

Advancing Energy Resilience and Cost Optimization through V2B Integration and Supportive Policy Frameworks

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ABSTRACT

Electrification of the transportation sector is accelerating across North America, driving rapid growth in the deployment of electric vehicle charging stations (EVCS) for private, public, and commercial transportation, including electric fleets. To meet the growing trends, jurisdictions are modifying codes and developing policies with supportive electric vehicle (EV) requirements. These measures play a critical role in decarbonizing the transportation sector and improving air quality. While electric vehicles (EVs) typically achieve lower lifecycle emissions compared to internal combustion engine vehicles (ICEVs), their embodied carbon is higher at the point of manufacture, emphasizing the importance of maximizing operational life to fully realize emissions reductions. While EVs are treated like ICE for the purposes of personal transportation, the heart of the technological revolution fueling their rise is the advancement of dense lightweight batteries, and the market has not yet fully acknowledged their potential and designed around additional functionality. At a time when billions are being invested to purchase EVs and deploy EV infrastructure, limiting the use of EV batteries to personal transportation risks underutilizing their full potential. These advanced batteries can supplement or replace the emergency backup power supply of buildings when paired with smart EVSE through vehicle-to-everything (V2X) integration with the grid and are a great asset for energy resilience. This paper provides a landscape review of the EV market, discusses the potential for EV batteries to provide benefits for buildings and the grid outside of their capacity for transportation, comparing the costs of standard EV & vehicle-to-building (V2B) system. Additionally, the study will examine how codes and policies can support the adoption of EV infrastructure to maximize and extend the benefits of V2B technology. This approach will shape a comprehensive vision for deployment of EV infrastructure integrated with V2X, benefiting and enhancing resilience for multiple stakeholders.

INTRODUCTION

A recent study by the National Academies of Sciences, Engineering, and Medicine (2025), Effects of Human-Caused Greenhouse Gas Emissions on U.S. Climate, Health, and Welfare, confirms that anthropogenic greenhouse gas (GHG) emissions are disrupting Earth's ecosystems, driving abrupt climate change and increasing the frequency and severity of climate-related disasters that adversely affect human health and well-being (National Academies of Sciences, Engineering, and Medicine 2025). Another technical report from IPCC proved that human-induced climate-changes are increasing number of weather and climate extremities (Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change 2022). U.S. EPA identifies agriculture, residential, and commercial built environment, industry, electric power, and transportation as prominent contributing sectors, with transportation alone being the largest, accounting for approximately 28% of U.S. GHG emissions. As a result, a primary mitigation pathway identified is the transition from fossil-

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fuel combustion to clean electricity generated from renewable sources (United States Environmental Protection Agency 2025).

In the decade preceding 2021 the cost of residential, commercial, and utility-scale solar photovoltaic (PV) dropped 64%, 69%, and 82% respectively (National Laboratory of the Rockies 2021). As the cost of renewable energy production has dropped, especially with solar PV cost plummeting in recent years, the pathway towards decarbonization in many sectors has been pursued as a two-pronged approach — electrifying energy end uses and renewable electricity generation. These strategies are being deployed across all major GHG-emitting sectors in various forms. Within the transportation sector, the adoption of electric vehicles (EVs) has emerged as a dominant decarbonization strategy, enabled by a staggering 97% decline in Lithium-ion electric energy storage cost since its commercial introduction in 1991 (Ritchie 2021).

EVs are now rapidly expanding into the personal transportation, public transit, and commercial fleet markets. To support this transition, jurisdictions and electric utilities have introduced funding programs and financial incentives, further positioning EVs as a reliable and cost-effective option for personal transportation. Tax Foundation's 2025 state-by-state analysis found that even though the federal tax credits are canceled, there are seventeen states offering an additional incentive beyond the federal credit, ranging from a \$1,500 incentive in Rhode Island to a \$7,500 credit in Oregon and Maine (Tax Foundation 2025).

