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# The Value of Vehicle Grid Integration in California

John Stevens, Ph.D.[1], Joe Hooker, M.S.,[2]

[1]*Energy and Environmental Economics, Inc. (E3). 44 Montgomery St., Suite 1500, San Francisco, CA 94104, john.stevens@ethree.com*

[2]*joe.hooker@ethree.com*

**Summary**

E3 used a suite of tools and modelling assumptions to evaluate the value of vehicle-to-grid integration (VGI) for 2020 through 2030 in California. E3 generated future wholesale electricity market price forecasts for 2020 through 2030. E3 used public datasets to determine battery electric vehicle (BEV) driving demand profiles. E3 then used its proprietary RESTORE model to determine annual BEV charging profiles and associated costs under different scenarios. E3 found the most value for VGI by allowing bi-directional VGI-enabled vehicles to bid into energy and ancillary services markets. This allows BEVs to earn energy arbitrage revenue in future solar-dominated California electricity markets.

*Keywords: dynamic charging, electric vehicle supply equipment (EVSE), BEV (battery electric vehicle)*

## 1 Introduction

Electric vehicles have transitioned from being a technology of the future to one that is projected to undergo massive deployment in the U.S. in the coming years [1]. The shift to a heavily electrified vehicle fleet will coincide with a transformation of the electricity grid; utilities across the U.S. are rapidly deploying renewable resources [2] in order to meet various clean energy and renewable portfolio standards (CES and RPS) [3]. As variable renewable energy resources, notably solar PV and wind facilities, claim a growing share of electricity deliveries, the need for and value of flexibility services from loads will increase. Battery electric vehicles (BEVs), along with electrified buildings and stationary energy storage, can meet this need. The mechanism by which BEVs can meet this need is via vehicle-to-grid integration (VGI).

Currently, most BEV charging is done at home [4], and in some cases BEV owners are encouraged or mandated to charge using time of use (TOU) rates that incentivize charging during off-peak electricity net demand hours (e.g. [5], [6]). To assess the value to the grid from unlocking BEV's charging flexibility, E3 assessed the value of VGI to reduce the charging cost of BEVs versus a TOU charging baseline. E3 investigated this value stream by evaluating smart unidirectional charging (V1G), as well as smart bidirectional charging and discharging (V2G). All results for this work are reported in real 2018 U.S. dollars.

## 2. Background

### 2.1 Overview

In this section, the authors describe the theoretical background of modelling VGI's value to market operators in wholesale electricity markets. The section begins with a discussion of the role that storage assets like VGI can play in electricity markets. Then, the evolution of these markets with time is discussed, from 2020 through 2030.

### 2.1 Electricity Markets and Vehicle Grid Integration

Electricity markets exist in multiple regions in the U.S. and abroad. Different types of electricity markets exist, from markets that price energy, but not products such as capacity (e.g. in the Electric Reliability Council of Texas (ERCOT)), to systems with many different energy, ancillary services and capacity market products into which grid assets can bid (e.g. in the California Independent System Operator (CAISO)). Other regions have no organized electricity markets, but instead have vertically integrated utilities that own and operate grid assets (e.g. in the Pacific Northwest). However, fundamentally all grid operators, remunerate owners of generation and transmission assets for maintaining the supply-demand balance for electricity at all times.

This study investigates the value of VGI for three different types of market products. Energy markets pay grid assets a time-varying price per unit of energy injected to the grid. Ancillary services markets pay grid assets for the ability to provide increases or decreases in the amount of electricity supplied to the grid, in case the net load of electricity varies from the forecast net load. Capacity markets pay grid assets for their ability to generate electricity during times of system need, ensuring system reliability. Capacity payments are typically in units of $/kW-year or $/kW-month.

VGI can provide value for energy, ancillary services and capacity markets. V2G-enabled BEVs can perform load shifting by charging during times of low net demand and energy prices and discharging during periods of high net demand. VGI can enable load shifting, peaker and distribution deferral by shifting charging away from (V1G) or discharging during (V2G) periods of high system or local energy demand. Finally, V2G-enabled BEVs can provide ancillary services by rapidly charging and discharging to increase or decrease the net demand on the electricity grid. These three categories of grid services are summarized below in Figure 1.

