V2X Round-Trip Efficiency Market Study

Final Report

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Source: (Toyota n.d.)

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Executive Summary

This report outlines the findings for a market study of bidirectional charging technology, also known as vehicle-to-everything (V2X). V2X is an emerging technology that enables electric vehicles to both draw and export power, transforming them into flexible distributed energy resources. The penetration of bidirectional EVs is forecasted to grow at a rapid rate in accordance with statewide electrification and decarbonization goals. An Electric Power Research Institute forecast estimates nearly 10.5 million bidirectional electric vehicles will be deployed by 2035, with 100 percent of them being able to provide energy resiliency services and 70 percent of them able to deliver grid services (EPRI 2023). Since electric vehicles can be a significant burden on electrical infrastructure, it is critical to understand the energy losses associated with bidirectional operation under real world conditions—which are higher than unidirectional operation due to the additional energy export stage.

This study investigated the commercial readiness of existing and emerging V2X use-cases, as well as industry standards for efficiency and classification. Like stationary energy storage systems, system round-trip efficiency—which includes both inverter and battery losses—was identified to be a key efficiency performance metric for V2X stationary use-cases. Unlike energy storage systems, no consolidated frameworks exist to support uniform measurement and evaluation of energy efficiency metrics (such as system round-trip efficiency) of V2X systems in stationary use cases. The team provided recommendations to address this gap, as well as others we identified during this study.

The key factors that had the most significant implications for V2X round-trip efficiency were power level and ambient temperature. State of charge had lower impacts and may not be a suitable parameter to target for energy efficiency improvements due to its influence on electric vehicle range and battery degradation. The V2X use-cases that had the highest traction across market segments were resilience (i.e., back-up power), load shifting, and peak shaving. Other emerging use-cases, such as frequency regulation, are still subject to barriers like interoperability and battery degradation concerns.

Despite limited existing research on the energy efficiency benefits of V2X smart charging and energy management, the team was able to estimate the impacts of some energy-efficiency-aware smart charging strategies. The results for three of these strategies are detailed below:

- One approach, which accounted for conversion efficiency of the charging infrastructure, provided conservative incremental energy loss reduction benefits of up to 1.68 kilowatt-hours per charging session for a simulated commercial fleet of 100 electric vehicles.
- Another strategy targeted minimization of round-trip energy losses and yielded 0.274 kilowatt hours per electric vehicle over the course of an eight-hour, simulated frequency regulation event involving 10 electric vehicles.
- Standby energy losses were estimated to be approximately 219 kilowatt hours per year for a single EV-EVSE system according to conservative assumptions. This could be addressed with emerging forms of sleep-state control for the charging infrastructure during periods of low utilization.

The incremental energy loss reduction benefit offered by optimized forms of V2X smart charging and energy management is a promising area of research; it should be investigated rigorously in future efforts to facilitate the integration of V2X technology into the existing landscape of energy efficiency and load flexibility incentive programs.

This report assessed the status of technology by conducting secondary research on existing literature and commercially available V2X products, such as electric vehicles and electric vehicle supply equipment. The research was supplemented by findings from V2X stakeholder engagement, and market outreach demographics included V2X stakeholders, such as electric vehicles and electric vehicle supply equipment manufacturers; standards bodies; and industry working groups.

Abbreviations and Acronyms

Acronym	Meaning
AC	Alternating current
AI	Artificial intelligence
AMI	Advanced metering infrastructure
Ah	Ampere-hour
BESS	Battery energy storage system
BEV	Battery electric vehicle
BTM	Behind the meter
CEC	California Energy Commission
CJEST	Climate and Economic Justice Screening Tool
C&I	Commercial and industrial
DAC	Disadvantaged community
DC	Direct current
DER	Distributed energy resource
DoD	Depth of discharge
DR	Demand response
EMS	Energy management system
EPRI	Electric Power Research Institute
EV	Electric vehicle
EVSE	Electric vehicle supply equipment
GWh	Gigawatt hour
HEMS	Home energy management system
HESS	Home energy storage system
HTR	Hard-to-reach
IOU	Investor-owned utility
IEEE	Institute of Electrical and Electronics Engineers
ISO	Independent system operator
kW	Kilowatt
kWh	Kilowatt hour
LBNL	Lawrence Berkeley National Laboratory
LP	Linear programming
LPC	Low power charging
MW	Megawatt
NEM	Net energy metering

NREL	National Renewable Energy Laboratory
OEM	Original equipment manufacturer
OCPP	Open Charge Point Protocol
PEV	Plug-in electric vehicle
PCC	Point of common connection
PNNL	Pacific Northwest National Laboratory
PV	Photovoltaic
TOU	Time-of-use
SoC	State of charge
SoH	State of health
RTE	Round-trip efficiency
SAE	Society of Automotive Engineers
SPI	System performance index
SGIP	Self-Generation Incentive Program
VPP	Virtual power plant
VGI	Vehicle-grid integration
V2X	Vehicle-to-everything
V2G	Vehicle-to-grid
V2H	Vehicle-to-home
V2L	Vehicle-to-load
V2V	Vehicle-to-vehicle

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Introduction

Bidirectional electric vehicle (EV) charging—also known as vehicle-to-everything (V2X)—is an emerging electrification technology that enables power to flow in both directions to and from an EV. This technology is gaining traction in markets like California, where high EV adoption and supportive regulatory framework are accelerating deployment. Key policies driving this growth include the Zero Emission Vehicle mandate (DOE 2025), which promotes the sale of zero-emission vehicles, and the Low Carbon Fuel Standard (P. Kumar et al. 2025), which incentivizes low-carbon energy sources. Unlike unidirectional EVs, which only draw power from an external source to charge the vehicle, V2X-enabled EVs can export power back to the grid (vehicle-to-grid, or V2G), to a facility (vehicle-to-building, or V2B), or to residence (vehicle-to-home, or V2H) via a bidirectional inverter. V2X technology represents the next stage of vehicle-grid integration (VGI) and marks a critical milestone in the broader electrification movement. It offers significant potential to enhance grid flexibility, supports renewable energy integration, and improves resilience across commercial and residential sectors.

Previous research on V2X technology has primarily focused on validating its basic functionality, often through the verification of grid interactivity in simulated environments or smaller scale pilots and field demonstrations. While current efforts highlight the technical feasibility and potential benefits of V2X technology, its full value proposition remains uncertain. To unlock its wider impact, it requires further validation through more real-world implementation and comprehensive performance data across diverse use cases and operating conditions.

Gaps in key research areas may limit a full understanding of energy and economic benefits of V2X technology for EV owners, utilities, and aggregators. For example, the lack of empirical data on round-trip energy losses across different V2X use cases—especially under realistic operating conditions—can lead to inaccurate feasibility modeling and undervaluation of the energy efficiency gains. This is particularly relevant for assessing the performance of various forms of optimized V2X smart charging and energy management strategies.

The absence of minimum efficiency requirements and standardized methods for uniformly evaluating V2X system performance may hinder the inclusion of high-performing products in established energy efficiency programs such as ENERGY STAR®. This gap also risks undervaluing any research and development (R&D) efforts that prioritize energy efficient product design in parallel with core functional capabilities. Without standardized metrics, the industry lacks a clear pathway to demonstrate the efficiency benefits of V2X technologies, potentially slowing innovation and market recognition.

This market study aims to assess existing opportunities and barriers to V2X adoption through a combination of secondary literature research and V2X stakeholder engagement. Additional objectives are as follows:

- Assess commercial readiness of high-value stationary V2X use cases and value streams.
- Establish clear nomenclature on V2X technical requirements, classification, and efficiency definitions.

- Quantify potential energy efficiency impacts of optimized V2X smart charging and energy management strategies.
- Outline operational considerations and key factors that influence energy efficiency in V2X deployments.
- Provide actionable recommendations that facilitate the following outcomes:
    - Integration of V2X technology into the existing energy efficiency and load flexibility program landscape.
    - Standardization of efficiency metrics for stationary V2X implementation scenarios.
    - Equitable V2X adoption in hard-to-reach (HTR) and disadvantaged communities (DAC).
    - Development of minimum efficiency recommendations to ensure proliferation of high-performing V2X products.

The findings from this study will inform future V2X research initiatives, guide the establishment of minimum efficiency standards, and promote greater awareness and integration of V2X technologies within existing energy efficiency and load flexibility frameworks.

Background

V2X technology is well-positioned to integrate into California's grid-interactive distributed energy resource (DER) ecosystem, supporting the state's medium- and long-term goals for electrification, load shifting, and decarbonization. Through bidirectional operation, EVs can function as flexible behind-the-meter (BTM) assets—serving both as dispatchable loads and distributed energy storage systems. Unlike internal combustion engine vehicles, EVs can interact with the grid on a scheduled or real-time basis by adjusting charging and discharging behavior in response to economic (e.g., $/kWh) and/or grid load signals (e.g., curtail charging power by 30 percent during a demand response event).

This grid-interactive capability allows EVs to participate in existing DER energy (measured in kilowatt-hours, or kWh) and capacity (measured in kilowatts, or kW) markets via third-party DER aggregators and/or virtual power plant (VPP) service providers. This allows EV owners to access novel revenue streams that reduce their total cost of ownership while simultaneously providing additional economic and reliability benefits to other V2X stakeholders. Thus, there is a compelling narrative for the overall value proposition of EV adoption.

Similar to stationary battery energy storage systems (BESS), bidirectional EVs can support use-cases such as peak shaving, load shifting, renewable energy storage, and ancillary services like voltage and frequency regulation. They can also be deployed as a resilience asset through the provision of backup power during grid outages or extreme weather events (such as wildfires), which continue to challenge California's grid infrastructure.

Due to their functional similarities with stationary BESS, V2X systems are well-positioned to leverage established interconnection and permitting frameworks—such as California Rule 21 for grid-tied DERs—offering a strong foundation for their integration into existing grid infrastructure. However, despite this key enabler, several barriers continue to impede widespread V2X deployment. Competitive pressures to establish early market dominance have led to fragmented product ecosystems and interoperability challenges. Additionally, concerns over accelerated battery degradation from bidirectional cycling remain a significant obstacle to broader adoption.