Although EVs do not have tailpipe emissions, they still have a substantial carbon footprint driven by the increased embodied carbon of EVs relative to ICEVs due to their Li-ion batteries. One 2020 study showed a range of embodied emissions of 40kgCO₂e-140kgCO₂e to produce lithium nickel manganese cobalt oxide (NMC), the dominant material makeup of Li-Ion batteries in the US market, with variability being attributable to the location of resource extraction and regionality of battery manufacturing and production (Winjobi, et al. 2022). Despite EV's higher embodied carbon, studies have demonstrated that even in current grid generation mix they achieve reduced life-cycle emissions (The International Council on Clean Transportation (ICCT) 2025).

This dynamic can be understood as a “carbon debt,” reflecting the front-loaded lifecycle emissions profile of EVs relative to ICEVs. This carbon debt is typically offset over time through lower emissions vehicle operation and reduced upstream emissions from electricity generation, even in regions with relatively carbon-intensive grids (McLaren, et al. 2016). Nevertheless, while EVs represent a critical decarbonization asset, their initial emissions burden presents challenges for meeting near-term climate targets, particularly efforts to limit global temperature rise to 1.5°C (National Academies of Sciences, Engineering, and Medicine 2025).

While billions of dollars are currently being invested in the purchase of EVs and the deployment of electric vehicle charging station (EVCS) infrastructure, it is important to recognize that EV batteries can serve more than vehicle propulsion. Through vehicle-to-everything (V2X)-enabled electric vehicle supply equipment (EVSE), EVs can provide power to buildings, devices, dedicated loads, homes. V2X covers broadly the range of bidirectional vehicle capabilities that includes vehicle-to-building (V2B), vehicle-to-home (V2H), vehicle-to-grid (V2G). Even where not back feeding to the grid, bi-directional vehicle power flow can support grid functions through participation in demand response (DR) and load management programs, optimize building energy use through time-of-use (TOU) billing programs, and serve critical building operations and life-safety systems in the event of grid disruption. Despite this capability, the dynamic use of EVs as distributed electric energy storage systems remains overlooked in conventional deployment strategies and is insufficiently addressed in existing incentive programs and policy frameworks supporting EV infrastructure.

By enabling the integration of EVs as flexible, distributed energy resources, V2X represents a future-ready solution that connects transportation and building-sector decarbonization efforts (Ibrahim, et al. 2025). Such integration can enhance system adaptability, scalability, and resilience, while advance climate mitigation goals and improving public health and overall societal well-being. This research aims to quantify the untapped potential of EVs through V2B technologies and to present a comprehensive value proposition for key stakeholders, including utilities, building owners, and code and policy developers. Additionally, the authors will make recommendations for how code and policy solutions can facilitate deeper penetration of V2X capable technologies in the market and increase accessibility to the various energy related benefits.

SCOPE AND METHODOLOGY

The scope of this study is limited to V2B-enabled EVCS primarily serving DOE prototype model of single-family home. The analysis incorporates time-of-use (TOU) rate structures within the selected study region to assess and optimize its value proposition for building owners, electric utilities, and policymakers. This study employs a systematic review of market analysis conducted in four stages to evaluate the technical, economic, and policy potential of V2B-enabled EV charging infrastructure.

The first stage involves a landscape review and market analysis to assess current EV and V2B technologies, adoption trends, state and utility incentives, and implementation barriers. This includes a review of industry case studies, product specifications, along with relevant market and technical reports.

The second stage focuses on developing a comparative cost analysis to evaluate standard electric vehicle charging stations (EVCS) relative to V2B-compliant EVCS. Cost comparisons are conducted for both new construction and retrofit scenarios and include equipment, installation, and associated electrical infrastructure requirements. This analysis is intended to quantify incremental costs and identify cost drivers associated with enabling V2B functionality.

The third stage applies scenario analysis to evaluate the value of V2B-enabled EVCS under TOU rates. According to the vehicle registration data derived from the National Laboratory of the Rockies, California had the highest number of EVs up to 1,256,646 in the USA, while New York had 131,250 (U. S. Department of Energy 2023). Both regions have advanced EV adoption, grid-interactive policies, and availability of utility programs; thus, they are considered the primary regions for this study. The objective of this stage is to identify optimization pathways that improve the value proposition of V2B systems for building owners and operators.

