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Value Assessment of DC Vehicle-to-Grid Capable Electric Vehicles

Analytical Framework and Results

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ABSTRACT

With a U.S. installed base of well over three million, the electric vehicle (EV) market is expanding at an annualized rate of more than 35% and is forecast to accelerate through 2040, resulting in between 80 million and 100 million registered EVs in the United States. The transportation sector is depending more and more on the electric grid for increasingly clean electricity, creating both a challenge and opportunity for the industry. The challenge, of course, is to ensure that the generation, transmission, distribution, and recharging infrastructures are adequately built and capacitized, and done so in time to ensure the delivery of safe and reliable electricity when and where required. The opportunity is in multiple dimensions. Environmentally, EVs help to slow the greenhouse gas inventory and climate change. Economically, for the EV owner, switching from $4/gallon gasoline or diesel to $1.25/gallon equivalent electricity generates significant savings. Although this operational cost advantage must overcome the cost of acquiring EVs, the introduction of lower-cost EVs will create a powerful push for customers to own them.

EV market proliferation is coinciding (not coincidentally) with meaningful reductions in the cost to store energy, resulting in large energy storage capacities—significantly higher than the expected daily round-trip energy use. Underutilized battery capacity creates an opportunity to equip EVs with bidirectional power capability so that they can both receive power from the grid and send power to it, as in vehicle-to-grid (V2G), or to a home, building, or anything (V2X). When plugged in, V2X-capable EVs can act as "energy storage on wheels." To use EVs as energy storage, however, the cost and complexity of the hardware and software used in bidirectional charging must be justified by the value to the EV or site owner and the grid. Therefore, assessing the value created by V2X-capable EVs operating in the appropriate contexts and use cases is paramount to manufacturers making V2X technology available on the EVs.

This report begins with the macro context—the potential for this technology to provide large-scale grid support at the national level and the impact that it could have. The focus shifts to a value assessment of V2X-capable EVs connected to an offboard, direct current (dc), bidirectional charger. Finally, the report covers local resiliency (backup power) and grid-specific use cases through on-bill incentives, appropriate tariffs, or market participation opportunities. The team used EPRI's Distributed Energy Resource Value Estimation Tool to analyze the results through 8760-hour profiles to assess the value created by dc V2X-capable EVs, net of costs. The results are presented per EV and scaled statewide for California. The results indicate an average benefit of between $500 and $1000 per EV per year and significant (up to $26,000) savings for using the EV as a backup generator by avoiding the cost of stationary storage. The data provide a sound justification for investing in this technology so that it is available to customers in large numbers.

Keywords

Distributed Energy Resource Value Estimation Tool
Electric vehicles (EVs)
Resiliency
Value assessment
Vehicle-to-anything (V2X)
Vehicle-to-grid (V2G)

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Vehicle-to-Anything (V2X)—A Primer

All plug-in electric vehicles (PEVs), including plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs), are equipped with an onboard charger that can recharge the battery at the rated power of the charger, which typically ranges from 6.6 kW to 19.2 kW. Almost all EVs can also charge at higher rates through offboard direct current (dc) chargers that can charge the EV significantly faster, typically topping at 350 kW. In either case, the direction of energy flow is from the grid to the EV battery.

If, however, the battery charger is designed to be a bidirectional converter, it could send and receive energy to and from the EV from and to the premises or the grid. The EV's ability to both receive energy and send it back to the circuit to which the vehicle is connected creates an opportunity to access the energy stored onboard for offboard energy services. The following are examples of offboard energy services:

- Providing backup power to the local home or building
- Helping manage local peak demand without incurring demand charges
- Maximizing the consumption of locally generated renewable energy
- Adding energy to the distribution grid or markets

The stored energy would be contributed in exchange for appropriate contractual compensation. The pros and cons of each of these configurations are shown in Figure 1.

Vehicle to Load (V2L)

- The vehicle carries the dc/alternating current (ac) inverter on board; grid-independent operation.
- Standby power with onboard 120-V/ 240-V outlets.
- The primary purpose is worksite/ camping/mobile applications; very similar to a portable generator.
- Vehicle charges from ac or dc but discharges via ac 120-V/240-V ports.
- It can also be offered on an internal combustion engine (ICE) or hybrid electric vehicle (HEV).

Vehicle to Home (V2H)

- Similar to V2L but primarily tied to the residential circuit through a dedicated emergency load panel or smart panel. The system sends reverse power only when isolated from the grid.
- Possible with ICEs, HEVs, or EVs, although the original equipment manufacturers (OEMs) are focused on making this an EV-only feature.
- Vehicle standby power source needs to be wired into the residential circuit by a licensed electrician to create a safe operating environment.
- EVs and their owners must govern how to use the onboard batteries for backup power versus mobility.
- Utility-side switch or notification might be required, if operated as a standby generator.

Vehicle to Grid (V2G)

- Like V2H, except that the system can send power back to the grid as well.
- Requires interconnection screening and approvals.
- Can participate in the energy services markets.
- The inverter can be on- or offboard and capable of grid-parallel or grid-forming operation.
- V2G is on all OEMs' roadmaps but not likely for another five years.
- Given the designs that the OEMs are pursuing, V2H to V2G will be an over-the-air software upgrade once the onboard and offboard equipment and systems are interconnection-capable.

Figure 1. Distinction between vehicle-to-load (V2L), vehicle-to-home (V2H), and vehicle-to-grid (V2G) modes

See the EPRI report *A Technology Overview: Vehicle to Grid (V2G)* [1] for in-depth descriptions of various V2X configurations. For this analysis, the two modes considered for value assessment are V2H (standby power mode), implying grid-isolated reverse power flow, and V2G, implying grid-interactive reverse power flow operation.

State of the V2X Industry

A short history of this technology can explain why it has existed more than 25 years but is still in its infancy regarding scale deployment.

The original concept of V2G [2] highlighted the capability of EVs to provide power back to the grid in a similar way that photovoltaic (PV) inverters connect to the grid and supply renewable energy; the only difference is that the energy in the EVs was likely received from the grid while charging. This mode of operation implied that the EV bidirectional charger was a grid-synchronized **current** source (or a sink) that absorbed or injected power into the grid as and when required **as long as the grid was energized and acted as the voltage source**. These grid-tied (often called *grid-parallel* or *grid-interactive*) inverters could not function without a grid voltage during an outage. The expectation was that market participation of the EVs injecting or absorbing electricity from the grid according to grid preferences for stability and reliability would yield monetary compensation for the EV owner.

A strong interest in allowing the EV owner to participate in the ancillary services markets led to most early implementations and trials [3] focusing on this “grid-interactive” V2G technology to find economically favorable jurisdictions to operate several EVs equipped with bidirectional chargers and show their economic potential. However, a few issues persisted until very recently. These were:

- No OEM-manufactured products (except Nissan Leafs) could support V2G. Indeed, the early implementations of V2G projects included rigged-up conversions that were not production-saleable vehicles, but proof-of-concept engineering vehicles with no path to production.
- The remuneration value from V2G operation through market participation varied from a few hundred dollars per month to a few dollars per month—two orders of magnitude variance—which failed to confirm the economics originally promised.
- Lithium-ion batteries did not exist in their current form in the late 1990s. Starting 2010, it took the technology the better part of a decade to mature. Therefore, the impact of incremental V2G charge-discharge cycles on the EV batteries was not known, resulting in the automotive OEMs’ reluctance to offer the technology at scale.
- The standards for grid interface and communications were not yet ready. Even today, the implementers often rely on proprietary standards (or proprietary overlay on open standards), which is not scalable. In addition, every pair of charger and EV must maintain its protocols, and there is no interoperability. Yes, the CHAdeMO protocol has been around and has been widely used, but it is currently offered by only one OEM, thus finding a limited audience.

- Until recently, the interconnection screening requirements for the bidirectional chargers were not fully defined. Currently, these are defined only for dc-connected V2G or grid-interactive systems, not ac-connected V2G (onboard charger) systems.
- Because all the provider effort to date has been on the “grid-following” inverters, which operate grid-synchronized as a current source only when there is grid power, they are not useful during power outages.

An MIT Lincoln Laboratory overview report of the U.S. Department of Defense V2G pilot described the state of V2G technology a mere five years ago in its first iteration appropriately:

> Costly equipment, low payments, and an immature market result in thin margins and a possibility of losing money due to inefficiency losses in the battery-inverter system. V2G ancillary services do not appear to reduce battery lifetime, and future laboratory testing could be performed to confirm this, but the ancillary services and vehicle charger markets need to improve to fully use the potential of electric vehicles to buttress the nation’s electrical grid. [4]

The technology, however, has not remained static, and many of the preceding barriers have waned. For example:

- OEMs and charging equipment manufacturers are firmly a part of the ecosystem, having articulated their strategies [5, 6] around energy products and services with EVs and the related software platforms at the core of their DER products and services.
- Several OEMs have made products available in the marketplace or are working feverishly to make them available for their customers.
- Pilots are underway at several locations worldwide, providing significant real-world lessons learned from this technology.
- Lithium-ion battery technology has proven robust and durable [7], raising the automotive industry’s confidence in the battery’s usefulness for non-mobility applications, especially for infrequent use.
- Instead of grid-interactive operation, the focus of the utility and automotive industry has shifted to prioritize the operation of the V2X systems in a backup power mode first and grid-interactive mode if the value proposition is favorable. As a result, the newer systems prioritize the “grid-forming” operation of the bidirectional inverters, which allow the EVs to act as a voltage source during an outage and switch to a current source (grid-following) mode automatically when the power is restored.

EPRI at the Forefront of V2X Research

The first V2G research project at EPRI was in 2007. The EPRI researchers evaluated the operating performance of an EV retrofitted with the same system used in the early University of Delaware experiments. Indeed, a similar system [8] was on display at the first Plug-in Conference in San Jose at the EPRI booth! Figure 2 highlights the continuum of research at EPRI in this field, which has resulted in technology advancements and technology transfer to the industry, institutionalizing the open standards and interoperability principles.