A critical yet underexplored aspect of bidirectional V2X operation is the energy loss associated with the discharge phase, which introduces a second stage of power conversion. An empirical study that simulated V2G operation in a laboratory environment measured round-trip efficiency (RTE) values ranging from 53 percent to 62 percent, which is substantially lower than the commonly assumed 80 percent to 85 percent (E. Apostolaki-Iosifidou et al. 2017).[1] These losses vary significantly based on system architecture (e.g., on-board versus off-board converters) and operational conditions (e.g., full- vs. partial-load scenarios). Minimizing these losses across the full charge-discharge cycle—including power rectification from alternating current (AC) to direct current (DC) and DC/DC conversion—is essential to realizing the full energy and economic potential of V2X on a broader scale. This challenge underscores the need for novel V2X smart charging and energy management strategies that can deliver additional energy efficiency benefits.

A similar gap that can adversely impact adoption is the absence of standardized protocols and methodologies for uniformly evaluating and comparing efficiency across similar V2X configurations. The lack of such methodologies creates uncertainty for stakeholders and limits the development of minimum efficiency requirements, eligibility criteria for enrollment in future V2X pilots, and more. Industry-wide collaboration is needed to establish consistent efficiency metrics to enable transparent performance benchmarking and support the integration of V2X technologies into energy efficiency programs, like ENERGY STAR, and load flexibility programs, such as Pacific Gas & Electric's (PG&E) Measured Savings for Summer Reliability program.

The market adoption of EVs continues to accelerate, with an EPRI study forecasting nearly 1.5 million V2X capable EVs deployed or sold in California by 2035 (EPRI 2023), as seen in Figure 1 below.

[1] The EVs utilized in the study were prototypes that were modified to support bidirectional operation.

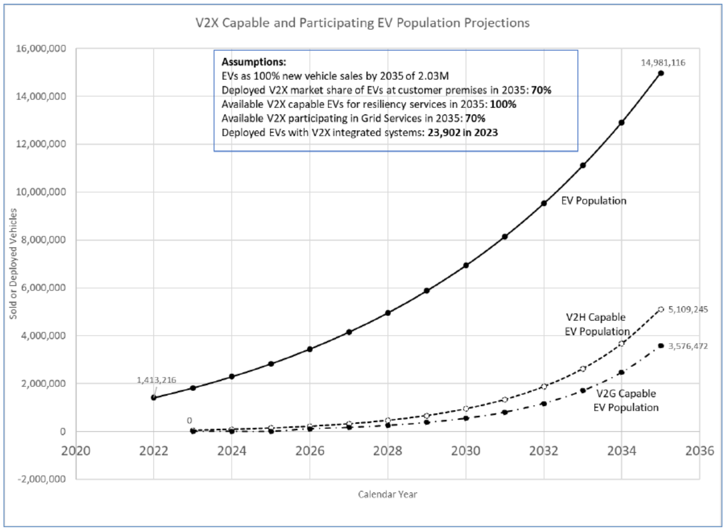

Figure 1: V2X technology acceleration forecast.

Source: (EPRI 2023)

Unchecked load additions without parallel implementation of energy efficiency strategies can have significant impacts on grid system and distribution feeder-level peaks, potentially leading to adverse reliability and carbon emission outcomes.

Currently, there are limited field demonstrations that assess the energy performance impacts of high efficiency control strategies—including energy-efficiency-aware dispatch algorithms and smart coordination schemes—tailored to electric vehicles enrolled in utility incentive programs. However, demonstrations in research settings show potential for scaling and eventual integration into existing energy efficiency program offerings. One field study demonstrated a smart dispatch control algorithm to reduce energy losses by 8.5 percent (E. Apostolaki-Iosifidou et al. 2017) under laboratory conditions over the course of a simulated V2G event relative to a naïve dispatch scenario. If this energy loss reduction were realized at scale, it could offset up to 3,740 gigawatt-hours (GWh) of energy consumption from electric transportation growth based on a California Energy Commission (CEC 2023) forecast that predicts electricity consumption from transportation in the state may increase 44,000 GWh over the next decade.

Classification of V2X

This section describes the various V2X implementation scenarios seen in the current market.

Vehicle-to-Everything (V2X)

As mentioned earlier, V2X technology refers to the general bidirectional capability of an EV to discharge power for purposes other than mobility. Bidirectional charging can be further categorized into non-exporting and exporting applications.

NON-EXPORTING BIDIRECTIONAL CHARGING

Non-exporting bidirectional charging involves electric vehicles providing power to on-site loads without exporting electricity back to the grid. This encompasses applications such as vehicle-to-load (V2L) and islanded V2B, where the EV acts as a backup or off-grid power source for appliances, critical equipment, or entire buildings. These systems are particularly valuable during grid outages, off-grid scenarios, or for managing BTM load during peak times without regulatory complexities typically associated with grid export. They avoid complex utility interconnection requirements and export compensation issues, thus streamlining implementation.

EXPORTING BIDIRECTIONAL CHARGING

Exporting bidirectional charging allows electric vehicles to inject power directly into the utility grid (V2G) or grid-connected loads. These systems can support grid services such as demand response (DR), load balancing, and ancillary services by returning stored energy from EV batteries back to the grid when needed. An exporting V2X system requires interconnection approval from the local utility or regional grid operator and is often subject to permitting and metering requirements, especially in California and other states with defined DER interconnection rules. The key V2X charging system configurations for exporting and non-exporting scenarios are depicted in Figure 2 below.

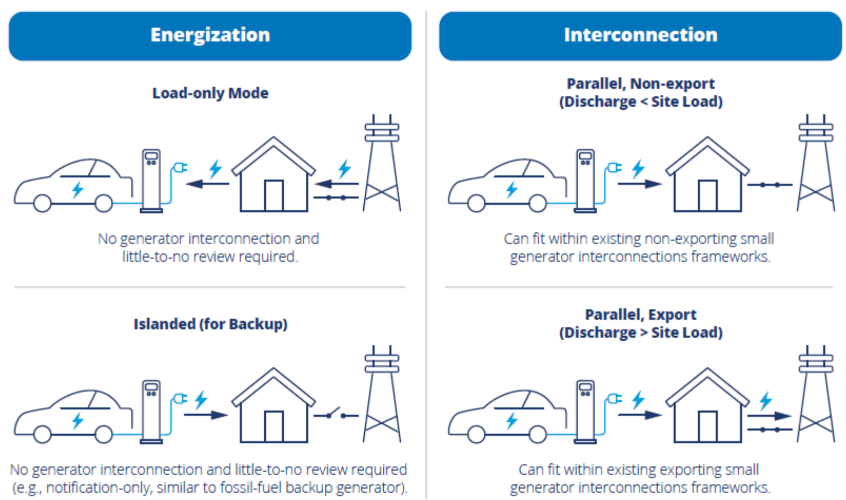

Figure 2: Common V2X charging system configurations for export and non-export.

Source: (Vehicle Grid Integration Council (VGIC) 2022)

Industry collaboratives such as the Vehicle-Grid Integration Council (VGIC) recommend characterizing V2X systems based on the energization and interconnection charging system configurations proposed above. Classifying V2X systems based on their level of grid integration—parallel, non-export, load-only, etc.— and export behavior provides a foundation for standardized evaluation. While terms such as V2H and V2G may be beneficial from a marketing standpoint, they may misrepresent the actual capabilities of the V2X system itself. A more well-defined grouping supports clearer communication and better policy development.

The actual use cases and supported functionalities of a V2X system are solely a function of its level of grid integration. For example, while V2H systems are typically not export-capable at current levels of technological readiness, they may support this functionality in the future as the technology advances.

The architecture of a V2X system can also have important implications for efficiency and standardization. Drawing from established classifications used in stationary BESS, V2X architectures may be further categorized into AC-V2X, DC-V2X, and hybrid V2X systems (Langdon 2025). An overview of these V2X system architectures is presented in Appendix B: V2X System Architectures.

Vehicle-to-Grid (V2G)

V2G functionality typically refers to the capability of a plug-in electric vehicle (PEV) to export power back to the grid in addition to managing its connected load. V2G also allows for participation in wholesale energy markets (day-ahead and/or intraday). While grid energy export is the primary attribute of V2G systems, they may support other use cases that are like those delivered by BESS such as frequency regulation services and renewable energy integration. This requires coordination between various V2G stakeholders—the EV owner, an electric charging station operator, utility aggregator, etc.—as well as the ability of the independent system operator (ISO) to recognize the individual electric vehicle or aggregated set of electric vehicles as grid resources. Grid services have historically been provided by large, synchronous generators. However, technological and market innovations are enabling DERs like V2X EVs to provide some of these grid services in a cost-effective manner.

Vehicle-to-Home/Building (V2H/V2B)

V2H/V2B applications involve EVs supplying power to residential or commercial buildings. This system typically discharges power to facility and home circuits under islanded or grid parallel operation. Residential buildings (V2H) tend to focus more on backup power, while commercial buildings (V2B) emphasize load shifting and peak shaving to benefit from time-of-use tariffs and demand-charge avoidance. V2H may also be implemented with a smart load panel to prioritize critical loads and enable more granular customization of customer preferences. Figure 3 provides a schematic representation of a V2H system in a grid-parallel non-exporting configuration that serves on-site loads.

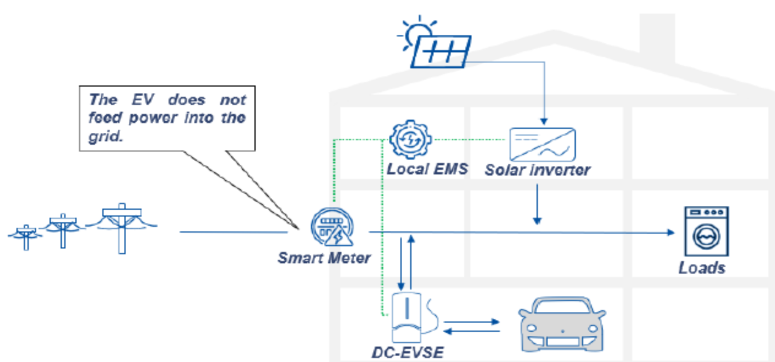

Figure 3: Schematic of grid-parallel non-exporting V2H system.

Source: (CharIN 2023)

Vehicle-to-Microgrid (V2M)

In V2M applications, an EV interfaces with localized grid systems, such as microgrids. The infrastructure typically includes renewable energy sources, energy storage systems, and advanced metering infrastructure (AMI). In V2M deployments, EVs are typically used to enhance renewable self-consumption and provide energy resilience via backup power supply during islanded operation. A schematic representation of a V2M system is depicted in Figure 4 below.