The final stage synthesizes findings to develop conclusions and policy-oriented recommendations, with a focus on integrating V2B considerations into building codes, standards, and programs to maximize the building- and grid-level energy benefits of EV deployment, and to support scalable, future-ready infrastructure.

LANDSCAPE REVIEW

Market Trends in EV Adoption

The potential benefits of V2X technology are broadly recognized, if not fully realized, as evidenced in the development and signing of the Memorandum of Understanding to Establish the Vehicle-to-Everything Collaboration by the DOE and stakeholders in 2022 (U. S. Department of Energy 2022) and its extension in 2024 (U. S. Department of Energy 2024). Recognizing the potential benefits, this collaboration aims to convene public and private stakeholders to explore bidirectional vehicle charging technologies and services, with a focus on commercial market viability.

Focusing on the EV market trends, the United States alone has experienced rapid growth in EV sales from 2018 to 2025 (Argonne National Laboratory n.d.). According to the International Energy Agency's (IEA) Global EV Outlook 2025, electric car sales in the United States climbed to 1.6 million in 2024, accounting for over 10% of total vehicle sales (IEA 2025). While year-over-year growth slowed by approximately 4% in 2025 compared to 2024, 2025 was still the second-best year for electric vehicle sales on record in the United States, despite ongoing economic and policy uncertainties (RMI 2025). In 2024, almost twenty-four new electric car models were introduced, expanding model availability by 15% over 2023 and increasing market competition (IEA 2025). Technological improvements, cost reductions, increased model choices, maturing charging infrastructure, and economic recovery have continued to drive and support increased sales, overall accelerating EV adoption.

Rapid growth in electric vehicle adoption has driven significant expansion of U.S. charging infrastructure. From 2019 to 2024, charging infrastructure grew at an average annual rate of approximately 25%, consistent with the deployment pace required to support an estimated 55 million EVs on U.S. roads by 2032 (Pierce 2024). Over this period, Level 2 chargers increased by nearly 29% (Pierce 2024), and total U.S. charge points are projected to reach approximately 35 million by 2030 (PWC n.d.). To meet increasing demand, publicly accessible EVCS are now available in all U.S. states. According to 2025 data from the U.S. Department of Energy's Alternative Fuel Data Center, California leads the nation in the number of public and private charging ports (73,568), followed by New York (20,016), Florida (15,376), and Massachusetts (11,366). These numbers exclude residential electric charging infrastructure (Alternative Fuels Data Center 2026).

In parallel, the electric vehicle supply equipment (EVSE) market is projected to reach nearly \$100 billion by 2040, growing at an estimated 15% compound annual growth rate, with multi-unit residential buildings emerging as a key growth segment (PWC n.d.). Collectively, these trends highlight increasing adoption of EV-ready and EV-capable infrastructure in both new construction & retrofit applications to support scalable and cost-effective transportation electrification. Although technological advancements in EV charging systems enable EV batteries to be utilized beyond transportation, positioning them as grid-interactive energy assets when paired with compatible chargers. The 2021 Infrastructure Investment and Jobs Act and the 2022 Inflation Reduction Act both provided unprecedented levels of support for EVs, EV charging infrastructure, electric grid infrastructure, and battery manufacturing (Environmental and Energy Study Institute 2023). While some of this funding

remains unavailable due to current political contexts, it is succeeding in instigating private investment that remains underway.

Vehicle-to-home (V2H) is a subset of V2B, and an emerging technology in the EV charging system, where V2H compatible EV coupled with bidirectional equipment can be a great asset for both its owners and the utility, serving more than a medium of transport.

Benefits to Homeowners

Through the V2H system, the battery capacity of the EV can be used to charge the house in the absence of grid services and lower electric bills through ‘peak shaving’. V2H-compatible EVs can replace traditional generators or stationary storage, enabling homeowners to utilize their EV as a backup power source, avoiding the cost of additional equipment.

