven by electricity and 10% by fuel, but only 50% of the available electricity (that was initially stored in the PHEVs) is consumed. Although a high AER causes displacement of a large amount of fuel, a large amount of potential electricity remains unused. The intersection of the two curves of Fig. 3 occurs at AER of 30, where the UF and ERUF are equal to 75%. As mentioned before, Fig. 2 indicates that 30 miles is also the most common daily driven mileage.

3) State of Charge (SOC): State of charge (SOC) is the percentage of charge remaining in the vehicle when it arrives. The SOC of a vehicle can be determined based on miles driven and the AER of the PHEV. SOC is expressed as a percentage of the total charge. Assuming that a fully charged PHEV-x drives x miles on electricity, the SOC of a vehicle driven by d miles is calculated as:

$$\mathrm{SOC} = \begin{cases} 100 \cdot \left(\frac{x-d}{x}\right), & d \leq x \\ 0, & d > x \end{cases} \tag{3}$$

where x is the AER of the PHEV and d is the total distance driven by the vehicle.

B. Vehicle Arrival Time Analysis

The second factor that forms the PCLP prism (see Fig. 1) is charging start time. The time at which vehicles are plugged in cannot be determined precisely, but end time of a vehicle trip provides some guidance. One can rely on the ENDTIME attribute based on the assumption that owners will plug in their vehicle once they arrive [11], [20]. The last arrival time of each vehicle is extracted from the 2001 NHTS data, and the values are shown in Fig. 4. The peak last arrival time is between hours 16:00 and 22:00.

C. Vehicles Type Analysis

The third side of the base of the PCLP prism (see Fig. 1), vehicles type, is determined from the VEHTYPE field in the 2001 NHTS. Types 1, 2, 3, and 4 (see Table I) are the focus of this study, and the number and percentage of each is shown in Table II. This table indicates that the most common vehicle is type 1. Different PHEVs require different amounts of energy based on their type and final SOC at the final arrival time. Based on [8], Table III proposes the energy required for four different types of PHEV-20 to finish their AER. By dividing the total kWh by 20 (PHEV-20), the required electrical energy per mile (kWh/mile) for each type of vehicle is obtained.

TABLE II
NUMBER AND PERCENTAGE OF EACH TYPE OF VEHICLE IN NHTS

Vehicle Type	1	2	3	4
Number	23,818	4,686	5,139	5,536
Percentage	60.85%	11.94%	13.1%	14.11%

TABLE III
ENERGY REQUIREMENT FOR FOUR TYPES OF PHEV-20

Type	Total kWh	kWh/mile
Compact Sedan	6.51	0.3255
Mid-size Sedan	7.21	0.3605
Mid-size SUV	8.75	0.4375
Full-size SUV	10.15	0.5075

In this study, the four PHEV types identified in Table III are mapped to VEHTYPEs 01 through 04 of the 2001 NHTS data (see Table I). Considering the number of kWh per mile of each vehicle type, the average energy per mile (epm in kWh/mile) is calculated as 0.37

$$\mathrm{epm} = \frac{\sum_{i=l}^{4}(N_i \cdot \mathrm{epm}_i)}{N} = 0.37 \tag{4}$$

where N_i is the number of type i vehicles, epm_i is kWh/mile of type i vehicles (see Table III), and N is the total number of vehicles. Some studies such as [17] considered this factor to be 0.22 kWh/km (or 0.354 kWh/mile).

IV. OTHER FACTORS ASSOCIATED WITH THE PCLP PRISM

A. Charging Level

After identifying the sides of the base of the PCLP prism, charging level, the height of the PCLP prism (see Fig. 1), is discussed here. Various studies have introduced several charging levels. For instance, [10] used a charging level of 2 kW without specifying the basis of this choice, and [11] used standard outlets of 110 V/15 A and 240 V/30 A, labeling them a normal charging level and a quick charging level, respectively. Another study, [13], used Belgian standard outlets (230 V, 4 kW). Table IV introduces two different sets of charging levels presented by EPRI and the SAE J1772 standard, both of which are applicable in the United States and used by many studies [21]–[23]. Moreover, the study in [24] introduced three levels, 1.44, 1.9, and 7.7 kW, an approach similar to that of EPRI.