2008-present – Standards Development

- SAE J2847/3 – Smart Inverter Functions for V2X Systems
- SAE J2847/2 – DC Charging Communications (harmonized with DIN70121)
- SAE J3072 – Bidirectional Power Transfer

2011-present – Demonstrations

- GM ARRA Project - V2X use cases
- On-Vehicle (AC) V2G
  - Phase 1 (2016-2019) – CEC EPC 14-086 Development and demonstration with Stellantis and Honda, at UCSD Microgrid
  - Phase 2 (2022-present) – SCE, Stellantis, Eaton, Kitu, EPRI – Formalizing production requirements including Rule 21 interconnection
- Off-Vehicle (DC) V2G – Smart Power Integrated Node (SPIN)
  - Phase 1: Concept /requirements development – EPRI TI
  - Phase 2: Proof of concept, production-intent design and integrated demonstration with Stellantis and (GM) – DoE VTO, DoE SETO, and CEC projects
- V2G Battery impacts testing with NREL – 4.3 years of data
- School Bus V2G pilot with Dominion Energy (Ben Y, Mark K)

2011-2015 – V2G Equipment Testing

- Two systems, tested in EPRI Knoxville lab

Current work

- Ford F150 Lightning grid interconnection requirements for V2H and V2G
- V2G-DERMS integration requirements
- AC and DC V2X backup power system integration/control systems into smart home systems
- Just put in large-scale School Bus V2G deployment proposal (DoE GRIP)
- V2G Cybersecurity – project just beginning within the SCE V2G Forum

Figure 2. Summary of EPRI research in V2X technology

EPRI has collaborated with automotive and equipment manufacturing industry stakeholders, standards organizations, and third-party providers to design, deploy, integrate, and test [9] open standards–based V2X systems [10], which have significantly accelerated the industry's understanding of how the systems can operate, integrate with both the local and grid infrastructure, and be technically viable. In addition, EPRI has led the work on the valuation assessment [11] of V2G-capable systems and defining the parameters for integrating V2G-capable vehicles as a resource class in the integrated resource planning process [12], thereby creating a pathway for their orderly participation in the energy markets. EPRI also recently completed a comprehensive evaluation of the EV battery subjected to the V2G-specific energy cycling profile to create a life-cycle impact prediction [7], which should inform practitioners of the practical ways to leverage onboard batteries for several local and grid-support functions.

EV Market Acceleration Forecasts

With the significant investment and production commitments across the automotive industry toward developing, manufacturing, and selling EVs, in addition to the battery manufacturing investments and accelerated production plans, the inflection point for EVs might have arrived.

Indeed, several recent forecasts [13] point to nearly 65% of the overall vehicle sales [14] by 2040 being EVs, with the installed base approaching 80–100 million nationwide by 2050 [15]. EPRI combined a few of these forecasts and put together the growth scenario shown in Figure 3 for the state of California (for a nationwide forecast, a doubling of the California market is a good approximation).

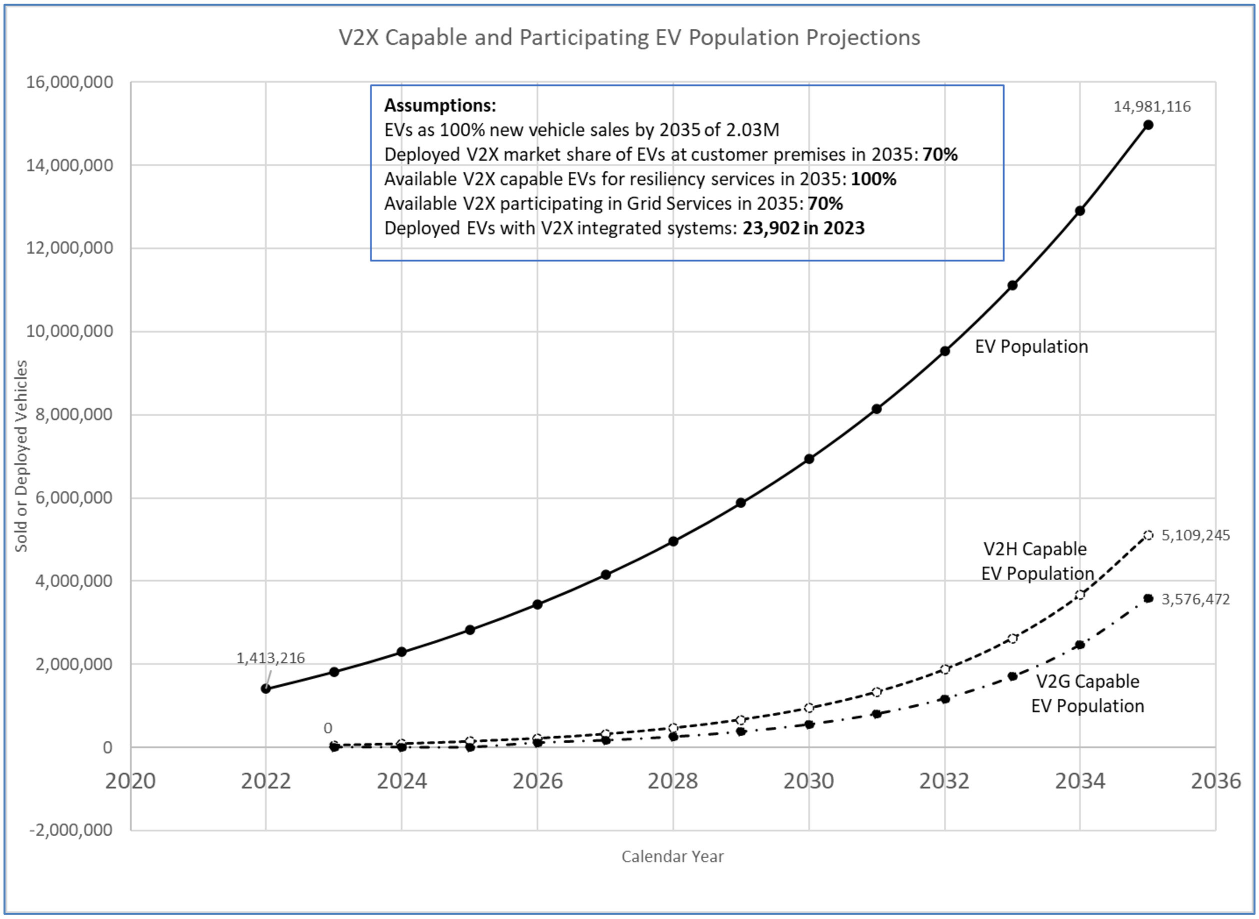
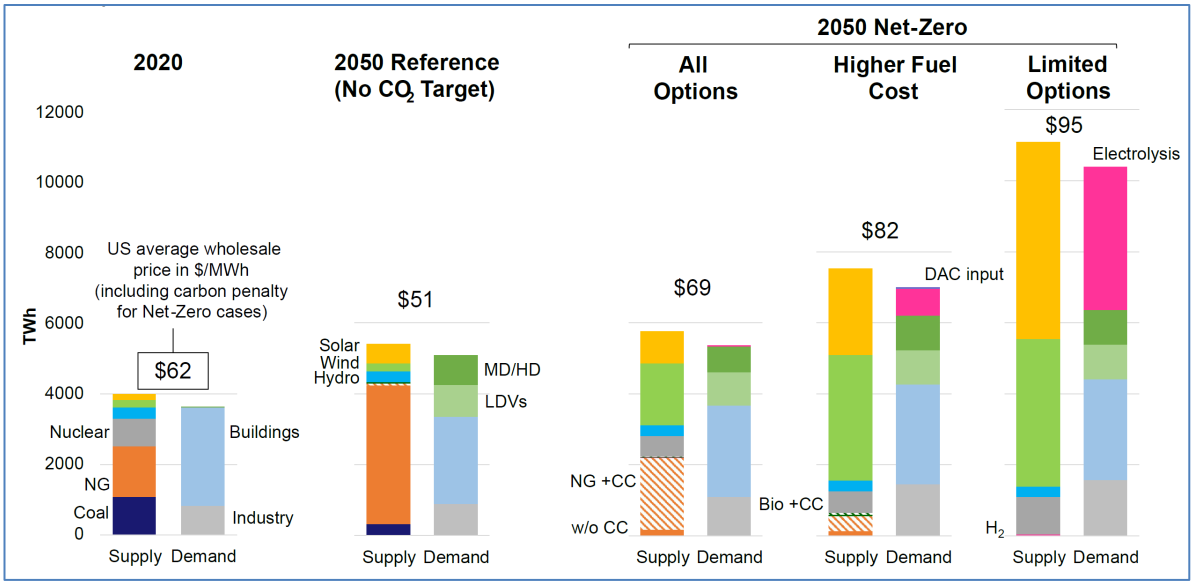


Figure 3. V2X technology acceleration forecast (EPRI analysis.)

What If V2G Is Big?—The Opportunity

The potential impact of V2G on electric power systems is hard to overstate. Figure 4 shows the energy consumption of EVs in different net-zero emissions scenarios from the EPRI Low-Carbon Resources Initiative. By 2050, the annual energy consumed by U.S. EVs could represent several hundreds of terawatt hours—comparable to the amount of electricity produced by the entire fleet of natural gas–fired power plants in the United States in 2020.



Notes: MD/HD = medium duty/heavy duty; LDV = light-duty vehicle; DAC = direct air capture; CC = carbon capture

Figure 4. 2050 economywide net-zero scenarios summary (EPRI analysis [16].)