For example, a typical U.S. home uses almost 30 kWh/day of energy depending on its size & appliance residents use, and with a typical home battery system like Tesla Powerwall with 13.5 kWh energy capacity, it can continue normal operation for approximately 10–11 hours, less than half a day, before the battery is depleted (Tesla n.d.) (U.S. EPA 2024). In contrast, the average EV battery as of 2023 is approximately 80 kWh, about six times the capacity of a Tesla Powerwall. Light-duty EVs vary widely, the 2024 Chevrolet Blazer EV, for example, offers 85–102 kWh battery option, while the 2024 Nissan Leaf, one of the few EVs with native bidirectional (V2X) charging capability, now offers a 75 kWh battery in its latest 2026 model (Chevrolet 2026) (Nissan Leaf 2026). Evidence suggests that if a bidirectional EVCS is coupled with a compatible EV, it can provide backup power ranging from approximately 1–2 days for standard passenger EVs to 3 days or more for large-battery trucks like the Ford F-150 Lightning, at an incremental hardware and installation cost of approximately \$7,000–\$12,000 (SEPA 2023) (EnergySage 2025). This is broadly comparable or lower than traditional whole-home standby generators (\$6,000–\$11,000) or dedicated battery systems (\$30,000–\$50,000), while also serving dual functions of mobility and backup power (Home Guide 2025) (Ramasamy, et al. 2023).

To use EV batteries as economic assets, customers can opt into time-of-use (TOU) rates and charge their EVs during low-price off-peak hours and discharge that stored energy to power their homes during high-price peak periods, reducing overall electricity costs. Homeowners can achieve substantial annual savings through such TOU arbitrage, depending on their location and usage patterns. The financial benefits can be further improved by leveraging incentives and combining with backup power value, creating compelling economic incentives for V2H adoption (SEPA 2023).

Benefits to Utilities and the Electric Grid

The United States electric grid is facing demand and load growth that it has not seen in over a decade (U.S. Energy Information Administration 2025). This growth is in part responsible for pushing five of the 23 assessment areas into the high-risk category in the North American Electric Reliability Corporations (NERC) 2026 Long-Term Reliability Assessment – up from zero high-risk areas in the December 2024 assessment (NERC 2026) (NERC 2024). Emerging research is demonstrating the potential for bi-directional EV’s to contribute both to building and grid emissions reductions, and to peak demand management and grid stabilization efforts. An international study evaluating bi-directional EV integration with a commercial building found 10.9% carbon emissions reductions, and 14.1% – 22.6% peak demand reductions – with reductions increasing when paired with PV systems (Ibrahim, et al. 2025). Deloitte published a 2024 article on the potential for residential distributed energy resources (DERs) to meet the projected load growth through 2035 – noting that EV capacity alone could meet peak demand in 2035 if bidirectional technology adoption scales (Thomson, et al. 2024).

In a recent request for information (RFI), Consolidated Edison Company of New York (ConEd) projected a grid reliability need in the New York City region of 125 MW in 2032, growing to 750 MW by 2036 (ConEd 2026). Meanwhile data from NYSEERDA indicates 79,773 EVs on the road in New York City—with 52,000 of them fully battery electric vehicles (NYSEERDA 2026). An assumed storage capacity of 65 kWh (a reasonable mid-range estimate for on-road EVs) and output capacity of 19.2 kw (the output capacity of the GM Energy Powershift Charger) arrives at 3,380 mWh of storage capacity and 998 MW of output capacity. Capturing even a fraction of this for participation in building or grid demand and load management programs could provide significant reliability benefit to ConEd.

Applying these estimates to 2025 EV sales of 1.3 million units yields 84.5 GWh of storage and 24.9 GW of output capacity, assuming full bidirectional capability. Compared to the record 18.2 GW of utility-scale storage deployed in 2025 (U.S. EIA 2025), , this highlights a significant untapped opportunity for distributed storage, as even modest V2G adoption could substantially increase total battery capacity.