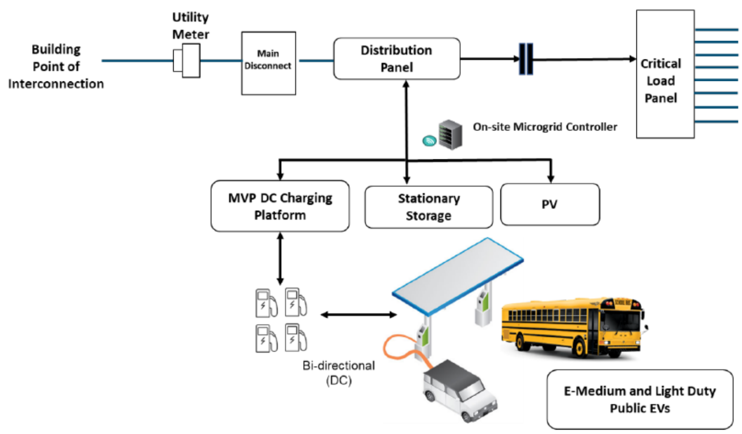

Figure 4: Schematic of V2M.

Source: (EPRI 2023)

Vehicle-to-Load (V2L)

This application involves using EVs as mobile power sources such as power tools or camping equipment, particularly for remote locations where grid power is unavailable.

Vehicle-to-Vehicle (V2V)

In V2V, one EV can charge another, which is particularly useful in emergency situations or when conventional charging infrastructure is unavailable.

Technical Description

V2X Requirements

The implementation of V2X can have several key hardware, software, and infrastructure prerequisites that depend on the application, system architecture, and overall sophistication of the equipment. While some V2X deployments may be non-standard and require additional specialization, the team determined the following list of prerequisites to be comprehensive for the most well-represented V2X configurations and use cases, which will be expanded upon in further sections.

Bidirectional EV

A bidirectional-capable EV is the foundational element for enabling V2X. Some EVs include an on-board inverter that allows charging from an AC source, using standards like SAE J1772. However, not all models have this feature. In such cases, charging is enabled by a DC power source, with the necessary power conversion handled externally by an off-board inverter. An example of a typical bidirectional charging system that can serve both DC and AC loads is indicated in Figure 5 below.

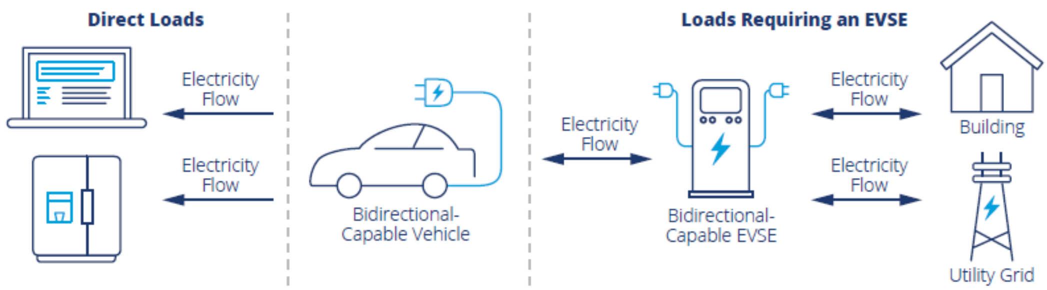

Figure 5: Schematic of bidirectional charging system.

Source: (SEPA 2023)

Bidirectional Electric Vehicle Supply Equipment

The electric vehicle supply equipment (EVSE) charging infrastructure acts as the interface between the EV and the grid or other external loads. It serves as a communication node with embedded software that coordinates and responds to grid and/or economic signals via a communication protocol, such as Open Charge Point Protocol (OCPP). Bidirectional inverter technologies used in power conversion stages (e.g., AC–DC, DC–DC) may be grid-forming and/or grid-following—referring respectively to the ability to operate as an independent voltage source or to synchronize with the grid supply. A prototypical V2X charger process flow diagram is indicated in Figure 6 below.

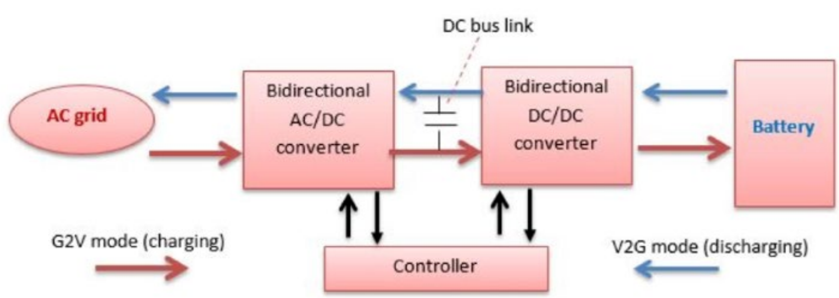

Figure 6: Prototypical bidirectional charger topology.

Source: (Al Attar 2021)

An EVSE is also classified based on the power level of the charging that it supplies; the charging infrastructure could be level 1, level 2 or level 3. Level 1 EVSE operates at 120V and delivers 1.3 kW to 1.9 kW, offering slow charging suitable for overnight residential use. Level 2 uses 208 V to 240V and provides 3.3 kW to 19.2 kW, enabling faster charging at homes, workplaces, and public stations. Level 3 (DC fast charging) ranges from 50 kW to 350+ kW at 400 V to 900V DC, ideal for rapid charging in commercial and highway settings.

Transfer Switch/Grid Isolation Device

A manual or automatic transfer switch governs the safe transition between utility service and EV-provided power. It ensures electrical isolation during outages and prevents back feeding to the grid, which is a key requirement per the Institute of Electrical and Electronics Engineers (IEEE) 1547 interconnection standard for DERs. These switches may either energize an entire home or facility (whole-house or facility backup) or route power only to a critical load panel. This component is needed to facilitate grid isolated operation and is indicated in Figure 7 below.

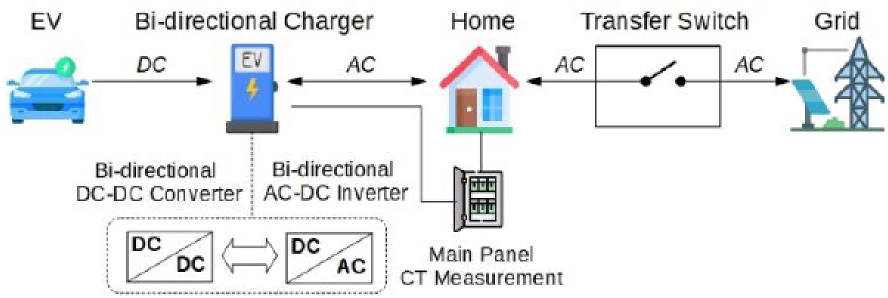

Figure 7: Diagram of a V2H system with transfer switch.

Source: (Saxena, Shivam & Farag, Hany & Nasr, Khunsha & Hilaire, Leigh. 2023)

Controller

A controller is a key component that enables optimal dispatch coordination commands from a utility aggregator or local energy management system (EMS) in a V2M or V2B scenario, respectively. Figure 8 below provides a single line diagram of a microgrid controller in a V2M scenario.

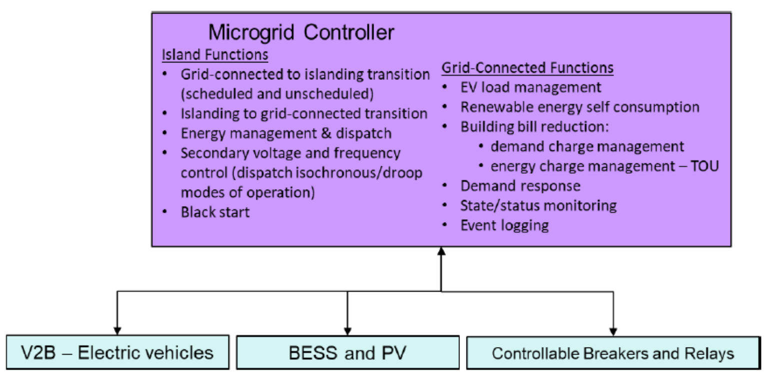

Figure 8: EV microgrid controller with V2X integration.

Source: (EPRI 2023)

The primary objective of a microgrid controller is to maintain voltage stability on the DC bus—after rectification from an off-board inverter in DC V2M architectures—while coordinating power sharing across all BTM DERs.

Smart Load Panel

A smart load panel is an advanced residential electrical panel that enables granular control over connected circuits and supports dynamic load prioritization, scheduling, and real-time reconfiguration. In V2H applications, smart load panels are used to allocate EV battery backup selectively to critical household loads, thus extending outage survivability and improving resilience outcomes.

Smart panels are especially valuable in non-exporting V2H configurations where energy delivery is constrained to essential loads during islanded operation. They integrate with home energy management systems (HEMS) and are often bundled with home backup offerings from solar and storage vendors. An example of a smart panel with a microgrid integration device (MID) and bidirectional EV is shown in Figure 9 below.

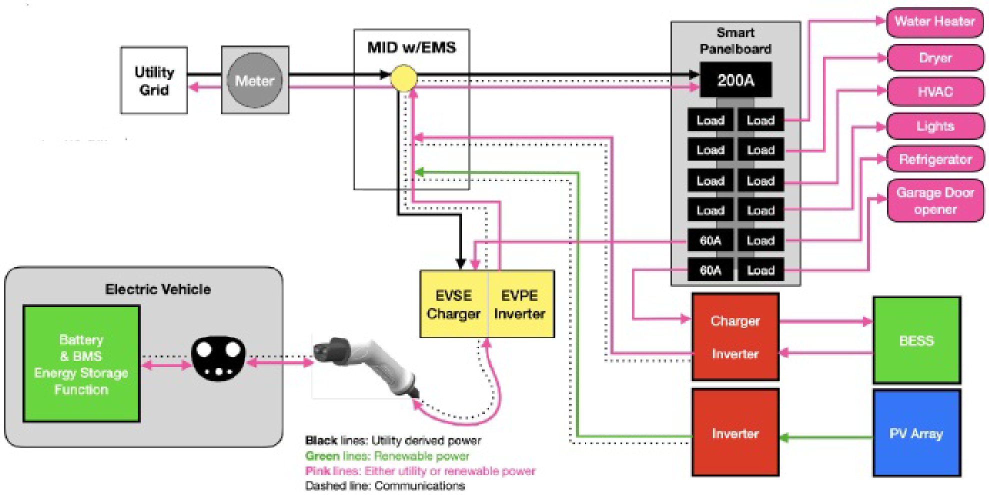

Figure 9: Smart panel integrated with bidirectional charger.