Charging level has a direct effect on the charging time length. For example, using higher levels decreases the time required for charging. In addition, vehicles with higher SOC are charged in a shorter time. Based on charging level 1, charging schedule for four types of PHEVs is depicted in Table V, providing that the SOC of the vehicle when it is plugged in at the end of its

TABLE IV
CHARGING LEVELS

Level Standard	1	2	3
EPRI-NEC	120 VAC, 15 A (12 A),1.44 kW	240 VAC, 40 A, single-phase	480 VAC, three-phase, 60 to 150 kW
SAEJ1772	120 VAC, 12 A, single-phase, 1.44 kW	208-240 VAC 32 A, single-phase, 6.66-7.68 kW	208-600 VAC, 400 A, three-phase, > 7.68 kW

TABLE V
POWER REQUIREMENT (kW) FOR FOUR TYPES OF PHEV-20 CHARGED AT LEVEL 1

Hour Type	1st	2nd	3rd	4th	5th	6th	7th	8th	Total kWh
01	1.4	1.4	1.4	1.4	0.91	0	0	0	6.51
02	1.4	1.4	1.4	1.4	1.4	0.21	0	0	7.21
03	1.4	1.4	1.4	1.4	1.4	1.4	0.35	0	8.75
04	1.4	1.4	1.4	1.4	1.4	1.4	1.4	0.35	10.15

last daily trip is zero. The total required kWh is broken down to 1.4 kW per hour. Based on this schedule, the power grid provides 1.4 kW of power per hour to charge a PHEV-20 through a 120 V/15 A plug until it becomes fully charged. This table was developed in study [8] as well.

B. Percentage of Energy Needed (PEN)

PEN is the proportion of total energy needed to fully charge the battery. Hence, the PEN of each PHEV is the complement of its SOC

$$\mathrm{PEN} = 100 - \mathrm{SOC}. \tag{5}$$

Two factors play a crucial role in determining the energy required to charge a PHEV: vehicle type and PEN. Table V shows the total energy required for each PHEV based on its type. The SOC and consequently the PEN of each vehicle can be estimated based on miles driven before arrival, as described in Section III and based on (3).

C. Charging Schedule

Considering the PEN of each vehicle, the charging schedule can be determined based on either of the following two approaches: 1) power scaling (or constant time) and 2) time scaling (or constant power).

1) Power Scaling (Constant Time) Approach: This approach scales the electric power delivered to each vehicle at each hour based on its PEN. In other words, the charging time is held constant, and the power delivered during each hour is scaled. The PEN is multiplied by each value shown in Table V in the row corresponding to the appropriate vehicle type. For example, if a type 2 vehicle is driven 12 miles, then its PEN is 60%. Therefore, the charging schedule for this vehicle is as shown in Table VI.

2) Time Scaling (Constant Power) Approach: This approach considers the maximum power based on the charging level that is available at each time and scales the total energy required. Vehicles are charged based on the maximum available power. Therefore, the PEN is not applied to the total charging power. For the example of the type 2 vehicle with a 60% PEN, 0.6 is multiplied by 7.21 kWh which yields 4.326 kWh. During the first three hours of charging, the most power possible (1.4 kW) is delivered to the battery and during the last hour, the remaining energy is transferred to it. Table VI shows the charging schedule.