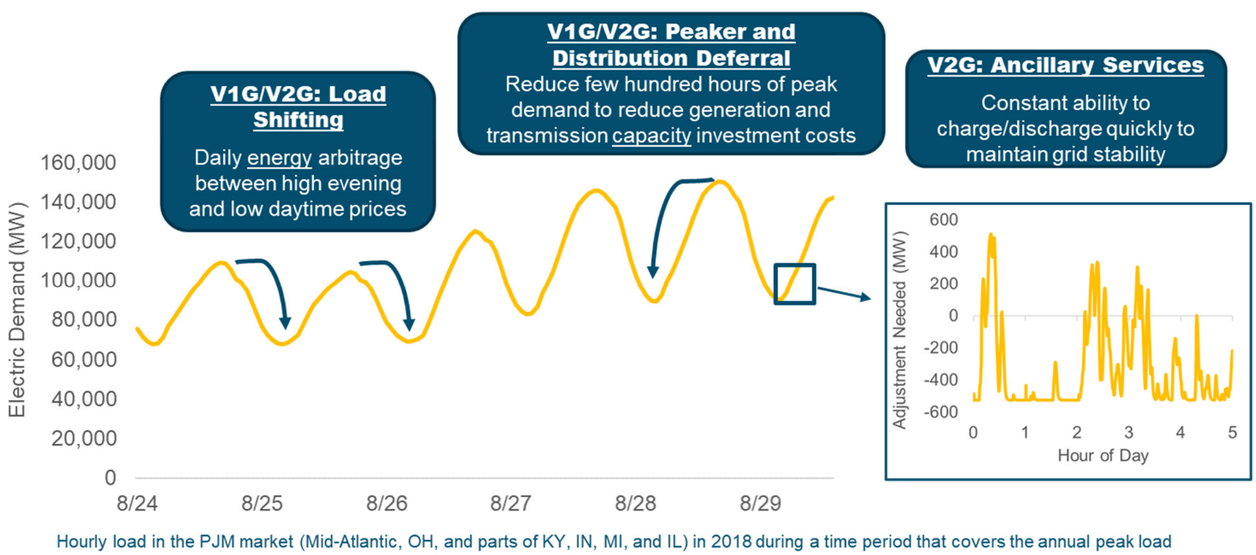


Figure 1: Grid Services that VGI can Provide

## 2.2 Evolving Electricity Markets in a Decarbonized Future

E3 generated future wholesale capacity, ancillary services and energy price forecasts for California electricity markets using Energy Exemplar's AURORA model [7]. To generate these price forecasts, E3 modified and customized AURORA in a proprietary fashion (including several modifications to the model logic) to reflect the capabilities of new resources like energy storage and BEVs, as well as to improve AURORA's ability to model typical electricity grid operations.

While the use of production simulation models such as AURORA is a well-known method for assessing electricity market dynamics, the evolution of market dynamics that result from California's climate goals is important to understand in order to understand how the benefits of VGI change from 2020 through 2030.

The need for utilities to be in compliance with California's high RPS, in conjunction with the relatively small resource potential of alternative zero-carbon resources, will drive the massive deployment of solar photovoltaic generating capacity in the state by 2030 [8]. This is projected to have a large effect on the overall evolution of energy prices in CAISO. This is shown in Figure 2 and Figure 3 for 2020 and 2030, respectively. In particular, the frequency and magnitude of negative pricing during midday hours are expected to increase significantly by 2030, due to persistent solar overgeneration during these hours. During the evening, large net load ramps will cause energy prices to spike, before they eventually decline in the late evening.

