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Electricity costs for an electric vehicle fueling station with Level 3 charging

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HIGHLIGHTS

- The cost of supplying electricity to a Level 3 PEV refueling station is evaluated.
- Most PEVs used for shopping and work trips are not eligible for Level 3 refueling.
- Demand charges for the station exceed $1.00 per kW h when PEV use is low.
- Increasing PEV use and parking management can reduce demand charges.
- Increasing refueling rate raises demand charges, but not number of fueled PEVs.

ARTICLE INFO

ABSTRACT

Three major perceived disadvantages of plug-in electric vehicles are limited driving range, slow recharge time, and availability of charging infrastructure. While increasing PEV range through larger and more efficient batteries may assuage concerns, public PEV charging infrastructure is required to increase the feasibility of widespread PEV adoption. In particular, Level 3 electric vehicle supply equipment (EVSE) can refuel a depleted PEV battery to 80% state of charge in half an hour. This work examines details of exact electric utility costs incurred by the operator of a public Level 3 EVSE used to refuel PEVs that perform two of the most common types of travel: driving to work and driving to shop. Both 44 kW and 120 kW EVSE refueling rates are considered. Utility rate models for Southern California are used to determine the cost of electricity. Cooperative game theory is then used to determine of the electrical demand charge incurred by each individual PEV that is charged. Results show that approximately 28–38% of typical travel results in a battery state of charge low enough to be eligible for Level 3 refueling. At low PEV total use, electric utility demand charges comprise an extremely high portion of electricity costs. Increasing PEV total use decreases demand charge contributions to the electricity costs, but must be coupled with parking management, such as valet parking, when dwell time at the destination is long (e.g., at work). Total energy costs to operate 44 kW Level 3 EVSE exceed $1 per kW h at low PEV use, but decrease as PEV use increases. The lowest costs occurred at the highest level of PEV use examined, resulting in a total energy cost of approximately $0.20 per kW h during the summer and $0.13 per kW h during the winter. Parking management may be avoided if multiple EVSE are installed, which is particularly effective in improving access for travel with a short dwell time (e.g., while shopping). Increasing EVSE refueling rate improves access to PEV refueling only if parking management is implemented, but always increases demand charges.

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1. Introduction

Three major perceived disadvantages of plug-in electric vehicles (PEV) are limited range, slow recharging time [1], and availability of charging infrastructure [2,3] . Numerous research efforts have

been made toward improving PEV range and charging infrastructure in an effort to overcome these perceived barriers to widespread PEV adoption [4]. Improvements to infrastructure have led to the installation of three types of electric vehicle supply equipment (EVSE) across the United States: the Level 1 (3.3 kW output), Level 2 (up to 14.4 kW output but typically 6.6 kW), and Level 3 EVSE (up to 240 kW output but typically 44–120 kW) [5]. Research focused on Level 1 and 2 type chargers has shown that

while increasing battery size may assuage concerns regarding PEVs, some public EVSE capable of providing power beyond what is available from a typical electric socket (i.e., Level 3 charging) can increase the feasibility of widespread PEV adoption [6]. As a result, many aspects of Level 3 EVSE are currently being investigated.

The integration of EVSE with the electrical grid introduces new challenges to operating and maintaining the electrical grid [7]. Grid reliability must be considered when selecting locations for EVSE installation [8]. Once the EVSE is installed, electric grid reliability may be reduced for densely populated areas as PEV adoption increases [9,10] and voltage stability may also be reduced in areas of high PEV use [11]. In distribution circuits, losses are greater for secondary voltages than primary voltages [12]. However, other work has shown that charging plug-in hybrid vehicles within residential distribution circuits has little effect on residential transformer life unless drivers start charging as soon as they arrive at home with Level 2 EVSE [13]. Also, [14] showed that unscheduled PEV charging will only increase peak demand by 1% for some regions in the United States if moderate grid growth and improvement occurs.

The optimization of PEV charging is another area that has received significant research attention. Research based on the Ireland grid has shown that charging PEVs at night versus during the day can result in lower greenhouse gas emissions and cost [15]. When controlled properly, PEV charging can also be used to improve overall grid performance [16–19]. Electricity cost to charge PEVs can also be minimized [20–23], while also minimizing emissions [24] or grid losses [25] with smart PEV charging. Other work has looked at the possibility of utilizing PEVs connected to EVSE to help minimize building energy costs through peak shaving and load shifting [26].

The optimal siting of EVSE has also been explored in the current literature. This problem has been formulated as a mixed integer nonlinear program that minimizes initial investment cost and grid losses [8], and both investment and operational cost [27]. Several integer programs have been proposed that optimize EVSE placement such that total power losses in the grid are minimized [28], customer coverage is maximized [29,30], PEV refueling is maximized subject to an EVSE investment limit [31], and transportation distance to the EVSE is minimized [32]. Corresponding work has focused on evaluating the economics and feasibility of public EVSE. Research focused on plug-in hybrid vehicles found that making public EVSE ubiquitous increases the overall cost of PEV operation substantially [33]. However, some public EVSE is required to maintain high feasibility for PEVs [6]. Other work has focused on developing pricing methods for public EVSE to minimize cost of operation [34] while reducing congestion at individual charge points [35], or to recover investment cost while remaining cost-competitive with conventional gasoline vehicles [36].

As of 2015, approximately 70% of all public PEV charging outlets are Level 2, 21.5% are Level 1, and 8.5% are Level 3 [37]. Despite being the least adopted charger type, Level 3 EVSE are capable of charging a PEV battery up to 80% state of charge quickly [5]. Currently high investment cost and uncertainty associated with PEV adoption rates make investment in fast charging equipment risky [38]. If this risk can be reduced and the number of Level 3 EVSE increases, it is important to understand the costs associated with operating a Level 3 charger in addition to understanding optimal placement, charging strategy, grid impacts, and pricing methods.

The current analysis determines the cost of electricity to supply an individual PEV with electricity through a Level 3 charger. Other costs, such as investment and maintenance costs, also influence the decision to invest in and operate public Level 3 EVSE. However, these costs are straightforward to analyze. Thus, the current work conservatively analyze the more challenging to estimate cost of

electricity of Level 3 EVSE operation. If these costs are too high then investment in this technology will not occur regardless of reductions in other costs. The US National Household Travel Survey (NHTS) was used to build a PEV travel model [39]. Charging scenarios that span most types of public EVSE operation were built and combined with the vehicle travel data to produce the electrical demand created by Level 3 charging. Models of PEV charging rates were then developed and used to determine the cost of meeting the total electrical demand. Finally, the individual cost to supply each PEV with electricity through Level 3 charging was determined using the Shapley value. Travel data and utility rates from California (with a focus on Southern California) are used. The goal of this work is to determine the cost to purchase electricity from a utility to supply electricity to a public Level 3 EVSE with careful consideration of existing electric utility rate structures, as well as the cost to refuel individual PEVs. Keep in mind that this analysis assumes that all PEVs that can be refueled using Level 3 EVSE are refueled if possible, conservatively presenting the most supportive case for using public Level 3 EVSE to power our most common types of trips.

2. Models

Models were developed to determine the monthly electrical demand and cost of electricity for a Level 3 fast charging station. These models consisted of a travel model, an electric utility cost model, and a Level 3 charging station model. Using these models, the cost of the total load supplied to all PEVs and the cost incurred by each individual PEV can be calculated. Fig. 1 shows a flowchart describing the simulation approach used in this study. Obround shapes represent model inputs using real data, squares represent built models or data selection processes, and diamonds represent model outputs.

2.1. Travel model

The purpose of the travel model is to determine the amount of electricity used by each PEV during travel. Since data on Level 3 charging stations was not readily available, the travel model was produced by generating vehicle travel profiles using probability density functions based upon PEV sales information and travel survey data. The PEV sales information was used to determine the model of PEV used for travel. The travel survey data was also used to determine day of travel, time of arrival, time spent at destination (or dwell time), and vehicle miles traveled. This information was then used to determine the battery state of charge.

2.1.1. Type of PEV

Four PEV models capable of fast charging that are available today are the Nissan Leaf, the Tesla Model S, the Chevy Spark, and the Mitsubishi i-MiEV. The battery size [40], vehicle range [41], and cumulative sales in the United States since 2010 [42] for these four vehicles are shown in Table 1.

It was assumed that any car utilizing a Level 3 charger would be one of these four cars, and that the chance of any of these cars using the station could be determined using the probability distribution created by the number of each model sold in the United States. Using PEV sales, a probability density function was created to determine what type of PEV arrived at a Level 3 charging station to be charged.

For a given number of total PEVs visiting the Level 3 charging station, the probability density function was then used to determine the model of each vehicle to be charged. Using the battery size and range information associated with each PEV, the trip
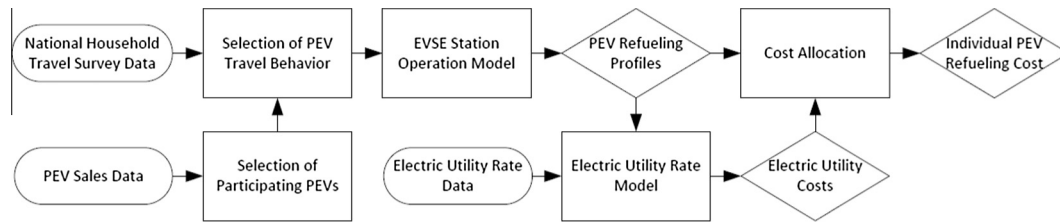
Fig. 1. Flowchart Level 3 EVSE electrical utility cost and cost allocation model.

Table 1
Battery size [40], vehicle range [41], and cumulative sales since 2010 [42] for PEVs compatible with Level 3 charging.

PEV model	Vehicles sold since 2010	Battery size (kW h)	Range (miles)
Nissan Leaf	47,306	24	84
Tesla Model S	25,141	60	208
Mitsubishi i-MiEV	1721	16	62
Chevrolet Spark	832	20	82

parameters (as are described in Section 2.1.2) were used to determine how much electricity was used during travel.

For many of the PEVs listed in Table 1, Level 3 EVSE compatibility is optional and typically increases purchase cost. The cumulative sales data presented in Table 1 undoubtedly include PEVs purchased without the Level 3 option. However, since sales data cannot be conveniently differentiated between PEVs capable and incapable of Level 3 charging, this work assumes that the sales data is representative of all purchased PEVs that are Level 3 compatible.

2.1.2. Travel information

The 2009 U.S. National Household Travel Survey (NHTS) was used to determine the travel information [39]. The NHTS data was filtered so that only trips occurring in California were considered. Level 3 charging is not typically associated with PEV charging at home and approximately 92% of all Level 3 chargers are located at public locations [37], so all travel data that listed "home" as the destination were excluded. Finally, the travel data were separated by destination. Of the remaining travel data, the four most common trips in order of most to least common were for shopping (30.1%), work (15.7%), getting or eating a meal (12%), and pick up or drop off someone (11.7%). For these four data sets, the following parameters were extracted: day of travel, time of arrival at destination, time spent at destination (or dwell time), and vehicle miles traveled from the beginning of the day on all trips leading to the destination. These four parameters are shown separated by season (winter and summer) for shopping travel in Fig. 2 and for work travel in Fig. 3. The individual parameters have little to no correlation with all other parameters and were considered to be independent of each other for all types of travel.

As shown in Fig. 2, travel for shopping primarily occurs between 8 a.m. and 6 p.m., occurs frequently throughout the week, results in short dwell times, and involves travel close to the drivers origin. As seen in Fig. 3, travel for work occurs primarily in the morning, occurs during the work week with few weekend trips, results in long dwell times, and involves travel that is further from a driver's origin than shopping travel.