Challenges to Deployment

Adoption of V2H technologies remains limited by vehicle compatibility and battery system design. Currently, not all vehicles have bidirectional functionality, with capabilities varying by manufacturer and platform. Key challenges include whether the vehicle battery is designed for bidirectional operation, and differences in battery capacity and maximum power output - which directly affect backup power performance – requirements around interconnection and back feeding to the grid, communication protocols, and participation in grid services (SolarTech 2025). These limitations highlight the need for standardized bidirectional requirements and clearer performance benchmarks to support broader V2X integration. NEMA recently published a standard (NEMA EVSE 40011-2024) for EV power export, outlining technical requirements for bidirectional capabilities and back feeding to the grid, addressing some of the challenges noted above (NEMA 2025).

Codes, Standards, and Utility Programs

The International Green Construction Code (IgCC) has included requirements for low emissions, hybrid, and electric vehicle parking since its inception in 2009 (ICC 2009). The national model energy codes – ASHRAE 90.1 and the International Energy Conservation Code (IECC) – have included optional energy credit compliance pathways for load management and demand responsive criteria since 2022 (for ASHRAE 90.1) (ASHRAE 2022) and 2024 (for IECC). The 2024 IECC additionally provided optional appendices related to electric vehicle charging infrastructure (ICC 2024). Bi-directional vehicle charging was addressed for the first time in model code language with ASHRAE 90.1-2025, which introduced a load management energy credit for projects that provide on-site vehicle infrastructure capable of bidirectional power output (NYS ASHRAE 90.1 Standard 2025 2025).

The Energy Policy Act of 2005 established a federal income tax credit for hybrid vehicles, which was later expanded to electric vehicles by the Energy Independence and Security Act of 2007. Since then, forty-three states have implemented one or more market incentives for EVs (World Population Review 2026). Despite the deep penetration of state level financial support for EV Adoption, the authors could not identify a single state incentive program that prioritized bidirectional EV functionality.

While not formally included in state level incentives, there have been some movements towards pilot and demonstration projects related to bidirectional EVs. Massachusetts Clean Energy Center (MassCEC) launched a statewide V2X demonstration project in 2025 aiming to deploy 100 bidirectional equipment to residential, educational, municipal, and fleet end-uses, citing energy costs, grid resilience, and renewable integration as project priorities (Resource Innovations 2025). Moving beyond pilot and demonstration projects, Maryland adopted requirements for V2G interconnection in 2025 that defines a V2G system, and includes requirements for DC systems, AC systems, and lays the groundwork for associated rates to be established (Vehicle-Grid Integration Council 2025).

In addition to early-mover state programs looking to advance bidirectional vehicle capability, there have been various utility level programs and pilots implemented. California's Pacific Gas & Electric (PG&E) launched a bidirectional vehicle program, providing incentives for residential and commercial customers to install eligible charging infrastructure and V2X microgrids (PG&E 2025). Eligible vehicles and technology include Ford, Nissan, and GM vehicles, and RIDE electric school buses. The program aims to deploy 1000 residential systems, 200 commercial systems, and 200 microgrid systems. Baltimore Gas and Electric Company (BGE) launched a V2H pilot project in partnership with Ford and Sunrun in 2024, citing the need to reach net-zero emissions by 2045 and 100% clean electricity by 2035 (BGE 2024). Fermata Energy, Xcel Energy, and the City of Boulder announced a V2X bidirectional power pilot in 2024, citing grid resilience and sustainability (Fermata Energy 2024). San Diego Gas & Electric (SDGE) partnered with Toyota and Fermata Energy to launch and test V2G capability at SDGE's Resilience Center in 2023 (SDGE 2023). Project goals included identifying customer benefits, developing communication strategies, understanding infrastructure needs, and further clarifying the role of bidirectional EVs as grid assets.

COST COMPARISON

A standard EV charger converts alternating current (AC) from a building into direct current (DC) to charge the vehicle battery. Bidirectional power flow capacity can reverse this process, allowing stored energy in the EV battery to be converted back to AC and supplied to a home, building, grid, or other end use. While installation is like Level 2 charging, bidirectional systems require a V2B-compatible vehicle, a compatible charger, and adherence to communication standards that enable controlled two-way power flow (SEPA 2023) (Energy-Solutions 2025).