During these curtailment hours, E3 assumed that ancillary services prices also drop dramatically, because curtailed solar and wind can be used to provide reliable ancillary services at zero marginal cost [9] [10] [11]. Average month-hourly ancillary services prices for 2030 are shown in Figure 4. Similar to energy prices, these ancillary services prices are expected to spike in the early evening by 2030, before declining in the late evening.

Owing to the large anticipated buildout of stationary lithium-ion batteries on the California grid to help shift solar energy from daytime to evening hours [8], the peaker deferral capacity revenue available to batteries in V2G-enabled BEVs is projected to drop. This is due to the declining expected load carrying capacity (ELCC) of grid-tied batteries with increased penetration(see, e.g. [12]). This decline in value is shown p.

BEVs can also provide value by charging and discharging in such a way as to lower the local peak demand and defer the need to make localized distribution investments. Capacity revenue available to BEVs from distribution deferral was set at $40/kW-yr, which is a typical value chosen based on historical utility filings [13]. This value is constant in all years of the analysis, whereas the peaker deferral value shown in Figure 4 declines below $40/kW-yr by 2030.

Currently, grid-tied battery storage developers stack multiple revenue streams (e.g. from energy, ancillary services, and other sources) in order to maximize profitability [14]. E3 projects that due to the above-mentioned electricity market dynamics, the market will ultimately evolve to be dominated by energy shifting revenues. This is illustrated below in Figure 5.

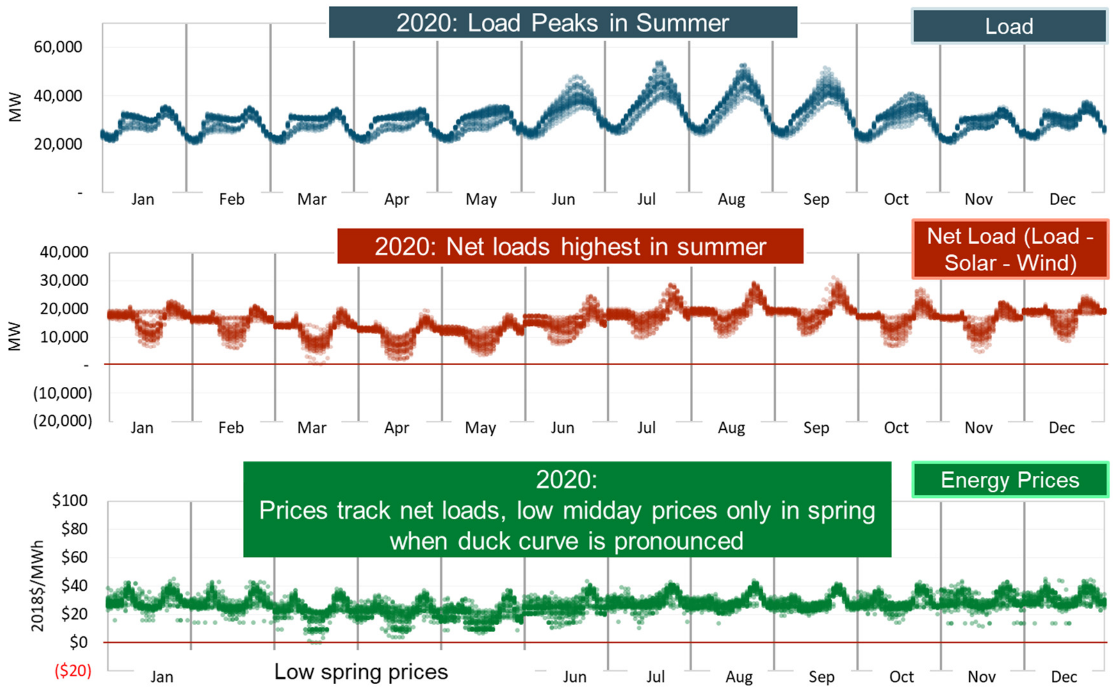


Figure 2: 2020 California Loads (MW), Net Loads (MW) and Energy Prices (2018$/MWh)