The amount of energy exported from EVs for V2G will depend strongly on the factors presented elsewhere in this report:

- How much does it cost to enable V2G?
- How does V2G participation impact battery life? Battery warranty?
- Which V2G services provide compelling compensation?
- How many vehicles will be plugged in and available at the right times and places?

In some cases, little or no energy might be used for V2G services. For example, emergency backup power might primarily involve being charged and available if needed. In other cases, more energy might be put through the EV battery for V2G services than is used for transportation. For example, as illustrated in Figure 5, an EV used to prevent solar curtailments could be five times as effective at doing so if it also uses V2G to export power.

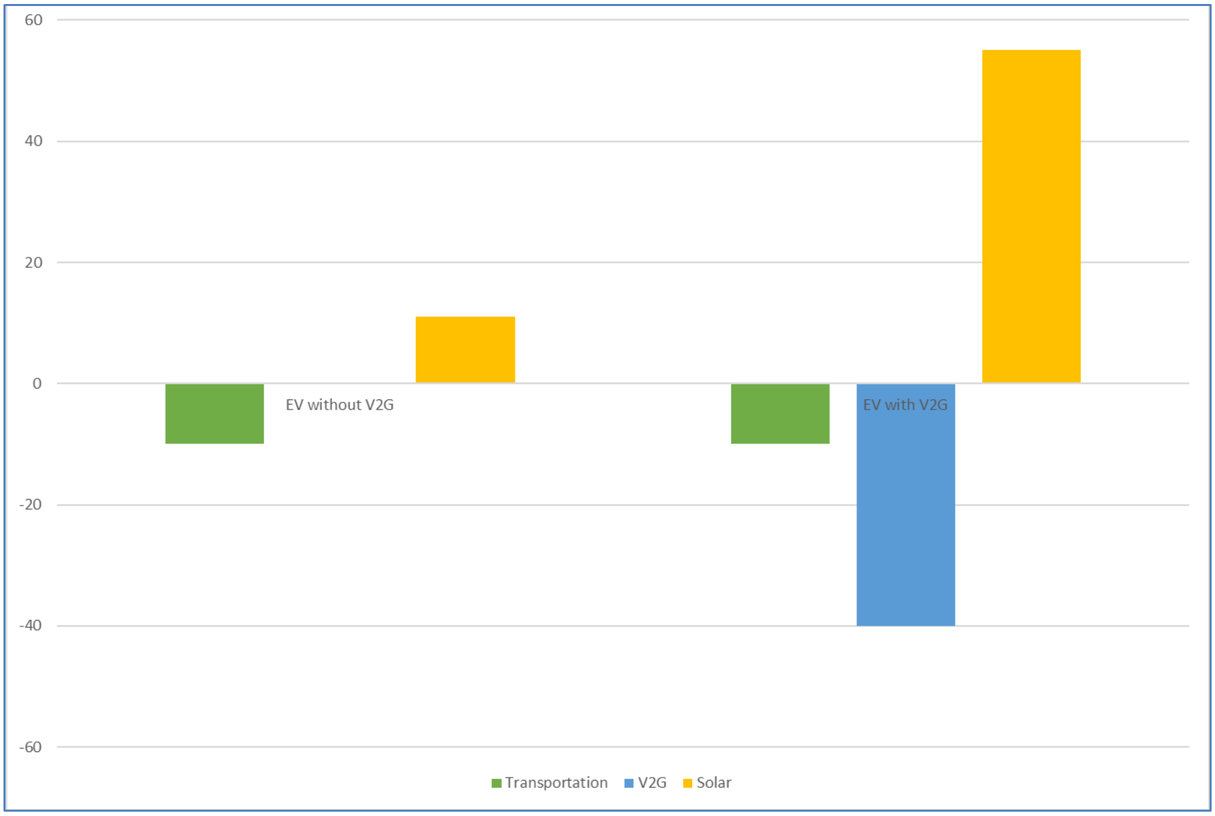


Figure 5. Daily solar consumption of an EV with and without V2G (EPRI analysis.)

This application of V2G technology might be part of the solution for the declining value of marginal solar generation in some markets—commonly called the solar *canyon curve* and shown in Figure 6. One million passenger EVs in California that use solar power for their daily driving needs would consume 1375 MW during an 8-hour solar charging window. The same million vehicles using V2G could use 6875 MW to charge during this window, use some for transport, and export the remainder back to the grid during non-solar hours, as shown in Figure 7.

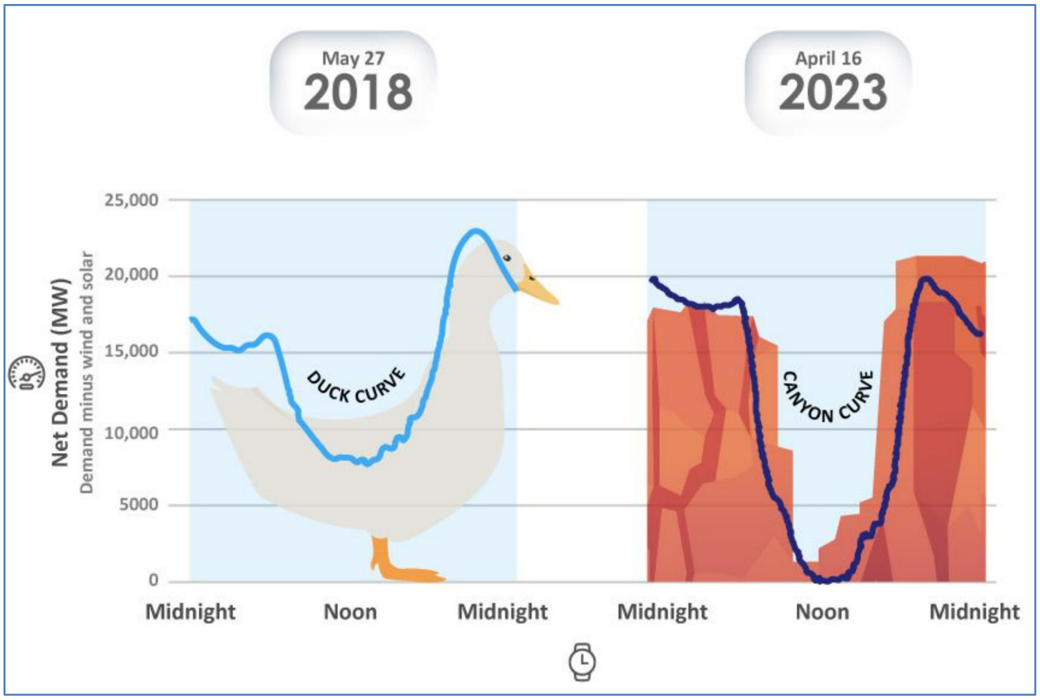


Figure 6. Duck and canyon curves (EPRI analysis.)

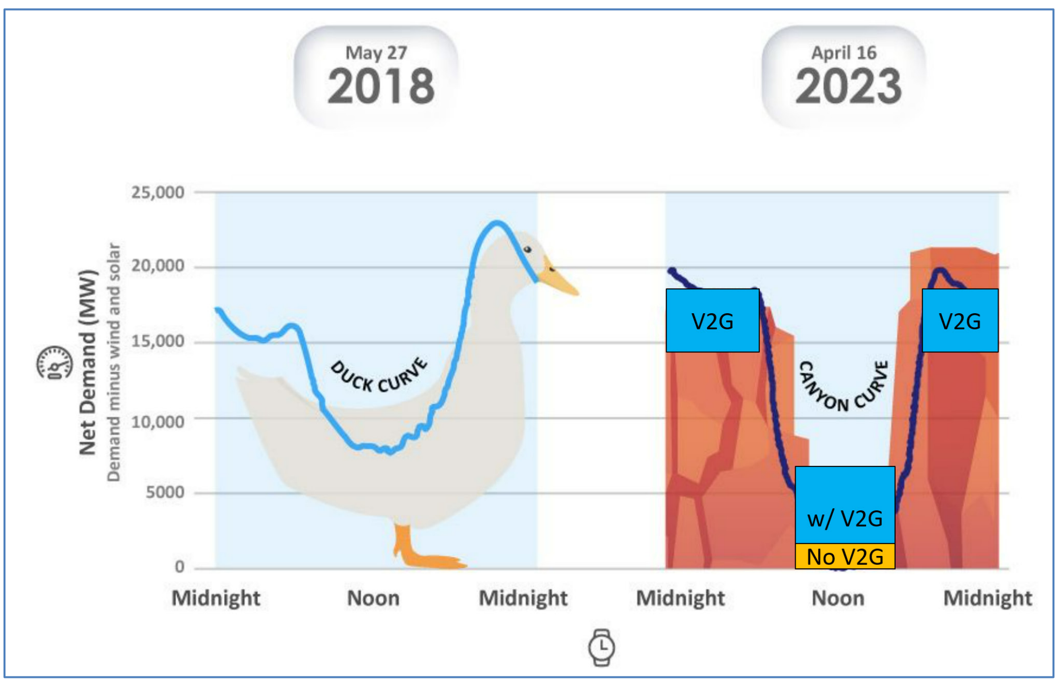


Figure 7. Duck and canyon curves with one million solar EV loads with and without V2G (EPRI analysis.)

There are many possible uses for V2G. Some might fit into the existing market structures; others do not. Some could require substantial infrastructure upgrades to unlock their value. Using V2G to maximize EV solar consumption would require that participating EVs have a place to charge during the day and export overnight. These might be different locations.

