Quantifying the Economic Value of Vehicle-Grid Integration: Case Study of Dynamic Pricing in Sacramento Region

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Abstract

This study develops a stochastic-systems approach in modeling vehicle-grid integration (VGI), where load management strategies can be compared in terms of their economic value to plug-in electric vehicle (PEV) consumers and their local utility companies. The proposed methodology is demonstrated in an assessment of VGI for the Sacramento Municipal Utility District (SMUD) in California. Monte-Carlo simulations have been performed to randomly assign PEV charging characteristics of the households based on given statistical distributions. Consumer adoption of time-of-use (TOU) rates is modeled as an optimization problem where consumers seek the earliest PEV charge start time among the charge schedules resulting lowest cost and satisfying their transportation needs. The preliminary results show that, considering today's grid system, the deployment of 60,000 PEVs in Sacramento Region will have significant but manageable impacts. These impacts included increasing annual peak demand by 86MWs (%5), and overloading up to 101 neighborhood transformers in the distribution system. On the other hand, adopting proper TOU rates presents a high potential for minimizing these negative impacts of widespread PEV deployment on the grid.

Research Question: How can VGI stakeholders quantify economic impacts of large-scale PEV deployment on the grid and evaluate PEV-based grid services?

Literature Review

The following table is a list of recent studies focused on the assessment of PEV-based grid services with respect to different aspects of grid operations. (Acronyms: DSM: demand-side management; DR: demand response; V2G: vehicle-to-grid).

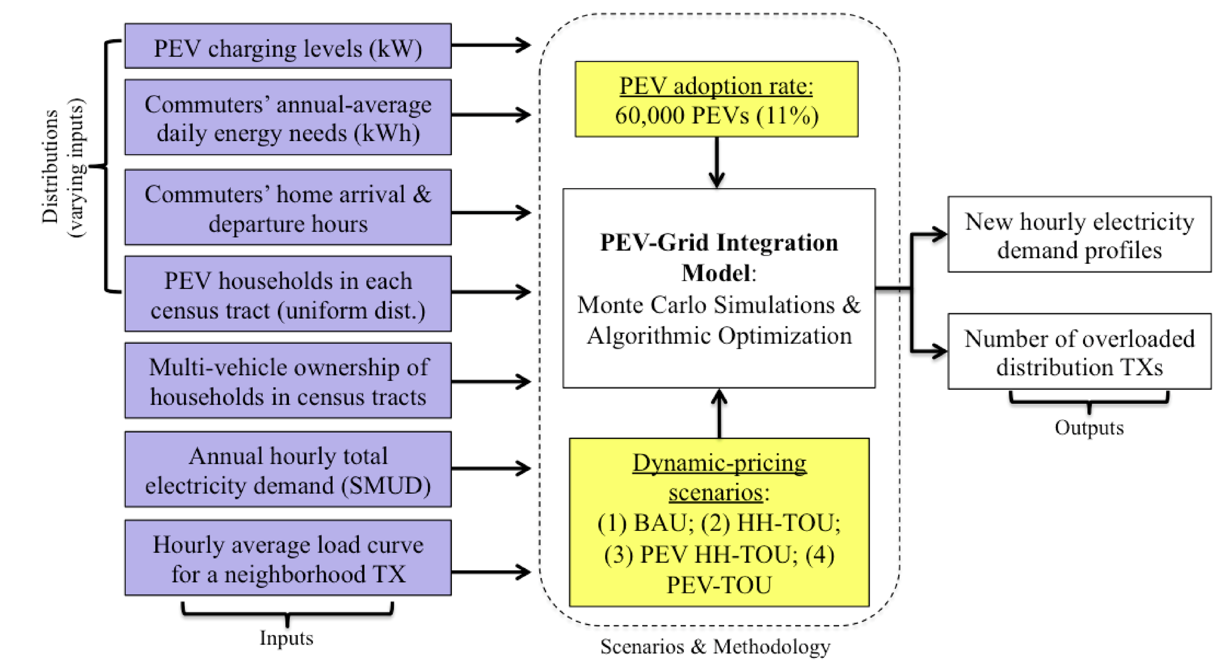
VGI Modeling Study	PEV Deployment Rate or Number	Region or Market	Load Management Scenario	Stochastic Inputs
Studies on Electricity Market Value for PEVs				
Sortomme and El-Sharkawi (2011)	10,000 (commuter-only)	Bonneville Power Admin.	Demand response: DLC*	None
Bessa et al. (2013)	3000	Iberian Electricity Market (2009-2011)	Demand response: DLC	PEV locations, battery size
Kempton et al. (2008)	100 and 300	PJM (2004-2006)	V2G: Scenario-based	None
Quinn et al. (2010)	96,000	CAISO (2006-2008)	V2G: DLC	None
Andersson et al. (2010)	500	Sweden & Germany (2008)	V2G: DLC	None
Pillai and Bak-Gensen (2011)	9000 and 18,000	Western Denmark	V2G: Scenario-based	None
Han et al. (2011)	1000	PJM (2004)	V2G: DLC	Charge levels
VGI Studies on Generation Dispatch and GHG Impacts				
Lund and Kempton (2008)	1.9 million	Denmark	V2G: Scenario-based	None
Axsen et al. (2011)	1 million (3.6% of LDV fleet)	CAISO	Demand response: Scenario-based	None
Dallinger (2012)	12 million	Germany (2030)	V2G: DLC	Energy needs
Sohnen (2013)	1 million (4.5% of Households)	CAISO	Demand response: Scenario-based	None
Kim and Rahimi (2014)	1 to 160 million	Los Angeles, CA (2012-2040)	Demand response: Scenario-based	None
VGI Studies on Distribution Systems				
Soares et al. (2010)	25% and 50% of LDVs	Flores Island	Unmanaged charging	PEV locations, charge levels, battery size
Moghe et al. (2011)	10% to 100% of LDVs	Phoenix and Seattle (selected areas)	Demand response: Scenario-based	PEV locations
Shao et al. (2012)	100	Blacksburg, VA (Virginia Tech)	Demand response: DLC	PEV locations, energy needs, charge duration