Qualitatively, the distance traveled and dwell time properties of the travel data to pick or drop off someone are similar to shopping travel data, while the day of travel property is similar to work travel with an increase in weekend day of travel. Data for getting or eating a meal travel are also similar to shopping data except for increasing travel during the weekend and an increased number

of trips resulting in a dwell time between 30 and 60 min. In this case, day of arrival for travel to get or eat a meal occurs most frequently during the weekend. However, since all travel to pick up or drop off someone and three of the four getting or eating a meal parameters are similar to either shopping or work travel and to simplify the analysis, only shopping and work travel were used in the travel model.

The NHTS data for shopping and work travel were used to create probability density functions for the four independent parameters. These probability density functions were then used to create travel information for each PEV model that arrives at the Level 3 EVSE. Coupling the vehicle miles traveled with the type of PEV, the amount of electricity used during travel was determined. If the vehicle miles traveled produced by the probability density function was ever greater than the range of the vehicle model, the vehicle miles traveled were reduced to the range of the PEV (i.e., assuming some refueling must have previously taken place).

2.2. Utility rate model

In California, public PEV charging equipment is typically supplied under either a PEV charging rate or the otherwise applicable commercial/industrial rate. These rates consist of fixed, energy (aka volumetric), and demand charges. Under most California rates, fixed charges are small relative to energy and demand charges. Both energy and demand charges have non-time of use (non-TOU) and time of use (TOU) components and can vary between summer and winter seasons. Energy charges depend upon the total amount of energy consumed. If non-TOU rates are applicable, all energy is purchased at the same rate. If TOU rates are applicable, energy is purchased at the cost of electricity as determined by the utility rate structure during the time of consumption. Demand charges are determined by the largest demand that is recorded during a period. Non-TOU demand charges are determined by the maximum demand during the entire billing period while TOU demand charges are determined by the maximum demand during a specific time of day. TOU energy and TOU demand charges are determined by energy consumption or power demand during individual peak periods.

The largest utility in Southern California is Southern California Edison (SCE) [43]. If maximum demand is under 500 kW, two PEV specific rates are applicable: TOU-EV-3 if maximum demand is under 20 kW [44], TOU-EV-4 if maximum demand is between 20 kW and 500 kW [45]. Otherwise, the TOU-8 rate is applicable [46].

For all three rates, summer is defined as June 1st through October 1st and winter is all other time. TOU-EV-3 and TOU-EV-4 define summer and winter on-peak hours as from 12:00 p.m. to 6:00 p.m., mid-peak as 8:00 a.m. to 12:00 p.m. and 6:00 p.m. to 11:00 p.m., and off-peak hours as all other time and weekends. TOU-8 defines summer on-peak hours as from 12:00 p.m. to 6:00 p.m., mid-peak as 8:00 a.m. to 12:00 p.m. and 6:00 p.m. to 11:00 p.m and off-peak as all other time and weekends. TOU-8
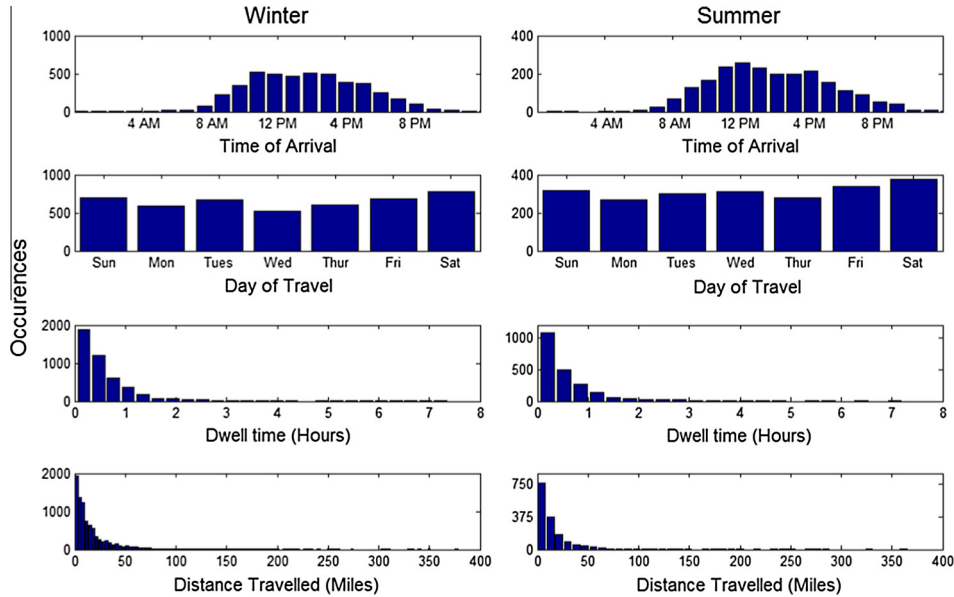
Fig. 2. NHTS arrival time, day of travel, dwell time, and distance traveled data for shopping trips in Southern California.
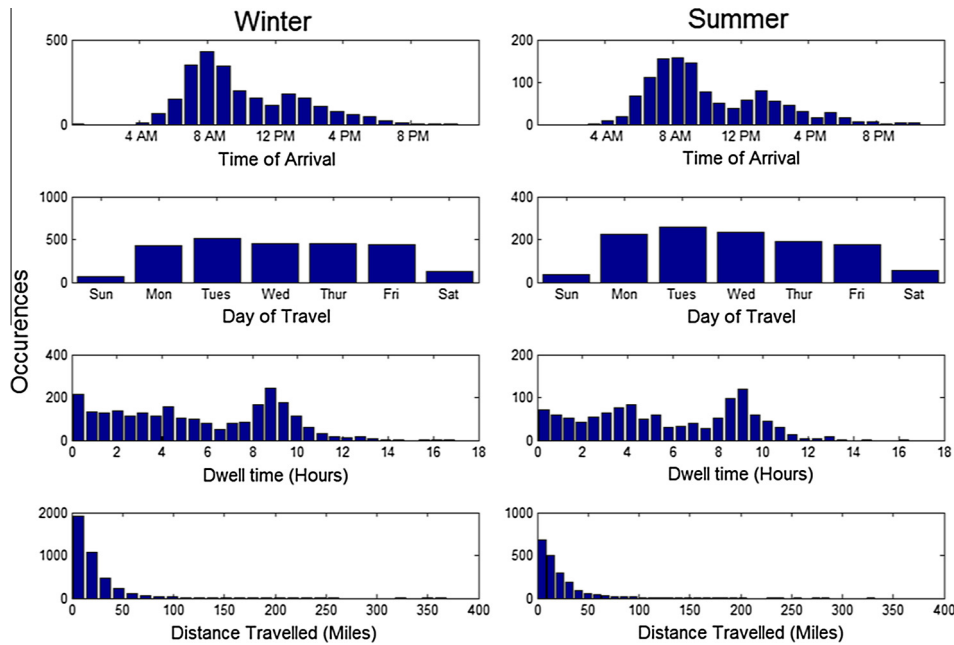

Fig. 3. NHTS arrival time, day of travel, dwell time, and distance traveled data for work trips in Southern California.

Table 2
Electric energy and demand charges for TOU-EV3, TOU-EV-4, and TOU-8 rate structures of Southern California Edison for 2015.

Rate	TOU-EV-3	TOU-EV-4	TOU-8
Energy charges ($/kW h)			
Summer on-peak	0.36386	0.29033	0.13711
Summer mid-peak	0.17469	0.12248	0.08308
Summer off-peak	0.09485	0.05356	0.05938
Winter on-peak	0.16221	0.10763	N/A
Winter mid-peak	0.14291	0.09402	0.08487
Winter off-peak	0.10374	0.06244	0.06473
Demand charges ($/kW)			
Summer on-peak	N/A	N/A	23.74
Summer mid-peak	N/A	N/A	6.55
Summer non-TOU	N/A	13.2	14.88
Winter non-TOU	N/A	13.2	14.88

defines winter mid-peak as 8:00 a.m to 9:00 p.m., off-peak as all other time and weekends, and does not use an on-peak charge. Energy and demand charges for the three rates are shown in Table 2 for the year 2015. The TOU-8 model was previously used in [47,48].

2.3. Level 3 charging station operation model

While much research is focused on developing optimal charging strategies for public EVSE, PEV charging is typically determined by availability of charging equipment and systems or rules used to increase the number of PEVs charged. These systems and rules include, but are not limited to, charging time limits and text messaging services that notify customers when PEV charging is finished.

Instead of attempting to capture any single type of system or EVSE operation strategy, two forms of EVSE operations are used to span the potential impacts of all systems or sets of rules that typically govern PEV charging. The "conventional parking" and "valet parking" forms of operation are selected and described below.

A typical gasoline fuel dispenser works with most conventional vehicles, regardless of brand or model, Level 3 EVSE is not necessarily compatible with all Level 3 capable PEVs. Numerous types of Level 3 EVSE exist, each with a unique power rating, PEV connector, and set of PEV models that are compatible. Even though adaptors that allow connection between previously incompatible PEVs and Level 3 EVSE are being introduced, a typical PEV can only be charged with a single type of Level 3 EVSE. As a result, any specific Level 3 EVSE can only provide charging to a fraction of Level 3 compatible PEVs.

Despite this compatibility issue, the following operation strategies assume that either a standard PEV connection has been adopted or EVSE adapters are available, allowing for all Level 3 compatible PEVs to charge using the Level 3 EVSE examined. This assumption allows for the full fleet of Level 3 EVSE compatible PEVs to have access to the tested refueling station configurations. Two different EVSE power ratings are explored (44 kW and 120 kW) corresponding to the range of Level 3 charging rates for vehicles currently available in the market. This work considers EVSE powered by a dedicated utility meter (electrical demand is determined only by PEV refueling).

2.3.1. Conventional parking operation

Conventional parking assumes that no rules or systems are implemented regarding EVSE operation. If a PEV arrives at an available EVSE equipped parking spot, the PEV will be parked and the battery charged to the desired level. If the driver returns to leave before the PEV is finished charging, the PEV is partially charged and the EVSE parking spot is vacated. Otherwise, the PEV is fully charged and the EVSE equipped parking spot is occupied until the drivers dwell time is finished. All other PEVs that arrive while the EVSE parking spot is occupied leave to find another spot and are not charged using the EVSE at that particular charging station.

2.3.2. Valet parking operation

Valet parking assumes that some system or technology is used to remove a PEV once charging is complete. According to this form of operation, if a PEV arrives at an available EVSE equipped parking spot, the PEV will be parked and the battery charged until either the battery is charged to the desired level or the driver returns to leave. If another PEV arrives while the EVSE equipped parking spot is occupied, the new PEV is queued and connected to the EVSE as soon as the currently charging PEV finishes charging or leaves. However, if the dwell time of the queued PEV is shorter than the time to charge the current PEV, the queued PEV leaves without being charged. Partial charges are also allowed under the valet parking scenario. Note that the assumptions of this valet parking scenario maximize the potential use of the EVSE installed, thus spanning the other potential methods of EVSE and PEV charging operations.

2.4. Cost to fuel individual cars

The total electrical utility cost can easily be calculated by using the applicable rate structure model as described in Section 2.2. The cost produced by this model is the aggregated cost to charge a set of PEVs during a winter or summer month with Level 3 EVSE. This total cost model, however, does not resolve the marginal cost to charge each of the individual PEVs in each scenario.