Enablers to V2X Achieving Scale

The enablers to V2X technology accelerating alongside the EV deployment can be broadly classified into three categories: technical maturity, proven value proposition, and regulatory push:

- **Technology maturity**: Although hardware and software solutions are being developed and deployed, they are likely to remain proprietary systems in the near term given a lack of mature standards. The standards need to be developed and ratified to serve the United States' and global needs for V2X systems from the automotive and utility side. The longer the debate over which standard is better continues, the more hardships experienced by the customers, and the less chance there will be to scale and bring the hardware and integration costs and interconnection times down. The time to interconnect and costs to integrate and deploy remain the two biggest barriers.
- **Economics:** As previously described, interoperable systems and stable standards will provide the technology developers with the certainty to invest in, develop, and certify their hardware to be widely available for the end customers. Also, the value derived from the services enabled by V2X capability must be understood in an appropriate context. That is the focus of this report. And the value derived must be more than the cost to deploy the hardware. This aspect is less understood because although the costs are known down to the last penny, the value remains somewhat amorphous given that no two jurisdictions on the grid value the grid services the same way.
- **Policy mechanisms:** Steadfast and steady policy stance coupled with the right incentives can help the fledgling V2X technology, giving manufacturers and services providers a touchstone to define and develop their systems. One way to enable this is to treat EVs as a class of energy storage and, therefore, eligible for incentives available to energy storage, subject to performance metrics. Another example is California bill SB233 [17], which will require EV manufacturers, starting with the 2027 model year, to enable V2X capability. If enacted, this bill will send a strong signal to the marketplace. Another way the regulations can help is to enable a way for the EVs participating in the grid services to be eligible for remuneration. One such pilot has been green-lighted by the California Public Utilities Commission, to be led by PG&E. Real-world assessment of the value proposition is critical.

Figure 8 recaps the key milestones that must be met to accelerate V2X technology proliferation.

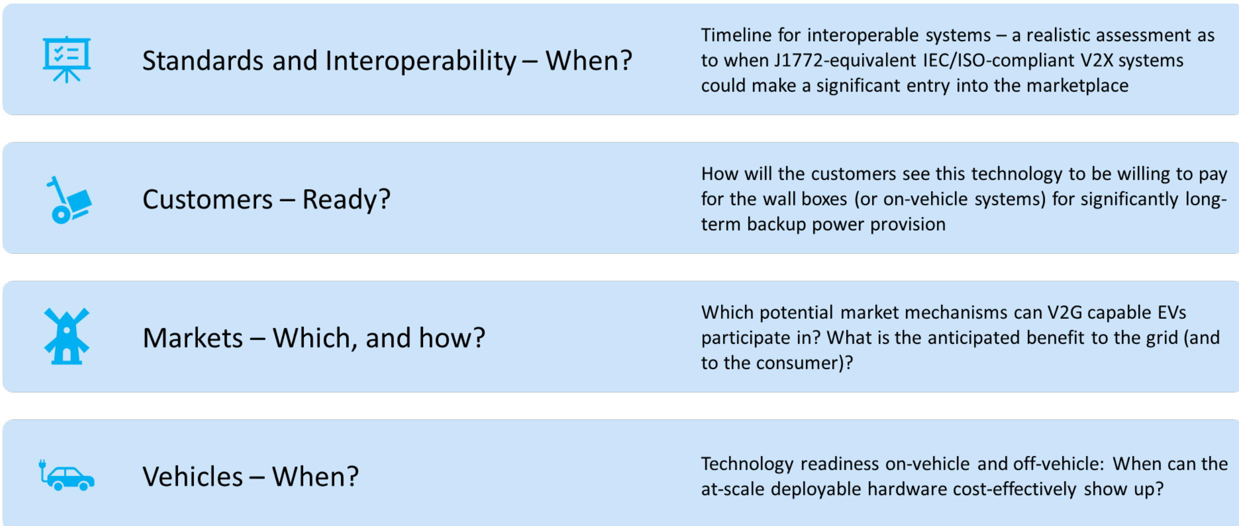


Figure 8. Roadmap to V2X technology acceleration: standards, customers, markets, and vehicles

The four dimensions identified in Figure 8 focus on technology, customers, and economics, which are interlinked:

- **Standards and interoperability** ensure that equipment manufacturers can produce and certify bidirectional charging equipment, such as how today's charging equipment is manufactured, without worrying about which standards and protocols to follow. This removes the cost and timing barriers to the introduction of this technology.
- **Customers**, on the other hand, are looking for the technology to work seamlessly, not curtail their use of EVs for mobility, and to be a low-cost solution for their resiliency needs. The data indicate a strong synergy between EV and PV ownership among customers—with the latest solar incentive and tariff regime under NEM3 in California, this could create a new incentive for EV owners to install bidirectional charging equipment rather than stationary storage to maximize the benefits from owning solar by maximizing the self-consumption in addition to energy arbitrage value.
- **Energy markets** can similarly accommodate grid services–capable bidirectional charging EVs into the programs that enable value for the EVs, such as how the stationary storage is treated. This additional value will certainly help the grid as well as EV owners.
- **Availability of EVs with the bidirectional capability** would be crucial. With OEMs already announcing plans to introduce EVs with this functionality, the previous three factors will determine how soon and in what numbers OEMs would introduce bidirectional EVs to the marketplace. It is clear that the dc bidirectional charging-capable EVs require only a software update onboard and that it is much easier to change the software retroactively for these vehicles. Because dc bidirectional charger interconnection requirements are also finalized (along the lines of energy storage), we anticipate the dc bidirectional charging-capable EVs to be available in large numbers sooner.

V2X Technology Acceleration: The Virtuous Cycle

Figure 9 shows the virtuous cycle such enablers can create, which progressively builds momentum toward better availability of V2X-capable EVs in the marketplace, paving the way for their large-scale application for alleviating several grid challenges.

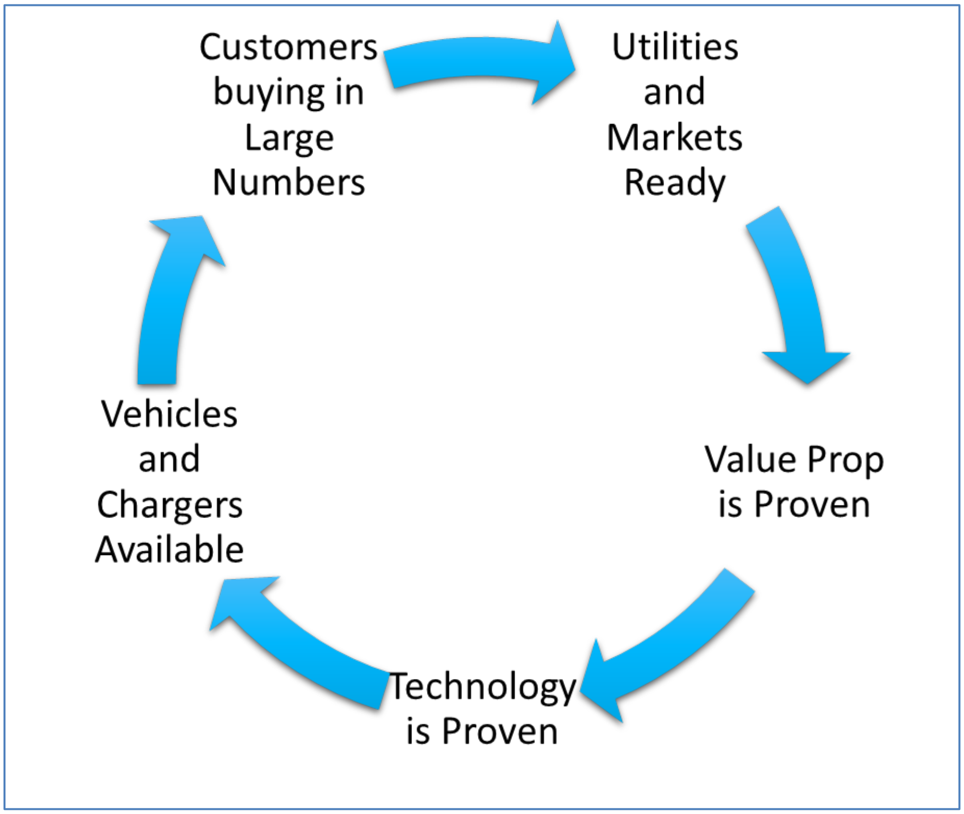


Figure 9. Virtuous cycle enabling V2X technology acceleration

The pilots currently underway (and expanding nationwide) will provide a simultaneous verification of the technology maturity as well as its value to the end users, grid, EV manufacturers, and society at large. The industry and technology providers have a good understanding of the costs, but the value with the right policy environment can create the certainty needed in the technology provider community to invest in making large numbers of EVs and bidirectional charging equipment. Once customers have a good grasp of how easy and convenient the technology is to own, install, and operate, there is a good chance that many of these systems will show up in practice, providing local and grid services automatically based on customer and vehicle preferences. The customer pull, combined with the policy nudge and the ever-expanding scope of the technology, could motivate a larger pool of automotive manufacturers and suppliers to continue to innovate, invest, and bring the costs down while raising the performance bar for their products and services.

This report focuses on the value that can be derived in the California market on a unitary basis and in the aggregate, leading to an understanding of how EVs equipped with this technology can create value today in California.

2 V2X VALUE ASSESSMENT

This project used the Distributed Energy Resource Value Estimation Tool (DER-VET) developed by EPRI to conduct techno-economic analyses on dc bidirectional charging technologies, such as the Smart Power Integrated Node (SPIN) system [19]. DER-VET uses load data and site-specific information to calculate the value of DERs, such as discharging PEVs. Several benefits analyses were conducted for different applications of bidirectional charging based on different assumptions regarding the number of PEVs deployed, battery size, vehicle availability, and other factors described in this report. Scenarios of benefits evaluated include use of a standalone SPIN system to provide resilient backup power at a single site as well as to provide distribution and bulk power system applications.