What is New?

"Our study provides an assessment on both, generation & distribution system impacts of PEVs on a 'utility-scale' grid system."

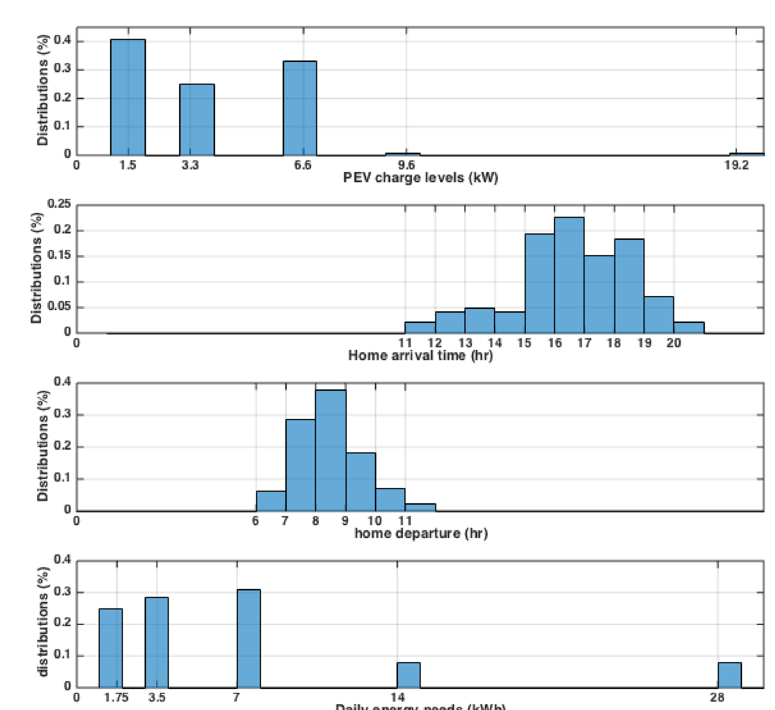
Modeling, Methodology and Data

The following chart demonstrates a conceptual design of the proposed systems model:

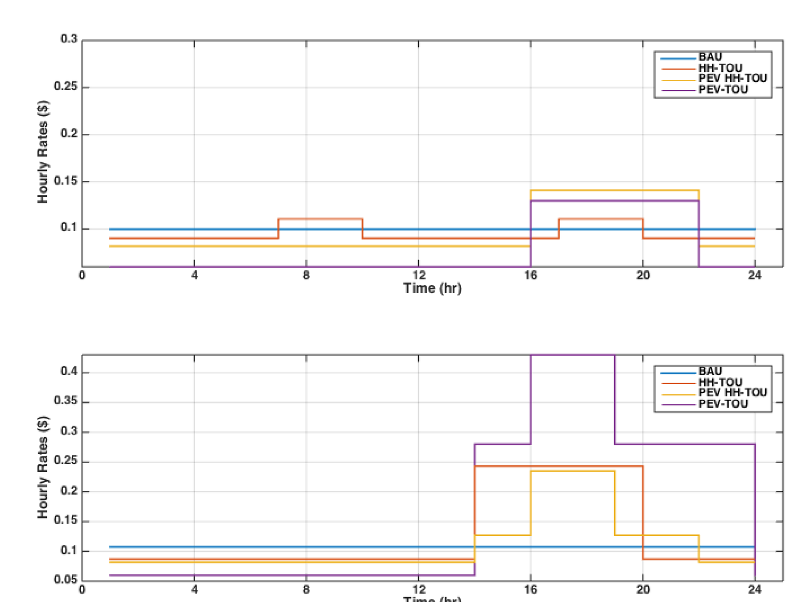


•TX is the neighborhood transformer which typically provides power to a total of 10 households in a single-unit residential neighborhood in the SMUD territory.
•SMUD is a mid-size utility region, which includes 317 census tracts and 512,496 households (US Census, 2013).
•California's goal of 1.5 million zero-emission vehicles (ZEV) corresponds to about 60,000 PEVs or 11% adoption rate for the Sacramento region.

Model Inputs: The following distributions considered in this study are the projected PEV charging levels (SMUD, 2013), daily energy needs (UCD PEV Market Tool, 2015), and home arrival hours (SACOG, 2012).



Scenario Formulation:
The PEV-grid analysis has been performed for three major scenarios: (1) business-as-usual (BAU), where fixed prices were considered (9.98 cents/kW in winter and10.76 cents/kW in summer); (2) household time-of-use (TOU-HH), where time-varying rates are provided for the households with a PEV. (2) PEV time-of-use (TOU-PEV), where the PEV charging load is billed separately through an additional utility meter or submeter.



Hourly seasonal electricity rates for winter and summer rate schedules (source: smud.org)

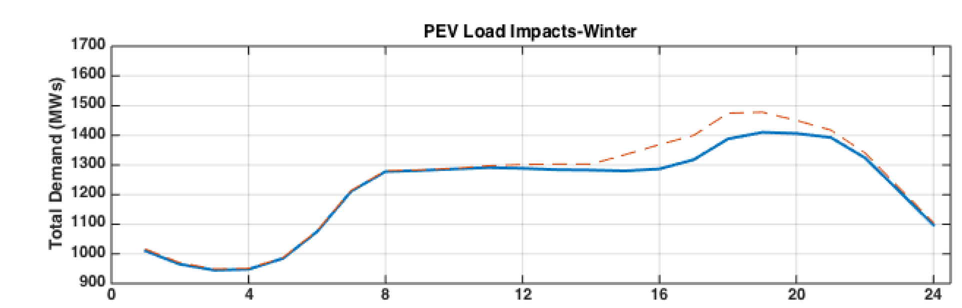
Algorithmic Optimization: PEV consumers are assumed to first determine lowest-cost charging schedules, then to choose the earliest charge start time from the available options. This algorithm is enabled for the dynamic-pricing scenarios.
➢The consumers' choice on charging schedule for the lowest-cost options are constrained based on their home arrival, home departure, charging level, and daily energy needs.