TABLE VI
CHARGING SCHEDULE FOR A TYPE 2 PHEV-20 CHARGED AT LEVEL 1 BASED ON POWER SCALING AND TIME SCALING

Hour Type		1st-3rd	4th	5th	6th	Total kWh
02 (PEN = 100%)		1.4	1.4	1.4	0.21	7.21
02 (PEN = 60%)	Power Scaling	0.84	0.84	0.84	0.126	4.326
	Time Scaling	1.4	0.126	0	0	4.326

In the time scaling approach, a more accurate analysis with a smaller round-off error relies on 15-min time intervals. In other words, we divided each hour into four 15-min intervals. For the above example, the total required energy is calculated in kW-quarter ($4.326\ \mathrm{kWh} * 4 = 17.304\ \mathrm{kW\text{-}quarter}$), then dividing the result by 1.4 kW ($[17.304/1.4] + 1 = 13$) gives the total number of 15-min intervals during which the vehicle is charged. Therefore, during the first 12 quarters, 1.4 kW of power is delivered, but during the last 15-min interval ($17.304 - 12 * 1.4 =$) 0.504 kW of power must be delivered.

V. DEVELOPING THE PCLP CURVES

This section represents developing the PCLP curves based on both power scaling and time scaling approaches for PHEV-20, 30, and 40. The PCLPs are for vehicle types 1, 2, 3, and 4 and calculated based on the final arrival time of the day. The total power demand at any given time is equal to the power required by vehicles arriving at that time plus the power required by vehicles that have arrived earlier but have not been totally charged yet. The paired PCLP curves (developed based on the power scaling and time scaling approaches), for 40 000 vehicles, and for three cases of PHEV 20, 30, and 40 are depicted in Fig. 5. For PHEV-30 and 40, similar procedures are used and the same assumptions are made. Table VII shows that the charging schedules based on the energy required by a PHEV-30 and a PHEV-40 are 1.5 and 2 times that for a PHEV-20, respectively.

Fig. 5 demonstrates that both charging schedules lead to almost identical PCLPs in case of PHEV 20. However, by increasing the AER of PHEVs, the differences of the PCLPs developed based on the time scaling and power scaling approaches become apparent. According to the PCLP of PHEV 40, the PCLP resulted by power scaling is better than that resulted by time scaling because it has a lower peak and the peak time is shifted to the right. This figure also shows that the peak time starts at 18:00 hours.

1) Battery Utilization Factor (BUF): This factor indicates the fraction of total stored electricity consumed. At the beginning of all trips, all vehicles are assumed to be fully charged;

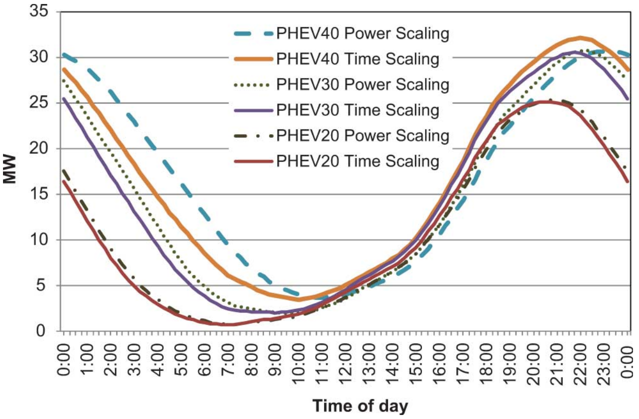

Fig. 5. Different PCLPs based on different AERs and charging schedules for level 1 charging.

TABLE VII
ENERGY REQUIRED (kWh) FOR FOUR TYPES OF PHEV-30 AND PHEV40

Hour / Type	PHEV 30	PHEV 40
01	9.765	13.02
02	10.815	14.42
03	13.125	17.5
04	15.225	20.3

TABLE VIII
COMPARING RESULTS FOR PHEV-20, 30, AND 40

	PHEV-20	PHEV-30	PHEV-40
Total miles driven from electricity	671,888	903,423	104,409
UF	0.522	0.703	0.812
ERUF	0.856	0.767	0.665
Consumed total electrical energy (kWh)	249,469.9	336,026.5	389,086.3
Energy growth rate based on PHEV-20 (%)	–	34%	56%
BUF	0.859	0.771	0.669
Peak load (MW)	25	30	32
Peak time	20:30	21:45	22:00

