

Electric Grid Integration Costs for Plug-In Electric Vehicles

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ABSTRACT

This paper evaluates the hidden costs of Plug-In Electric Vehicle (PEV) integration into the electric grid. The topic of PEV infrastructure is traditionally associated with the direct costs of installing chargers. However, there is also the indirect cost of infrastructure upgrades required upstream of the customer service point (meter). This is a case study of indirect infrastructure costs for PEV integration along with ways to mitigate and manage this cost transferred to customers for the Sacramento Municipal Utility District (SMUD). The costs are estimated using Monte Carlo methods applied to the geospatial and temporal diversity of SMUD's distribution network. An estimate of economic value added by Time of Use (TOU) incentives and Smart Charging for SMUD's service region is also provided.

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INTRODUCTION

The introduction of series-production vehicles such as the Chevrolet Volt, supported by federal tax credits, has provided mainstream accessibility to PEVs for customers. Recent legislature such as the California 2012 ZEV Action Plan [1] and the updated Corporate Average Fuel Economy (CAFÉ) standard [2] also encourage the manufacture PEVs. An increasing electric vehicle population could pose unique challenges for the current electric grid. The PEVs' electric loading profile is uniquely demanding of the grid because the charging of an electric vehicle is a large and sustained load. Conventional high demand house appliances such as air conditioners, electric heaters, or electric stoves have cyclic loading rather than sustained loading.

There have been a number of studies regarding the grid impacts of electric vehicles. In [3], a single transformer is modeled with a load of one or multiple PEVs. Some studies have evaluated grid impacts through a distribution network approach on a statistical basis of secondary effects relating to supply/demand, voltage imbalance, and power quality issues such as [4]. Other studies such as [5] have attempted to minimize these secondary effects using optimal "smart charging" strategies. The study by EPRI [6] attempts to "capture the spatial diversity in PHEV penetration and temporal diversity in charging patterns of PHEV adaptors" using Monte Carlo simulations. EPRI's study models a variety of effects including thermal overloads, under/over voltages, losses, and imbalance among other distribution-level effects. The study of this paper is similar to EPRI's study in that it attempts to

capture geospatial and temporal diversity through Monte Carlo simulations, but for SMUD's distribution network. This study addresses distribution network power capacity, excluding power quality measures, which is limited in comparison to EPRI's study. In addition to modeling efforts, utilities with smart meters deployed and PEV customer programs, such as San Diego Gas & Electric [7] and SMUD, are also reviewing transformer loading based on real world PEV use.

This study also provides an economic assessment of distribution network upgrade costs necessary to maintain the current level of reliability in service. An estimate of costs avoided by Time of Use (TOU) incentives and Smart Charging for SMUD's service region is also provided. Most existing PEV infrastructure estimates focus on the cost of charging infrastructure downstream of the customer service point or meter, while this study provides a detailed estimate of infrastructure costs upstream of the customer meter.

It is important for electric utilities and auto manufacturers to work together to allow for a seamless transition during this early market growth of electric vehicles. It is in the best interest of both the electric utilities and the auto manufacturers to ensure that shared customers can reliably recharge their vehicles at the lowest possible cost. The management of electric grid impacts due to PEVs would ensure that PEV customer charging costs are controlled and minimized. This paper concludes with recommendations for both electric utilities and auto manufacturers.

BACKGROUND AND MODELING ASSUMPTIONS

Geographic Boundary and PEV Adoption

The model simulates Sacramento Municipal Utility District (SMUD) service region as shown below in [Figure 1](#). SMUD is a publicly owned electric utility that operates independently of other local government and functions as a nonprofit entity. SMUD provides electric power to the majority of the Sacramento County as well as a portion of Placer County in Northern California. In total, SMUD's service region covers approximately 900 square miles and serves around 550,000 residential customers and 50,000 commercial accounts.