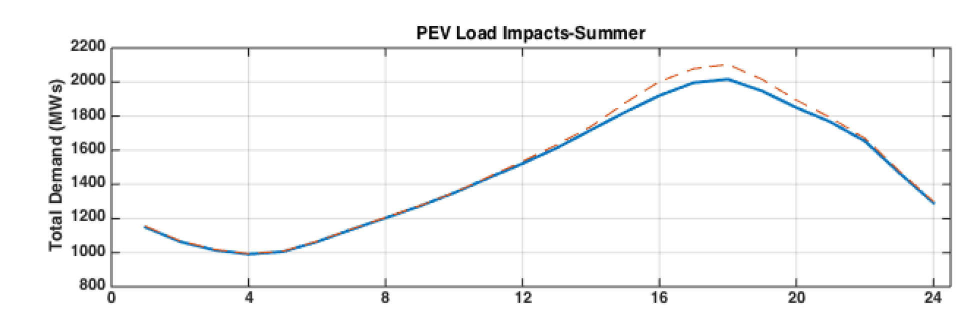
Results

➢Monte-Carlo based analysis is repeated 1000 times where the average coefficient of variation for 24 hour data approaches 0.02. Charging levels, daily energy needs, and home arrival/departure hours are randomly assigned to the PEV households based on the given distributions, and inverse transform sampling in Matlab.

"This additional PEV load increased the winter peak by 68 MWs, where summer peak is increased by 86MW. This increase is observed due to summer peak overlaps where the peak for PEV load is at 6pm."

"In high PEV adoption (60K) case, most of the additional electricity demand during the peak hour is shifted to 10pm or 12am based on the time-varying price signals."





"The BAU scenario resulted in an annual cost of $286 for the commuting-related electricity consumption. This amount is reduced to $233 in PEV HH-TOU and $185 in the PEV-TOU scenario."

"Although, PEV-TOU provided the lowest-cost electricity option for the PEV consumers, the additional metering system cost is expected to be significant. "

	BAU (reference)	HH-TOU	PEV HH-TOU	PEV-TOU
Total Annual Cost	$17,389,040	$11,409,565	$10,168,485	$9,801,648
Energy	$9,669,550	$8,170,908	$7,111,418	$6,767,068
Losses	$787,993	$562,470	$457,312	$436,300
Ancillary Services	$127,837	$78,402	$43,713	$42,542
Environmental (CO2)	$2,255,451	$1,955,862	$1,814,628	$1,805,501
Capacity Increase	$4,548,210	$641,923	$641,415	$650,237
PEV Program Admin	N/A	N/A	$100,000	$100,000
Total Revenue	$17,172,382	$15,076,355	$14,014,198	$11,158,139
Net Annual Profit (Utility)	-$216,658	$3,666,790	$3,845,713	$1,356,490
Net Annual Savings* (Utility)	N/A	$5,979,475	$7,220,555	$7,587,392
Average Annual Cost of PEV Charging	$286.21	$251.27	$233.57	$185.97
Net Annual Savings (All PEVs)	N/A	$2,096,028	$3,158,184	$6,014,244
Net Annual Savings (per PEV)	N/A	$35	$53	$100

* "Net annual savings" are the savings relative to BAU scenario

"Annual cost and benefit estimates for each TOU rate scenarios."

"The range in cost of transformer upgrades in the BAU scenario is found to be $334,362 to $804,062. This amount decreased as little as $23,883 in the PEV-TOU scenario."

	BAU (reference)	HH-TOU	PEV HH-TOU	PEV-TOU
Estimated Cost Range	$ 334,362-$804,061	$ 947,359-$1,608,122	$ 286,596-$740,373	$ 23,883-$199,025
Average Cost	$541,348	$1,273,760	$453,777	$103,493
Cost Savings (Relative to BAU)	N/A	-$732,412	$87,571	$437,855

"Estimated costs for the distribution infrastructure upgrades related to PEV charging under various TOU rate scenarios."

Key Takeaways:

1.Widespread PEV adoption, especially at the adoption rate of 7% or higher, may have a significant impact on the "utility-level" grid operations such as increasing peak demand and overloading distribution infrastructure.

1.Demand-side management programs, notably time-of-use rates, have enough potential for mitigating adverse grid impacts of the PEV load on both peak demand and distribution infrastructure.

2.The proposed method of PEV-grid assessment can be applied to other utility regions in the State, and can be improved by adapting grid infrastructure data with higher levels of detail.

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