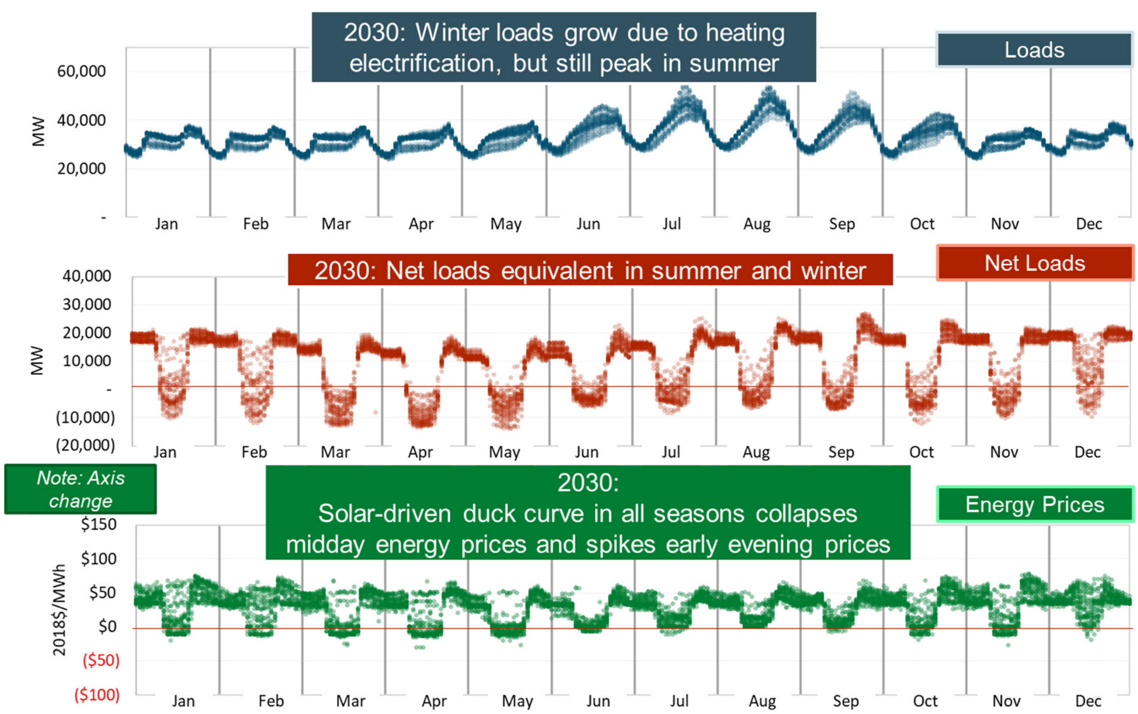


Figure 3: 2030 California Loads (MW), Net Loads (MW) and Energy Prices (2018$/MWh)

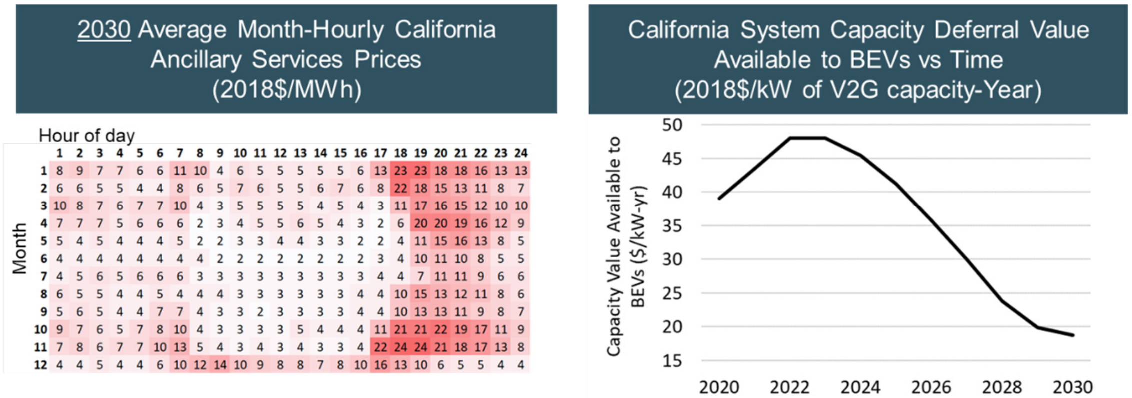


Figure 4: Evolution of California Ancillary Services (2018$/MWh) and Capacity Revenue (2018$/kW of V2G Capacity-Year)