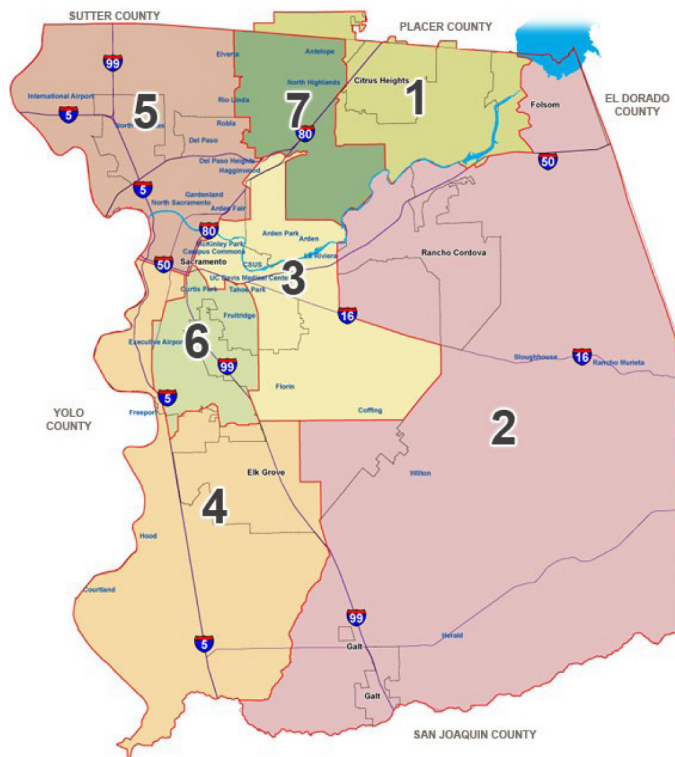


Figure 1. SMUD Service Region

The model assumes that the total number of electric vehicles in SMUD's service region will follow the trend of [Figure 2](#). The California Air Resources Board (ARB) estimates PEV penetration to grow linearly up to approximately 5% of new car sales by 2020 for the state of California [8]. This estimate is proportionally scaled to the SMUD service region population to generate [Figure 2](#).

Focus on Distribution Infrastructure

The electric utility infrastructure is comprised of three general parts of a system: power generation, transmission, and distribution, which is depicted in [Figure 3](#). Power generation involves the production and balancing of power from various

power plants. From this point, the transmission infrastructure transports the bulk generated power over large distances from the power plants to the local areas through high voltage transmission lines. SMUD's transmission network is at a voltage range of 230 kV down to 69 kV. Once the power has reached the local areas of need, the distribution infrastructure steps down the voltage and distributes the power over shorter distances to individual locations of need such as residential and commercial properties. SMUD's distribution network consists of 21 kV and below. A high level view of SMUD's power generation, transmission, and distribution system is shown in [Figure 4](#).

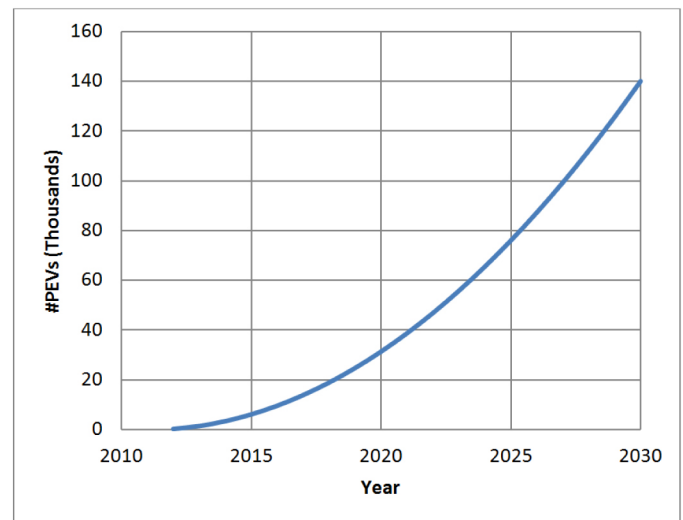


Figure 2. Projected Number of PEV in SMUD's Service Region

Power generation and transmission form the backbone of the electric utility infrastructure and are scaled to handle growth or contraction in both the load and distribution infrastructure. However, the distribution side of the system is significantly impacted by the increased sustained loading of PEVs. At the residential end of the distribution infrastructure, capacity is sized on a per home basis. Service transformers in the distribution system are the bottleneck for new residential electrical loads, as elaborated in the following section.