Customer Resilience Improvement

This analysis evaluated the potential site resilience and economic benefits achievable through bidirectional PEV charging with the SPIN system when used to provide power to critical loads during outages. The analysis assumed that the PEV battery had a usable capacity of 40 kWh for grid services (representing approximately 60–70% of a commercially available midsize PEV battery capacity) and could discharge at 10-kW peak with a round-trip efficiency of 85%. Load profile assumptions for a residential and commercial customer are shown in Table 1.

Table 1. Peak and average demand and energy profiles for residential and commercial customers

	Residential Customer	Commercial Customer
Average Annual Demand	0.79 kW	4.44 kW
Peak Annual Demand	12.88 kW	28.78 kW
Average Daily Energy	19.06 kWh	106.5 kWh
Peak Daily Energy	90.96 kWh	209.73 kWh

Based on these assumptions and load requirements, a critical load coverage probability metric was calculated for all outage durations up to 96 hours. This metric represents the likelihood that the 40-kWh bidirectional PEV and charger could meet the peak load requirements of the site. The critical load coverage probability was calculated by taking the ratio of all times the system could meet the required load to the total number of simulations, which includes instances when the system could not meet the site load.

The critical load coverage probability for a representative commercial and residential customer is shown in Figure 10. With the assumed 40-kWh battery capacity, the PEV could serve the commercial customer through an outage lasting up to approximately 10 hours with load coverage probability around 60%. The system could serve a residential customer for around 50 hours with a load coverage probability of about 60%. It is intuitive that the residential customer would be served for longer given their smaller power and energy requirements compared to commercial customers.

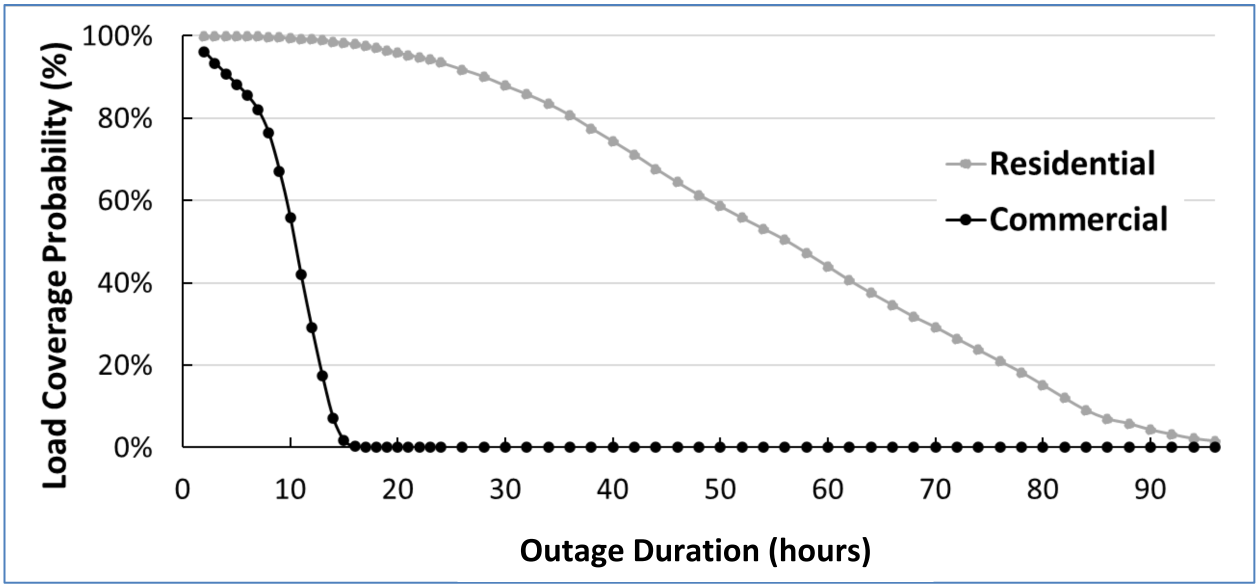


Figure 10. Critical load coverage curve for representative residential and commercial customer

Economic Assessment of the SPIN System for Site Resilience

Because electricity outages are relatively infrequent, it can be difficult to quantify the economic cost of short- and long-duration outages or estimate the value provided by backup power solutions. For residential customers, one approach is to consider their willingness to pay for available alternatives (for example, diesel backup generators or stationary storage) as a measure of their monetary value of that service. A diesel generator rated at 7.5 kW could be purchased for approximately $6500 and installed for around $8000, not including operations and maintenance. However, because diesel generators release local air pollutants and greenhouse gas emissions, this analysis focuses on a comparison to commercially available stationary lithium-ion battery energy storage systems (BESSs).

Cost estimates for a representative dc V2X system, such as SPIN, are derived from bottom-up accounting of the parts costs as well as the amortized investment, warranty, distributor, and sales markups that are prevailing in the industry, assuming a production volume of 10,000 units per year. Purchase and installation prices for both BESS products were obtained from EnergySage data [20]. The upfront capital costs of two equivalently sized (40-kWh) commercially available stationary storage systems are compared to the SPIN system in Table 2.

Table 2. Upfront capital cost comparison of 40-kWh BESS products and the SPIN system for residential customer resilience (Sources: EnergySage.com and Flex Power Controls.)

	BESS Product 1	BESS Product 2	SPIN DC V2X System
Battery Cost ($)	21,000	36,000	N/A
Inverter and Installation Cost ($)	2,000	2,000	1,000
Hardware Cost ($)	1,000	1,000	6,000
Total	24,000	39,000	7,000

Although 40 kWh is unrealistically large for residential BESS installations, it reflects the advantage of large available storage capacity built into PEVs. Because battery cost is the largest fraction of total system cost (around 90% for both BESS products shown), bidirectional charging with a vehicle purchased for mobility is a significantly lower cost strategy to providing backup power for infrequent outages (effectively subsidizing home electricity storage costs with the vehicle purchase).

Unlike most residential customers, commercial customers can more easily quantify the value of outages as the economic loss incurred if an outage were to occur (for example, in lost sales or spoiled merchandise). For a commercial customer like a supermarket, the annual benefit of resilience improvement was estimated to be $3660 using Lawrence Berkeley National Laboratory's ICE calculator tool [21].[1] The upfront capital cost and net present value (NPV) of the different backup options, assuming 2% inflation and a 7% discount rate over 15 years, are shown in Table 3.

Table 3. Cost comparison: 40-kWh BESS products and V2X system for commercial customer resilience (Sources: Homeguide.com, Energysage.com, and Flex Power Control.)

	Gas Generator[2]	BESS Product 1	BESS Product 2	SPIN V2X System
Upfront Unit Cost at Year 0	($8000)	($23,600)	($38,600)	($7000)
NPV After 15 Years	$26,346	$10,746	($4254)	$27,346

The gas generator is shown as a reference, although it is not an equivalent comparison because it relies on fossil fuels and has high emissions. The SPIN system and PEV with up to 10-kW discharge and 40-kWh capacity provide approximately the same value as the gas generator, which only improves with rising gas prices. Furthermore, this analysis quantifies only resilience benefits and does not include additional savings or revenue-generating opportunities from

[1] The following inputs were entered in the ICE tool: Location – California; Annual customer income - $56,800; System Average Interruption Frequency Index – 10; System Average Interruption Duration Index – 10.

[2] Gas generator is not an appropriate comparison given the non-zero emissions. It is included as a reference given its prevalence as a backup power generator today.

performing electric services. This suggests that on a direct-cost basis, the SPIN system coupled with a PEV capable of bidirectional charging provides significant customer benefit with an estimated $6000 purchase price.

Customer Bill Savings and Distribution System Peak Shaving

This analysis evaluated the potential electricity bill savings for individual representative residential and commercial sites using bidirectional charging to shift building load to low-cost times and limit site peak demand based on a time-of-use (TOU) tariff. Building on these individual customer savings, DER-VET was used to evaluate how aggregation of many customers' bidirectional PEVs can help smooth demand on a single distribution feeder based on different scenarios of the number of bidirectional PEVs available. The total annual bill savings were estimated and allocated evenly between all customers participating in the service.

For this analysis, the PEV battery capacity was assumed to be 20 kWh for grid services (representing approximately 20–30% of a commercially available midsize PEV battery capacity) with a power rating of 10 kW and a round-trip efficiency of 85%. The distribution feeder is assumed to serve 700 residential and 100 commercial customers. The representative load profile of the commercial and residential customers as well as the distribution circuit for the peak day of the year is shown in Figure 11. The annual peak load of the commercial and residential customers is approximately 28 kW and 12 kW, respectively, and the distribution circuit has an annual peak load of 9.35 MW.

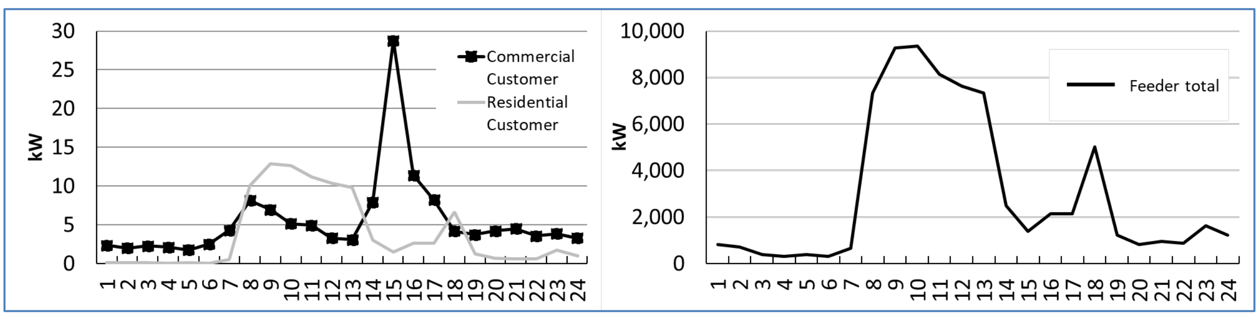


Figure 11. Customer and distribution circuit 24-hour peak load profile (Source: EPRI, DER-VET analysis.)