Source: (Sustainable Energy Action Committee 2024)

V2X-Compatible Aggregation Platform

Aggregation platforms serve as the digital interface between EV fleets and utilities or ISO markets. They optimize dispatch of EV energy for grid services—such as DR, frequency regulation, or time-of-use (TOU) arbitrage—by executing control strategies based on fleet availability, load forecasts, and market signals. V2X integration with an aggregation platform is typically facilitated via a gateway compliant with the California Smart Inverter Profile, which adheres to the IEEE 2030.5 standard for DER communication. A representation of an aggregator that integrates DERs through communication nodes, such as gateways, is shown in Figure 10 below.

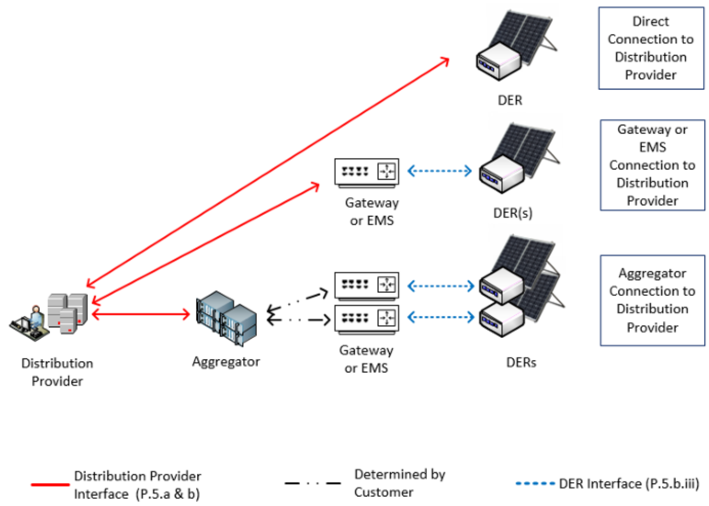

Figure 10: Schematic of aggregation platform.

Source: (Xanthus 2024)

EMS

V2H systems may also integrate with a HEMS. Similarly, a V2B system could integrate with a distributed energy resource management system or building EMS. This can enable various smart features such as power flow optimization and BTM coordination with other flexible loads. An example of the user interface of a V2X-compatible EMS that indicates real-time EV state and operating parameters is shown in Figure 11 below.

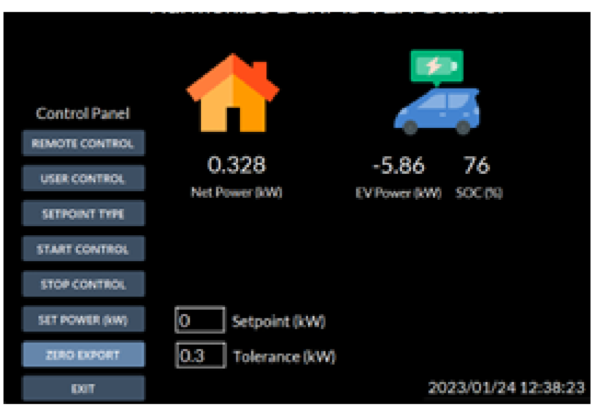

Figure 11: V2X HEMS user interface.

Source: (Saxena, Shivam & Farag, Hany & Nasr, Khunsha & Hilaire, Leigh. 2023)

Telematics

Telematics infrastructure refers to the onboard vehicle systems and external communication interfaces used to transmit real-time data, such as battery state-of-charge (SoC), availability status, GPS location, charging parameters, and power flow telemetry to authorized parties like aggregators and grid operators.   .

AMI

AMI—also referred to as smart metering—enables bidirectional, near-real-time communication between utilities and customer-side energy devices. In the context of V2X, AMI can provide sub-hourly metering data to measure net energy import and export and verify participation in DR, net energy metering (NEM), or grid services programs. It also monitors power quality and enables time-variant compensation under TOU or dynamic rates. Figure 12 below depicts the smart meter location between BTM loads and the grid.

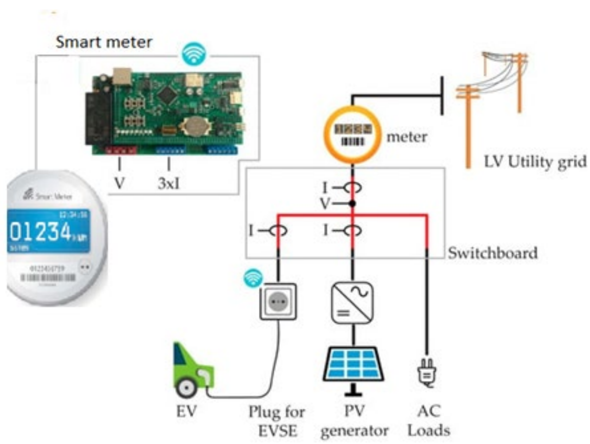

Figure 12: AMI configuration with V2X.

Source: (Newark n.d.)

V2X Efficiency Definitions

This section contains the key efficiency definitions typically used to characterize the performance of different stages of bidirectional energy transfer and storage. For more comprehensive information on supplemental efficiency definitions, please see Appendix J.

Charging Efficiency

Charging efficiency is the unidirectional conversion efficiency of the EV battery charging process, which refers to the proportion of electrical energy drawn from the grid or other external power sources that is successfully stored in the EV's battery pack during the charging phase of a V2X cycle. It is a critical component of system RTE, as losses during the charging phase can substantially affect the total usable energy available for reverse power export, such as V2G and V2H. Charging efficiency can be expressed formulaically as:

$$\eta_{Charging} = \frac{E_{DC\ Bus,in}}{E_{AC,Input}} \times 100\%$$

Where:

- $E_{DC\ Bus,in}$: Electrical energy (in kWh) measured immediately prior to storage within the EV battery.
- $E_{AC,input}$: Electrical energy (in kWh) supplied to the EVSE from the grid or generation source.

The system boundary for charging efficiency typically follows a grid-to-busbar reporting convention, where the input is measured at the point of common connection (PCC) between the load(s)—i.e., home, facility, etc.—and the utility or alternative energy source. The output is measured at the DC bus of the battery pack, after AC-to-DC rectification and DC-to-DC conversion.

This boundary convention encompasses losses due to power electronics and cable impedance but excludes battery-specific losses, such as internal resistance and thermal dissipation, which are instead attributed to coulombic efficiency. More information on these losses is available in Appendix J.

Discharging Efficiency

Discharging efficiency is the unidirectional discharge conversion efficiency, which refers to the proportion of electrical energy stored in an EV battery that is successfully delivered to an external load (grid, building, or device) during the discharge phase of a V2X cycle. Like charging efficiency, it is a key contributor to the overall system-level RTE. Discharging efficiency can be expressed formulaically as:

$$\eta_{Discharging} = \frac{E_{AC,Output}}{E_{DC\ Bus,out}} \times 100\%$$

Where:

- $E_{DC\ Bus,out}$: Electrical energy (in kWh) measured immediately after discharge prior to rectification.
- $E_{AC,output}$: Electrical energy (in kWh) delivered to the external load after passing through the EV power electronics and inverter.

The system boundary for discharging efficiency typically follows a busbar-to-terminal reporting convention. This boundary convention encompasses all power conversion and conditioning losses occurring between battery discharge and usable export.

Battery (DC-DC) Round-Trip Efficiency

Battery round-trip efficiency, often referred to as DC-to-DC or DC round-trip efficiency, represents the proportion of electrical energy that is recovered from the battery during discharge relative to what was initially stored during charging. This metric quantifies total DC energy throughput as perceived at the battery's input/output terminals prior to external power conditioning. It is also mathematically related to voltage efficiency and coulombic efficiency through the following relationship:

$$\eta_{battery,DC-DC} = \eta_{coulombic} \times \eta_{voltage}$$

The boundary convention for this metric is strictly internal to the EV battery and includes all electrochemical and internal conversion losses within the EV battery system. It does not account for any losses due to power inversion.

System (AC-AC) Round-Trip Efficiency

System RTE, also referred to as AC-AC or AC RTE, represents the total energy throughput efficiency of a V2X-enabled EV system when energy is drawn from the grid (or another AC source), stored in the vehicle battery, and subsequently discharged back to an external AC load (e.g., grid, building, microgrid, etc.). It encompasses all energy losses incurred between the grid PCC and the EV battery, and can be expressed formulaically as:

$$\eta_{RTE,AC} = \frac{E_{AC,output}}{E_{AC,input}} \times 100\%$$

Where:

$E_{AC,input}$: Total AC energy (in kWh) drawn from the grid during charging.

$E_{AC,output}$ Total AC energy (in kWh) delivered back to the load (grid, building, etc.) during discharging.

It can also be decomposed into the product of charging, discharging and battery RTE efficiencies, according to the formula:

$$\eta_{RTE,AC} = \eta_{charging} \times \eta_{discharging} \times \eta_{battery,DC-DC}$$

Hybrid System (DC-DC-AC) Round-Trip Efficiency

This efficiency definition is a special case of system RTE during which the EV is charged with DC power from other collocated DER generators such as photovoltaic (PV) arrays and fuel cells. This introduces an alternative DC-to-DC power conversion stage that is needed to condition the DC power received from the alternative generation source. It can be formulaically expressed as:

$$\eta_{RTE,hybrid} = \eta_{charging,DER-to-battery} \times \eta_{discharging} \times \eta_{battery,DC-DC}$$

Where:

- $\eta_{charging,DER-to-battery}$: Unidirectional charging efficiency from an alternative DER generation source (e.g. PV array)

Objectives

The purpose of the market assessment of this technology is to:

- Assess high value V2X use cases and value streams.
- Assess impacts of key V2X operational parameters, such as power level (kW) and ambient temperature on round-trip efficiency and/or other efficiency metrics.
- Assess the efficacy and readiness of smart charging and energy management strategies and/or algorithms. Quantify potential energy efficiency impacts of optimized control strategies.
- Improve market awareness and penetration of commercially available V2X products.
- Create a technical resource to be leveraged by pilot programs and existing investor-owned utility (IOU) programs for residential, commercial, and/or industrial sectors
- Provide an informative resource that facilitates the establishment of minimum efficiency requirements.
- Provide recommendations to facilitate the development of standardized frameworks for evaluating energy efficiency of V2X systems based on emerging trends and existing industry standards identified in secondary research and/or market outreach.
- Provide recommendations to ensure equitable adoption of V2X in HTR and DAC market segments.

Methodology and Approach

To achieve the above objectives, the following methodologies and approaches are proposed:

1. Conduct a detailed secondary literature review to assess the readiness and efficacy of smart charging strategies and algorithms that have implications for mitigating energy losses during normal V2X operation

2. Catalogue key commercially available V2X enabling technology into a matrix that can be leveraged as a resource by program staff and industry stakeholders to facilitate easier integration into existing programs offerings and for more optimal future program and pilot design and implementation.