A standard Level 2 charger such as the Wallbox Pulsar Plus 48A costs approximately \$799.99 (Wallbox n.d.). By comparison, the Wallbox Quasar 2 bundle, which supports ISO 15118-compliant vehicles such as the Kia EV9, the hardware costs around \$6,440 (Edelstien 2025). GM also has its own V2H bundle that includes GM Energy Powershift Charger with the GM Energy V2H Enablement Kit for up to \$ 8,098 before taxes (GM Energy 2026). After applying, the federal 30C tax credit (30% of installation costs up to \$1,000) the incremental cost of bidirectional capability for residential systems is typically \$5,000–\$6,000 above a standard Level 2 charger.

When compared to dedicated battery backup solutions, bidirectional power flow can be cost-competitive. A whole-house battery backup system typically requires multiple units of 5 kW / 12.5 kWh battery, pushing total system costs to \$30,000–\$50,000 including permit and inspection fees (up to \$1,600), and annual maintenance or inverter reserve costs (Ramasamy, et al. 2023). This excluding additional expenses such as electrical panel upgrades (\$2,000–\$4,000) (NV5 2022). Alternatively, a fuel-based standby generator such as a Honeywell 22 kW unit typically costs between \$10,000 and \$14,000, plus installation (PowerOutage 2025). Ongoing fuel and maintenance costs vary depending on regional energy prices and climate conditions.

By opting for a V2B setup, households can combine mobility and backup power in a single asset, potentially avoiding the capital cost of a separate backup system. In addition to resilience benefits, bidirectional systems can offer financial value when functioning as a battery storage system.

SCENARIO ANALYSIS

A comparative analysis was conducted to quantify the benefits of V2H technology for multiple peak load shifting scenarios under TOU tariffs. The analysis used DOE prototype models for single-family homes with slab foundations in two climate zones—CZ 3C (San Francisco, CA) and CZ 4A (New York) (U.S. DOE n.d.). The resultant energy consumption profiles of both the models were examined under their respective utility-specific TOU structures: Consolidated Edison (ConEd 2024) and Pacific Gas and Electric (PG&E 2025). The sensitivity analysis compared the baseline (no-load shifting) with four load shifting scenarios — whereby 25%, 50%, 75%, and 100% of peak load was supported by V2H compliant EV under TOU rates. The calculated results were evaluated based on three economic metrics: annual savings during the first year, Net Present Value (NPV), and simple payback period.

The equation calculates TOU savings as the difference between $B1_d$, the baseline daily utility cost without load shifting, and $B2_d$, the daily cost under the proposed scenario where a part of peak load is shifted to off-peak hours using V2B.

$$TOU\ Savings = \sum_{d=1}^{365} (B1_d - B2_d) \quad (1)$$

Nomenclature

$B1$ = Baseline daily utility cost without load shifting under residential TOU rate (\$)

$B2$ = Daily utility cost under V2B load-shifting scenario under the same residential TOU rate (\$)

d = Day index (1–365)

Here, the calculation for $B2_d$ follows two slightly different approaches to account for two separate TOU rating structures. In case of New York city (NYC), it is calculated as the sum of the shifted peak load priced at the off-peak TOU rate, the remaining peak load priced at the peak TOU rate, and the baseline off-peak cost. For San Francisco (SF), $B2_d$ is calculated similarly, with the addition of a baseline credit applicable to the given PG&E territory. In addition, the analysis also accounted for differential peak and off-peak pricing rates to evaluate the economic impact of load shifting under varying consumption during two seasons, summer (June 1 to September 30) & winter (October 1 to May 31).

Further, for NPV & payback period calculations, the study accounted for upfront cost of V2B EVSE (CAPEX) of \$8098 (GM 2026), annual maintenance (O&M) of \$50/yr, a 3% discount rate, and 2.5% annual battery degradation (EPRI 2023), which was analyzed over a 10-year period. Further, annual rate escalation factor for both the utilities was considered as 3%. Supplementary assumptions for the V2H system include a maximum EVSE discharge power of 9.6 kW (GM 2025), EV battery round-trip efficiency (η) of 85% (Iwafune and Kawai 2024), and battery capacity of 75 kWh (Nissan Leaf 2026).