Determining the cost of charging individual PEVs using pubic Level 3 EVSE can be viewed as a cooperative game with all utility costs being allocated to the charging of the individual vehicles. While individual drivers may not work together to minimize total electricity cost for the refueling station, they may cooperate so that they each pay a fair price to refuel. No customer wishes to subsidize the charging of another customer's PEV, so a method that efficiently and fairly allocates electric utility cost must be used. One possible solution to this problem is the Shapley value [49]. The Shapley value is not applied in real time. Rather, it is applied a posteriori to determine the fair share of total electricity charges for each customer. This method can be used to assist with the design and evaluation of PEV customer refueling rates used to charge drivers to use public Level 3 EVSE by determining if a rate fairly allocates electric utility charges.

The Shapley value is a method to determine the "fair" allocation to a coalition of players. In the case of PEVs charged using public EVSE, the coalition of players, as defined by set N of n players, are all of the PEVs that are charged. S is any coalition of PEVs that form a subset of N. The function $\upsilon(S)$ is the characteristic function, which determines the cost incurred by the subset S. The characteristic function for this work is either the utility demand or energy charge. With these definitions, the Shapley value can be found using the following equation to find the allocation φ_i of player (or PEV) i:

$$\varphi_i(i) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!(n-|S|-1)!}{n!} (\upsilon(S \cup \{i\}) - \upsilon(S))$$

The Shapley value is deemed a fair allocation due to all costs being allocated, any two participants with the same contribution (same total electric energy used to recharge their PEV) receive the same allocation, participants who contribute nothing receive no allocation, and scaling the cooperative game up by any real number a results in the Shapley value of each member being scaled by a. Note that the allocation of demand charges is analogous to the runway problem explored by Littlechild and Owen [50], resulting in a simplified calculation of the Shapley value that is determined by the following solution:

1. Divide the cost of providing the minimum power for which a demand charge is incurred (20 kW) by all PEVs that incur a demand of 20 kW or greater.
2. Divide the incremental cost of providing power to the next smallest power demand incurred by all PEVs that draw at the next smallest power demand or greater.

Step two is repeated until the incremental cost created by the PEVs that create the largest power demand is divided equally among all PEVs that create this level of demand. Note that while the Level 3 charging creates a demand of over 20 kW, any PEV or group of PEVs that are fueled by Level 3 EVSE but do not create an aggregated demand that averages 20 kW or greater for a 15 min period receives no allocation for the given 15 min period because this level of charging would fall under TOU-EV-3, which has no demand charge.

3. Level 3 EVSE analysis

The travel model described in Section 2.1 was used to produce a set of trips made by Level 3 compatible PEVs. The number of trips considered per simulation ranged from 50 PEV trips per month to 10,000 PEV trips per month. Using the assumption that the PEVs started each day with a fully charged battery, the end state of charge was determined. The trips were then separated between PEVs with a battery state of charge greater than and less than

80%. All PEVs with less than an 80% state of charge were charged according to the Level 3 EVSE operation model as described in Section 2.3 The resulting electricity demand profile was used with the utility rate model described in Section 2.2 and cost allocation model described in Section 2.4 to determine the total utility cost and demand charge cost incurred by each individual PEV.

These simulations and calculations, described above, were performed for Level 3 EVSE with two power ratings; 44 kW and 120 kW. For both the 44 kW and 120 kW charger, one, two, four, and eight EVSE supplied by a single utility meter were tested. Under these scenarios, the applicable utility rate structure is either TOU-EV-3 or TOU-EV-4, depending upon the maximum power demand.

The results of this work are the averaged results of numerous simulations. At each given number of PEV trips per month, the probability density functions described in Section 2.1 are used to generate a randomly selected set of trips performed by PEVs. Using the randomly generated set of PEV trips, a charging profile is then determined using the Level 3 charging station operation model described in Section 2.3. The resulting electrical load profile is then combined with the utility rate model as described in Section 2.2 to find the cost of electricity. This process is repeated until the average cost of electricity of all simulations performed at the given number of PEV trips per month experiences negligible changes due to an additional simulation. At this point, no additional simu-

lations are performed for a given number of PEV trips per month. Variation in energy and demand charge cost results across the different simulations is presented in Section 3.3.

3.1. Single 44 kW EVSE results

A single Level 3 44 kW charger servicing either shopping or work trip types is examined in Sections 3.1.1 and 3.1.2 respectively. Increasing both charger power and number of chargers per electricity meter is explored in Section 3.2.

3.1.1. Shopping travel

Assuming that all PEVs start each day with a full battery, approximately 28% of all winter and summer shopping trips result in arriving with less than an 80% state of charge. Fig. 4 shows example load profiles for a Level 3 charging station using both conventional and valet parking. The same set of PEV trips were used to simulate demand profiles for conventional and valet operations. The load profiles range from 27 to 2787 PEV shopping trips serviced per month by the charging station. These values correspond to a total number of PEV trips of 100–10,000 per month. The allocated cost for each time step is also included in Fig. 4. The total cost includes the demand charge allocation as well as the energy charge cost using the cost of energy at the time of purchase. At low levels of PEV use, the demand profiles are similar between conventional
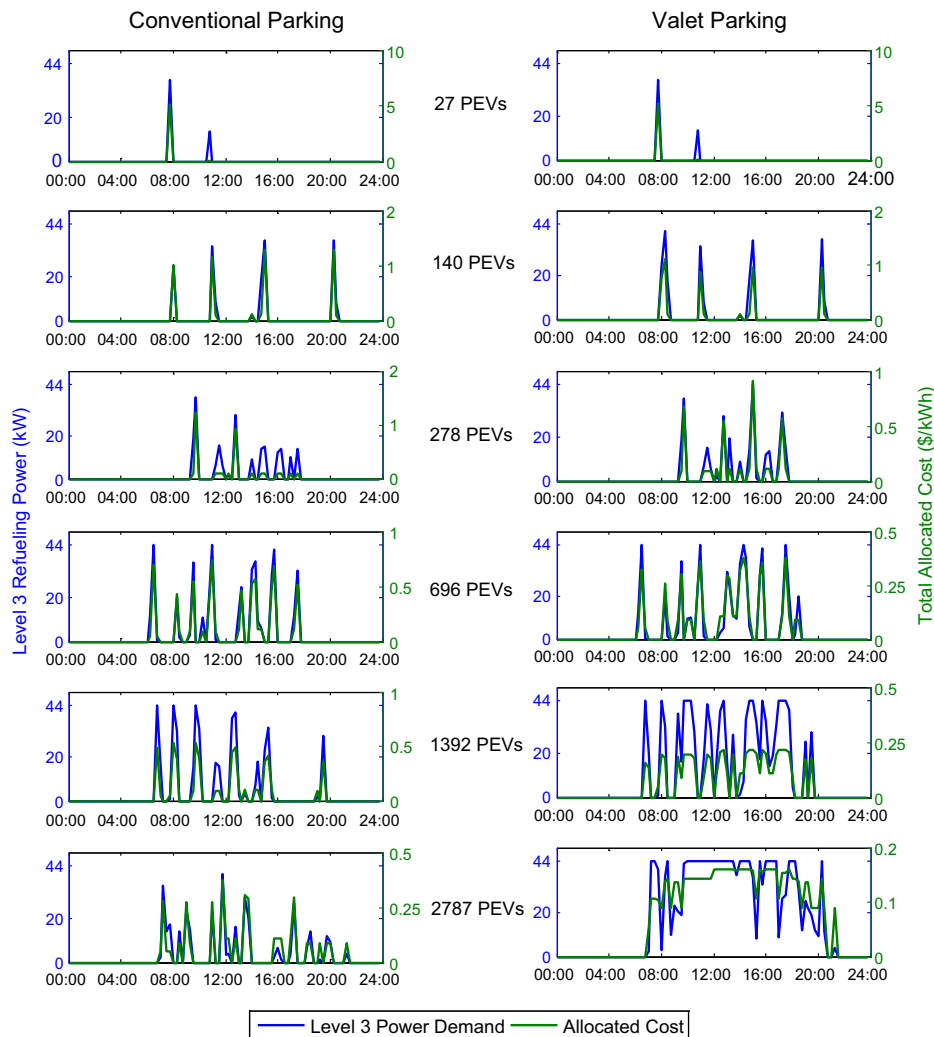

Fig. 4. Example load profiles and resulting cost allocations for 27, 140, 278, 696, 1392, and 2787 shopping trips per month using PEVs.
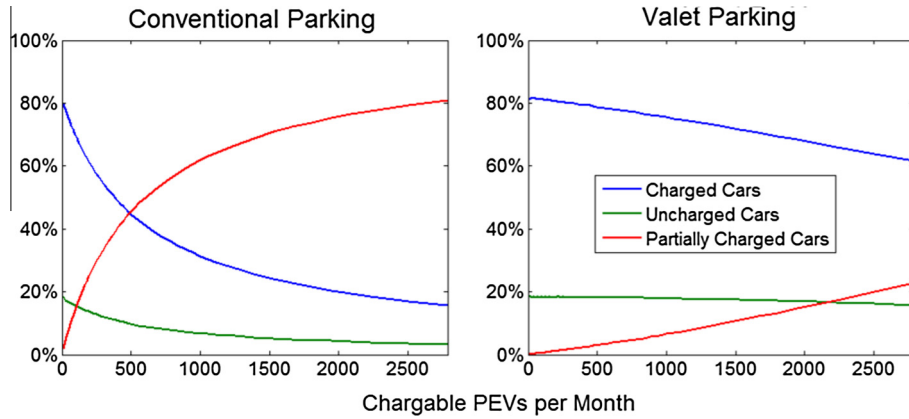
Fig. 5. Percent of cars that are fully charged, partially charged, or uncharged by the 44 kW Level 3 charger after a shopping trip type for conventional and valet parking scenarios.
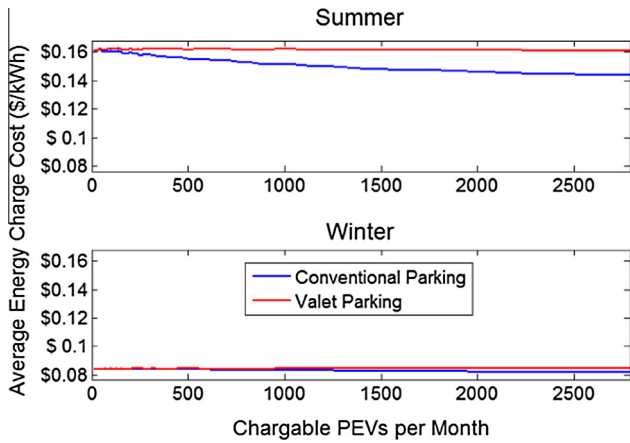

Fig. 6. Average energy charge cost versus number of chargeable PEVs per month for shopping trips occurring during the summer and winter.
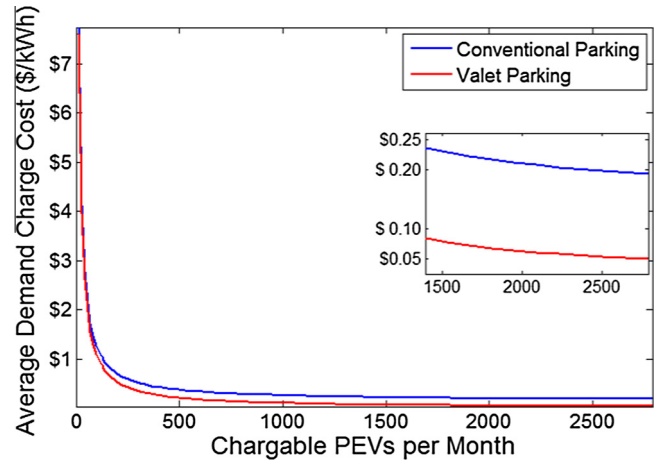

Fig. 7. Average demand charge cost versus number of chargeable PEVs per month for shopping trips occurring during the winter.

and valet operations. However, as the number of PEV cars increases, the electrical demand for valet operations increases due to the queuing and subsequent refueling PEVs that arrive while the EVSE is occupied. This is apparent in the demand profiles at 696 PEV trips serviced per month. The total cost of operation also decreases as the number of PEV trips serviced increases.