3. Conduct market outreach and in-depth interviews with V2X industry partners, including but not limited to V2X subject matter experts, original equipment manufacturers (OEMs), IOU program implementation staff, standards bodies, third party aggregators, non-profit research

institutions, and other stakeholders to collect and analyze efficiency related data and assess emerging trends in V2X efficiency.

4. Report on key findings, barriers, and next steps and strategies for utility intervention to advance adoption.

V2X Stakeholder Engagement

Adequate representation from key V2X stakeholders was achieved during market outreach component of this study. The captured demographics are indicated in Table 1 below:

Table 1: Summary of interviewed V2X stakeholders.

Company/Organization	Demographic
Electric Power Research Institute (EPRI)	Non-Profit Research Institute
National Renewable Energy Laboratory (NREL)	Non-Profit Research Institute
Nuvve, Inc.	V2X Aggregator/Software Provider
California Energy Commission (CEC)	V2X Regulatory Policy Developer
Fermata Energy	EVSE OEM
Vehicle Grid Integration Coucil (VGIC)	Industry Working Group
Smart Electric Power Alliance (SEPA)	Non-Profit Research Institute
The Mobility House	V2X Aggregator/Software Provider
Nissan	EV OEM
General Motors	EV OEM
University of Delaware	Non-Profit Research Institute
Redwood Energy	V2X Implementor
Society of Automotive Engineers (SAE)	Standards Body
Bidirectional Energy	V2X Aggregator/Software Provider

The insights of these stakeholders were leveraged along with findings from secondary research to inform subsequent sections, such as Recommendations and Assessment of V2X Use Cases and Value Streams.

V2X Operational Considerations

This section outlines key operational considerations and parameters relevant to V2X systems, emphasizing those with the greatest impact on overall efficiency, performance, and reliability. The list below is informed by a review of secondary literature and engagement with V2X stakeholders. While not exhaustive, the parameters presented are deemed sufficiently comprehensive for assessing the feasibility of V2X system implementation. For each consideration, findings related to both quantitative and qualitative impacts on energy efficiency are included when available.

Battery Degradation

The economic viability of V2X is highly dependent upon the EV battery degradation behavior over its lifecycle. Bidirectional energy flow in V2X-capable EVs introduces additional stressors on the battery beyond standard mobility use. Battery degradation effects are typically characterized by calendar aging and cycle aging mechanisms, which result in adverse battery performance outcomes via capacity fade and power fade. The degree of degradation varies depending on charging patterns, thermal management strategies, and duty cycles associated with specific V2X use cases. Key factors that influence battery degradation are the total energy throughput (kWh) handled by the EV battery, as well as the ambient temperature. Further detail and findings from secondary research on these degradation mechanisms are presented in Appendix I.

State of Charge (SoC)

State of charge (SoC) refers to the current level of charge in the EV battery, expressed as a percentage of total capacity. It is generally strongly correlated with EV battery voltage and directly impacts the EV range. It is also a key control variable for the EV battery management system (BMS). The BMS will typically adjust the charging behavior to increase or decrease based on the proximity to the lower or upper SoC limit, per the OEM-recommended SoC safe window of operation specified to maximize battery health.

The impacts of SoC on RTE have been quantified from empirical measurements: A study demonstrated that system RTE fell from 84.6 percent at mid-range SoC to 83 percent and 83.7 percent at high and low SoC, respectively, for a lithium ion (Li-ion) battery chemistry under simulated V2G operation, as seen in Figure 13 below (Schram, Wouter & Brinkel, Nico & Smink, Gilbert & wijk, Thijs 2020).

This supports the best practice for charging and discharging within moderate SoC windows, if mitigation of energy losses over repeated battery cycles is a priority. However, since the SoC dictates the driving range, this is not always possible—V2X EV users typically prioritize mobility over energy efficiency. The charging environment (e.g., workplace charging, municipal fleet charging, or highway corridor fast charging) and EV type (e.g., buses, garbage trucks, passenger EVs, etc.) will have a direct impact on the accessible SoC for V2X use-cases that involve depleting the battery. For example, electric school buses have firm range requirements during certain times of the day to fulfill their basic services. However, they are readily available to leverage V2X functionality outside of those periods (early morning and early afternoon).

EV drivers customize their charging and discharging behavior to meet their specific SoC requirements. This constraint impacts an EVs ability to support grid services and must be considered when scheduling EVs to participate in coordinated dispatch events.

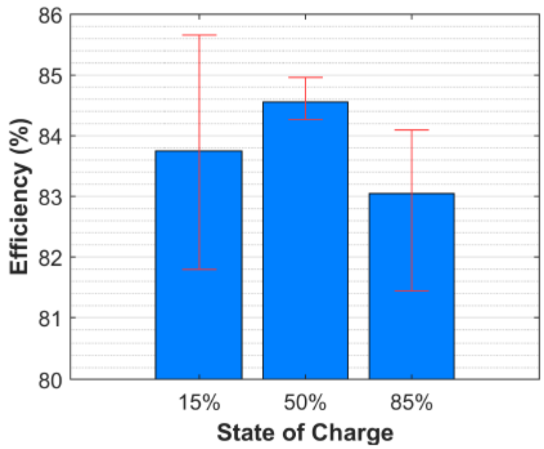

Figure 13: System RTE at different average SoCs

Source: (Schram, Wouter & Brinkel, Nico & Smink, Gilbert & wijk, Thijs 2020)

State of Health (SoH)

State of health (SoH) is a parameter that characterizes the remaining energy capacity and power capability of a battery as a percentage of its original performance capability. As SoH degrades, internal resistance rises, leading to more heat loss and lower conversion efficiency during V2X events. It must be monitored over time to capture the performance of a V2X system over its lifecycle. Therefore, it quantifies the degree of battery degradation at a given point in the life cycle. The SoH at a given time can be expressed as follows:

$$SoH_t = SoH_0 - [k \times (Number\ of\ lapsed\ charge\ cycles)] - [\alpha \times (Charge\ Rate) \times t];$$

Source: (Hari Prasad Bhupathi 2022)

Where k and α are empirical degradation coefficients.

Charging Power (kW)

Charging power determines the rate at which energy is transferred into the EV battery during the charge phase. From an operational standpoint, it determines the time needed to reach a target SoC prior to a driving event. However, it is also a key energy efficiency driver. Empirical data from an experimental V2G setup indicated a positive trend between charging power setpoint and system RTE, as seen in Figure 14 below.[2]

[2] System round-trip efficiency tests were conducted at the Smart Grid Interoperability Laboratory (JRC, Petten, Netherlands) using a controlled laboratory setup. The study evaluated V2G/V2H configurations across various charging/discharging power levels. An EV with a 40 kWh lithium-ion battery was used as the test vehicle. The charger employed was a bidirectional DC charger with integrated grid interface and control systems. Measurements included AC-to-battery and battery-to-AC conversions, accounting for losses in power electronics, cabling, and battery thermal management. The reported RTE values (~80%) reflect the combined efficiency of the EV, charger, and grid interface under steady-state conditions.

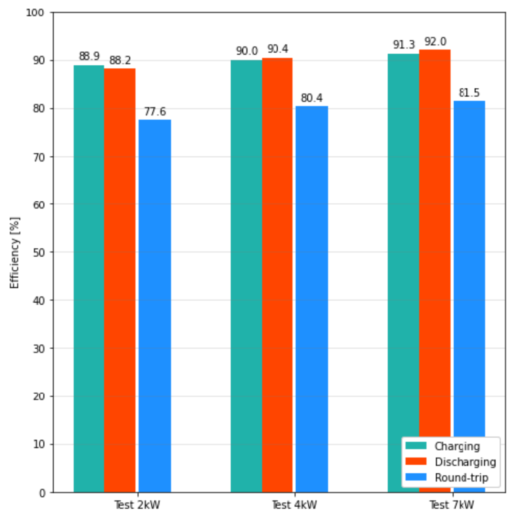

Figure 14: Empirical relationship between system RTE and charging power setpoint.

Source: (Videgain Barranco 2021)

These findings highlight the importance of maximizing operational time at the V2X system's best efficiency point, which is strongly influenced by inverter part-load efficiency. The decay of efficiency performance under part-load conditions is consistent over a wide range of operational conditions, as observed in Figure 15 below.[3]

[3] The data that corresponds to the figure was obtained from steady-state AC-to-DC efficiency results for a bidirectional EVSE under nominal test conditions that was validated for V2G capability. Testing was conducted at Idaho National Laboratory using a single-port, 50 kW-class DC bidirectional EVSE connected to an EV emulator (DC load/source) to ensure repeatable and accelerated testing across a range of voltage and current levels. The EV emulator simulated battery behavior, eliminating variability from real EV battery states. V2G-EVSE10 consists of a power cabinet with AC-DC conversion and a dispenser with communication and standardized cabling. Efficiency measurements were taken at 300 VDC across varying current levels. The EVSE operated under manufacturer default settings and was controlled via a cloud-based V2G energy management system. No real EVs or battery packs were used; instead, the emulator enabled precise control of charge/discharge conditions.

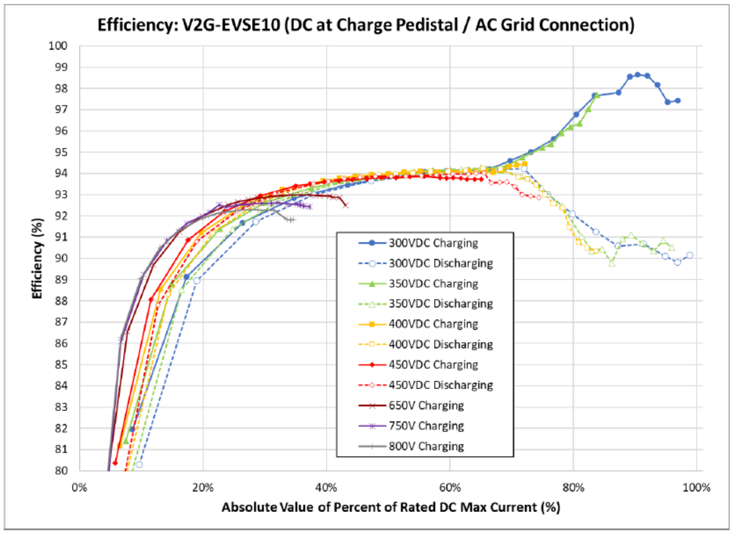

Figure 15: Charging efficiency test results for bidirectional EVSE at different power levels.