RESULTS

The economic viability of integrating the V2B system under TOU tariffs, estimated from the above sensitivity analysis across different load-shifting scenarios, are summarized as follows. The Table 1 below shows the results of above analysis in case of New York city under Con Edison's residential customer rate (Con Edison n.d.) schedule.

Table 1. Comparison of V2B Load Shifting Scenarios under TOU Rates from ConEd in NY

Metrics	Scenario-1 (25%)	Scenario-2 (50%)	Scenario-3 (75%)	Scenario-4 (100%)
Annual Savings \$	\$393.18	\$786.36	\$1,179.55	\$1,572.73
10-yr NPV \$	-\$4,592.69	-\$660.87	\$3,270.96	\$7,202.78
Payback (yrs)	23.6 yrs	11.0 yrs	7.2 yrs	5.3 yrs

Similarly, Table 2 presents the economic impacts of using V2B system in SF's PG&E territory under the TOU rate schedule E-TOU-C .

Table 2. Comparison of V2B Load Shifting Scenarios under TOU Rates from PG&E in CA

Metrics	Scenario-1 (25%)	Scenario-2 (50%)	Scenario-3 (75%)	Scenario-4 (100%)
Annual Savings \$	\$62.13	\$124.26	\$186.39	\$248.52
10-yr NPV \$	-\$7,903.20	-\$7,281.89	-\$6,660.59	-\$6,039.28
Payback (yrs)	667.6 yrs	109.0 yrs	59.4 yrs	40.8 yrs

Results from Table 1 indicate that annual TOU cost savings increase progressively as the proportion of peak load shifted, while the payback period decreases correspondingly. For the NY (ConEd) case, the 10-year NPV transitions from negative in Scenarios 1 and 2 (25% and 50% shift) to strongly positive in Scenarios 3 and 4 (75% and 100% shift), suggests that shifting more than 50% of peak-hour load is the financial viability threshold for V2B adoption under ConEd's rate structure.

In contrast, Table 2 shows that while the CA (PG&E) case yields consistent incremental savings as off-peak shifting increases, the payback period under full 100% load shifting still exceeds twice the average EV battery lifespan of 10-20 years. The 10-year NPV remains negative across all scenarios, indicating that V2B is not financially feasible under PG&E's standard residential TOU rate.

The divergence between the two cases is primarily attributable to two structural rate differences. First, ConEd's peak window spans 16 hours (8 AM-12 AM), compared to PG&E's 5-hour peak window (4-9 PM), meaning the NY building accumulates significantly more shiftable peak load daily. Second, the rate difference between peak and off-peak is wider under ConEd, maximizing the per-kWh savings from each unit of load shifted. PG&E's comparatively narrow rate spread limits the economic benefit of V2B, regardless of shift fraction, making the \$8,098 CAPEX difficult to justify over a 10-year horizon.

DISCUSSION

Overall, the comparative analysis across both regions demonstrates that TOU rate structures create financial incentives for load shifting. Bidirectional EV systems allow households to charge vehicles during lower-cost off-peak hours and discharge stored energy during high-cost peak periods, thereby reducing total annual electricity expenditures. Although, the savings depend on the peak-to-off-peak price differential and the percentage of load that can be shifted. However, these findings indicate that integrating V2B technology with TOU rate plans can provide meaningful economic benefits to residential customers and help off-set incremental first costs associated with bidirectional infrastructure. The nature of TOU rates reflecting utilities distribution and generation constraints would imply that this use also benefits electric grid operators.