The commercial and residential customers are assumed to be subscribed to Southern California Edison's TOU GS-1 Option D and Option E tariff, respectively [22]. The utility bill consists of energy charges ($/kWh) that vary based on season and time of day as well as a demand charge ($/kW) for commercial customers, as summarized in Tables 4 and 5.

Table 4. Representative TOU tariff structure (Used with permission from Southern California Edison.)

Customer	Summer			Winter			Summer and Winter	Summer
	Energy Charge ($/kWh)						Demand Charge ($/kW)	
	On-Peak	Mid-Peak	Off-Peak	Mid-Peak	Off-Peak	Super Off-Peak	All Hours	On-Peak
Commercial	$0.177	$0.16	$0.104	0.172	$0.113	$0.092	$13.25	$4.41
Residential	$0.491	$0.299	$0.194	0.319	$0.242	$0.150	—	—

Table 5. TOU tariff schedule (Used with permission from Southern California Edison.)

Season	Period	Hours
Summer	On-peak	16:00–21:00 (weekdays)
	Mid-peak	16:00–21:00 (weekends)
	Off-peak	0:00–16:00 and 21:00–00:00 (weekdays and weekends)
Winter	Mid-peak	16:00–21:00 (weekdays and weekends)
	Off-peak	0:00–8:00 and 21:00–00:00 (weekdays and weekends)
	Super off-peak	8:00–16:00 (weekdays and weekends)

PEV charging and discharging are managed differently for commercial and residential customers because of the different rate structures. The residential customer charges during low-energy-price hours and discharges during high-energy-price hours. Conversely, the commercial customer discharges the PEV predominantly to shave the peak load of the individual customer to avoid demand charges. Figure 12 shows the original facility load, modeled charging and discharging behavior, and resulting net load for the residential and commercial customer. For a distribution feeder serving 700 residential and 100 commercial customers, aggregation of hundreds of PEVs operating the same bidirectional charging pattern could contribute 300 kW and 750 kW peak load reduction for 100 and 200 participating PEVs, respectively. Figure 13 shows the net load reduction on the distribution circuit assuming different numbers of participating PEVs.

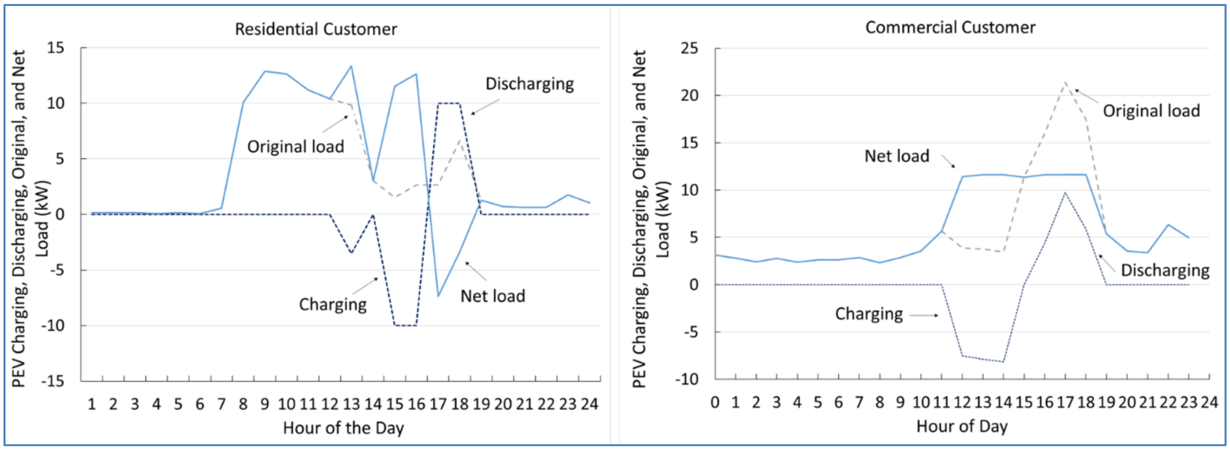


Figure 12. Customer load profiles with and without bidirectional PEV

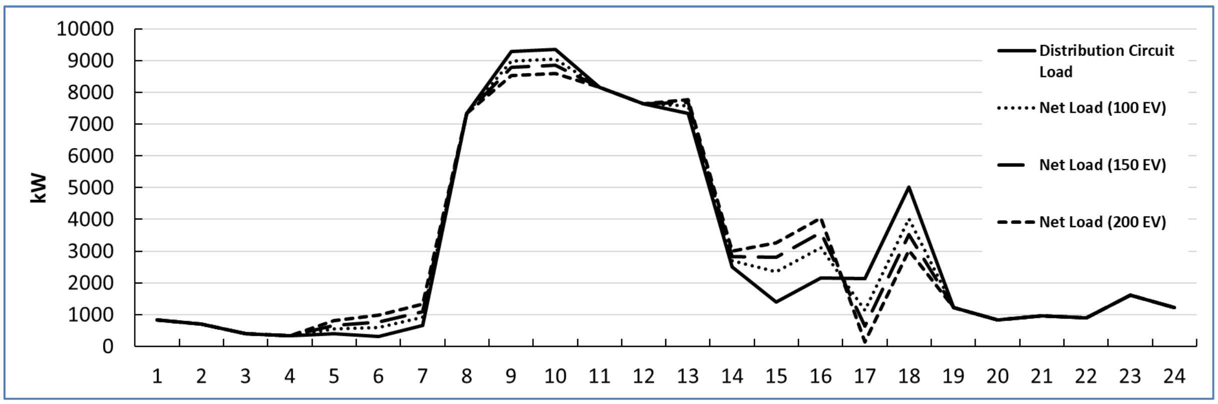


Figure 13. Distribution feeder load profile on peak day with different numbers of bidirectional PEVs

Peak load on the feeder reduces nearly linearly with increasing numbers of bidirectional PEVs, as shown in Table 6. Thus, most PEVs are operated for TOU bill reduction, with increased charging at low-cost times (4:00–7:00 and 14:00–16:00) as well as discharging (8:00–11:00 and 16:00–18:00) at a total of 20-kWh capacity at 10 kW per PEV daily.

Table 6. Distribution circuit peak load comparison with different numbers of bidirectional PEVs

PEV Count	0 PEVs	100 PEVs	150 PEVs	200 PEVs
Annual Peak Load	9.348 MW	9.048 MW	8.848 MW	8.598 MW

Economic Assessment of the SPIN System for Customer Bill Savings

Simulations of daily operation for a full year using the PEV characteristics, load data, and TOU tariff structure previously described suggest that a commercial customer with a bidirectional PEV charger like the SPIN system could save approximately $2070 per year on their electricity bill. This annual savings comes from the use of lower-cost electricity (approximately $400 in savings, representing an 8% reduction) as well as avoided demand charges ($1660 in savings, representing a 46% reduction). Similarly, for a residential customer, the annual bill savings is estimated to be $1195 (representing a total savings of 73%), which comes entirely from lower-cost electricity based on TOU rates.

The cost comparison of the two equivalently sized 20-kWh BESS products and the SPIN system are shown in Table 7. Based on estimated annual bill savings of $2070 and $1195 for a commercial and residential customer, respectively, the 15-year NPV is thousands of dollars more for the SPIN system for both customer types.

Table 7. Cost comparison of 20-kWh BESS products and the SPIN system for customer bill savings

	BESS Product 1	BESS Product 2	SPIN DC V2X System
Battery cost (S)	10,500	18,000	N/A
Inverter and installation cost ($)	2,000	2,000	1,000
Hardware cost ($)	1,000	1,000	6,000
Total upfront cost ($)	13,500	21,000	7,000
NPV at year 15 in year 0 dollars (residential/commercial)	$4,967/$14,435	($1,915)/$8,297	$6,681/$16,710

There would also be potential for utility and ratepayer savings arising from the annual peak load reduction of 300 kW, 500 kW, and 750 kW achievable with 100, 150, and 200 bidirectional PEVs, respectively. For example, assuming an avoided cost of infrastructure upgrade of $25/kW per year in Southern California Edison's service territory, the net savings for the utility could be anywhere between $112,500 and $281,250 over the 15-year period [23].

Systemwide Demand Response

This analysis explored opportunities for bidirectional charging to contribute to system reliability by having PEVs discharge during times of peak demand with a compensation structure like resource adequacy demand response programs administered by utilities. Specifically, this analysis assumed 10 demand response events per year with a duration of 4 hours for which participants are paid $9.50 per kW load reduction provided [24]. Scenarios of different levels of PEV deployment and participation were evaluated, assuming that each bidirectional PEV and charger pair has 20 kWh of capacity rated at 5 kW and a round-trip efficiency of 85%.

The 10 days with highest peak demand of 2021 were identified using historical load data from the California Independent System Operator (CAISO), all of which occurred in the months of July, August, and September [25]. The impact on net CAISO system load of the aggregated charging and discharging of 100,000, 200,000, and 300,000 bidirectional PEVs participating in the modeled demand response program is shown for September 8, 2021 in Figure 14.