Fig. 5 shows the percent of PEVs with a state of charge below 80% that are fully refueled, partially refueled, or unfueled for both conventional and valet parking scenarios. Predictably, valet parking provides greater access to the EVSE. The valet results show that approximately 20% of all shopping travel has a corresponding dwell time that is shorter than what is required to completely refuel. While valet parking significantly increases the percent of PEVs refueled at moderate to high levels of traffic, additional EVSE is required if all Level 3 eligible PEVs are to be refueled.

The average energy charge costs for both the summer and winter seasons versus the number of chargeable PEVs per month are shown in Fig. 6. The average energy cost for valet parking remains stable regardless of the number of PEVs refueled per month. While an increase in PEV traffic increases the number of PEVs refueling during on-peak times, PEV use during the weekend also increases. As a result, the increased EVSE utilization during summer and winter on-peak times due to increased PEV use is counter-balanced by increased usage during mid-peak and during the weekend (off-peak) leading to relatively stable energy costs. With conventional

parking, the average energy cost decreases as PEV traffic increases due to arrival of PEVs during off- and mid-peak, decreasing the access that PEVs have to the EVSE when arriving during on-peak.

On the other hand, Fig. 7 shows the average demand charge cost for the winter season versus number of chargeable PEVs per month. Since summer and winter demand charges are the same and the difference between summer and winter shopping travel is small, the average demand charge cost versus chargeable PEVs for summer is nearly identical in amplitude and dynamics as that shown in Fig. 7 for the winter demand charge costs. While it is clear from Fig. 7 that the demand charge cost is the dominant electrical energy cost, increasing the number of PEVs charging per month can quickly reduce cost.

The demand charge cost shown in Fig. 7 is the average demand charge cost that a Level 3 EVSE operator must pay the utility. This curve is the product of an aggregated refueling load produced by supplying electricity to numerous PEVs. The actual cost incurred by each individual PEV can be allocated using the method described in Section 2.4. The results of this analysis can be separated into the two categories of PEVs that do and those that do not receive demand charge allocations. PEVs that receive no demand charge allocation are PEVs that, when aggregated with all other refueled PEVs, do not produce an EVSE demand greater than 20 kW for any 15 min period, or the electrical demand required to shift the EVSE from the utility rate TOU-EV-3 to
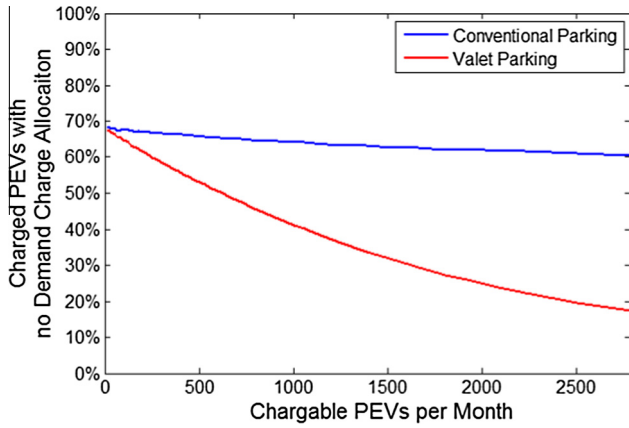
Fig. 8. Percent of PEVs that are refueled but do not receive a demand charge allocation for shopping type travel during the winter.

TOU-EV-4. Fig. 8 shows the percent of all refueled PEVs that received no demand charge allocation. PEVs that receive a demand charge allocation either directly produced or were aggregated with other vehicles to produce a maximum 15 min average demand greater than 20 kW. Fig. 9 shows the distribution of allocated demand charge costs for all simulations performed across various amounts of PEVs charged per month. This figure displays the percent of PEVs that receive an allocation that results in a specific $/kW h cost for all simulations. The distribution shows the percent of vehicles that incur a specific demand charge cost for all simulations performed at each level of PEV trips per month.

Fig. 8 shows that, under conventional parking, the majority of PEVs do not contribute to an EVSE demand greater than 20 kW and are not allocated any demand charge cost. If valet parking is implemented, the percent of vehicles contributing to a demand greater than 20 kW increases with PEV use, reducing the number of vehicles receiving no allocation. Fig. 9 shows that the demand

charge allocation can vary greatly depending upon the number of PEVs charged per month. At a low number of PEVs charged per month, allocations can vary drastically. As the number of PEVs refueled per month increases, this variability in allocation starts to disappear as the demand charge is allocated across a greater number of PEVs. This variability can be reduced even further if valet operations occur since more vehicles can be refueled through this method than through conventional parking. Although costs are lowest and cost allocation spread is the tightest at high PEV use, the EVSE is unable to meet the full demand as some PEVs remain uncharged regardless of operation type. As seen in Fig. 5, at the highest levels of PEV use examined, 20% of PEVs receive no charging. Fig. 9 also shows that, at low PEV use, some PEVs may deserve to pay a price of up to $20 per kW h for the demand charge incurred during recharging, and, on average, a PEV receiving a cost allocation averages approximately $4 per kW h. At the highest levels of PEV use tested, the cost allocation range shrinks to between no allocation and $0.50 per kW h for conventional parking and no allocation to $0.10 per kW h for valet parking.

3.1.2. Work travel

Assuming that PEVs start the day with a fully charged battery, approximately 37% of all work related travel results in a PEV with less than 80% state of charge. In addition to an increase in the number of PEVs that are eligible for Level 3 refueling, the long dwell time associated with work travel can have a significant impact on the resulting demand supplied to the EVSE. Fig. 10 shows example load profiles for Level 3 EVSE under conventional and valet operations for various levels of PEV use and the corresponding refueling cost. The 37 and 3711 PEVs per month correspond to approximately 100 and 10,000 total work trips per month made by Level 3 compatible PEVs. Fig. 11 shows the percent of Level 3 eligible vehicles that are completely refueled or not fueled at all. Simulations using work type travel resulted in PEVs being either completely refueled or not fueled with virtually no PEVs receiving partial refueling.
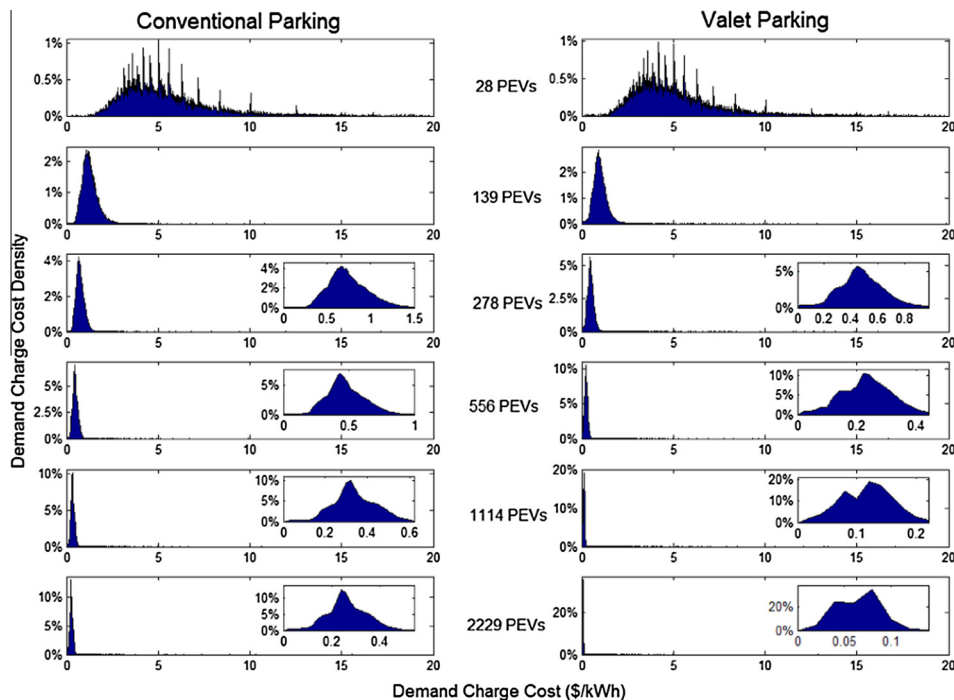

Fig. 9. Distributions of demand charge cost allocations to individual PEVs used for shopping type travel during the winter.
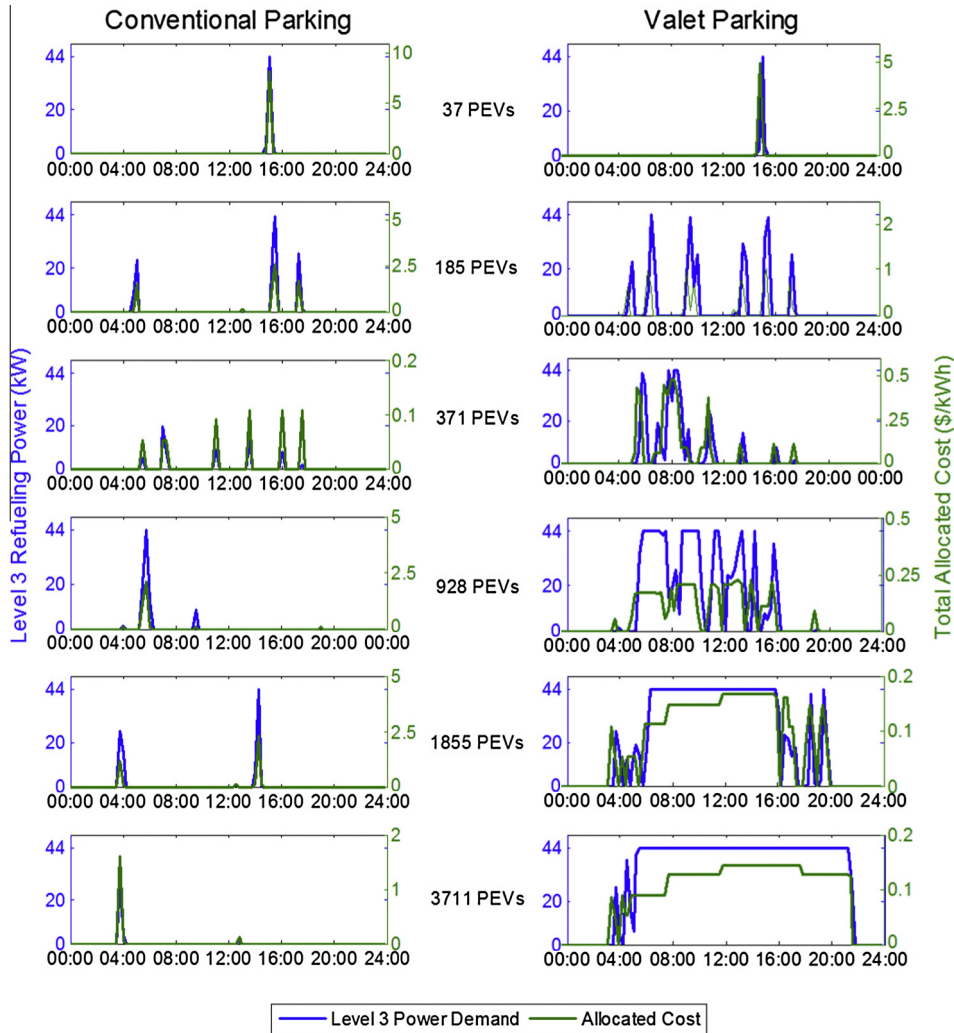
Fig. 10. Example load profiles and resulting cost allocations for 37, 185, 371, 928, 1855, and 3711 work trips per month using PEVs.
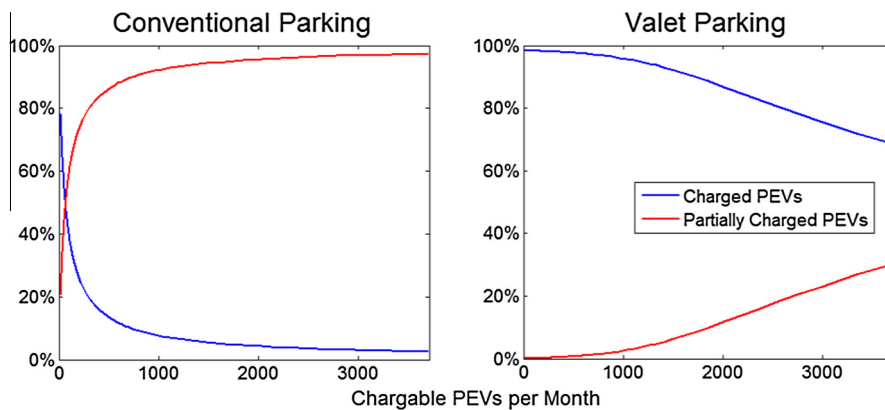