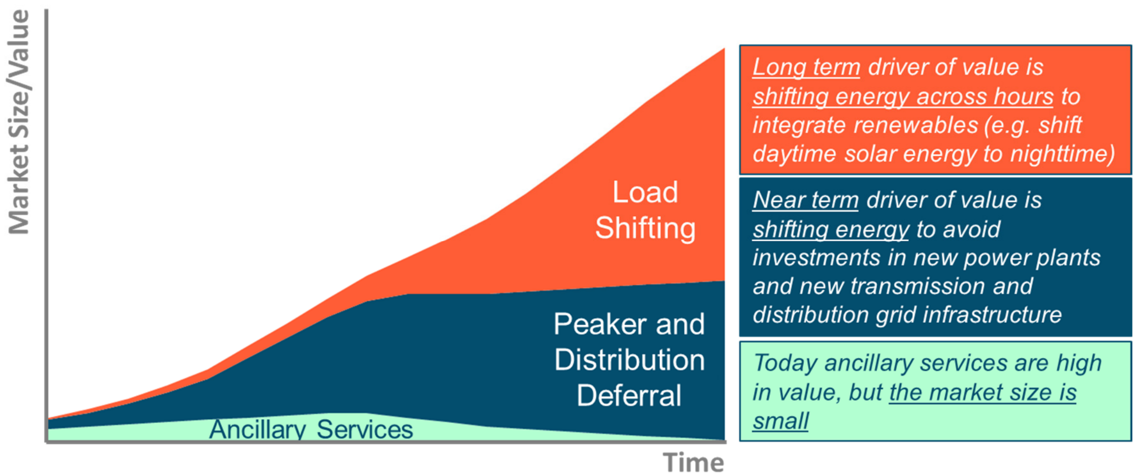


Figure 5: Illustrative Evolution of Electricity Market Dynamics

## 3. Methods

### 3.1 Overview

E3 used a suite of in-house and commercial modelling tools to assess the value of VGI-enabled vehicles in California providing load shifting, peaker and distribution deferral, and ancillary services to the grid for the years 2020 through 2030. This methodology is outlined in Figure 6 below. E3 used AURORA to generate energy, capacity and ancillary services prices, as discussed above. E3 used National Household Travel Survey [15] (NHTS)data to develop a database of potential EV trips and to determine typical 250-mile BEV (BEV-250) driving demand profiles. Finally, E3 relied on reasonable estimates of future BEV-250 attributes, including maximum electric vehicle supply equipment (EVSE) charging/discharging power ratings, BEV-250 battery sizes and BEV charger power capacities, which were based on existing BEVs. These data were fed to E3's proprietary RESTORE model [16] to determine annual BEV charging costs under different scenarios, using a price-taker approach. Further details of the BEV-250 vehicle and charger attributes, as well as the RESTORE modelling are detailed in the following sections.

