Harnessing the Power of Electric Vehicles

Vehicle-Grid Integration for a Cleaner, Cheaper, More Reliable California Electricity System

HIGHLIGHTS

A growing transition away from fossil fuel–powered vehicles to electric vehicles (EVs), and toward more renewable energy on its electricity grid, is helping California make critical reductions in air pollution and heat-trapping emissions. Besides producing no tailpipe emissions, EVs have another benefit: their batteries can act as electricity storage. Vehicle-grid integration (VGI) is the practice of intentionally integrating EVs with the electricity grid through managing the time, rate, or location of charging (V1G) and, in some instances, energy in the battery could be sent to the grid, a process known as V2G.

To better understand the extent to which VGI of light-duty EVs could aid the state's transition to clean electricity, the Union of Concerned Scientists partnered with Evolved Energy Research to conduct an analysis of different levels of hourly managed V1G and V2G. This analysis shows that VGI enables electricity system savings, ranging from $1.8 billion (1 percent of system costs) to $11.7 billion (5 percent of system costs) per year in 2045. It also found that V2G creates significant incremental benefits over V1G alone.

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June 2025

www.ucs.org/resources/harnessing-power-electric-vehicles

https://doi.org/10.47923/2025.15888

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Introduction

California is well on its way to electrifying the vehicles on its roads as the state seeks to cut local air pollution and heat-trapping emissions from the transportation sector, with cars and light-duty trucks leading the way in the electrification transition. Sales of light-duty battery electric vehicles (EVs) continue to grow, with plug-in vehicles making up more than 25 percent of new passenger vehicles sales in 2024, and the state had 1.9 million total electric cars and light trucks by the end of 2024 (CEC 2025). Meanwhile, the electricity system in California continues to reduce its heat-trapping emissions. As of the end of 2022, annual heat-trapping emissions from electricity production in the state are more than 40 percent lower than in 2000 (CARB 2024a). Reducing emissions from electricity generation is critical not only for cleaning up longstanding uses of electricity. Reducing electric sector emissions also enhances the benefits of transitioning technologies that have historically used fossil fuels to alternatives that use electricity. See Box 1 for more on why it is important to electrify transportation.

The futures of both the electricity and the transportation system have clear direction in California. By 2035, all new light-duty vehicle sales will be zero emission vehicles, predominantly battery EVs, in accordance with the state's Advanced Clean Cars II regulation (CARB 2022).[1] This goal also appears in a 2020 executive order.[2] Previously, the state set ambitious global warming emissions reduction targets, including reaching net zero carbon emissions across the economy and 100 percent zero-carbon electricity by 2045.[3]

Operation of the electricity and transportation sectors is increasingly intertwined. Vehicle-grid integration (VGI) is the practice of intentionally integrating EVs with the electric grid to maximize the use of renewable energy resources, increase efficient use of grid infrastructure, and avoid otherwise necessary—and often costly—grid upgrades. Through VGI, drivers support the reliable operation of the grid, and both driver and grid should benefit from VGI arrangements.

VGI takes two primary forms: unidirectional managed charging and bidirectional managed charging. Unidirectional managed charging, or smart charging, refers to managing when, how, or where EVs are charged. Bidirectional managed charging refers to managed charging plus managed discharging of the EV battery through a charging station to the grid to power uses that would otherwise pull electricity from the grid. Bidirectional charging also includes use of an outlet in a vehicle or an adapter in a charging port to power equipment directly.

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[1] *This report and the analysis herein include regulations that were enacted as of January 2025.*

[2] Exec. Order No. N-79-20 (2020). https://www.gov.ca.gov/wp-content/uploads/2020/09/9.23.20-EO-N-79-20-Climate.pdf

[3] Exec. Order No. B-55-18 to Achieve Carbon Neutrality (2018). https://archive.gov.ca.gov/archive/gov39/wp-content/uploads/2018/09/9.10.18-Executive-Order.pdf; SB 100 California Renewables Portfolio Standard Program: Emissions of Greenhouse Gases (2018). https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB100

As California incorporates more renewable electricity and deploys more EVs, the Union of Concerned Scientists (UCS) has sought to understand how much VGI could aid California's transition to clean electricity. We set out to answer three key research questions:

1. To what extent do varying levels and types of VGI reduce the need for additional grid infrastructure and its associated costs?
2. What incremental system benefits does electricity discharge from EVs provide over managed charging alone?
3. How much must vehicle batteries be used to provide the benefits of battery discharge to the grid?

This report's analysis confirms that VGI provides benefits to the grid. It shows increasing benefits as managed discharging is added to managed charging, resulting in improved peak demand reduction and providing energy back to the grid when demand is highest. Importantly, the benefits found do not assume any change in the use of vehicles for mobility.

Box 1. Why Electrify?
Light-duty vehicles as a group—the cars, pickups, and SUVs in the driveways of many households and on the lots of some businesses—produce a significant amount of both local air pollution and global warming emissions. In California, those vehicles contribute 16 percent of oxides of nitrogen and 28 percent of fine particulate matter to the total of those health-harming air pollutants produced by all mobile sources (CARB 2024b). At 73 percent, light-duty vehicles are the transportation sector's largest source of heat-trapping emissions, and they produce 28 percent of the total of such emissions (CARB 2024c). UCS and other researchers have long established that EVs produce fewer global warming emissions than their combustion engine counterparts over the vehicle's lifecycle, a difference that has continued to improve as the electricity grid has reduced its emissions (Reichmuth, Dunn, and Anair 2022; IEA 2024).

VGI Terminology and Vehicle Capability Requirements

As noted, VGI takes two primary forms: (1) unidirectional managed charging and (2) bidirectional managed charging and discharging to the grid or to power a load otherwise connected to the grid.