Fig. 11. Percent of cars that are fully charged, or uncharged by the 44 kW Level 3 charger after a work trip type for conventional and valet parking scenarios.

It is clear from Fig. 10 that there is little difference between the demand produced by a small number of PEVs versus a large number for conventional operations. This is due to a long dwell time associated with work travel, resulting in PEVs occupying the EVSE long after refueling is complete. This also results in only a small fraction of Level 3 eligible PEVs having access to the EVSE. Compared with shopping type travel, a much smaller percent of PEVs

used for work travel that are refueled even at a low number of total PEVs visiting the station, which results in and refueling costs that are high regardless of the number of eligible PEVs.

In contrast to conventional operations, valet operations benefit from the long dwell time. Even though the number of eligible PEVs is increased for work type travel, the extended dwell time ensures that a single 44 kW EVSE can refuel the majority of PEVs. As a
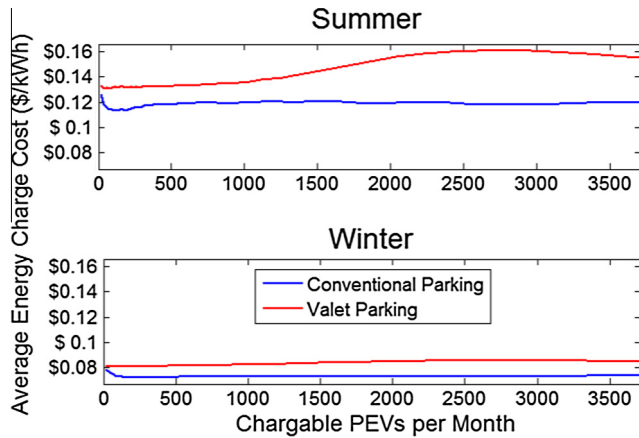
Fig. 12. Average energy charge cost versus number of chargeable PEVs per month for work trips in the summer and winter.
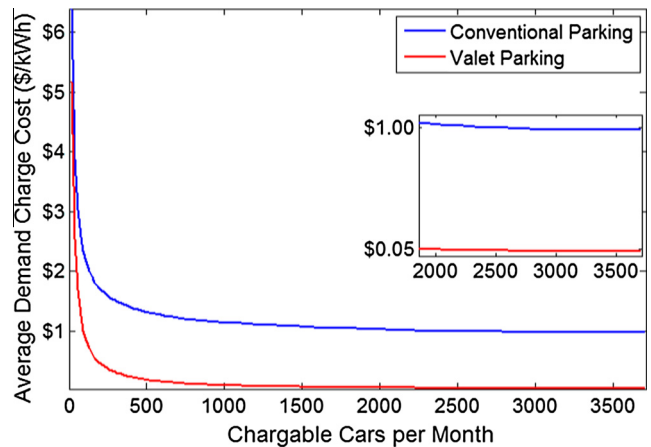

Fig. 13. Average demand charge cost versus number of chargeable PEVs per month for work trips occurring during the winter.

Fig. 14. Percent of PEVs that are refueled but do not receive a demand charge allocation for work type travel during the winter.

result, total cost is reduced from approximately $10 per kW h at low number of PEVs to below $0.15 per kW h at a high number of PEVs if valet operations are implemented. However, as PEV use increases, so does the percent of unfueled PEVs.

Fig. 12 shows the average energy charge cost versus number of chargeable PEVs per month. During summer and winter, a drop in average energy cost can be seen for conventional parking and low levels of PEV use. This is due to a switch in electric rate structure from TOU-EV-3 to TOU-EV-4. Referring to Table 2, energy charges are higher for TOU-EV-3 than TOU-EV-4. At low levels of PEV use, it is possible that the few eligible PEVs do not create an electrical demand of greater than 20 kW. In addition, the long dwell time associated with work travel coupled with low PEV use can result in a maximum monthly demand lower than 20 kW and the selection of TOU-EV-3 as the utility rate. If valet parking is implemented or PEV use increases beyond 100 total PEVs per month, EVSE demand surpasses 20 kW and TOU-EV-4 is selected as the utility rate.

With conventional parking, the early arrival and long dwell time associated with work type travel results in early arriving PEVs being refueled using off-peak electricity, but occupying the station through mid-peak and on-peak, resulting in the EVSE only using low cost utility energy. Conversely, the long dwell time results in a higher cost of energy for valet parking due to an increased use in mid-peak and on-peak electricity. While PEVs may arrive early in the morning, increasing the number of vehicles that are queued increases the amount of electricity purchased during mid-peak and on-peak, resulting in a higher overall cost of electrical energy. Between 2500 and 3000 PEVs refueled per month, the EVSE is constantly utilized during on-peak. If additional PEVs arrive, refueling occurs during the later mid-peak, reducing the average energy cost at high levels of PEV use. This behavior can also be seen in Fig. 10 at 3711 PEV trips per month, where the additional PEV traffic results in increased PEV refueling after the on-peak period.

Similar to shopping type trips, there is negligible difference between summer and winter demand charge costs as a result of similar seasonal travel patterns and no difference in demand charge rates from summer to winter (for the rate structures considered). Fig. 13 shows the average demand charge costs incurred for using Level 3 EVSE to refuel PEVs. Similar to shopping type travel, a low number of PEV trips per month results in a large demand charge cost. For conventional parking, demand charge cost remains high regardless of the number of PEVs available to be charged due to the long dwell time associated with work type travel. However, for valet parking, demand charge costs are reduced to being on the same order of magnitude as energy charge costs once a moderate
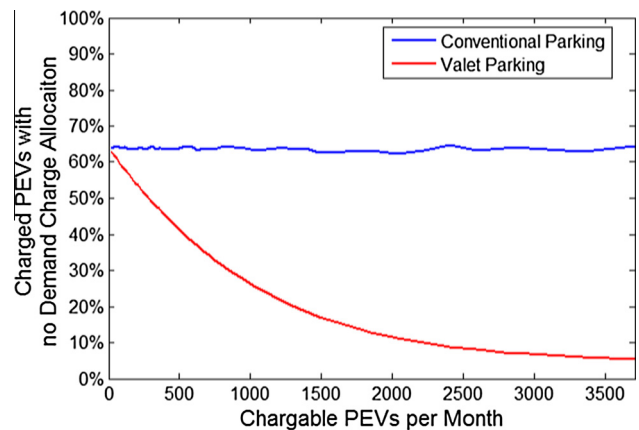
number of PEV trips to the Level 3 EVSE occur (around 650 Level 3 eligible PEVs per month).

Using the method described in Section 2.4, the cost to fuel individual PEVs can be determined. Fig. 14 shows the percent of PEVs that would receive no demand charge cost allocation. Fig. 15 shows the resulting demand charge cost for PEVs that do receive an allocation. The density plot in Fig. 15 represents the total percentage of cars that receive a demand charge allocation that results in the specified $/kW h cost. Similar to shopping type travel, the electrical demand incurred by most PEVs is not large enough to produce a demand charge allocation, as seen from the conventional parking results in Fig. 14. With conventional parking, increasing the number of PEVs that can be charged using Level 3 EVSE has almost no impact on reducing demand charge cost once a small number of PEVs are available to be charged each month. As a result, only a small number of PEVs are responsible for incurring a demand charge, resulting in both a high cost to refuel those particular PEVs, but a large distribution of incurred costs. Under valet parking, the increase in eligible PEVs can be accommodated using the single EVSE, increasing the aggregated load while also increasing the number of vehicles that receive a demand charge allocation. More PEVs share the demand charge, thus reducing the average cost of operation and the cost allocated to each PEV. Similar to the cost allocation for shopping travel, incurred demand charges are expensive at low PEV use, sometimes reaching up to $20 per kW h delivered to the PEV. As PEV use increases, the range of demand charge
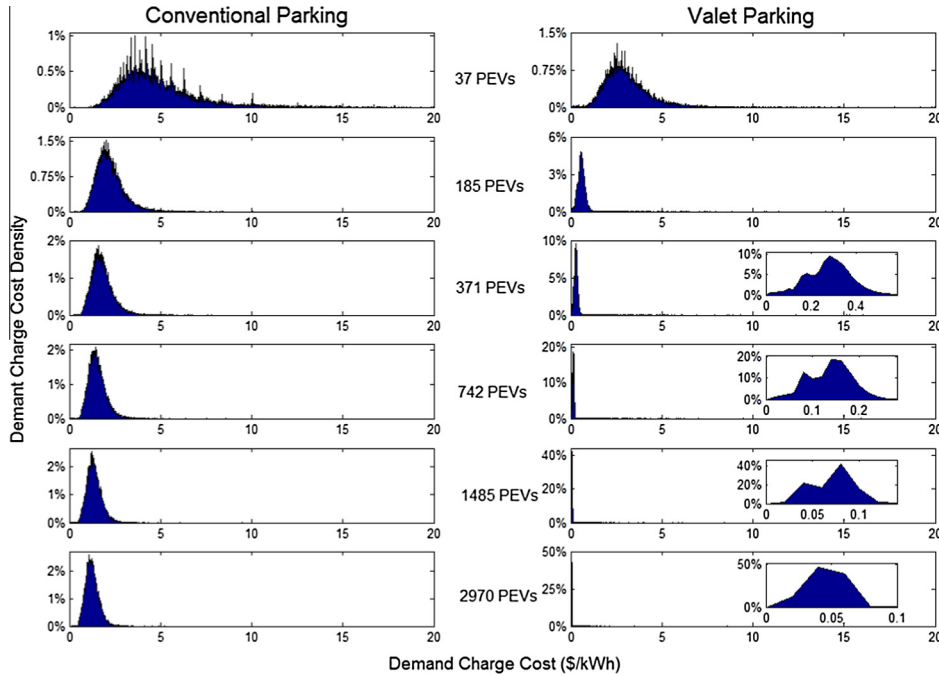
Fig. 15. Distribution of demand charge cost allocations to individual PEVs used for work type travel during the winter.
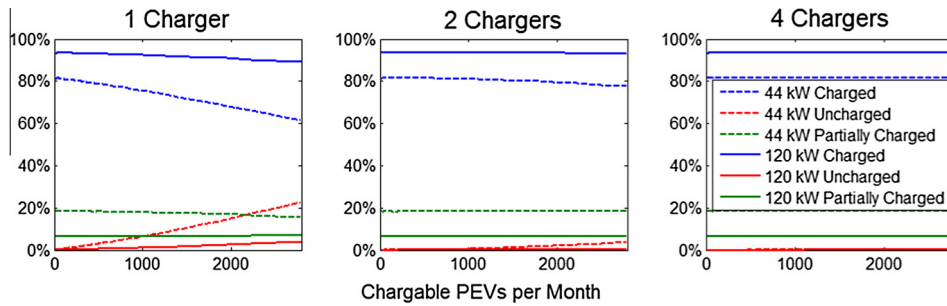

Fig. 16. Percent of vehicles that are fully charged, partially charged, or uncharged during shopping trips to locations with one, two, and four Level 3 chargers with a power output of 44 kW or 120 kW under valet operations.

allocation shrinks for valet operations to between no allocation and $0.07 per kW h. Costs also decrease under conventional operations, but typically range between no allocation and $2 per kW h, with some vehicles incurring ng upwards of $5 per kW h to recharge.