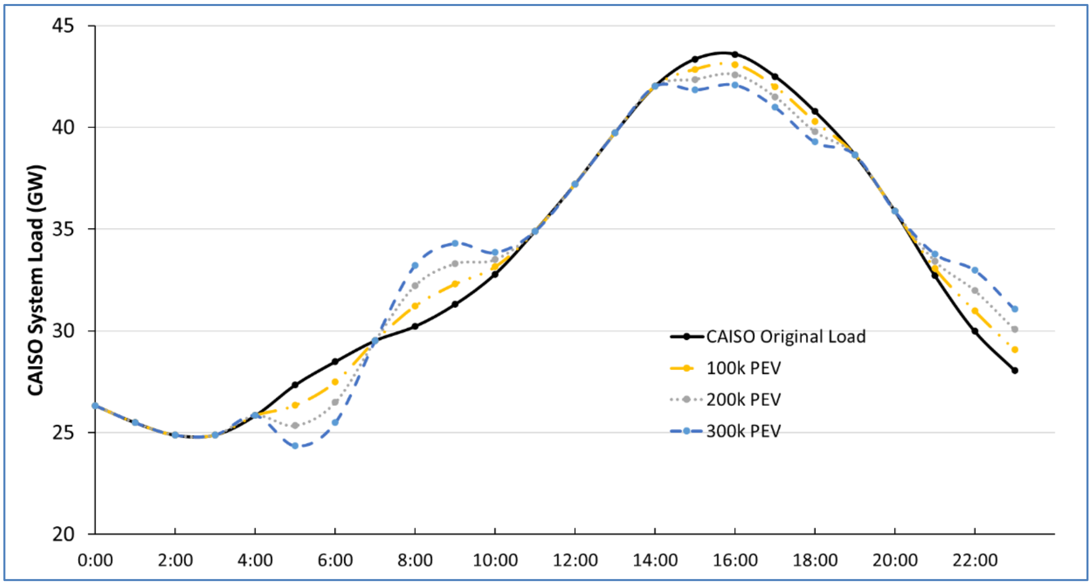


Figure 14. Original (September 8, 2021) and net CAISO load with different numbers of bidirectional PEVs participating in demand response programs

The potential CAISO annual peak load reduction increases with the number of bidirectional PEVs participating in the customer load reduction service, as shown in Table 8. The PEV batteries charge more during nighttime and early morning (approximately 20:00–24:00) and discharge to reduce peak load (approximately 13:00–19:00), contributing between 0.5 GW and 1.5 GW reduction in peak load for 100,000 and 300,000 PEVs participating, respectively. Given forecasts for millions of PEVs to be deployed in California over the coming decade, these estimates are reasonably achievable targets [26].

Table 8. CAISO peak load comparison with different amounts of bidirectional PEVs

Number of participating PEVs	0	100,000	200,000	300,000
Peak load (GW)	43.59	43.09	42.59	42.09

Economic Assessment of the SPIN System for Demand Response

Assuming a monthly payment of $9.50/kW per month for participating in the demand response program, the annual revenue per PEV could be up to $570. (This level of compensation is similar to existing demand response programs in California; see, for example, PG&E [24].) With the 20-kWh BESS product and SPIN system costs estimated in Table 7, an inflation rate of 2% and discount rate of 7%, the 15-year NPV is estimated as negative $474, reflecting the relatively low compensation associated with demand response.

Systemwide Renewable Curtailment Mitigation

This analysis evaluates the potential reductions in renewables curtailment and greenhouse gas emissions enabled through aggregated charging and discharging of bidirectional PEVs and chargers following changes in locational marginal prices (LMPs) across the CAISO system. The LMP reflects a combination of the cost of generation, congestion on the transmission system, and line losses when delivering power to a specific location. The LMP is calculated for thousands of market nodes in real time. Renewable wind and solar resources have a near-zero marginal cost of generation and, when combined with inflexible baseload plants, can result in negative LMPs at some locations where generation exceeds demand. Most utilities or grid operators curtail generation from wind and solar plants when minimum generation levels of baseload generation are reached. This is because frequent stopping and restarting of these units for short periods can be significantly more expensive than paying for curtailed renewable generation. In California in 2020, approximately 1500 GWh of renewable energy was curtailed. The hourly breakdown of the total curtailment is shown in Figure 15, with about 80% of this curtailment occurring between January and June [27].

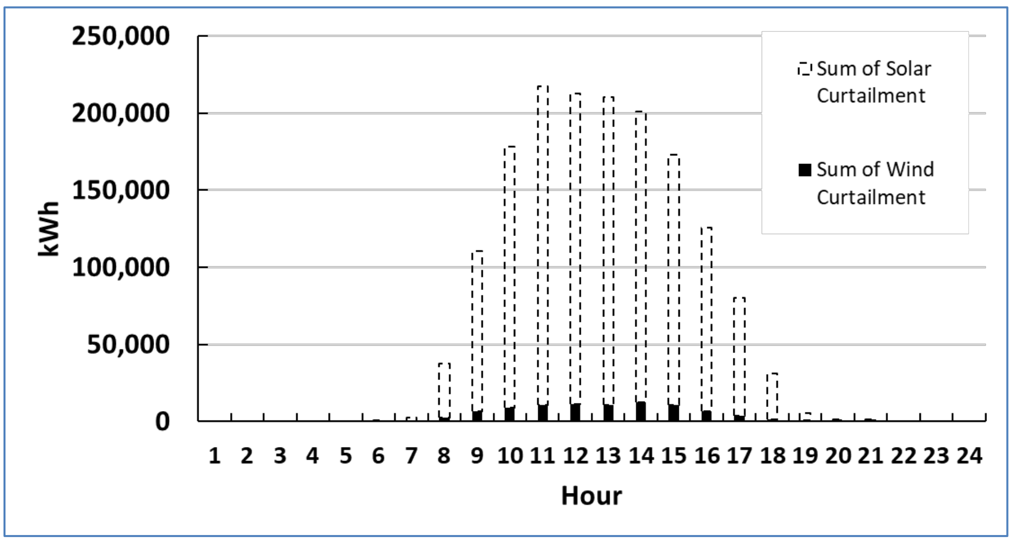


Figure 15. Renewable curtailment by hour in CAISO in 2020

Customers with flexible resources, such as bidirectional PEVs and chargers, could charge during instances of low or negative LMP, consuming renewable electricity that would otherwise be curtailed. Assuming that each bidirectional charger and PEV discharges an average of 20 kWh daily at 10 kW with a round-trip efficiency of 85%, the aggregate impact of different numbers of PEVs operating to mitigate curtailment was evaluated. The charging and discharging behavior of a single bidirectional PEV and charger is shown in Figure 16, along with the battery state of charge and LMP profile of a representative CAISO market node.

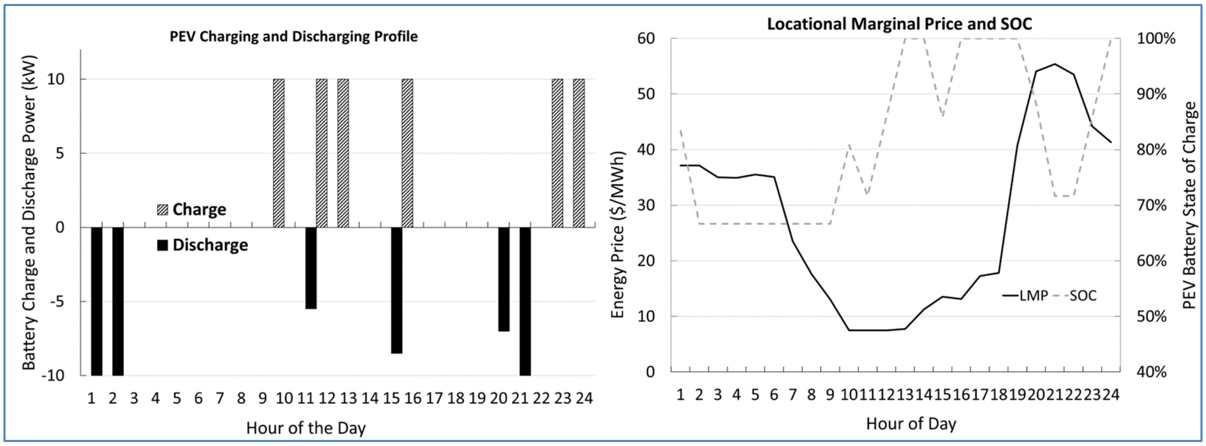


Figure 16. Daily PEV charging and discharging profile, battery state of charge, and LMP

Note that the day shown here (June 7, 2017) is one of the high-curtailment days in the year in which large changes in LMP result in more extensive discharge of more than 40 kWh. In most months, the variation in LMP is smaller and the PEV is discharged less; thus, the energy drawn from the battery on an annualized basis averages out to be about 20 kWh per day. The DER-VET algorithm is simplified and does not consider factors such as temperature, warranty, degradation, and customer constraints. Consequently, the benefits estimated in this analysis are likely the upper limit of the values.

The PEV charges during hours of low LMP (predominantly late morning and late night) and discharges during times of high demand and price (early morning and later afternoon). The aggregated impact of 100,000, 250,000, and 500,000 PEVs following this charging and discharging pattern could reduce annual curtailment in 2020 by 66.6 GWh, 165 GWh, and 332 GWh, corresponding to a 4.2%, 10.4%, or 20.9% reduction, respectively.

The otherwise-curtailed renewable energy stored in the PEV battery is discharged later (minus conversion losses), offsetting production that would otherwise come from conventional resources, such as natural gas plants. This would contribute to electricity sector greenhouse gas emissions reductions. Based on the marginal hourly emission of CO_2, approximately 16,484 metric tons, 41,412 metric tons, or 82,424 metric tons of CO_2 emissions could be avoided annually with 100,000, 250,000, or 500,000 PEVs, respectively [28].

Summary of Value Assessment for Bidirectional Applications

Table 9 summarizes the estimated potential economic, environmental, and resilience benefits of the SPIN system for residential and commercial customers as well as distribution and bulk power system operators.