From a technology standpoint, all EVs are capable of managed charging (V1G). Opportunities range from time-varying rates that guide users' behavior on when to plug in and charge, to programs that provide more direct, dynamic signals to the EV or EV supply equipment. In any case, the effect is to funnel charging to times of abundant renewable resources or to times when the system has spare capacity because demands on it are relatively low. In this way, shifting charging can reduce system or local grid peak demand. This helps reduce grid costs because the grid has to be built to handle the highest loads. Lower peak loads mean lower cost to build and operate the grid. Because all electricity utility customers must contribute to covering grid costs, managed charging that reduces peak demand to lower costs can benefit all utility customers.

To participate in bidirectional charging opportunities, EVs must be able to both charge and discharge energy in the battery from and to an external entity that can receive power. EV battery discharge may be conducted in synchronized, or “parallel,” operation with the grid or when the discharging site is isolated, or “islanded,” from the grid.

In a grid-parallel configuration, discharged energy flows through a charging station either to meet electricity demand in the household or business premises (that is, non-exporting grid-parallel operation) or to feed power back onto the grid (that is, exporting grid-parallel operation). For example, a non-exporting grid-parallel EV could be used to offset the power a home consumes during the peak hours of a heat wave. Meanwhile, an exporting grid-parallel EV whose power output exceeds the home’s electricity needs could push the excess power to the grid during the peak hours of a heat wave. This report’s analysis models VGI in a highly aggregated manner that does not distinguish between export and non-export battery discharges that serve electricity demand otherwise connected to the grid. The term vehicle-to-grid, or V2G, will be used to refer to grid-parallel battery discharge, without differentiating between export or non-export. See Table 1 for a comparison of V1G and V2G.

When islanded from the grid, discharged energy can flow through a charging station to meet site load not connected to the grid, for example by providing backup power to a home or community center during an emergency.[4]

EV battery discharge through an outlet in the vehicle or connected directly to the charging port can be used to power a home appliance or worksite tool. This is often referred to as vehicle-to-load (V2L). See Table 2 for a summary of VGI terms and definitions.

[4] *The grid-isolated or islanded configuration is sometimes referred to as vehicle-to-home (V2H) or vehicle-to-building (V2B), terms also often used to refer to grid-parallel operation. To avoid confusion, we use the term islanded to refer to discharge isolated from the grid.*

Table 1. VGI Arrangements and Distinctions

Feature	V1G	V2G
Charge an EV on the grid	✓	✓
Discharge an EV to the grid		✓
Discharge an EV to a home while grid-connected		✓
Set a schedule and other charging preferences	✓	✓
Set preferences and constraints for discharging		✓
Support efficient grid operation	✓	✓
Support the grid during extreme events	✓	✓
Reduce grid upgrade costs	✓	✓
Reduce participant's electricity bill	✓	✓
Key benefits	Adjust charging to increase grid efficiency and save money	Use an EV as a grid-connected battery and save money

Table 2. VGI terms and definitions

VGI Terms	Details
Managed charging	The management of when, how, or where EVs are charged
Grid-parallel, exporting bidirectional charging	The management of when, how, or where EVs are charged and discharged back to the grid
Grid-parallel, nonexporting bidirectional charging	Powering a home or business with an EV battery while connected to the grid
Islanded bidirectional charging	Powering a home or business with only an EV battery while disconnected from the grid
V2L	Powering a device with an EV battery via an outlet in an EV or a connector at the charging port

V2L can provide grid value. However, simple V2L functions, such as a power port adapter or outlet inside the vehicle, typically provide only the power level of a 120-volt or 240-volt outlet and may not be set up to receive signals from the grid. Full V2G integration can be responsive to grid conditions and export at a higher power level to meaningfully reduce grid stress and reduce the need to expand grid capacity to handle peak loads. All these benefits can help reduce the cost of operating the grid and therefore benefit all electricity utility customers, not just the EV drivers participating in VGI programs.

A growing number of EV models are coming off the production line with various levels of bidirectional charging capability. Most are designed for V2L or islanded power discharge, stopping short of grid-parallel, V2G functionality. See Box 2 for additional details on current bidirectional capabilities.

Box 2. Current Vehicles with Bidirectional Charging Capability

Several manufacturers currently offer light-duty EVs with V2L capability in the United States. For example, versions of Ford's F-150 Lightning EV pickup truck can provide up to 9.6 kW alternating current (AC) power from 120- and 240-volt outlets in the truck's cargo bed. Select vehicles from General Motors, Hyundai, Kia, Rivian, Tesla, and Honda can also do V2L power transfer.

Ford, General Motors, Kia, Nissan, and Tesla also now offer solutions that would allow an EV to power an entire home or business in a blackout. The larger batteries in pickup trucks made by some of these manufacturers can provide enough energy for multiple days of full household power and over a week if home electricity use is reduced. This capability requires compatible charging and switching equipment to isolate the home power from the nonfunctioning grid.

Bidirectional charging capability is not limited to light-duty EVs. Indeed, school buses, with their suitable daily and seasonal use patterns, have years of history demonstrating V2G integration. Since the beginning of 2024, the Hybrid and Electric Truck and Bus Voucher Incentive Project has required V2G capability for school buses receiving incentive funds, and the catalogue of eligible vehicles boasts over two dozen models (CARB n.d.; California HVIP n.d.).

Analysis Methods

UCS partnered with Evolved Energy Research (EER) to conduct this analysis (Farbes and Jones 2025). We used two existing models developed by EER with additional, novel VGI model structures to analyze changes to the California energy system due to varying levels of adoption. EnergyPATHWAYS is a demand-side model that includes a detailed representation of energy use, technologies, and costs in the transportation, buildings, and industrial sectors. That model's outputs are then fed into the Regional Investment and Operations (RIO) model, which was used to conduct a least-cost optimization of supply-side options for producing, transporting, and storing electricity, fuels, and carbon dioxide. EER developed novel functionality to represent VGI capability in RIO for this analysis.

We used the assumptions and inputs from the central scenario of EER's 2024 Annual Decarbonization Perspective (ADP) as a starting point for this analysis (Jones et al. 2024). From that starting point, we made a limited number of adjustments to the electricity system assumptions. Assumptions related to the novel VGI model component were each made specific to this analysis.