3.2. Increased charger power and EVSE number

The 44 kW Level 3 charger considered in Sections 3.1.1 and 3.1.2 is the baseline for all other Level 3 charging analyses in this work. All scenarios presented can be expanded by increasing the number of EVSE supplied by a single utility meter and/or by selected Level 3 EVSE with higher power output. Both options are explored in this section. EVSE with a power output of 120 kW will be considered, and the number of EVSE per utility meter is increased from one to two, four, and eight for both 44 kW and 120 kW Level 3 EVSE.

Under valet operations, the increase in number of chargers and the increase of charger power output increases the number of PEVs that can be charged for both shopping and work trip types. Figs. 5 and 11 show that, for the range of PEV use tested, a single 44 kW Level 3 charger is capable of refueling the majority of PEVs that are eligible for Level 3 refueling. However, at high levels of PEV use, either additional Level 3 EVSE must be installed or refueling

power must be increased to satisfy the demand of all vehicles. Figs. 16 and 17 show the amount of PEVs that are fully refueled, partially refueled, or not refueled for shopping and work respectively when increasing refueling power and number of available EVSE. Both figures show that increasing the refueling power increases the number of vehicles that have access to the EVSE, nearly reducing the percent of unfueled PEVs to zero for all levels of PEV use tested. Increasing the number of EVSE has the same effect for 44 kW EVSE. At high levels of PEV use, either multiple 44 kW EVSE or higher power EVSE must be adopted if all eligible PEVs are to have access to being refuel.

Fig. 5 and 11 also show that more than a single 44 kW EVSE is required to refuel the majority of PEVs if conventional parking occurs and PEV use is moderate. The impacts of increased EVSE power and number of available EVSE on the percent of PEVs refueled, partially refueled, or unfueled for conventionally operated EVSE servicing PEVs used for shopping travel are presented in Fig. 18. This figure shows that increasing the number of EVSE reduces the percentage of Level 3 eligible PEVs that are unfueled. At the highest level of PEV use tested, installing two chargers reduces the percentage of unfueled PEVs from 80% to 65%, while installing four chargers reduces unfueled vehicles to 40%, and installing eight chargers reduces unfueled vehicles to 11%. At
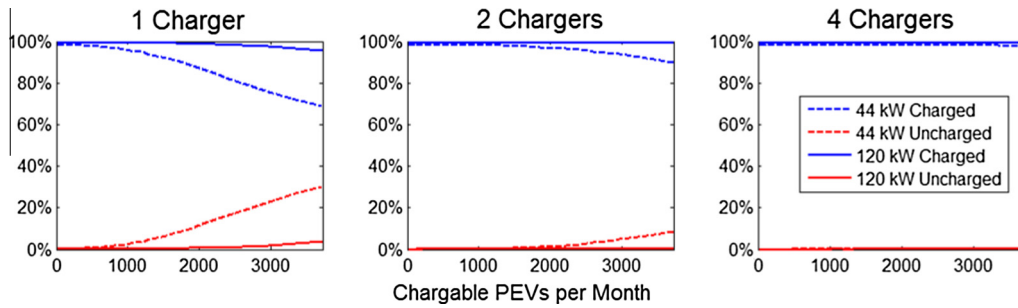
Fig. 17. Percent of vehicles that are fully charged, partially charged, or uncharged during work trips to locations with one, two, and four Level 3 chargers with a power output of 44 kW or 120 kW under valet operations.
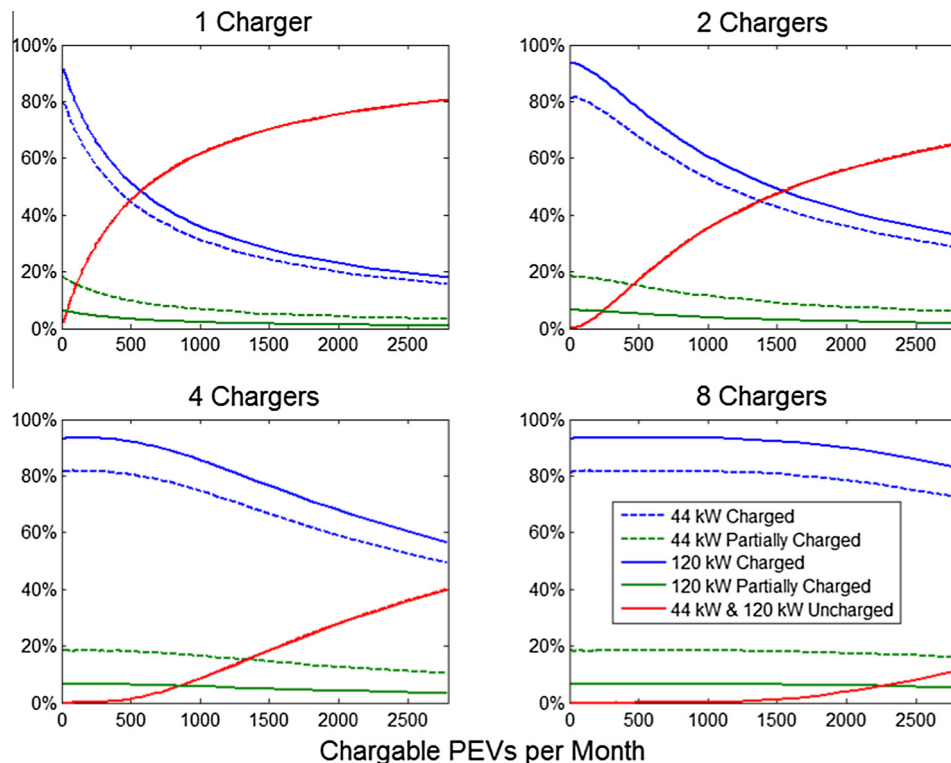

Fig. 18. Percent of vehicles that are fully charged, partially charged, or uncharged during shopping trips to locations with one, two, four, and eight Level 3 chargers with a power output of 44 kW or 120 kW under conventional operations.

moderate levels of PEV use, additional EVSE must be installed if all eligible PEVs are to have access to being refueled. Increasing EVSE power only increases the rate at which PEVs are refueled, ensuring that more PEVs are fully refueled, not partially refueled. The number of PEVs unfueled does not decrease when EVSE power is increased.

Likewise, increased EVSE power does not reduce the number of uncharged PEVs used for work travel. In addition, as a result of the extended dwell time associated with work travel, the number of PEVs refueled when using 44 kW and 120 kW EVSE is nearly identical across all ranges of PEV use, with any difference due to random variations in travel patterns (results fall on top of each other in Fig. 19). Fig. 19 shows the number of PEVs that are either charged or uncharged for the various numbers of EVSE station size tested for 44 kW EVSE. The results presented in Fig. 19 are nearly identical to results produced using 120 kW EVSE and have therefore been omitted for the sake of brevity. Increasing the number of EVSE improves the number of PEVs serviced.

However, due to the extended dwell time associated with work travel, the majority of PEVs do not have access to EVSE once a moderate amount of PEV traffic is present, and even eight EVSE is insufficient to refuel the majority of PEVs. These results suggest that increasing refueling rate is not necessary or useful for work travel.

While increasing EVSE power has little to no effect on increasing the number of PEVs refueled over the range of PEV use tested, the demand charge cost increases. Fig. 20 shows the change in demand charge due to increasing EVSE power output for both shopping and work travel. For all scenarios considered, increasing the refueling rate from 44 kW to 120 kW increases cost without providing either additional fast charging access or extent of recharge gains.

The impacts of increasing the number of EVSE supplied through a single electrical utility meter is not as clear as simply increasing EVSE power. Figs. 21 and 22 show the demand charge cost incurred by use of multiple EVSE behind a single utility meter to refuel PEVs for both shopping and work travel. As seen in both figures, if a
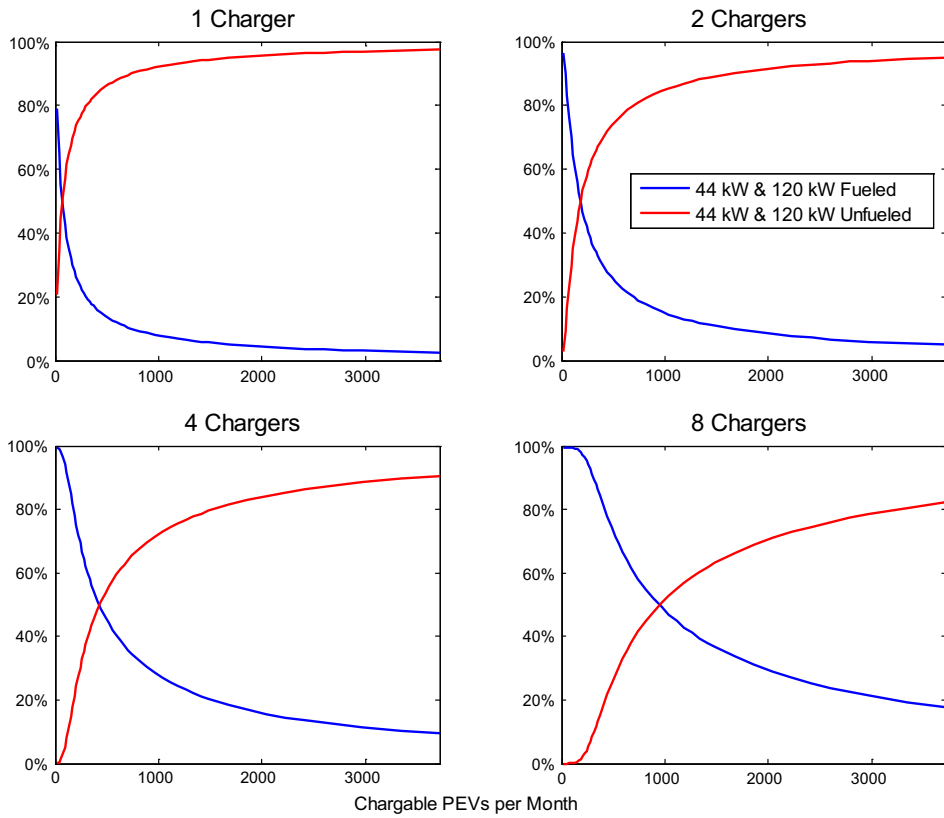
Fig. 19. Percent of vehicles that are fully charged, partially charged, or uncharged during work trips to locations with one, two, four, and eight Level 3 chargers with a power output of 44 kW or 120 kW under conventional operations.
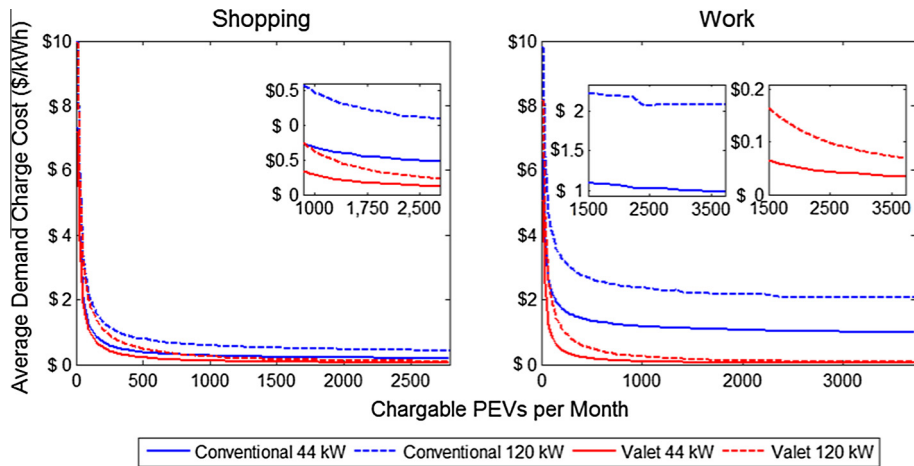