Upstream of the service transformers are feeders that connect to substation transformers. The estimated load diversity and headroom in substation transformer and feeder capacity across SMUD's service region suggest that no incremental substation transformers will require being upgraded for the PEV market size depicted in [Figure 2](#). For this reason, substation transformers and feeders are not included in the simulation model. It should be noted that this assumption is heavily dependent on utility design standards and history of load growth. As a result, other electric utilities may see a need for substation upgrades due to PEVs earlier than projected in this study.

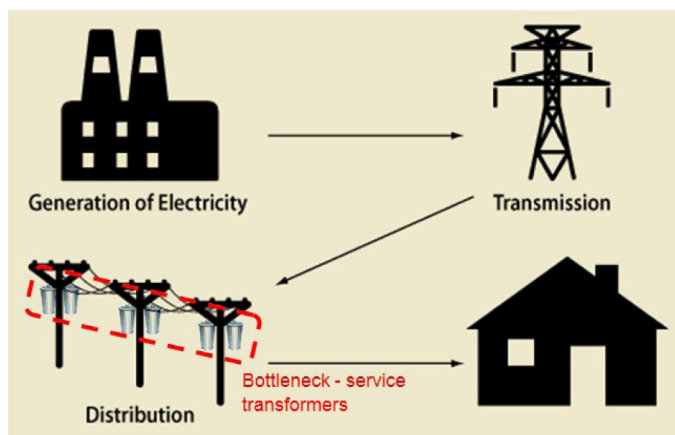
Figure 3. Electric Utility Infrastructure¹

Figure 6. Pad-mount transformer

The 3-year average replacement unit cost across different capacity transformers and site-specific situations at SMUD is approximately \$4,855 for pole-mount transformers and \$6,654 for pad-mount transformers. The residential transformer, associated secondary side, and service conductor are usually the bottleneck for residential distribution whereas the primary side conductor is often sized for quite high capacity. Sometimes the secondary side conductor and/or the service line between the transformer and the house meter requires being upgraded to a higher rated conductor depending on the age of the home and secondary side distribution system. Figure 7 is an example of typical capacity ratings for a single residential transformer. The 3-year average upgrade cost for secondary side conductors at SMUD is approximately \$8,063 per home. It is assumed that one out of five transformers overloaded due to PEV charging in SMUD's service region will require a secondary side conductor upgrade.

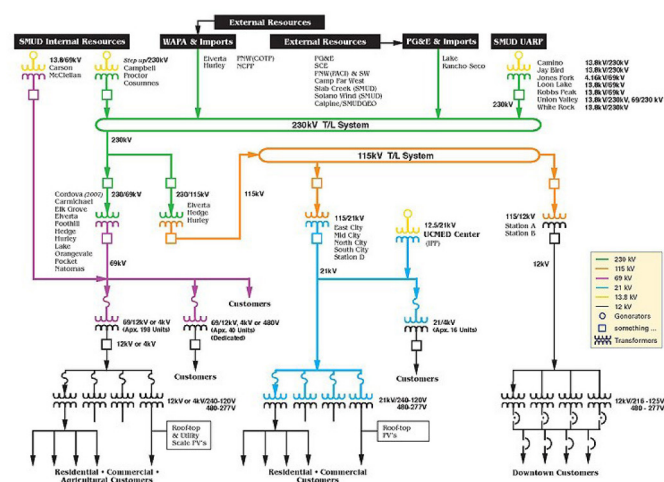


Figure 4. High-Level View of SMUD's Electrical System

Transformer Replacement Criteria and Costs

At SMUD, a transformer is considered overloaded and in need of replacement if it experiences sustained loads over 115% of the device's nameplate rating. The cost of replacing a transformer varies based on the type (pole-mount vs. pad-mount - Figure 5 and Figure 6), capacity (kW rating), and site-specific installation labor.