Source: (Idaho National Laboratory 2025)

Discharging Power (kW)

Discharging power determines the rate at which energy is withdrawn from the battery. There is empirical evidence that may indicate an inherent asymmetry between efficiency performance during charging versus discharging. An experimental V2G measurement indicated higher average energy loss incurred during discharging (19.23 percent) relative to charging (5.77 percent) at the same current level, as seen in Table 2 below (E. Apostolaki-Iosifidou et al. 2017). This phenomenon was observed during another performance testing event for a bidirectional EVSE, which indicated a trend of higher total average dissipated power (i.e., power loss) during charging relative to discharging at similar conditions over multiple test cycles, as seen in Figure 16 below.[4]

[4] Figure 16 illustrates the relationship between dissipated power and heat sink temperature for a bidirectional V2G charger tested under controlled thermal conditions. Each point on the graph corresponds to a charge or discharge event at a different SoC, power setpoint or supply voltage. The bidirectional charger was placed in a thermostatic chamber and operated at ambient temperatures of -20°C, 20°C, and +40°C. Only the converter was thermally conditioned, isolating its thermal behavior from battery effects. Power dissipation was measured using a double load configuration and monitored via calibrated Type K thermocouples and a GEN7tA data acquisition system. The test assumed steady-state operation at 10 kW power setpoints, with no battery pack involved. Caveats include the exclusion of battery thermal dynamics and potential deviations due to heat sink thermal inertia and ambient chamber fluctuations.

Table 2: Total grid-interactive vehicle system percentage losses: Building and EV components.

Component	AC Current (A)	Charging Losses (%)	Discharging Losses (%)
EV Battery	10	0.64	0.64
	40	1.69	1.91
EV PEU	10	6.28	16.67
	40	5.77	19.23
EVSE	10	0.1	1.42
	~40	0.29	1.39
Breakers	10	0	2.8
	~40	1.3	0.6
Transformer	10	10.2	14.6
	~40	3.33	6.65
Total	10	17.22	36.13
	40	12.38	29.78

Source: (E. Apostolaki-Iosifidou et al. 2017)

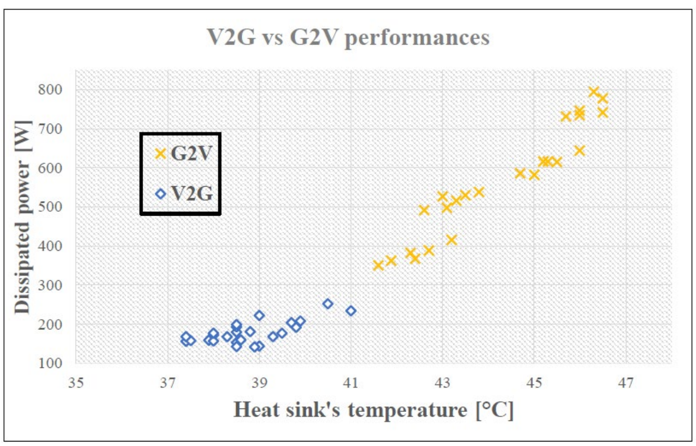

Figure 16: Dissipated power versus heat sink temperature for multiple charge and discharge test cycles.

Source: (Vero 2022)

The observed asymmetry between charging and discharging conversion efficiency during representative test cycles could be a relevant consideration to ensure feasible V2X operation for applications that involve frequent energy export.

Standby Power Consumption (kW)

Standby power consumption refers to the baseline power consumption of EVSE, inverters, and communication and control hardware when the system is online but not actively charging or discharging. Standby losses capture the cumulative kWh wasted during these inactive periods. Standby consumption diminishes overall energy efficiency by consuming energy without delivering usable output—an effect that is especially pronounced in low-utilization scenarios or long-duration V2H idle periods. Field data collected from a home EMS for V2H scenario indicated idle energy losses ranging from 92 kWh to 142 kWh annually (Y. Iwafune and T. Kawai 2024), which is equivalent to the total battery energy storage capacity of some larger commercial V2X PEVs.

Ambient Temperature (°C)

The ambient temperature surrounding the EV battery and power electronics during operation can affect both battery internal resistance and the behavior of thermal management systems, leading to round-trip energy losses under temperature extremes. Colder temperatures increase battery internal resistance losses (depending on chemistry), while hotter temperatures can cause the BMS to trigger auxiliary cooling systems to maintain safe operational temperature conditions.

Empirical measurement of system RTEs during simulated operation of a V2G system attributes a decrease from 87 percent (at 15.3°C) to 85.6 percent (at 5.5 °C) to ambient temperature effects (Schram, Wouter & Brinkel, Nico & Smink, Gilbert & wijk, Thijs 2020).

Another study closely examined the impact of ambient temperature on bidirectional charging and discharging conversion efficiency in a V2G application under varying operational conditions (Vero 2022).[5] A heatmap of the charging and discharge efficiencies at different power setpoints and ambient temperature conditions developed from the empirical data is indicated in Figure 17 below.

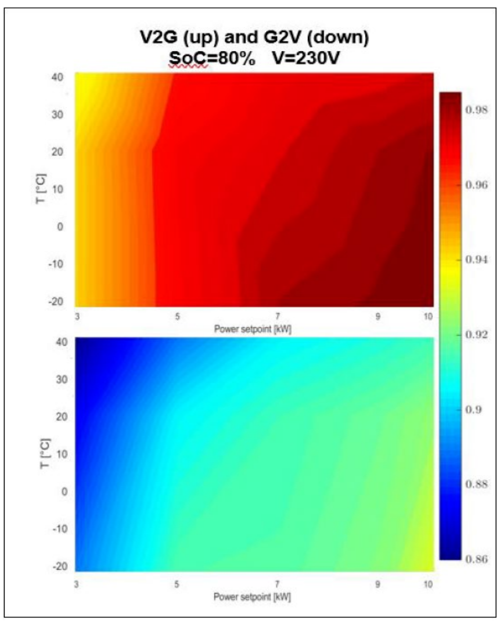

Figure 17: Heatmap of charging and discharging efficiencies at different ambient temperature and power setpoint conditions.

Source: (Vero 2022)

[5] As part of the experimental setup, the charger was decoupled from the battery for all measurements. This setup isolated the temperature effects on the converter. Conversion efficiencies for charging and discharging were measured across multiple power setpoints and AC voltages.

Visual analysis of the color gradient at a fixed power setpoint on the X-axis indicates a generally low impact from temperature on inverter conversion efficiency. This finding suggests that the primary energy losses incurred during V2X operation in cold temperatures are due to the battery internal resistance rather than power conversion in the EVSE.

Aligning EV charging and discharging windows with ambient temperature conditions that minimize battery internal resistance losses can be a viable energy efficiency strategy in more extreme climates depending on the battery chemistry.

Depth of Discharge (DoD)

Depth of discharge (DoD) refers to the percentage of battery capacity discharged during a V2X event. Shallow DoD cycles within OEM-recommended SoC limits are typically associated with higher energy efficiency and lower degradation, while deep cycles increase resistance losses and thermal buildup, reducing battery RTE via higher capacity fade.

Battery Capacity (A-h/Wh)

Battery capacity represents the total electric charge a battery can hold and is typically expressed in ampere-hours (Ah). However, the battery capacity may also be reported in Wh.

Battery Chemistry

This refers to the chemical composition of the EV battery. Each battery chemistry type has distinct thermal, cycling tolerance and efficiency characteristics. Some common types used in V2X EVs include nickel manganese cobalt, lithium iron phosphate, and nickel cobalt aluminum.

Availability

The availability refers to the degree to which a V2X system can function as a stationary DER without compromising the performance of its primary function, which is mobility. The availability is dependent on EV driver behavior and may be forecasted based on a combination of parameters such as SoC constraints, weather variables etc.

Energy Throughput (kWh)

Energy throughput refers to the cumulative energy handled across a V2X system over a charge - discharge cycle. Higher throughput can accelerate battery degradation over time and subsequently reduce battery capacity. An empirical relationship between load (kW), energy throughput (kWh) and efficiency at different SoC levels was developed based on empirical measurements as seen in Figure 18 below.[6]

[6] Figure 18 illustrates the system RTE of a V2G/V2H setup across various charging and discharging power levels, as tested at the Smart Grid Interoperability Laboratory (JRC, Petten, Netherlands). The experimental setup involved an EV with a 40 kWh lithium-ion battery and a 10 kW CHAdeMO bidirectional DC charger. The tests were conducted indoors at a stable ambient temperature of ~20°C. Charging and discharging cycles were performed sequentially, with the battery charged from 10% to 100% and discharged back to 10%, using power levels ranging from 2.3 kW to 10 kW. The graph plots RTE as a function of power level, showing a peak efficiency near mid-range power (~6.6 kW) and reduced efficiency at both low and high extremes. This trend reflects the nonlinear losses in power electronics and battery thermal behavior.

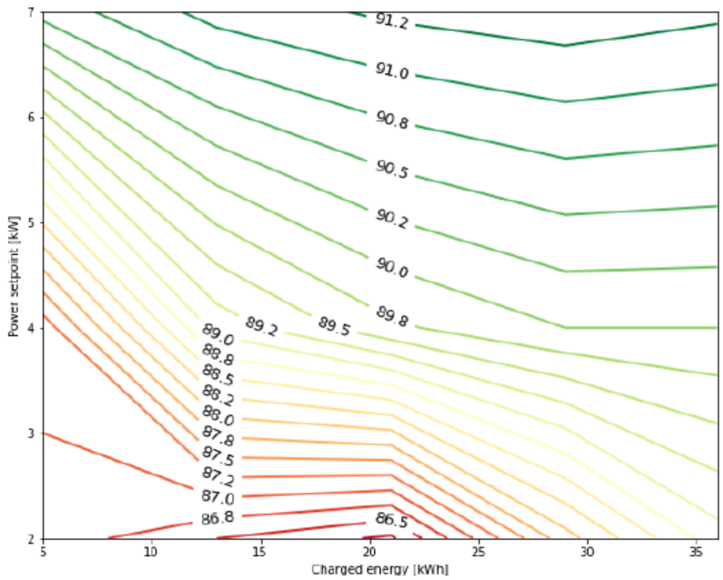

Figure 18: Charging efficiency as a function of power setpoint and charged energy.