Key Modeling Assumptions

For the purposes of this analysis, we focused on the grid integration of light-duty, battery EVs in California. The stock of these vehicles in the analysis is aligned with real-world data for historical years and grows in future years by EV sales consistent with policies as of January 2025, including the California Air Resources Board's Advanced Clean Cars II regulatory requirements, while also accounting for vehicle retirements. The number of light-duty battery EVs on the road for key timestep years is shown in Table 3. To determine the storage potential of the fleet, we assumed the average EV battery pack size increases to 80 kilowatt-hours (kWh) by 2030 and remains constant in subsequent years.

Table 3. Light-Duty Battery EV Stock

Year	Number of Battery EVs (millions)
2025	2.0
2030	6.2
2035	14.0
2040	23.0
2045	30.1
2050	34.1

The stock of vehicles on California roads is reported by major timestep year. The stock grows by sales consistent with the Advanced Clean Cars II regulation, accounting for retirements.

In the modeling, EV charging was allocated across four archetypal grid feeder types: residential, commercial, industrial, and direct current (DC) fast chargers. Feeders are representative of electricity distribution systems serving different customer classes and their associated end uses. The electricity demand and storage potential of the EV stock are then allocated across those feeders while accounting for the power level of charging: Level 1, Level 2, and DC fast charging.[5]

Within the stock of light-duty EVs, managed charging and discharging was limited to EV load plugged into Level 2 charging. Level 2 charging takes place on three of the feeder types: residential, commercial, and industrial. We focused on Level 2 charging because of its

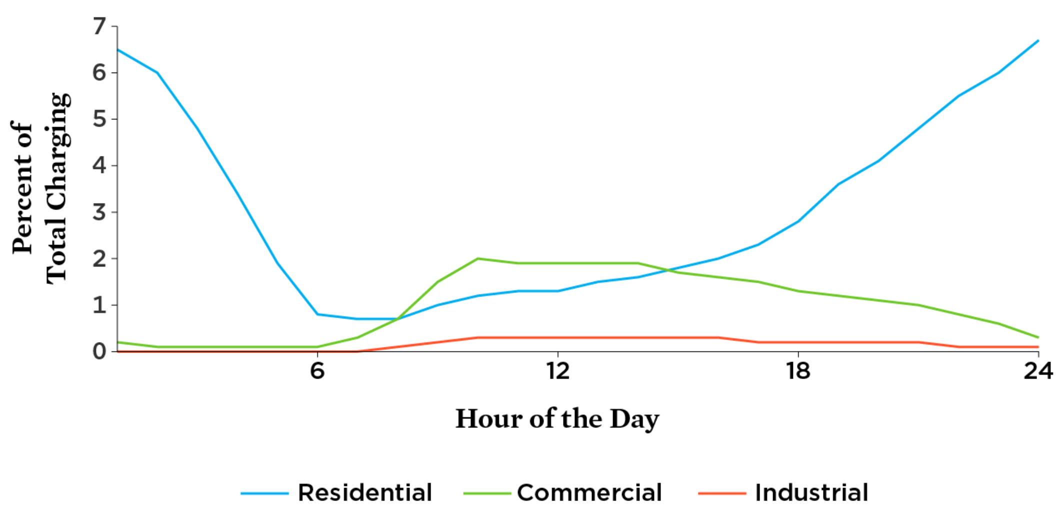
[5] *Level 1 charging power is typically 1.9 kW, while Level 2 charging power can reach 19.2 kW. Both Level 1 and Level 2 charging use AC power. DC fast charging typically starts at 50 kW and can reach 450 kW for light-duty vehicles. A few charging equipment providers also offer DC products with power levels under 50 kW (SDG&E, PG&E, and SCE 2025).*

sufficient charging speed to flexibly replenish energy used for driving or power export, which Level 1 charging lacks. We excluded DC fast charging because it is typically inflexible.

For the baseline EV charging behavior, we adapted the EV charging profiles used in the California Energy Commission's 2024 Integrated Energy Policy Report (CEC 2024a). The baseline profiles assume current enrollment in time-of-use electricity rates reflecting typical bulk system conditions and behavior that largely aligns charging with off-peak periods among time-of-use rate participants, behavior that we assume persists into the future. The use of a baseline that accounts for some charging shift in response to time-of-use rates produces results that are more conservative than if we were to assume totally unmanaged baseline charging behavior. It helps ensure that our results do not overstate the benefit of hourly managed charging (V1G) and discharging (V2G) in this study.

This analysis used different charging profiles for weekdays and weekends/holidays. Figure 1 shows the baseline EV charging load shape by feeder for a weekday. The same baseline profiles were used for all years in the study.

Figure 1. Baseline Charging Behavior by Feeder Type



The baseline load profile for each type of feeder is shown. The values are percent of load for that feeder type (vertical axis) across each day (horizonal axis), labeled with time ending each of the 24 hours in a day. The load shape is reported as the percent of load so that it can scale for the number of EVs at each timestep.

In the analysis, V1G and V2G are done on an hourly basis. Hourly dispatch for V1G differs from charging that is managed to a time-of-use electricity rate. The time-of-use electricity rates typically have two or three periods with varying electricity price, and EV charging is typically programed to begin when the lowest cost period begins each day. This sort of "set it and forget it" can help relieve some grid stress but leaves value on the table relative to more granular scheduling.

The EVs on each feeder are treated in aggregate as one big battery. This aggregated approach simplifies the optimization while still providing a reasonable representation of the EV fleet as a whole. The level of aggregation in the model does not distinguish between grid parallel exporting bidirectional charging and grid parallel non-exporting bidirectional charging. We use the term V2G to mean either in the analysis. The level of aggregation in the analysis also does not give insight into the colocation of rooftop solar and EVs. A correlation in the adoption of these two technologies is unlikely to materially affect the savings found in this analysis because the modeling does not distinguish between grid-parallel export and grid parallel non-export battery discharging. Moreover, we expect any effect in the real-world practice of V2G to be diluted as EV adoption becomes widespread, reaching those for whom installing rooftop solar or self-consumption of installed rooftop solar energy is not feasible (for example, some apartment and condominium residents or drivers who cannot charge at home).