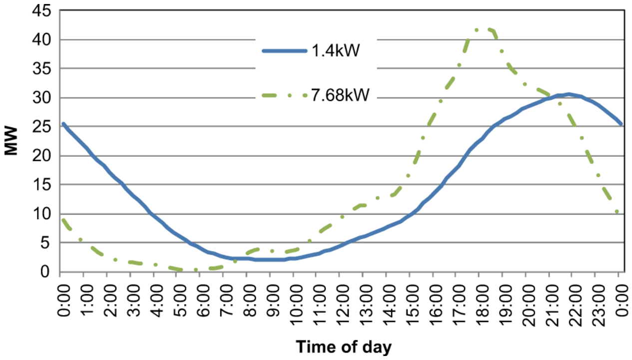

Fig. 6. Comparing PCLPs of PHEV-30 based on charging levels of 1.4 and 7.68 kW.

therefore, the potential electrical energy is the sum of the electricity stored in the batteries. The batteries are depleted based on the miles driven. BUF determines the percentage of the potential electricity consumed. Therefore,

$$\mathrm{BUF} = \frac{E}{\sum_{i=l}^{4} (N_i \cdot E_i)}. \tag{6}$$

E, the total energy consumed, is calculated based on the area under the PCLP curve. N_i, the number of vehicles of type i, is available in Table II, and E_i is the electrical energy stored in a type i vehicle in its fully charged state which is available in Table III. The concepts behind *BUF* and *ERUF* are almost similar. *ERUF* is formulated based on mileage and *BUF* is based on energy. The values of these two factors (see Table VIII) will be exactly the same provided that all vehicles are the same type.

2) Comparing PCLPs of Different AERs: Based on factors defined above, this section compares the PCLPs and their associated results, shown in Table VIII, for PHEV-20, 30, and 40. As this table shows, by increasing AER, UF is improved, but other parameters are negatively affected. The percentage of energy growth rate, however, shows that this growth is not linear, and doubling the AER (from 20 to 40) does not double the energy required, but increases it just by 56%.

Fig. 5 visualizes the differences among PCLPs. As can be seen, in most cases, the PCLP of PHEV-40 overlies those of PHEV-30 and PHEV-20s. Nevertheless, from 11:00 to 17:00, the three PCLPs are almost the same. In addition, the windows of peak times of all three PCLPs are between hours 18:00 and 23:00. Moreover, the PCLP of PHEV-30 is closer to that of PHEV-40, rather than being in the middle, so that between hours 11:00 and 19:00 these two PCLPs are almost the same.

VI. IMPROVING POLICIES

Since PHEVs are considered as flexible loads, charging policies are applicable to them. Utilities are seeking a flat domestic load profile. Therefore, most of the charging policies for PHEVs presented in various studies follow two main objectives which are shaving the peak of PCLP and shifting the peak time to late hours. Further, there are two key variables needed in order to define different policies. They are the charging start time and charging level.

A. Higher Charging Levels

As mentioned in Section IV, several charging levels have been proposed in previous studies. This section describes three PCLPs, each based on a different charging level. These PCLPs are constructed based on time scaling approach and for PHEV-30s because the most common driving distance is about 30 miles, as indicated in Figs. 2 and 3. Fig. 6 shows the PCLPs of PHEV-30 for charging levels of 1.4 and 7.68 kW.

As can be seen from Fig. 6, when the charging level increases, the peak point moves to the left. With higher charging levels and, therefore, shorter charging times, vehicles are charged faster. Therefore, the peak point becomes closer to the peak point of the arrival time which is about 18:00, as shown in Fig. 4. Moreover, the peak rises as the charging level rises. Both of these behaviors of the PCLPs are undesirable. Therefore, regulatory policies are required to ensure that the peak power demand does not grow as well as the peak time does not shift to the left. The following three policies are suggested here.