Source: (Videgain Barranco 2021)

While the relationship between power level, charged energy and charging efficiency indicated in the above curves is specific to the experimental set-up and testing conditions, similar curves could be developed for various combinations of EVs and EVSEs over representative testing conditions to rigorously characterize the dependence of system RTE on energy throughput.

Duty Cycle

Duty cycle refers to the pattern of charge and discharge cycles over time that is associated with a given V2X use case. This includes the frequency, magnitude, and duration of the charging and discharging behavior, as well as requirements for other operational parameters like response time.

C-Rate

The C-rate is a dimensionless metric that normalizes charging and discharging power to the battery capacity and defines how quickly a battery is charged or discharged relative to its rated capacity. It allows for uniform comparison between different batteries, since it is independent of factors like size and chemistry. While charging and discharging power levels typically characterize the load behavior on the AC side of a V2X system, C-rate is inherently a DC-side parameter. A battery operating at 1C means that the battery will be fully charged or discharged in 1 hour; a 0.5C rate means a full cycle takes 2 hours, while a 2C rate implies a full cycle in 30 minutes. C-rate can be expressed formulaically as:

$$C - Rate = \frac{Power\ (kW)}{Battery\ Energy\ Capacity\ (kWh)} = \frac{Current\ (A)}{Battery\ Capacity\ (Ah)}$$

Power Factor (PF)

PF is an important operational parameter for EVSE, as it impacts power quality and energy losses in the distribution network. A low-power factor can result in energy penalties incurred at local transformers and result in the need for accelerated infrastructure-upgrade investments.

Assessment of V2X Use Cases and Value Streams

There are several mechanisms through which V2X systems generate value to owners, fleet operators, utility aggregators, and the grid. The use cases may be further grouped based on the spatial and temporal resolution of the service they support or provide. While not comprehensive, the use cases and value streams below represent the highest potential areas of opportunity based on current technology readiness levels across the V2X value chain and should be prioritized accordingly to facilitate V2X adoption.

Transmission-Level Services (Bulk System Resolution)

Frequency Regulation

EVs with larger battery capacities and faster response times can help stabilize the grid frequency by rapidly injecting or storing power in response to grid demand fluctuations. This grid service is primarily coordinated by utility aggregators and is of primary interest to commercial fleets, as it allows them to be compensated for the provision of readily available capacity to support grid reliability. During a regulation event, EVs undergo rapid, shallow charge/discharge events every 2-4 seconds to meet the system frequency setpoints, which is typically 60 Hz in US markets.

When aggregated and coordinated via an aggregation platform or VPP, distributed EVs become effective assets for frequency regulation in wholesale markets such as the Pennsylvania-New Jersey-Maryland (PJM) Interconnection, California Independent System Operator (CAISO), and Electric Reliability Council of Texas (ERCOT). V2G frequency regulation is being explored as a viable use case in California and has shown promise for scaled adoption in field demonstrations.

A V2G capable school bus fleet with a combined capacity of 55.2 kW successfully responded to an automated generation control signal simulating participation in a CAISO frequency regulation event. The fleet achieved a maximum accuracy of 69.21% for a regulation up command and 56.73% for a regulation down command, well-above CAISO's minimum accuracy threshold of 25% (Nuvve Holding Corporation 2022). These results can be interpreted as a good indicator of technological readiness from an efficacy standpoint.

Frequency regulation involves shallow, frequent bidirectional cycling, which typically avoids deep depth-of-discharge (DoD). Figure 19 below illustrates how the value of electricity losses relates to frequency regulation price for different empirical system RTE scenarios. It highlights the sensitivity of frequency regulation services to net energy losses. For this analysis, the value of electricity losses offsets total revenue for system RTE values of 62 percent (Y.A Shirazi, D.L. Sachs 2018).

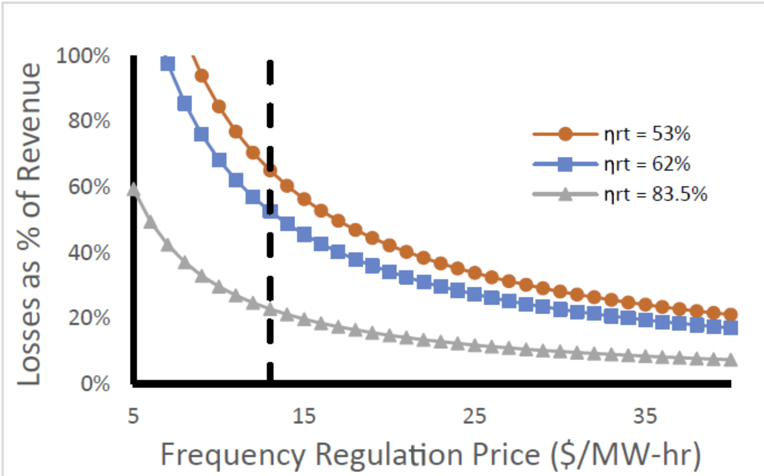

Figure 19: Value of electricity losses as a percentage of revenue compared to frequency regulation price at three empirically measured values of RTE.

Source: (Y.A Shirazi, D.L. Sachs 2018)

Despite current technological challenges and variability in compensation across jurisdictions, frequency regulation service remains a promising medium- to long-term use case for V2X. As market access mechanisms evolve and technology approaches commercial readiness, the viability of this service is expected to improve.

Distribution-Level Services (Feeder or Substation Resolution)

Deferred Distribution Infrastructure Upgrades

V2X-capable EVs can act as a non-wired alternative solution by relieving power flow through at-risk segments of the distribution system that deal with capacity constraints due to aging or degraded infrastructure. According to the Brattle Group's technical appendix to California's Virtual Power Potential study, avoided distribution system upgrade values are estimated at $24.75 per kW-year (Brattle Group 2022). With this figure in mind, a large V2G commercial fleet that can dispatch 2 megawatts (MW) of aggregated capacity during peak periods could defer nearly $50,000 per year of distribution infrastructure costs.

BTM Services (C&I and Residential)

Load Shifting and Energy Arbitrage

Energy arbitrage refers to the strategic charging and discharging of V2X-capable EVs to exploit time-based electricity price differentials while parked. Vehicles charge during low-cost periods and discharge during peak pricing periods to reduce net energy costs or export to the grid. This use-case is compatible with various pricing structures such as TOU, real-time pricing, and critical peak pricing tariffs, and is accessible to both commercial and residential EV operators.

The profitability of energy arbitrage is closely tied to system RTE, especially under tariffs with narrower price differentials. Energy losses during the charge-discharge directly reduce the net energy available for export and import as illustrated through the following relationship:

$$Net\ Gain\ (\$) = \left(\frac{\$}{kWh_{Peak}} - \frac{\$}{kWh_{Off-Peak}}\right) \times RTE_{System} \times E_{transcated}$$

Where:

$\frac{\$}{kWh_{Peak}}$: Peak period price ($/kWh)

$\frac{\$}{kWh_{Off-Peak}}$: Off-peak period price ($/kWh)

RTE_{System}: System (AC-AC) Round trip efficiency

$E_{transacted}$: Energy (kWh) transacted

This formula underscores the critical role of RTE for ensuring the viability of energy arbitrage under marginal pricing differences. Further, since arbitrage can involve cycling large amounts of cumulative energy throughput (kWh), it is essential to account for battery degradation when evaluating the long-term performance and economic potential of V2X systems.

Despite the barriers mentioned, arbitrage presents a strong case to offset V2X system total cost of ownership. An EPRI simulation of DC V2G indicates residential arbitrage opportunities have the potential to yield total cost savings up to 73 percent under representative TOU tariff structures and load profiles (EPRI 2023, 17-18).

Renewable Energy Integration and Self Consumption Enhancement

While stationary, EVs can leverage their batteries to help absorb excess solar or wind energy during periods of overgeneration and discharge when renewable output declines. This mitigates renewable curtailment at the grid level, enhances local load flexibility, and may offset the need for costly stationary BESS. The alignment between EV charging behavior and renewable generation patterns makes this use-case particularly viable. In California alone, approximately 1,500 GWh of renewable energy was curtailed in 2020 (EPRI 2023, 20). This challenge could be addressed by compensating V2G-capable fleets with large battery capacities for participating in aggregated storage dispatch during overgeneration events.

Figure 20 below highlights the potential for significant improvement in renewable self-consumption if equipped with an energy export capability such as V2G, as seen by the increase in energy charged from solar (yellow bar) and the increase in energy exported to local loads or the grid (blue bar).

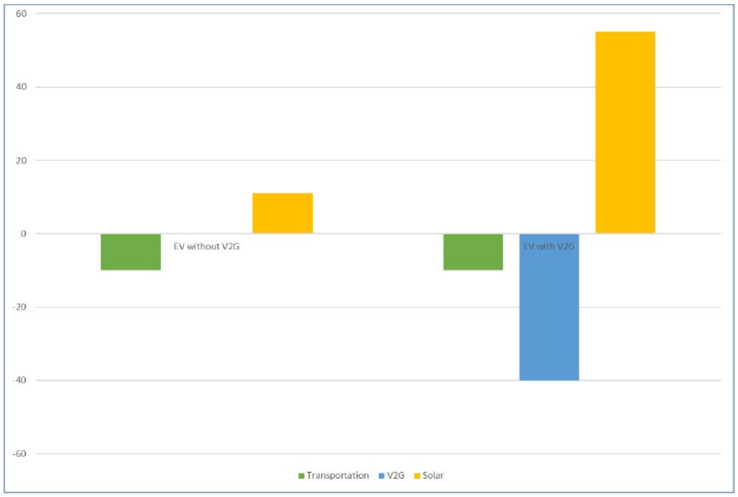

Figure 20: Daily solar consumption of EV with and without V2G.

Source: (EPRI 2023, 7)

Peak Shaving for Demand Charge Management

Demand charges are typically calculated based on a customer's peak 15-minute power draw in a billing period. V2G-enabled commercial vehicles (especially in fleet depots) can strategically discharge to reduce these peaks. This approach can yield significant annual savings on demand charges depending on the tariff structure.

A V2B demonstration using a single EV and a single bidirectional charger achieved an average monthly demand reduction of 13 kW during its first year of operation. This translated to $247 in cost savings (SEPA 2023).

There may be an additional GHG reduction benefit associated with V2X systems due to the potential to displace carbon-intensive marginal generation, typically from natural gas peaker plants, that would otherwise dispatch to meet the facility peak demand. Using the Environmental Protection Agency's AVERT tool for California, which estimates an average marginal displacement rate of 0.45 metric tons CO_2 per MWh, (Synapse Energy Economics, Inc. 2015), a large commercial site deploying 2 MW of V2B export capacity across 50 summer peak demand events (each lasting 2 hours) could avoid approximately 90 metric tons of CO_2 annually. This estimate assumes discharges during periods when marginal grid generation is predominantly supplied by natural gas peaker plants.