Absent any VGI, EV charging demand in the analysis follows the baseline charging behavior, shown above, which includes no ability to delay or advance charging. V1G capabilities allow EVs to delay or advance charging from the grid on an hourly basis when it is advantageous to shift feeder or system demand. However, V1G must still meet vehicles' daily energy demand for driving, and it is constrained within a maximum average charging level within each feeder type, which varies throughout the day. V1G charging also incurs a penalty for deviating from a target state of charge, which limits the use of V1G to account for customer preferences for maintaining an 80 percent state of charge for driving use.

V2G includes all aspects of V1G, and it adds the ability to conduct managed discharging to the grid, also on an hourly basis. V2G power export is constrained by a maximum discharge level that varies throughout the day, and it has a higher penalty than V1G for moving batteries away from their ideal level of charge. In addition, V2G discharge in this analysis incurs a cost of $100 per megawatt-hour (MWh) of energy used, which we calculated to be the implied cost of additional wear on vehicle batteries. This assumption may be conservative if the practice of V2G includes parameters to promote battery heath.[6] Additional information on this assumption can be found in the technical report on this analysis from EER (Farbes and Jones 2025). The $100 per MWh cost can be seen as a variable operation and maintenance cost paid by the grid operator to the driver participant to make up for potential battery degradation due to extra battery cycling, thereby neutralizing battery wear as a disincentive to participating. Finally, we assume a round-trip V2G efficiency of 80 percent.

Although the model in this analysis has the ability to adapt charging behavior on an hourly basis, the amount of charging or discharging that can be shifted from the baseline behavior was constrained to reflect real-world facts. These constraints are represented primarily in the maximum charging and discharging shapes described above. While conservative, these assumptions account for the fact that some vehicles share a charger with others, not every vehicle will be plugged in at the same time, and some vehicles that are plugged in may be unable to charge or discharge at maximum power. These constraints also ensure that vehicles are available for their primary function, namely the mobility of the households and businesses.

[6] *For some battery chemistries, cycling the battery within certain state of charge limits can promote battery longevity. See, e.g., Bui et al. 2021.*

Scenarios

To answer our research questions, we examined three groups of scenarios. Each group held constant the fraction of Level 2 EV charging enrolled in VGI at 20 (Low), 50 (Medium), or 80 (High) percent. For any particular VGI event, the number of enrolled vehicles is discounted to a subset of those vehicles to reflect the real-world facts that some vehicles share a charger and not all plugged-in vehicles can participate at a given time. These constraints are represented by the maximum average charging and discharging shapes described above.

The Low VGI group scenarios could, for example, represent incremental improvement in the status quo. In this group, advanced, hourly VGI is a niche practice. This could represent a future in which VGI is limited by one or more factors. For examples, only high-trim vehicles come with bidirectional charging; most drivers are not willing to accept external control of their vehicle charging; or the regulatory environment and program or market offerings do not evolve to offer a variety of options to appeal to more drivers. The High VGI group scenarios could represent widespread adoption of advanced VGI, while recognizing 100 percent adoption is virtually impossible due to driving needs and other factors. The Medium VGI group represents an intermediary scenario.

Within each group, different scenarios vary the mix of VGI between V1G and V2G. The full range of VGI scenarios is listed in Table 4. Each of the 15 VGI scenarios is compared to the baseline scenario with no hourly VGI.

Table 4. VGI Enrollment Scenarios (Level 2 Charging)

Scenario	Scenario Group	V1G	V2G
1	Low Enrollment	20.0%	0.0%
2		10.0%	10.0%
3		0.0%	20.0%
4	Medium Enrollment	50.0%	0.0%
5		37.5%	12.5%
6		25.0%	25.0%
7		12.5%	37.5%
8		0.0%	50.0%
9	High Enrollment	80.0%	0.0%
10		66.7%	13.3%
11		53.3%	26.7%
12		40.0%	40.0%
13		26.7%	53.3%
14		13.3%	66.7%
15		0.0%	80.0%

Three scenario groups (Low, Medium, and High), totaling 15 scenarios, were run in the models and then compared to the baseline (no hourly VGI) scenario results. The listed percent of V1G and V2G refer to the percent of Level 2 loads enrolled in each type of VGI.

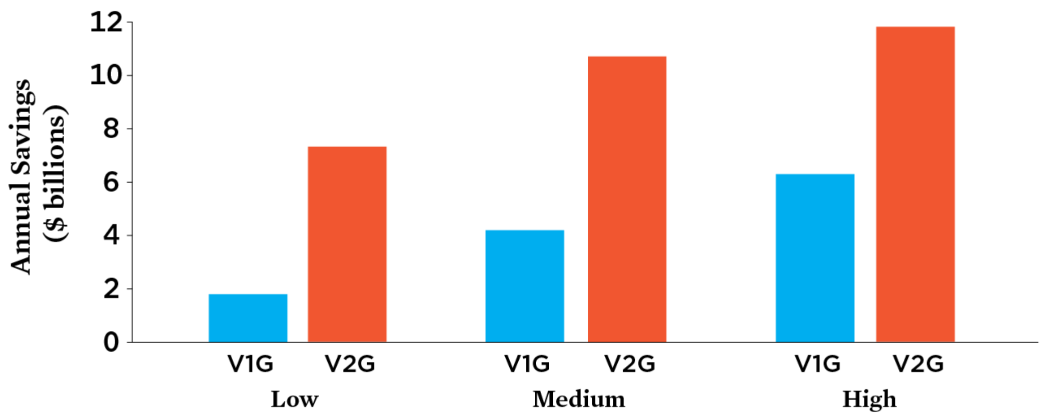
Findings

1. VGI Enables Electric System Savings

Across all scenarios studied, VGI produced annual savings in 2045 for California's electricity system relative to the baseline charging behavior.[7] Across all scenario groups, savings increase with participation in V2G, discussed further in Finding 2. The savings categories are discussed in Finding 3. Annual savings across scenarios range from $1.8 billion (1 percent of system costs) in the Low VGI enrollment scenario with all V1G to $11.7 billion (5 percent of system costs) in the High VGI enrollment scenario with all V2G.