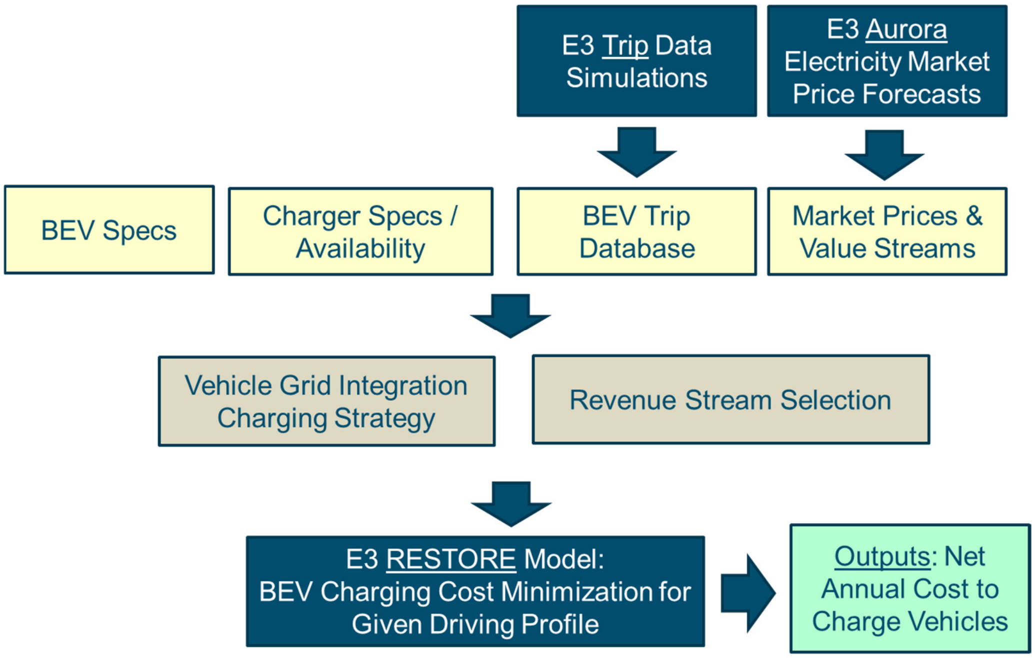


Figure 6: E3 Model Flow Diagram for VGI Benefits Analysis

## 3.1 BEV and EVSE Attributes

For this analysis, E3 made a variety of assumptions about the BEV and EVSE fleet that were meant to reflect typical system characteristics. BEVs are uniformly modelled as BEV-250s, each travelling approximately 11,500 miles/year and consuming 0.35 Wh/mile. V2G round trip charging efficiency was set at 81%. EVSEs were modelled as available at home, work and public settings. All EVSE were rated as 7.2 kW Level 2 chargers.

## 3.2 RESTORE Modelling

E3's RESTORE model was used to determine the value that VGI can provide to the grid. RESTORE employs linear optimization methods to optimally charge and discharge the BEV to provide services to the grid while also meeting all energy demand related to driving. The optimization logic seeks to minimize total charging costs per vehicle, given a price-taker assumption for BEVs and perfect foresight of the price signals described below. To assess the benefits associated with moving from the current paradigm of charging BEVs with TOU rates to VGI, E3 calculated BEV charging costs under the following operational paradigms:

- **TOU rate**: Unidirectional BEV charging was optimized using a TOU rate price signal. This price signal is based on the wholesale market price signals.
- **V1G**: Unidirectional BEV charging was optimized by using hourly wholesale electricity energy price signals from the market price forecasts.
- **V2G**: Bidirectional BEV charging was optimized by using wholesale electricity energy price signals, and in some cases, wholesale ancillary services and wholesale or utility capacity price signals.

For each of the three operational paradigms, E3 chose to calculate total annual BEV charging costs as the sum of hourly wholesale energy, ancillary services and capacity costs, multiplied by the hourly BEV charging demand. E3 chose to use a consistent set of wholesale hourly energy, ancillary services and capacity prices across each paradigm because this assessed the avoided wholesale costs incurred per year to generate and deliver electricity to each modelled BEV. Using retail rates would lead to an assessment that is more dependent on a specific utility's rate structures.

# 4 Results

The annual benefits of V1G and V2G for a BEV-250 are summarized below in Figure 7. This figure shows the relative savings in net annual BEV charging cost from switching from charging base on a TOU rate to the V1G or V2G charging strategies indicated in the figure. In the V2G cases that are not energy-only, two different price signals (all cases use an energy price signal, and they also use a peaker deferral, distribution deferral or ancillary services price signal) were fed to RESTORE to inform charging and discharging optimization logic.