Table 9. Summary of analyzed benefits of the SPIN system

Application	Customer Resilience Improvement	TOU Optimization and Distribution Feeder Peak Shaving	Systemwide Demand Response	Renewable Curtailment Mitigation
PEV Capacity and Power Rate	40 kWh 10 kW	20 kWh 10 kW	20 kWh 10 kW	20–40 kWh 10 kW
Number of PEVs	At least one per site	At least one per site, scenarios of 100, 150, and 200 per distribution feeder	Scenarios of 100,000, 250,000, and 300,000 (statewide)	Scenarios of 100,000, 250,000, and 500,000 (statewide)
Annual Benefit Realized	24 hours backup residential/8 hours backup commercial/value of lost load is $3661 for commercial customer	300–750 kW load reduction with 100–200 PEVs; $2070 and $1195 savings per commercial and residential customer, respectively	$1140 per PEV/ 500–1120 MW load reduction with 100,000–300,000 PEVs	$460 per PEV/ 363 lb (165 kg) CO_2 avoided per PEV/ 16,484 MT CO_2 reduced per 100,000 PEVs

In conjunction with rooftop solar, the SPIN system can both power the building and charge a PEV during the daytime and then discharge the PEV to power the building during night or an outage (for up to 24 hours, depending on the building's energy use). Beyond resilience applications, the SPIN system can manage PEV charging and discharging to mitigate demand charges and limit distribution-level peaks, resulting in local grid benefits of approximately $1140 per year per PEV. If bidirectional charging is coordinated with renewable overgeneration, the SPIN system could enable savings of $460 per year while cutting 363 lb (165 kg) of greenhouse gases per year per PEV from avoided fossil generation. Even if system operation is non-ideal due to variability in PEV availability, building energy use, electricity greenhouse gas intensity, or tariff structure, the SPIN system remains a lower-cost substitute for stationary battery storage or polluting and noisy fossil-based generators. In the near term, backup power applications that require limited use of PEV batteries during occasional outages can drive market growth for the SPIN system and other bidirectional charging technologies while other compensation mechanisms for grid services mature.

Summary of Customer and Ratepayer Benefits

By using a portion of a PEV's battery capacity for grid services (ranging from 60% to 70% for resilience applications and approximately 30% for bill management or demand response applications), customers can receive resilience and economic benefits from bidirectional chargers. Customer savings are dependent on access to rate or other signals with associated compensation mechanisms being available, including TOU rates, demand response programs, or more advanced real-time retail rates. By reducing peak load on individual distribution feeders or providing demand response, the SPIN system can also provide benefits to distribution and bulk power system operators. By enabling more efficient utilization of existing electricity infrastructure, bidirectional charging technologies can reduce ratepayer costs while helping to reach state targets for simultaneous transition to zero-emission transportation and zero-carbon electricity systems.

The economic analyses presented in this section suggest significant potential customer and ratepayer benefit, but grid-responsive operation of bidirectional charging technologies on a large scale will require both policy and technology advances.

3 SUMMARY AND FUTURE SCOPE

Near-Term V2X Enablers

In response to the following, several automotive manufacturers have introduced EV products [29] capable of serving emergency power to the home using an on-vehicle battery:

- The emergence of public safety power shutoff [30] as a preemptive response to mitigating wildfire risk
- The Emergency Load Reduction Program [31] in California, which provides incentives for customers to reduce demand or send energy to the grid during critical peak periods
- More confidence from the automotive manufacturers in their EV batteries

A second near-term enabler is the emergence of dc V2X technology based on a combined charging system protocol, where the bidirectional charger can reside offboard while the vehicle is converted to a bidirectional-power-capable EV with a simple software change. This is an implementation method verified and documented in another EPRI report [32]. It creates a cost-effective pathway for OEMs to create EVs capable of bidirectional charging, while leaving the decision to install the dc V2G charging equipment to customers.

Third, the lithium-ion battery technology has matured sufficiently and the OEMs and battery vendors have enough data to be confident about their ability to provide offboard power during very specific events without affecting battery life. EPRI research also experimentally verified this aspect [7] using a technology that is at least a decade old (meaning, the later technologies are even more durable). The fact that daily energy use for EVs is about 15–20 kWh for a round-trip commute whereas the EVs carry a minimum of 70 kWh of energy onboard leaves them with significant surplus capacity that can be deployed during emergency or very selective local or grid services scenarios. And the ever-increasing battery capacity for EVs is in no small measure a result of the declining lithium-ion battery costs per kWh.

Finally, the policy [17] environment for V2X is becoming favorable with the emergence of discussion around making V2X capability a requirement for all EVs.

At a macro level, the nationwide deployment of EVs in significantly large numbers creates a latent resource pool that can rival the capacity provided by several peaker plants, and significant investments in transmission and distribution.

The incorporation of EVs as a resource class participating in the energy markets and remunerated for this participation is essential for this value to be available for the EV owners as an incentive, further improving the business case for their EV ownership. This same increased economic appeal is also an enabler for EV manufacturers to install this capability on their EVs at scale, as well as for equipment manufacturers to make the investments necessary to produce the bidirectional charging equipment in large numbers cost-effectively. The open standards and interoperable systems have a role to play because they enable large-scale production of bidirectional charging equipment and make the deployment of integrated systems convenient and cost-effective.

Assuming that these enablers become effective with full intensity, this report developed a value assessment framework and then created value estimates for several relevant use cases, including local premises benefits, distribution system benefits, on-bill incentives, and market participation benefits within the existing market structure.

Summary: Grid and Premises Benefits of the V2X-Capable EVs

Table 10 summarizes the benefits accrued to the dc V2X systems focused on only a few specific use cases with the highest value.

Table 10. V2X system: summary of estimated benefits (Source: EPRI analysis with DER-VET.)

Application	Customer Resilience Improvement	TOU Optimization and Distribution Feeder Peak Shaving	Systemwide Demand Response	Renewable Curtailment Mitigation
PEV Capacity and Power Rate	40 kWh 10 kW	20 kWh 10 kW	20 kWh 10 kW	20–40 kWh 10 kW
Number of PEVs	At least one per site	At least one per site, scenarios of 100, 150, and 200 per distribution feeder	Scenarios of 100,000, 250,000, and 300,000 (statewide)	Scenarios of 100,000, 250,000, and 500,000 (statewide)
Operating Benefits	24 hours backup residential/ 8 hours backup commercial	300–750 kW load reduction with 100–200 PEVs	500–1120 MW load reduction with 100,000–300,000 PEVs	363 lb (165 kg) CO_2 avoided per PEV/16,484 MT CO_2 reduced per 100,000 PEVs
Annual Benefit Realized	Value of lost load is $3661 for commercial customer	$2070 savings per commercial and $1195 per residential customer	$1140 per PEV	$460 per PEV

The analysis was performed by assuming that an EV, which carries a minimum 70-kWh battery onboard, is making available 20 kWh of capacity during infrequent grid services events and 40 kWh during power outages for the EV battery to provide the standby power, leaving the remainder of the battery for mobility-related applications. In each case, 10 kW of charging capacity was assumed per EV, although this is likely to go up to 19.2 kW in the next round of upgrades (which would effectively double the benefits).

The analysis yielded the grid benefits ranging from $460/year from the renewable curtailment mitigation market to $1140/EV every year while participating in a demand response or resource adequacy marketplace. The analysis also estimated the avoided costs of distribution upgrades due to the ability of the EVs to supply peak demand, to the tune of $1200 per EV per year.

Finally, the benefit to the premises in terms of standby power availability was calculated for a commercial enterprise in terms of the value of lost load. For the residence, this was calculated by measuring how long the affected family can stay on standby power supplied from the EV. The value of lost load benefit to the commercial enterprise was $3661 for 8-hour backup capacity; for the residential customer, the backup power capacity was 24 hours.

Recommendations for Future Work

The analysis and numerical estimates demonstrate that there is significant latent value that can be unlocked by making the dc V2X capability available on the EVs. Several unknowns in this analysis can be resolved only through real-life demonstrations involving real customers and real EVs in a geographically, demographically, and jurisdictionally diverse environment. Some of the items that need further validation are:

- **Customer participation and relationship with incentives to offer the EVs for utility services.** The PG&E V2X pilot, for example, offers $2500 for EV owners to join the V2X pilot upfront and another $2500 at the end of the pilot on a sliding scale based on the degree of engagement in the pilot throughout its duration. These are significant numbers, and as the benefits analysis points out, they far exceed the per-EV benefit numbers. So, it remains to be seen how many customers participate in the utility programs and how many install V2X systems similar to energy storage systems just as a backup power system.
- **Energy efficiency of V2X systems.** The analyses assume a certain power transfer efficiency for the bidirectional charger (round trip of 85%). However, for the EVs to be available for grid services, they need to be kept awake, requiring onboard electronics and battery-cooling systems to be energized from the grid. This could consume about 400–600 W continuously during the time the EV is awake. These energy losses must be factored into the battery degradation calculations as well as the discharge-recharge cycle energy consumption calculations, and the net effect could be assumed to be negative.
- **Cost and complexity of the setup resulting in installation cost variations.** Currently, a lack of standards and guidelines regarding the installation of V2X-capable systems integrated with the customer’s residential circuits will result in custom designs, possible permit delays, and installation cost overruns. Standardization would help, but it is not there yet. Understanding the best practices from solar and storage installations and adapting them to V2X systems would be a positive step.
- **Interconnection requirements.** Although dc V2X system interconnection requirements are known, the OEM implementation of these requirements has not been verified for grid-interactive/grid-isolated operation. The requirements need to be standardized, verified, and transferred to the OEMs, V2X equipment providers, and third-party integrators.

- **Building awareness among the utilities, customers, OEMs, equipment providers, and third-party system integrators.** Making stakeholders aware of the issues, barriers, solutions, and functional implementations in their own jurisdictions would raise the confidence in the technology's viability, ease of operation, and grid integration, resulting in accelerated technology adoption. Nationwide pilots involving hundreds of customers per jurisdiction and tens of utilities, as well as all the OEMs and equipment providers, would create the momentum to adopt and deploy the technology in meaningful numbers to be of benefit to customers, the grid, and society at large.

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