Figure 2 shows the range of annual net savings for the three scenario groups in 2045. Within each group, the all-V1G scenario (blue bars) has the lowest savings, while the all-V2G scenario has the highest (orange bars).

Figure 2. California Electricity System Savings from V1G vs V2G for Each Scenario Group in 2045



The net annual savings for the all-V1G and all-V2G model runs are shown for each scenario group. The all-V1G scenarios represent the minimum net savings found in each group, with all-V2G scenarios representing the maximum net savings within each group. The Low VGI group produced the lowest savings while the High VGI group produced the most savings.

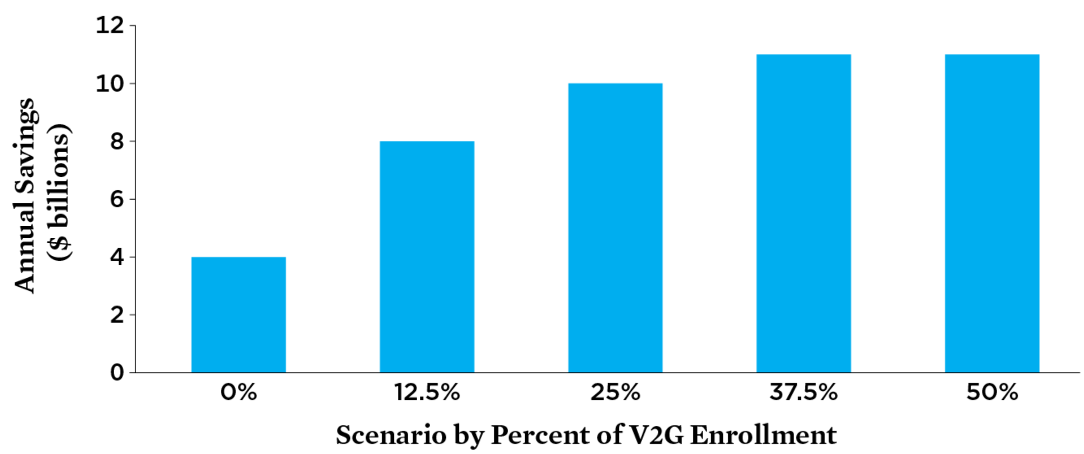
[7] *In the later years of the analysis period, VGI produces some small but meaningful impacts on fuels used in the broader energy system. Those impacts include changes in electricity balancing that make electro-fuels less competitive and biofuels more competitive. For simplicity, we group these together with changes in the electricity system.*

2. V2G Creates Significant Incremental Benefits Over V1G Alone

In all scenario groups, each shift in the balance of VGI-enrolled EV load from V1G to V2G resulted in incrementally higher annual savings in 2045. Taking the Medium VGI enrollment group as an example (see Figure 3), we see that each bar from left (all V1G) to right (all V2G) increases in height, representing an increase in system savings as V2G share increases. From the 0 percent V2G scenario (50 percent V1G) to the scenario with 12.5 percent V2G (37.5 percent V1G), savings nearly double from $4.2 billion to $7.7 billion. Compared to the 0 percent V2G scenario, the 25 percent V2G scenario (with 25 percent V1G) has nearly 60 percent more benefit.

While savings increase for each increase in V2G availability, each successive increase found a lower incremental benefit, shown as shallower steps up from bar to bar within the group from left to right. For both the Medium and High VGI enrollment groups, these diminishing returns become very pronounced at scenarios with more than a quarter of Level 2 charging available for V2G. These diminishing returns are primarily due to limitations to how VGI can reduce peak demands on the grid, as described further in Finding 3. Even so, the all-V2G scenario saves more than 60 percent more than the all-V1G scenario within the Medium VGI enrollment group.

Figure 3. California Electricity System Savings in 2045 with Medium VGI Enrollment



The annual net savings from each Medium VGI enrollment scenario is shown by percent V2G enrollment. Each additional increment of V2G enrollment produces additional net grid savings, although with a smaller marginal increase in savings from each increment.

3. VGI Savings Come from the Reduced Buildout of Electricity System Infrastructure

Savings and incremental costs for each scenario were assessed across categories of electricity system infrastructure, namely renewable generation, thermal generation, electricity storage, fuels,[8] and electricity delivery. Savings by electricity system infrastructure category are shown for the Medium VGI enrollment in Figure 4.