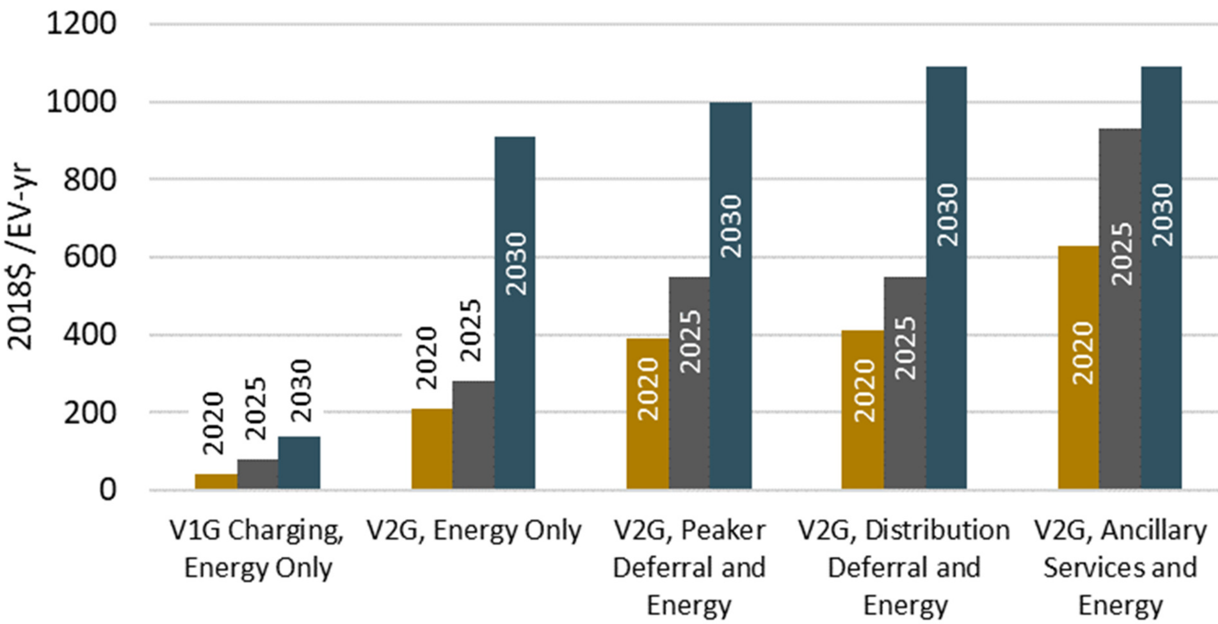


Figure 7: Value of Managed BEV-250 Charging vs. TOU Baseline for 2020, 2025 and 2030

# 5 Discussion

## 5.1 Discussion of Modelling Results

The results shown above show many of the trends illustrated in Section 2.2. As can be seen in Figure 7, market revenue for load shifting grows significantly from 2020 through 2030 (see "V2G, Energy Only"), and by 2030 comprises the majority of the value of V2G possible by bidding into various different market products. As shown in Figure 2 and Figure 3, this trend is due to the ability of V2G-enabled BEVs to capitalize on the growing spread between daytime and early evening energy prices as solar energy by buying excess electricity midday, then selling electricity that owners do not need for driving in the evening.

There is a large incremental benefit in all years from moving from V1G to V2G. This is because properly designed TOU rates can incentivize BEVs to charge with almost the same behaviour as BEVs with V1G, whereas V2G enables arbitrage. The authors developed their own TOU rates for this study for each year, which reflect the evolving AURORA wholesale electricity market prices. It is therefore possible that there is more incremental value to moving from TOU to V1G in many locations, as real TOU rates do not necessarily truly reflect wholesale costs, given the large amount of stakeholders involved in typical retail ratemaking processes.