The methodology is a simplified, high-level analysis intended to inform V2B policy development and assess economic viability for both customers and utilities. The study is limited to a PNNL DOE prototype building. The analysis assumes full EV availability during all on-peak hours and does not account for stochastic availability driven by commute patterns or state-of-charge variability. The NPV framework accounts for utility rate escalation & discount rate, however it does not account for the degradation rate. Since even after linear degradation at 2.5% per year (EPRI 2023), the battery retains approximately 58.22 kWh of usable capacity by year 10, sufficient to cover the maximum daily peak load of ~57 kWh in the ConEd territory. Given the evolving nature of the technology, data on costs, technical specification, and warranties for V2B-compliant vehicles and charging systems remain limited. Since the existing TOU rates are not specifically designed for VBH applications, the most appropriate available rate structures were used.

While the NPV analysis for CA was negative, there are additional potential benefits to the building resident and vehicle owner through V2H functionality, including backup power operation to the building during planned or unplanned grid disruption, that are not factored into the analysis and may influence decision-making around whether to pursue V2H.

Where bidirectional EVs are being integrated into state and local programs in support of clean energy goals, care should be taken to understand the full lifecycle carbon performance of EVs functioning interactively with the grid. Lifecycle assessment (LCA) is the predominant method used to compare the emissions profiles of EVs and ICEVs; however, methodologies and system boundaries vary widely across studies. Most LCAs are limited to resource extraction, vehicle and battery manufacturing, vehicle operation, and end-of-life disposal, and typically exclude ancillary vehicle uses such as vehicle-to-everything (V2X) applications and their potential emissions benefits (Nealer & Hendrickson, 2015). Incorporating V2X benefits into LCA frameworks is further complicated by the relative technological immaturity of V2X systems and the lack of standardized definitions, performance metrics, and use cases. Additional research is needed to clarify and quantify full lifecycle carbon benefits of bidirectional EVs, including the potential for reduced operational lifespan.

Bidirectional EVs have demonstrable benefits to both building owners and utility electric grid operators, but their needs and priorities differ. For example, utilities may rely on bidirectional EV storage capacity to reduce grid stress during extreme weather or other grid management events, while homeowners or vehicle owners may be relying on the storage capacity anticipating a grid outage during the same event. Understanding these conflicts and resolving them through effective program design and rate structures will be key to effective deployment and use. Additionally, current TOU and DR rate structures are typically structured around utilities transmission and generation needs, which may or may not be aligned with generation emissions profiles in a way that reliably reduces emissions. Given this, buildings looking to use bidirectional vehicle capability and other load management strategies to reduce operational emissions would need to evaluate local or regional grid emissions profiles to align their usage with low emissions generation periods.

CONCLUSIONS AND RECOMMENDATIONS

While these technologies and applications may be nascent, there is a clear recognition of the potential value of bidirectional vehicle capability as a building energy management strategy and as a grid resilience and reliability strategy helping to control direct energy costs, power buildings during grid disruption, and reduce energy system maintenance and upgrade costs. This is already being recognized through state-, local-, and utility-level pilot and demonstration programs providing incentives for deployment to study and better understand the operational benefits.

Considering upcoming extensive investments in EVs and EV infrastructure, directing government and utility spending towards bidirectional capability is a clear strategy to align building and transportation decarbonization, while providing benefits to vehicle owner, building owners, and electric utility stakeholders. Continuing to develop standards around bidirectional vehicle technology and integrating their requirements and compliance pathways in energy codes can help scale adoption and extend grid and customer facing energy benefits. Manufacturers, utilities, and jurisdictions should clearly communicate the full financial value of V2X systems, spanning backup power savings, peak demand reduction, and grid services participation, while educating customers on optimizing bidirectional power flow for maximum benefit.

Given the limited nature of this study, more research should be conducted evaluating additional utility grid regions with time and demand-based rate structures and comparing real-world building usage profiles under standard, TOU, and demand-based rate structures. Capturing additional value streams such as energy resilience, emergency generator replacement, and utility DR compensation would reframe V2B as a strategic energy asset and accelerate broader adoption.

More research is needed to evaluate load management as a strategy for reducing operational emissions. Currently available TOU rate structures, DR signals, and load management programs are not structured for grid emissions reductions or around low emissions generation periods. As utilities with renewable portfolio standards turn to load management as an emissions reduction strategy there will be a need for emissions-based signals to realize decarbonization benefits.

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