VGI Reduces Peak Demand to Reduce the Cost of Delivering Electricity

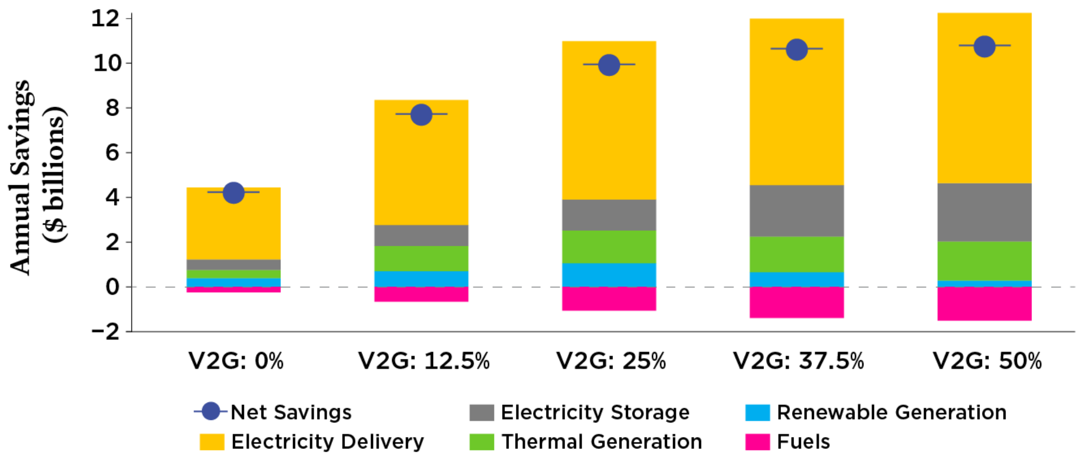
The largest savings component in every scenario came from reduced buildout of electricity delivery infrastructure (see Figure 4, yellow bars), largely from avoiding distribution grid investments. VGI reduces electricity delivery costs by reducing peak demand on the distribution system. For example, high levels of V2G could reduce residential and commercial net peak demand by up to 33 percent and 10 percent, respectively, in 2045. These large reductions in peak demand translate to a reduced need to build additional substations, transformers, service lines, and other distribution infrastructure, which leads directly to significant cost savings for the distribution system. V1G generates 40 to 50 percent of these benefits, while V2G creates even more. However, there is a limit to how much V1G can shave peak demand and how much V2G can alleviate remaining peak demand on the grid. This limitation is a key factor in the plateau we see at high levels of V2G, above which more V2G is characterized by the diminishing returns discussed in Finding 2.

VGI Matches Charging Demand to Variable Renewable Generation, Reducing the Buildout of Thermal Generation and Storage Capacity

VGI also produces savings by better matching energy demand to variable renewable energy production, reducing the overall need to build new utility-scale thermal generation (green bars) and energy storage resources (gray bars). However, these results are heavily dependent on the amount of V2G deployed. In scenarios with vehicles participating only in V1G, savings from reduced buildout of utility-scale thermal generation and energy storage are much more modest. Increasing levels of V2G are critical to unlocking these savings, with the storage savings driven primarily by building less long-duration storage.[9] The savings from avoided renewable energy deployment are more variable across scenarios as V2G increases because it causes shifts in capacity from solar to wind generation on the margin to optimally take advantage of V2G EV storage potential.

[8] *Fuels include, for example, electrolytic hydrogen and biofuels.*
[9] *In line with the assumptions for EER's ADP 2024, long-duration storage technologies have a minimum duration of 24 hours.*

Figure 4. California Electricity System Savings by Category in 2045 with Medium VGI Enrollment



Annual electricity system savings and costs are shown by category for the year 2045. Values above zero reflect savings from avoiding the buildout of extra infrastructure relative to the baseline scenario. Values below zero represent additional costs. The dark blue dot on each column shows the net savings.

4. The Grid Benefits of V2G Can Be Achieved with Limited Use of EV Batteries

To assess the extent of EV battery use as a proxy for V2G-related wear and tear, we examined EV battery use in the Medium VGI enrollment scenario with all V2G. We found that, on average, each vehicle in the V2G-enrolled pool exports power equivalent to driving an extra 700 miles per year in 2045. That is less than a 7 percent increase in battery use for a vehicle traveling an average of 10,000 miles per year (US DOT BTS 2024). This assumes that vehicles, essentially, take turns participating in V2G when EVs are called to export power. (Further explanation is available in the appendix.) If instead of distributed participation, V2G contributions were characterized by some drivers being super participants while others contribute infrequently, then the equivalent mileage of V2G would scale up or down based on level of participation.

Most of the V2G calls occurred in the evening, between 5 p.m. and midnight, regardless of feeder type. These times are well aligned with the times when vehicles are parked. For the single hour of the year with the highest energy discharge from EVs, 2 million EVs participate, providing a cumulative 17.2 gigawatts of electricity. Those 2 million vehicles comprise one-quarter of VGI-enrolled vehicles, a realistic fraction a program might have available to participate at any given time.

5. Per-Vehicle Annual and Lifetime VGI Savings are Significant

Taking the Medium VGI enrollment group as an example again, we can look at the average annual savings per enrolled vehicle. Dividing the annual net grid savings across enrolled vehicles gives a per-vehicle value from $503 in the all-V1G case to $1,177 for the all-V2G case. As with total savings, per-vehicle savings increase with each increase in V2G, although with diminishing returns. If these values were accumulated over the average lifetime of a vehicle, the cumulative grid savings per vehicle would range from about $6,300 to $14,700.[10]

Recommendations

Our analysis shows that scaling up VGI in California has the potential to enhance reliability and reduce the costs of building and operating a highly decarbonized grid. This analysis shows that hourly V1G can provide significant electricity system savings, while adding V2G can more than double those benefits compared to a baseline with only time-of-use rate adoption.

EVs are just beginning to realize their potential as storage assets in California. Only a handful of vehicles on the road have full V2G capability, as discussed in Box 2, and only a few pilot programs put V1G or V2G capacity to work. To achieve widespread VGI, California policymakers, regulators, and grid operators must act now.

Prepare the Electricity System and Plan on VGI

The California Energy Commission (CEC) and Public Utilities Commission (CPUC) should continue their work on standardizing the use of VGI communication protocols covering all relevant linkages (for example, among grid controls, EV supply equipment, energy management systems, and vehicles). Regulators should also accelerate the deployment of technologies that give more visibility into grid conditions. These elements are essential to operating a highly dynamic grid and the EV resources distributed on it.

The ability of vehicles to support the grid through V1G and grid-parallel V2G must also be included in grid forecasting and investment planning processes to ensure utilities will harness the power of EVs in a way that results in the least-cost option for building and operating the grid.

Establish Systems for Efficient Interconnection

To harness the power of EVs as a V2G resource, CPUC must work with utilities to increase the efficiency and throughput of EVs in the interconnection queue. Current interconnection timelines would not be able to accommodate levels of V2G participation contemplated in this analysis in a timely manner.