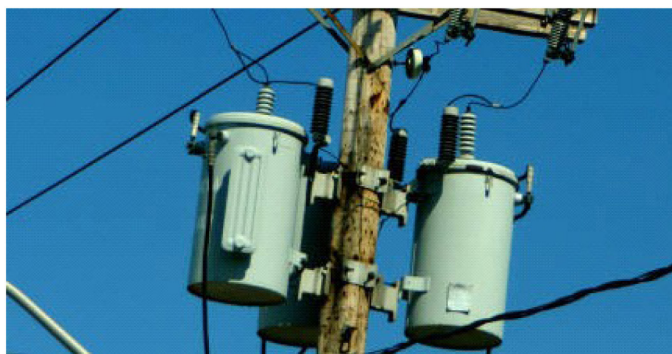


Figure 5. Pole-mount transformer

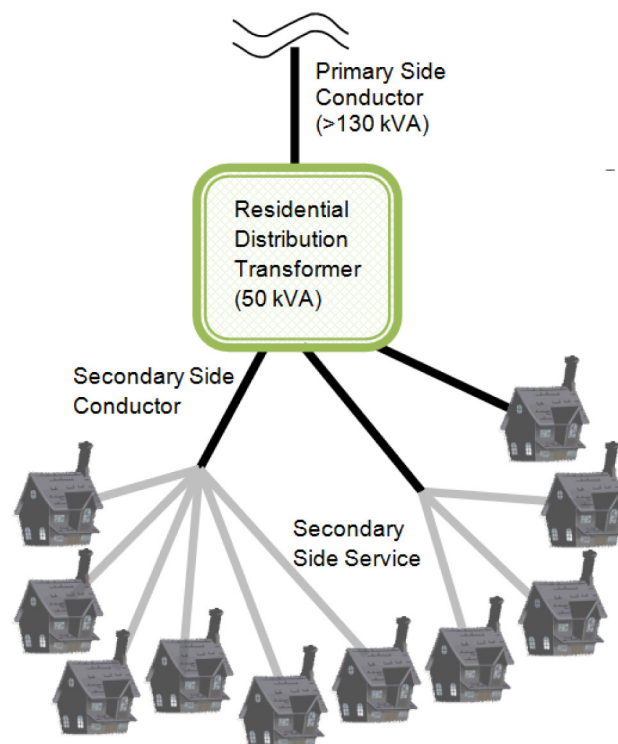


Figure 7. Example of Residential Distribution Capacity Ratings

1. diagram from the US Energy Information Administration

PEV Average Energy Demand

For Sacramento County, the average daily drive per automobile is about 22 miles [9]. A conservative figure for real world electrical fuel economy is 35 kWh/100 miles [10]. The product of these two numbers suggests that the average PEV driver will charge about 7.7 kWh per day.

At 140,000 PEVs projected in SMUD's service region by 2030 (shown in Figure 2), the incremental annual energy demand for these PEVs will be 393 GWh. This is about 4% of the 10,232 GWh of energy delivered to SMUD's service region in 2010 [11]. A typical PEV daily energy demand of 7.7 kWh will increase a single home's annual energy consumption by 33% (8.5 MWh on average for SMUD's service region with no PEV [11]). Although these figures provide context for energy consumption, it is really coincident power consumption that impacts capacity limitations.

PEV Household Location Selection

Meters loaded with PEV charging are randomly selected from a candidate pool of residential service points/meters stored in SMUD's Geographic Information System (GIS) database. The simulation candidate pool consists of residential single phase customers with transformers loaded between 10% and 115% of nameplate capacity (transformers not already overloaded or under loaded). This results in a candidate pool of around 436,000 meters eligible for simulated PEV charging load.