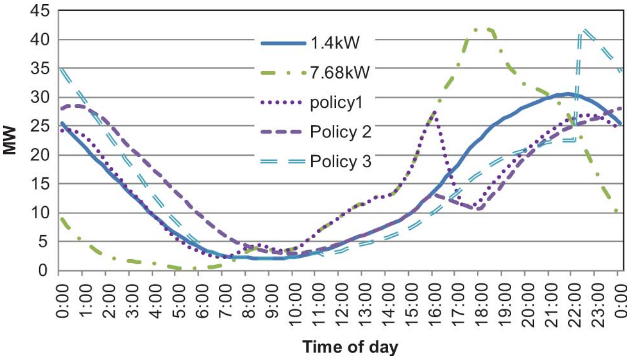

Fig. 7. Comparing PCLPs of PHEV30-based various charging levels and policies 1, 2, and 3.

B. Policy 1

As discussed above, increasing the charging level pushes the PCLP to the left and also the peak value rises. To avoid this, one could make sure that vehicles arriving during off peak times should be charged at high levels, and those arriving during peak hour times should be charged at low levels. For example, vehicles arriving between 0:00 and 16:00 would be charged at 7.68 kW, while others would be charge at 1.4 kW. Fig. 7 shows the changes in the PCLP when this policy is enforced. As shown, there are two peak points for the PCLP when policy 1 is enforced, and they are drifted in opposite directions. Further, the power demand at these two new peaks is lower than the peaks in the other two previous PCLPs.

C. Policy 2

Another way of shifting the peak point is not to charge vehicles right at their arrival time. For instance, vehicles arriving after 16:00 would have to wait for 2 hours to start charging. Fig. 7 shows the PCLP when this policy is enforced, based on a charging level of 1.4 kW. Although the amount of peak enforcing this policy is higher than policy 1, it is still lower than the peak value of the uncoordinated PCLPs. Moreover, the peak point of this policy is located after midnight which is the most promising scenario.

D. Policy 3

Electricity price is an effective motivation for shifting flexible loads such as PHEVs to off-peak hours. Policy 3 is price-based and defined based on a scenario described in [25]. Table IX shows the electricity tariffs from Dominion Virginia Power (DOM) in the summer [25]. The scenario assumes that if the time of use price is increased by 100% from its corresponding flat rate, 20% of drivers are willing to shift their charging time. Table IX represents a 130% of increase during the peak hours over the flat rate. Therefore, in this policy 26% of PHEVs, arriving between hours 11:00 and 22:00, are not plugged in immediately. Instead, they are plugged in after 22:00. Fig. 7 shows the PCLP resulted by this policy which is developed based on the charging level of 1.4 kW. In this policy, there is a large peak at 22:00 when the price decreases.

TABLE IX
TIME OF USE AND FLAT RATE FROM DOMINION VIRGINIA POWER IN THE SUMMER

Pattern	Period	Price Based on Time of Use ($/kWh)	Flat Price ($/kWh)
On-peak	11:00-22:00	0.15085	0.06507
Off-peak	22:00-11:00	0.01514	

E. Discussion

According to the PCLP curves for different policies in Fig. 7, policies 2 and 3, having peaks after 21:00, are the most promising ones. Based on the price and domestic load profile, different policies can be defined; however, enforcing the policies has short-term (immediate) and long-term (dilatory) costs. More restrict policies usually cost more. The up-front cost includes establishing sensors and the communication network. The long-term cost is the impact of such policies on PHEVs popularity. It is worth noting that these PCLPs are developed for 40 000 PHEVs, considering their miles driven (required energy) based on the NHTS data. Therefore, for other numbers of PHEVs the curves can be scaled.

VII. CONCLUSION

In order to estimate the impact of PHEVs on the electricity demand profile, more accurate data is needed. This paper extracts real data from the NHTS to develop PHEV load profiles. As the data pool is large and it is also distributed over a broad enough portion of the U.S., it can be used for developing stochastic analyses. It was found that the all-electric range of PHEVs has a direct affect on their aggregated load profile. Such results can be used for predicting variation in total load demand in a specific region due to the penetration of PHEVs. Moreover, this work suggests several charging policies and predicts their impact of the PHEV load profile. Finally, the developed load profiles can be used for examining vehicle-to-grid potentials.

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