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[10] *This number assumes the vehicle remains in the fleet an average of 12.5 years (US DOT BTS 2024). It further assumes the vehicle achieves the reported VGI value annually for all years.*

The process for interconnecting EVs as distributed energy resources should be tailored to the size and level of risk of interconnecting them. Interconnection processes, guidance documents, forms, and application portals should be made clearer and more streamlined to mitigate confusion and time burdens for applicants. Fees should be reassessed to ensure they are based on the actual cost to process applications and do not pose an undue barrier to households and businesses wishing to pursue V2G opportunities. Any costs allocated to the applicant for project-related grid upgrades should be determined up front, and measures should be taken to ensure additional costs are not a surprise to applicants late in the process.

Support and Incentivize Drivers

Legislators, the CEC, and the CPUC (through the utilities it regulates) should expand support for driver investments in VGI-enabling technologies at the driver's property, including electrical equipment, EV supply equipment, and vehicles. Incentives and other forms of support should prioritize low-income households to ensure those communities have the ability to participate in VGI opportunities and to use EVs for backup power. For many low-income households, turnkey installation programs that fully cover the up-front cost of V2G capable systems will be the only viable option to access V2G programs or islanded backup power. Policymakers should promote programs that offer this level of comprehensive support for means-tested households.

In addition to supporting the upfront installation of VGI equipment at homes and businesses, policymakers should work with utilities and aggregators to increase the number and variety of VGI programs offered to customers, for both V1G and V2G, and grow the participation capacity of these programs. These programs should appropriately incentivize drivers to enroll in V1G and V2G, as well as participate in (that is, not opt out of) load shift (V1G) and power export (V2G) events. Customers should have clear, accessible rate and program choices that offer incentives commensurate with the value provided to the grid. Such options could include event-based demand response or "virtual power plant" programs, dynamic rate designs, direct wholesale market integration, or a combination of these options, as long as customer contributions are not double-counted or double-compensated.

Policymakers should track how upfront installation support and ongoing participation incentives can help make switching to an EV economically viable to the lowest-income households. These households are likely to represent a growing share of drivers stuck driving gasoline vehicles absent comprehensive financial and technical support.

Require Bidirectional Charging Capability in Vehicles

The CEC should urgently pursue bidirectional charging requirements for vehicles, including full V2G capabilities for light-duty EVs. To the extent that bidirectional charging capabilities increase the cost of vehicles or EV supply equipment, vehicle incentive programs should offer incremental incentives to cover this capability for new and used vehicle purchases by low-income drivers to ensure that the technology is affordable.

This analysis shows diminishing returns on V2G enrollment and, therefore, suggests an optimal level of V2G participation less than 100 percent among the EV fleet from the grid perspective. However, to ensure enough vehicles in the fleet have the capability and to provide equitable opportunity to participate in grid-parallel and islanded bidirectional charging opportunities, a universal requirement for light-duty battery EVs is warranted for several reasons.

First, it will be difficult to predict who will be able to enroll in V2G programs. Some drivers may charge exclusively at publicly accessible charging locations because they do not have access to charging at home or work. These locations, particularly DC fast-charging locations, may offer little to no ability to conduct V1G and V2G. Other drivers may charge at Level 1 at home, which, as discussed in the VGI modeling assumptions, is unlikely to provide enough power to participate while still meeting a driver's mobility needs. Bidirectional capabilities in vehicles is a threshold issue for conducting V2G, so policymakers must ensure that capability is widely accessible.

Second, everyone who would like to enroll should have the option to enroll in V2G programs. Matching the desire to enroll with the ability to do so is complicated by the dynamics of how vehicles diffuse into the on-road fleet. Vehicles are durable goods, and many change hands multiple times before they are retired. Indeed, 70 percent of cars are purchased on the used car market. Car buyers' choices in the used market are limited to the stock of vehicles on the used market, which is shaped by the preferences of generally wealthier new car buyers, who are mostly White (Cooke 2021). To guarantee used car buyers can choose full V2G capability, new cars must enter the fleet with this capability.

Requiring V2G within bidirectional charging capabilities will also enhance the opportunity for EVs to provide other services to households and businesses, including islanded bidirectional charging to provide backup power during an outage. The benefits of using EVs for backup power is not within the scope of this analysis. Many of backup power benefits would accrue to the driver, distinct from and additional to any incentives or other payments for participating in V2G programs a driver may pursue.

Update Battery Warranty Protections to Cover Discharging

Purchasing a vehicle is a significant financial commitment. V2G can bring an extra consideration for wear on the vehicle battery, as captured in the variable operation and maintenance cost included in this analysis. Automakers should include battery discharging, including V2G, as acceptable use under their EV warranties to increase drivers' confidence to use this functionality.

Regulators can help promote the evolution of automakers' battery warranty policies to accommodate a reasonable amount of battery discharge when they are making warranty requirements. For example, the Advanced Clean Cars II regulation contains important battery warranty requirements to protect consumers purchasing EVs, particularly those purchasing in the used car market. However, these requirements do not give clear criteria for what would constitute acceptable battery discharge for nondriving purposes as that relates to required longevity guarantees in battery warranties. In rule updates or future rules, CARB should include a meaningful level of nondriving discharge in warranty requirements. One approach could be to update odometer miles as a longevity measurement to a measure that tracks total miles-equivalent on a battery energy use basis. Not only will this advance V2G, but it will also protect drivers using their vehicles to power their homes during emergencies.

Appendix: Additional Methods and Results Detail

Two Key Adjustments to the ADP 2024 Central Scenario

Interstate Transmission Buildout

We limited new interstate transmission for California to include only the SunZia and TransWest Express transmission projects. The CAISO board has already approved both projects for participation in the CAISO system, and both projects are already under construction. We limited the buildout of any additional interstate transmission to prevent varying levels of VGI from triggering additional interstate transmission buildout, which is an unlikely outcome given the challenges of building new transmission.