The model assumes that the electric vehicle adoption in the region would initially be geographically similar to the past Toyota Prius adoption, which was offset to start in the year 2012. To reflect the geographic clustering, the model applies a geographic weighting on the random selection of meters experiencing a PEV charging load to reflect an increased likelihood of electric vehicle adoption for certain zip code areas over others. This distribution is based on Toyota Prius zip code registration records provided by the California Department of Motor Vehicles. Table 1 shows the top 5 zip codes for Prius adoption for the SMUD service region beginning in the year 2000. Beyond the first 5 years, the geographic weighting for random selection is uniform.

Table 1. Top 5 Zip Code Prius Distributions (Sample)

Zip Code	Year				
	2000	2001	2002	2003	2004
95630	2.70%	6.43%	3.13%	6.33%	6.29%
95608	8.11%	6.43%	8.93%	5.67%	8.81%
95628	5.41%	6.43%	6.70%	7.00%	5.17%
95758	0.00%	1.43%	4.02%	2.67%	4.20%
95818	8.11%	5.00%	4.02%	6.67%	5.31%
⋮	⋮	⋮	⋮	⋮	⋮

Two PEV Households Limited

In order to diversify and widen the scope of possible service transformer impacts for this study, only 10,000 customers were allowed to be selected twice. This represents households which may be likely to purchase and own multiple electric vehicles in SMUD's service region. Note that it is assumed that only one electric vehicle would charge simultaneously at a single location.

Non-PEV Loading

The model requires simulation of non-PEV loading to contribute to the total load per transformer. We assume SMUD peak day transformer loads of the year 2010 to use as a conservative base. The residential load profile from the year 2010 is shown in Figure 8, which resembles a typical peak day. This load profile was then applied to simulate different load levels at various times of the day, for a worst case day that the grid infrastructure needs to be able to support.

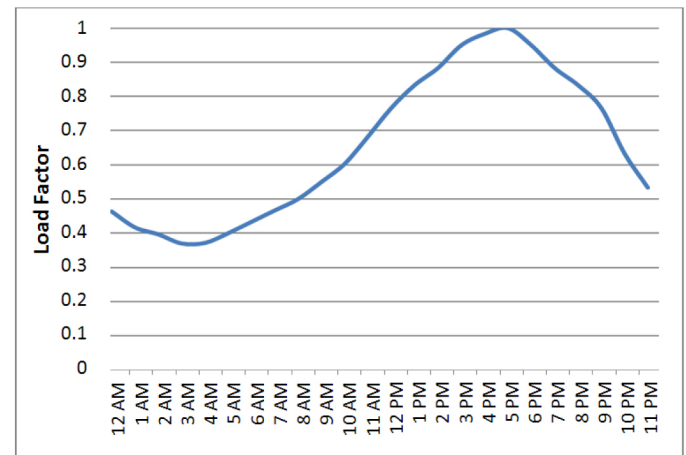


Figure 8. SMUD Service Region Coincidence Factor [11]

Probability Distribution of PEV Charging Rates

Table 2. Residential PEV Charging Rate Distribution

Charging Type	Charging Rate (kW)	2012 US Estimated Distribution ²	Projected Long Term Distribution for SMUD region
Level 1	1.4	71%	41%
Level 2 - Low	3.3	12%	25%
Level 2 - Low	6.6	14%	33%
Level 2 - High	9.6	2%	0.5%
Level 2 - High	19.2	1%	0.5%
DC Fast Charging	≥ 25	0% ³	0% ³

2. [17] provides sales figures by charging rates. [16] projects that about 71% of PEV users will charge at the 1.4 kW wall charging rate. These figures additionally assume that one-third of 9.6 kW users opted for the 19.2 kW charging option and that twice the percentage of 3.3 kW capable users charge chose to charge with the 1.4 kW rate than the 6.6 kW capable users.

3. DC fast charging is expected to have a negligible market share for residential applications compared to Level 1 and Level 2 charging. DC fast charging is expected only to appear in commercial settings due to barriers in hardware cost and electric utility demand charges.