Fig. 20. Average demand charge cost for 44 kW and 120 kW Level 3 EVSE used to service shopping and work type trips.

charging station uses conventional parking, the impact ranges between a slight decrease in cost to negligible cost impact. Increasing the number of EVSE serviced by a single meter may potentially result in the simultaneous refueling of multiple PEVs, leading to an increased demand charge. However, conventional operation results in EVSE being occupied by PEVs that are fully charged. As a result, the maximum power demand achieved by a single charger is typically not surpassed despite the presence of multiple EVSE. The demand charge is maintained at a low level relative to the maximum possible demand created by all EVSE refueling a group of PEVs. The number of PEVs refueled increases while not substantially increasing the maximum demand, and no change to the average demand charge cost.

Conversely, demand charge costs increase as the number of EVSE is increased under valet operations. Due to the instant availability of EVSE after refueling any individual PEV, the demand supplied through the electric meter can be maintained if another PEV either arrives or has been queued for refueling. As PEV use increases, arrival and dwell times of the individual PEVs start to coincide with the arrival and dwell time of other PEVs, resulting in sustained refueling. Without any additional management of when PEVs are refueled, the maximum utility demand is easily increased along with the average demand charge cost. Both shopping and work travel results shows that as more Level 3 eligible PEV vehicles arrive at a refueling station with multiple EVSE and valet operations, demand charge cost
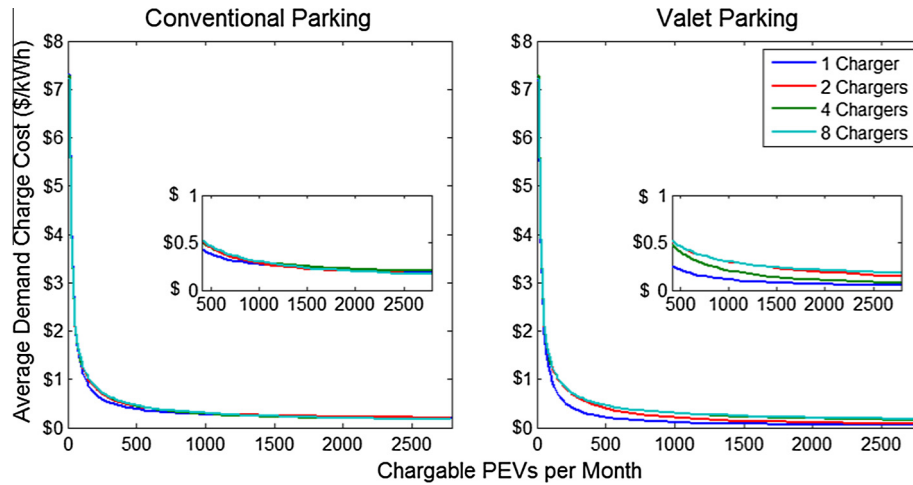
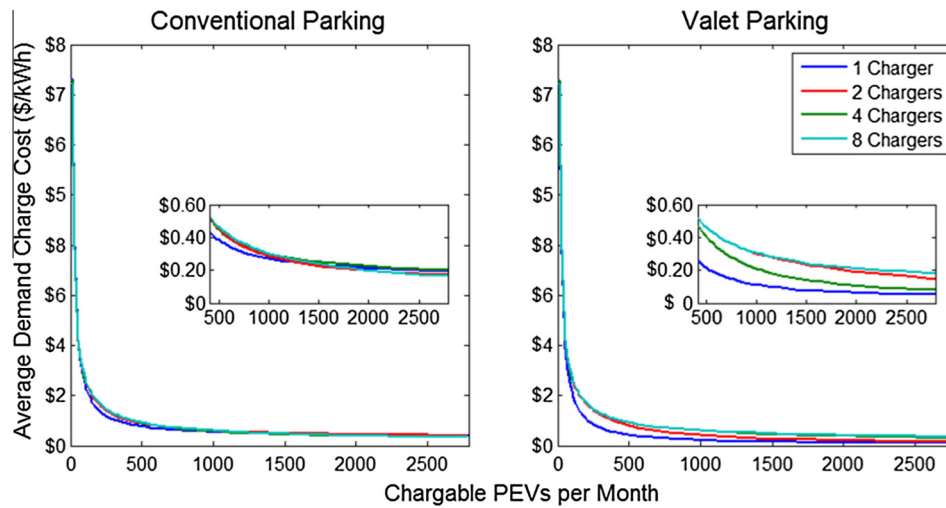**Fig. 21.** Average demand charge cost for multiple 44 kW EVSE to refuel PEVs used for shopping travel.

Fig. 22. Average demand charge cost for multiple 44 kW EVSE to refuel PEVs used for work travel.

increases for the EVSE operator, and ultimately, for the individual PEV drivers.

Installing multiple 120 kW EVSE results in similar trends as seen in Figs. 21 and 22 for 44 kW EVSE and have therefore have been omitted for the sake of brevity. However, due to the increased power, the results are shifted up on the average demand charge cost versus PEVs plot for all scenarios due to the higher demand charge incurred by using the higher power 120 kW EVSE.

Energy costs experience little to no change as a result of increasing either EVSE power or multiple EVSE because energy cost is determined by PEV time of refueling, not the maximum demand supplied during the refueling process.

3.3. Sensitivity of utility costs

The results presented in Sections 3.1 and 3.2 are the averaged results of numerous simulations using the model described in Section 2. Each individual simulation stochastically produces different energy and demand charge costs that are averaged to produce the results presented in Sections 3.1 and 3.2. This section presents the variation of individual simulations versus the average results.

Figs. 23 and 24 show the standard deviation of average energy charge during the summer versus number of chargeable

PEVs per month for shopping and work travel respectively for one, two, four, and eight 44 kW EVSE. For both shopping and work travel, the standard deviation decreases as PEV traffic increases. A high deviation is due to the arrival of PEVs at different utility peak periods during the day. With little PEV traffic, arrivals at unexpected times produce results that vary significantly from the average. As PEV traffic increases, and arrival time at expected hours becomes more common and then begins to dominate travel behavior, the effect of a PEV arriving at an unexpected hour is reduced and variation across simulations decreases except for work with conventional parking. Under this scenario, a PEV that arrives at an unexpected time may have a long dwell time. When this occurs during a peak period when PEV refueling does not typically occur, the simulation cost differs from the average energy cost. However, as more EVSE are installed, expected arrival behavior begins to dominate all of the simulations, reducing variation between simulations.

Winter results are similar to summer results, only shifted down due the elimination of the on-peak period, reducing the number of peak periods to two (summer has three). As a result, the cost difference between a PEV arriving during an expected peak period versus an unexpected peak period is reduced. Increasing EVSE power does not affect variations in the simulation results.

Fig. 23. Standard deviation of average energy charge cost for shopping travel during the summer for one, two, four, and eight 44 kW EVSE.

Fig. 24. Standard deviation of average energy charge cost for work travel during the summer for one, two, four, and eight 44 kW EVSE.
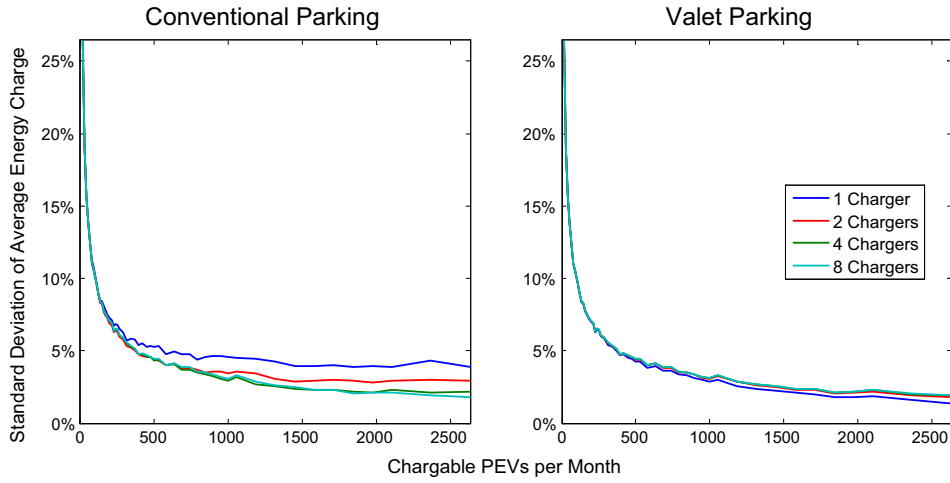