Geothermal Costs

The 2024 ADP study includes revised cost assumptions for advanced geothermal technologies, leading to a significant buildout of electricity-generating geothermal capacity in California. However, that level of geothermal buildout is inconsistent with state planning processes for the power sector, such as the CPUC's Integrated Resource Planning process and the CEC's Senate Bill 100 planning process. To align better with these planning processes, we adjusted geothermal cost assumptions, which in turn led to a buildout of geothermal resources similar to the buildout in state planning processes.

For more information, see EER's technical documentation for the analysis (Farbes and Jones 2025).

VGI Model Component Detail

Choice to Focus on Light-Duty Battery EVs

For the purposes of this analysis, we focused on the grid integration of light-duty battery EVs. While this is a conservative assumption, we chose not to include medium- and heavy-duty vehicles for two main reasons. First, limiting participation to light-duty EVs allowed us to isolate the value that this class of vehicles can provide in order to inform policy and program design to target these vehicles. Second, limiting participation to light-duty EVs limited the scope and complexity of the modeling exercise to enhance the feasibility of the study.

Baseline Charging and Representation in the Model

For the baseline EV charging behavior, we adapted the EV charging profiles used in the CEC's 2024 Integrated Energy Policy Report (CEC 2024a). The CEC provided us with their underlying charging profiles for different vehicle categories, and we combined these categories to generate baseline charging profiles for the four sample feeder types. These profiles assume current enrollment in time-of-use electricity rates with observed behavior that largely aligns charging with off-peak periods among time-of-use rate participants, behavior that we assume persists into the future. We also used expert judgement to smooth spikes in the charging profiles that are unlikely to persist in the future, given that there are relatively simple strategies to eliminate these peaks (for example, by using a randomized charging delay to avoid peaks at the start of an off-peak time period).

In the modeling, EV charging loads were allocated across four archetypal feeders, which are representative of distribution systems serving different customer classes and their associated end uses. The four feeder types where charging can occur are residential, commercial, industrial, and DC fast charging. The electricity demand and storage potential of the EV population are then allocated across those feeders while accounting for the power level of charging: Level 1, Level 2, and DC fast charging.

The Level 2 charging load is assumed to be 59 percent of vehicle electricity demand in this study. This figure was extrapolated from the National Renewable Energy Laboratory's EVI Pro Lite tool to more recent data from the CEC. Use of the CEC data is described above in this section. Level 2 vehicle charging loads vary by feeder type and time of day.

To operationalize the constraints around shifting vehicle charging, we used the National Renewable Energy Laboratory's EVI Pro tool to develop an envelope within which charging could be shifted for each of the three feeder types. These profiles vary on an hourly basis, with a maximum average charging power of 1.4 kW per vehicle across the pool of vehicles available for managed charging. To determine the discharging envelope, we start with a maximum power export value for a single vehicle of 9.6 kW. To determine the maximum, average discharge power across all vehicles, we discount the power rating for vehicles sharing a charger (1.5 vehicles per charger) and to account for vehicles that may be away from their chargers at any given time (assuming 20 percent are unavailable at any given time). That gave a maximum average discharge power of 5.12 kW per vehicle across all vehicles available for V2G.

For more information, see EER's technical documentation for the analysis (Farbes and Jones 2025).

Off-Model Calculations and Results Detail

Equivalent Mileage

The Medium VGI enrollment scenario with 50 percent V2G participation was used as an example to assess the number of vehicles required to participate in each V2G discharge event and the average amount of energy discharged per vehicle across all events. It was assumed that vehicles would discharge at 9.6 kW from the vehicle and that the effective export to the grid would be 8.59 kW after efficiency losses.

If V2G discharge was allocated across the enrolled fleet of vehicles, the average annual V2G discharge would be 214 kWh per vehicle. Using a sales-weighted average efficiency of the 15 battery EV models with the highest sales from 2015 to 2024 (0.300 kWh per mile), this equates to the energy required to drive 712 miles per year (rounded to 700 miles in the report discussion).

Highest V2G Demand Hour

The highest hourly V2G use in the Medium VGI enrollment 50 percent V2G scenario in California in 2045 was 17.2 gigawatts. Assuming every participating EV discharges at an effective power of 8.59 kW (from the grid perspective), this would require 2 million vehicles discharging. This represents 24 percent of all V2G enrolled EVs that are assigned to a Level 2 charging connection and 6.7 percent of all EVs on the road in 2045 (30.1 million). This hour represents the most extreme value seen during a year. In the Medium enrollment 50 percent V2G scenario, 3,984 hours had V2G discharge in 2045. However, 83 percent of those hours (3,290 hours) had total V2G discharge requirements in California of less than 1 percent of the peak hour (less than 172 MW).

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Acknowledgments

This analysis was made possible by the generous support of Foundation M, Heising-Simons Foundation, the William and Flora Hewlett Foundation, and members of the Union of Concerned Scientists.

For their expert input, feedback, and support through the analytical and writing processes, the authors thank UCS colleagues Don Anair and Steve Clemmer.

For their partnership in conducting the analysis and reviewing this report, the authors thank Jamil Farbes and Ryan A. Jones from Evolved Energy Research.

The authors are also grateful to UCS colleagues Michele Canales, Juliet Christian-Smith, Lana Cohen, Jeff Deyette, Jessica Dunn, Steven Higashide, Mike Jacobs, Julie McNamara, Cecilia Moura, Marisa Vertrees, Claudia Ward-de Leon, and Kye Witmore for their feedback on this report.

Thank you to Zach Franklin of GRID Alternatives, Patty Monahan, and Zach Woogen of the Vehicle-Grid Integration Council for their review of this work.

Special thanks to Leslie Brunetta, Cynthia DeRocco, Heather Tuttle, and Bryan Wadsworth for their roles in the report's editing and production.

Organizational affiliations are listed for identification purposes only. The opinions expressed herein do not necessarily reflect those of the organizations that funded the work or the individuals who reviewed it. The Union of Concerned Scientists bears sole responsibility for the report's content.

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