In all cases, bidding into both energy and ancillary services markets is shown to be the optimal means of avoiding generation and transmission costs for charging BEVs. This is due to the frequent overlap in periods of low and high ancillary services and energy prices, as shown in Figure 2, Figure 3 and Figure 4. By 2030, capacity revenue from distribution deferral is more valuable than that from peaker deferral. This is likely due to the constant value E3 chose for distribution deferral ($40/kW-year), versus the peaker deferral value, which declines below $40/kW-year by 2030. E3 believes that peaker deferral is a more reliable revenue source for BEV owners than distribution deferral, as distribution feeders are periodically upgraded as more load is added to them.

Given that RESTORE is a price-taker model, large deployments of VGI will likely earn less revenue per BEV than indicated in these figures, as the demand for the services modelled herein would be saturated by BEVs. Additionally, there are many regulatory barriers for VGI-enabled BEVs to participate in CAISO, which means that this work shows a high estimate of the potential avoided costs per BEV resulting from enabling VGI in California. Actual markets would likely underbid BEV participation in CAISO markets to reduce the risk of having insufficient grid-connected BEV charging and discharging capacity at any given time.

### 5.2 Broader Implications of Results for VGI Deployment Strategies

In the short term, designing TOU rates that closely reflect wholesale electricity costs in California, and installing workplace EVSE can enable BEVs to reap most of the benefits of V1G without the added expense and regulatory hurdles of V1G. This strategy will also allow BEVs to charge during periods of high solar energy production, which will reduce grid emissions from transportation electrification, and reduce solar energy curtailment.

By 2030, E3 believes that it is critical for OEMs, regulatory bodies and utilities to enable home V2G BEV charging to unlock the greatest VGI value to the grid. V1G does play a role in shifting BEV charging away from peak net demand periods, but the overall value is much lower than that for V2G. Additionally, enabling aggregators, utilities or OEMs to bid BEVs into energy markets into CAISO will reap most of the benefits as simultaneously bidding BEVs into multiple markets (e.g energy and ancillary services). Only bidding BEVs into energy markets may reduce technology and regulatory barriers to enabling V2G, such as BEV telematics communication latency.

Given E3's extensive experience forecasting electricity market prices [17], E3 believes that these results can broadly be extended to many different regions that rely heavily on solar energy. Regions with wind-dominated grids are likely to have less certain price signals. The authors state this because, in renewable-heavy grids, there can be multiple days with very low wind production, whereas even during overcast weather, some amount of solar energy production will occur [18].

## 6 Conclusions and Future Work

E3 demonstrated a novel method of ascertaining the total avoided costs of BEV charging that can be enabled via VGI. E3 found that deploying vehicles with V1G had similar total charging costs as vehicles charging using well-designed TOU price signals. However, V2G unlocked significantly greater value than V1G alone.

E3 believes the most important future work to perform following this analysis is to determine how the value of VGI changes under different realistic scenarios of organized electricity market participation, and to also assess the costs of VGI equipment and total market size possible for enabling VGI under each of these scenarios. The authors believe that using an agent-based, market equilibrium approach to valuing VGI that does not have perfect foresight may be one solution to estimating the full value of VGI that is likely to be realized in CAISO and other markets.

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## Authors

Dr. Stevens received a Ph.D. and an M.S. in Mechanical Engineering from the University of California at Berkeley, and a B.S. in Mechanical Engineering from Tufts University. Dr. Stevens' interests lie in decarbonizing the global economy. Dr. Stevens is currently a Senior Consultant at Energy and Environmental Economics, Inc. (E3). He works on evaluating zero carbon fuel production pathways, managing renewable energy production uncertainty, and transportation and industrial electrification. Prior to joining E3, Dr. Stevens worked at the U.S. Department of Energy.

Mr. Hooker received an M.S. in Energy Engineering from École Polytechnique and a B.S. in Industrial Engineering from Northwestern University. Mr. Hooker is currently a Senior Consultant at E3, where he works on projects related to grid decarbonization via transportation electrification, resource planning for utility generation portfolio decarbonization and the evaluation of the economic viability of various low-carbon technologies. Prior to working at E3, Mr. Hooker worked at Électricité de France in Paris, France.