Fig. 25. Standard deviation of average demand charge cost for shopping travel during the summer for one, two, four, and eight 44 kW EVSE.
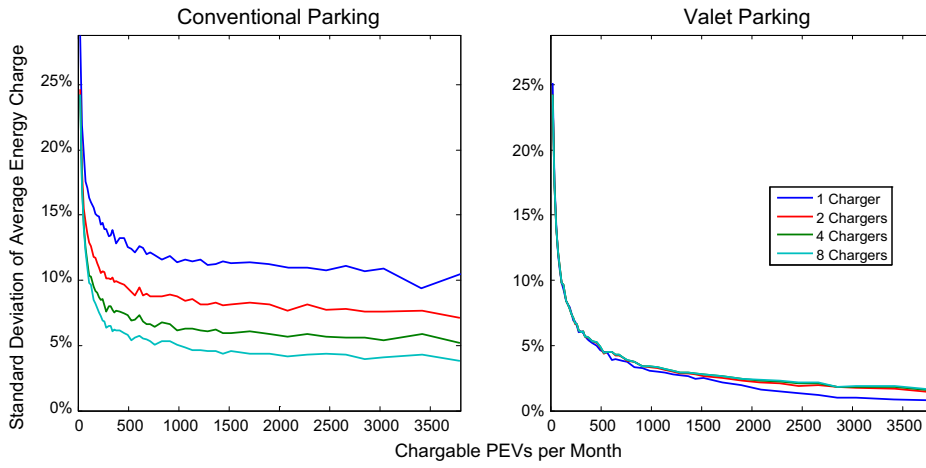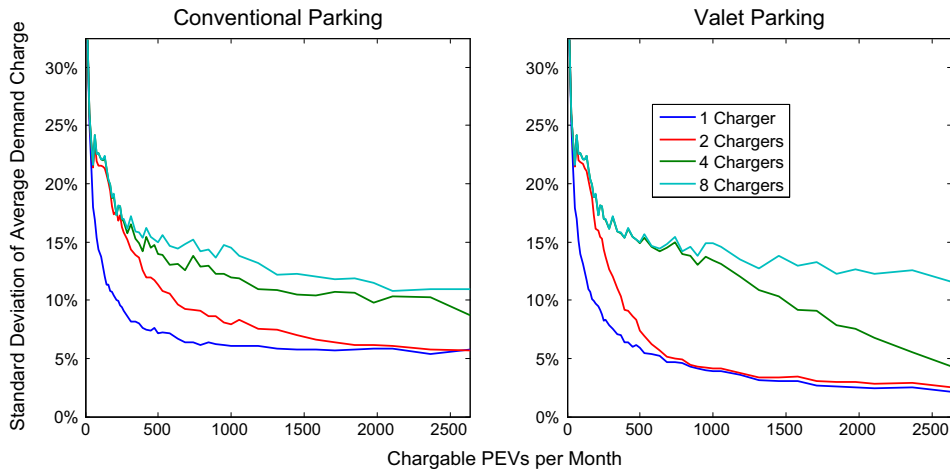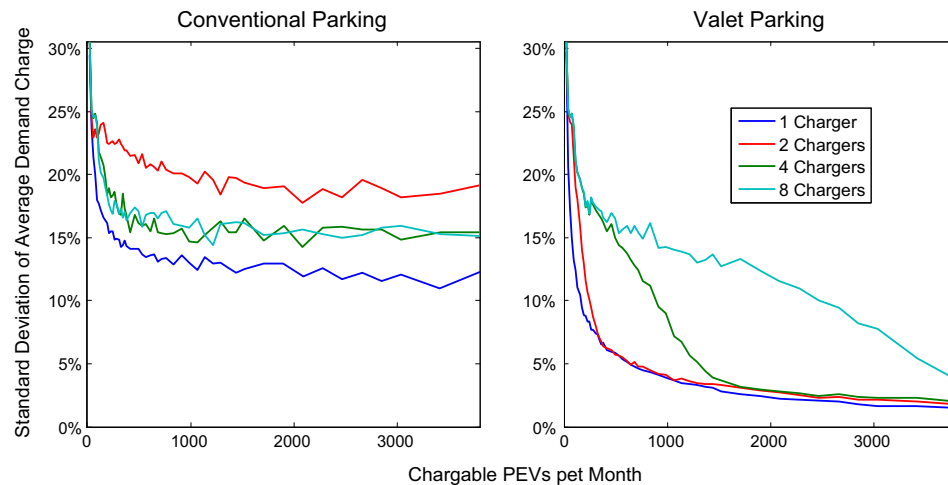
Fig. 26. Standard deviation of average demand charge cost for work travel during the summer for one, two, four, and eight 44 kW EVSE.

Figs. 25 and 26 show the standard deviation of average demand charge during the summer versus number of chargeable PEVs per month for shopping and work travel respectively for one, two, four, and eight 44 kW EVSE. Similar to the energy charge statistics, the standard deviation decreases as PEV traffic increases.

When considering a single EVSE and low levels of PEV traffic, the 20 kW threshold may not be exceeded during some simulations. This creates a large variation when compared to simulations that do surpass the 20 kW threshold. As PEV traffic increases and a demand charge occurs consistently, the standard deviation decreases, and any variation in demand charge is due to differences in the total number of kW h delivered to the PEVs (which changes depending upon the randomly selected PEV trips).

For all scenarios except work with conventional parking, increasing EVSE increases the number of PEVs required to consistently reach the new maximum demand charge, increasing variation in demand charge cost between simulations. Once the demand charge is increased consistently across the simulations, variations are caused by differences in the total energy delivered to the PEVs.

Due to the typically long dwell time associated with work travel, a single EVSE operated under conventional parking can be occupied indefinitely by a PEV that does not incur a demand charge. With low PEV traffic levels, it is possible to have an entire simulation with no demand charge, increasing variation in the average demand charge across all simulations.

Increasing EVSE in this situation to two further increases variation in the simulation results, as shown in Fig. 26, because multiple EVSE must arrive at approximately the same time to use available EVSE and refuel at the maximum power during the entire time window over which the demand charge is determined. When this occurs for some simulations, but not others, the standard deviation increases. However, increasing EVSE beyond two allows for a higher demand charge to be produced more consistently across the different simulations, reducing variation in simulation results. This increased demand charge can still vary between simulations, resulting in a permanently high standard deviation across all levels of PEV traffic.

3.4. Discussion

It is clear from the results that Level 3 EVSE can be prohibitively expensive with little PEV use. Average utility rates for these scenarios range from $0.08 to $7.90/kW h. For all scenarios tested, between 100 and 150 trips per month must be made by PEVs that are compatible with Level 3 EVSE and have a battery state of charge below 80% to reduce average demand charge costs below $1.00 per

kW h. In some instances, such as for conventionally operated EVSE refueling PEVs used for work travel, average demand charge cost cannot be reduced below $1.00 per kW h. If the EVSE is operated using valet parking, approximately 550 refueling events during the winter (or 1500 total PEV trips), and 800 charging events during the summer (or 2000 total PEV trips) must take place in order to reduce the average total utility cost below $0.25 per kW h. For shopping travel and valet operations, 670 refueling events per month during the winter (or 2400 total PEV trips), and 1400 refueling events per month during the summer (or 5000 total PEV trips) are required in order to reduce total average utility cost below $0.25 per kW h. Under conventional operations at shopping centers, costs never fall below $0.27 per kW h during the winter and $0.33 per kW h during the summer. If a goal of installing the Level 3 EVSE is to provide an economically competitive transportation fueling option, Level 3 compatible PEV use must significantly increase, and in some instances, parking management is required. Only in scenarios when both of these facts were considered (valet parking and high PEV use) did utility rates drop below $0.25 per kW h.

If PEV use does increase, certain types of travel are more conducive to improving EVSE availability and operational costs. The relatively small difference in average demand charge cost between conventional and valet operations for shopping travel suggest that trips resulting in a short dwell time do not need as much parking management as trips that result in a long dwell time, such as work travel. As dwell time increases (e.g., work travel), parking management must be implemented to maintain a driver satisfaction and keep utility costs low. The benefit of a long dwell time is the potential to fully refuel all PEVs that arrive at any particular charging station, regardless of the amount of PEV use. As such, the most attractive scenario is the situation where numerous PEVs arrive with below an 80% state of charge, stay near the EVSE for an extended period of time (e.g., work travel), and a system is enacted that follows the valet parking strategy. This combination has the potential to reduce total average cost, including demand charge cost, to $0.13 per kW h during the winter and $0.21 per kW h for summer with shopping travel and $0.12 per kW h during the winter and $0.19 per kW h during the summer for work travel.

The results also clearly show that while increasing the number of available EVSE can improve access to refueling, using a "valet" system can significantly increase PEV refueling throughput and reduce cost of electricity while limiting the number of required EVSE. Increasing EVSE power, however, does not improve access while increasing cost of electricity.

When multiple Level 3 EVSE on a single utility meter, additional management beyond the simple "valet" system must be implemented in order to ensure that demand charges are not unnecessarily increased. Much work has been done on the optimal refueling of PEVs [20–23]. Including demand charge costs in PEV refueling optimization would ensure that PEVs are refueled while maintaining as low of a demand charge as possible.

The cost allocation analysis illustrates the challenge of rate design for PEV refueling. At low to moderate levels of PEV use, it is impossible to design a simple rate (fixed fee, time of use, $ per kW h) that fairly chargers drivers to refuel; the demand charge cost incurred by a few is borne by all. This task becomes easier as the number of PEV trips resulting in a battery state of charge below 80% increases. However, if the average trip length to the charger remains short, as with shopping travel, and only a fraction of the refueled PEVs will have incurred a demand charge, fair rate design will remain difficult. A shift toward rates that allocate costs fairly would help to eliminate this problem, which could be assisted by sharing information with incoming PEV drivers allowing them to opt out of charging if such would incur increased demand charges. But such a system may create another barrier to increasing PEV adoption due to increased public confusion as to how much it costs to charge a PEV using public charging infrastructure.

The results presented in this paper are specific to utilities that have rate structures for PEV charging similar to Southern California Edison. If the EVSE were located within the territory of a different utility that did not apply demand charges to public PEV refueling in favor of increased energy charges, the high costs faced by charging stations when PEV use is low and/or conventional parking is in effect may be eliminated. For example, if the EVSE were located within the service territory of Pacific Gas and Electric, the second largest utility in California, the applicable rate structure would be either the A-1, A-1 TOU, or A-6 TOU rate structure if the maximum demand stayed below 200 kW. None of these three rates include demand charges, and with the exception of summer on-peak under A-6 TOU, feature energy charges that are between $0.14 per kW h and $0.28 per kW h. While the high capital cost associated with Level 3 EVSE may still block an investment decision, the issue of electricity being too expensive may be significantly reduced in this case.

4. Conclusions

This work examines the cost of purchasing electricity to power public Level 3 EVSE using real electric utility rate structures, and allocates the cost to the individual PEVs that refuel using the EVSE. Models that simulate the travel patterns and subsequent refueling of Level 3 compatible PEVs are developed and combined with utility rate models to determine the cost of supplying electricity to a Level 3 refueling station in Southern California. Two types of Level 3 refueling station operations were considered (conventional parking and valet parking). The main findings of this analysis are:

- When a Level 3 compatible PEV is used for travel, approximately 28% of shopping trips and 38% of work trips result in the PEV having a battery state of charge below 80% making them eligible for Level 3 charging. For both shopping and work trips, the ability of the EVSE to refuel all eligible vehicles heavily depends upon the type of station operation. For both shopping and work travel, more PEVs are refueled using valet parking versus conventional parking. However, when dwell time is short (as with shopping travel), the number of PEVs with access to EVSE increases.

- At low levels of PEV use, demand charges are extremely high (> $1.00 per kW h). If PEV traffic increases, demand charges decrease. However, parking management is required for trips that include a long dwell time if demand charges are to decrease with increased PEV use.

- Increasing the number of available EVSE can increase the number of PEVs refueled. Valet operations require a lesser number of EVSE than conventional operations to achieve the same number of EVSE refueled. Demand charges do not increase with increased EVSE under conventional operations but do increase under valet operations due to coincident refueling of multiple PEVs.

- Increasing refueling power increases the number of PEVs refueled under valet operations but not conventional operations. Regardless of the type of parking operation, increasing refueling power increases demand charges in all scenarios. Increasing charger power from 44 kW to 120 kW approximately doubles the demand charge.

This study offers the most supportive analysis of Level 3 EVSE because it is assumed that all eligible PEVs are refueled. An individual PEV driver's decision to refuel their vehicle based on refueling rates and the remaining PEV range is not considered. Future work should consider the individual PEV driver's future trips, Level 3 EVSE refueling rates, and the possibility of using Level 1 or 2 EVSE in order to obtain a more realistic number of Level 3 EVSE customers.

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