This service is typically managed via a building energy management system (EMS) or aggregator control logic and is often synchronized with building load profiles and on-site solar generation to ensure effective and accurate peak shaving.

Figure 21 below illustrates modeled distribution circuit loads on a peak day under varying levels of bidirectional PEV penetration scenarios, assuming prototypical commercial load profiles. Table 3 indicates a near linear reduction in distribution circuit peak load as bidirectional EV penetration increase for the same scenario modeled in Figure 21.

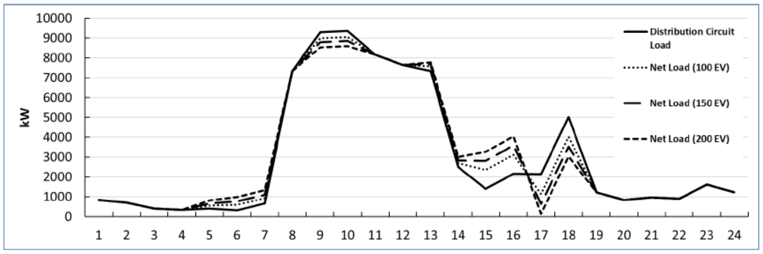

Figure 21: Distribution feeder load profile on peak day with different numbers of bidirectional PEVs.

Source: (EPRI 2023)

Table 3: Distribution circuit peak load comparison with different numbers of bidirectional PEVs.

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

Source: (EPRI 2023)

Backup Power

V2X-enabled EVs can provide backup power during grid outages by supplying power to critical household or building loads, particularly during public safety power shutoffs (PSPS) or natural disasters. This function is distinct from economic services and offers resilience value. Figure 22 below illustrates the simulated critical load coverage probability of a bidirectional mid-size PEV with 40 kWh battery capacity, discharging at 10 kW-peak with an assumed system RTE of 85 percent under prototypical California residential and commercial peak and average demand and energy profiles.[7]

[7] The critical load coverage curve assumes a 40 kWh usable battery capacity per PEV, 10 kW peak discharge rate, and 85 percent round-trip efficiency. Residential and commercial load profiles are modeled separately, with coverage probability calculated over outage durations up to 96 hours. Tariff assumptions include Southern California Edison's TOU GS-1 Option D for commercial customers and Option E for residential customers.

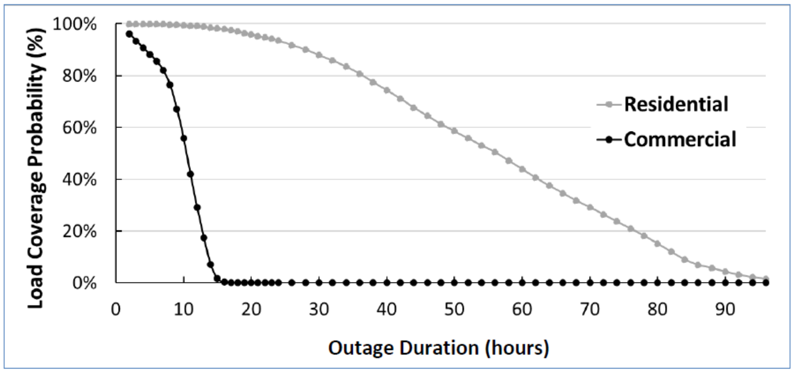

Figure 22: Critical load coverage curve for representative residential and commercial customers.

Source: (EPRI 2023)

The results suggest significantly greater coverage during extended outage periods for residential customers, primarily due to the typically higher ratio of battery energy storage capacity to connected load in residential settings. These findings align with the operational characteristics of V2H systems, which tend to emphasize back-up power during islanded operation and enhance self-generation from on-site generation.

V2X Smart Charging Control and Energy Management Strategies

This section evaluates the efficacy, readiness, and objectives of various smart charging control and energy management strategies that have potential to deliver electric benefits to the grid. While not an exhaustive list of all available opportunities, the approaches identified below were determined to be the most relevant given current levels of technology maturity described in secondary research and V2X stakeholder engagement.

For an overview of the broader classes of control strategies (e.g., centralized, decentralized) and scheduling approaches (e.g., real-time, day-ahead) related to V2X charging and discharging behavior, see Appendix D: Overview of V2X Control Strategies and Scheduling Approaches.

Energy Efficiency-Aware Smart Charging

For context, a naive charging event is the least sophisticated form of charging. During naïve charging, a PEV charges at a specified rate that complies with minimum operational requirements such as its OEM prescribed safe SoC limits and pre-configured user mobility preferences such as the desired SoC by a certain time. The control logic is generic relative to other similar PEVs and allows for little to no dynamic adjustment of the charging behavior based on actual grid conditions or ambient temperature. It may also disregard charging efficiency entirely or assume constant efficiency over the entire range of operating conditions, which is not representative of real-world operation.

On the contrary, an Energy Efficiency-Aware Smart Charging strategy uses more sophisticated methods to modulate charging or discharging rates so that driver requirements—such as scheduled charge completion—and electric capacity constraints—such as distribution feeder congestion and local electrical panel limits—are met while simultaneously mitigating energy losses (kWh) better than other strategies.

Some examples of these methods include optimizing EVSE operation according to the specific empirical relationship between load and charging efficiency or adjusting charge rate based on the ambient temperature effects on EV battery charge efficiency. Further examples are presented in Appendix G.

For this class of smart charging approaches, energy efficiency accounts for energy losses during all the power inversion (AC-to-DC) and conversion (DC-to-DC) stages between the grid PCC and the EV's on-board battery. To implement an efficiency-aware charging strategy, a system boundary that captures all the losses incurred along the energy transfer pathway must be defined. An example of a system RTE boundary for a bidirectional EV served by a single EVSE is proposed in Figure 23 below.

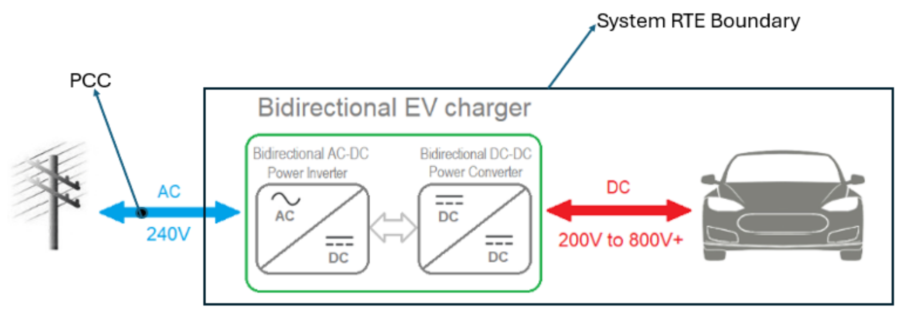

Figure 23: Example of a V2X system RTE boundary.

Source: (Svarc, Bidirectional EV Chargers Review - V2G & V2H 2025)

Energy-efficiency-aware charging strategies may be implemented in various ways, typically by defining a hierarchy of scheduling rules and charge rate—or discharge rate, in the case of V2X—constraints. These constraints must be sophisticated enough to satisfy baseline operational requirements and driver expectations, while delivering additional energy benefits to other stakeholders, such as the grid, individual users, or third-party aggregators. A more detailed framework for developing EV dispatch scheduling and charge or discharge rate adjustment rules is provided in Appendix H.

One study implemented compared the performance of two energy-efficiency-aware smart charging strategies with their non-efficiency-aware counterparts. Each strategy was implemented in a simulated environment[8] to assess customer satisfaction and utility profit (Francesco A. Amoroso 2012). The efficiency-aware approaches adjusted the charge rate by utilizing an empirical relationship between C-rate and charging efficiency, which is illustrated in Figure 24 below. The

[8] MATLAB simulations analyzed the evolution of 100 different charging points with maximum available power of 25 kW in the presence of 1000 total vehicles (total available power of 2.5 MW) with random arrival and departure times. The battery capacities were assumed to be randomly distributed in the range 10–25 kWh, corresponding to small and mid-size PEVs models. An electricity rate of 0.20 €/kWh was considered (fixed during the day for the sake of simplicity), according to typical electricity costs in Europe.

summarized results are indicated in Table 4 below, and details on the working principle of the specific smart charging strategies are provided in Appendix H.

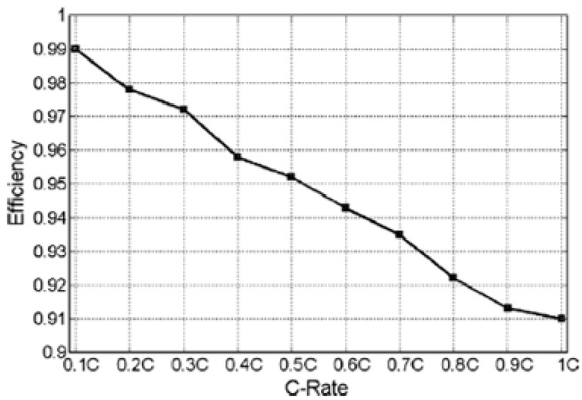

Figure 24: Empirical relationship between C-rate and charging efficiency.

Source: (Francesco A. Amoroso 2012)

Table 4: Results from simulations of efficiency-aware smart charging strategies.

Smart Charging Strategy	Customer Average Satisfaction Degree (%)	Utility Profit (€)
Variable Rate Concentrated Energy	63.3%	2,544
Variable Rate Spread Energy	67.5%	2,532
Efficiency-Aware Variable Rate Concentrated Energy	74.5%	2,770
Efficiency-Aware Variable Rate Spread Energy	77.3%	2,838

Source: (Francesco A. Amoroso 2012)

Variable-Rate Concentrated-Energy (VRCE) sets the charge rate to complete the charging event over a specific time increment whereas Variable-Rate Spread-Energy (VRSE) spreads the energy required by the EV over the entire remaining period available. Although the simulation findings did not explicitly report the energy-efficiency (kWh) benefits, they predict improved customer satisfaction and utility profits based on realistic technology and market conditions.

Efficiency-aware variable-rate dispatching strategies can yield higher utility profits compared to non-efficiency-aware approaches since they account for energy losses during charging and adjust the charging rate accordingly. This ensures that users receive the actual energy needed to meet their battery requirements, leading to more complete charging sessions and a greater total volume of energy sold. In contrast, non-efficiency-aware strategies often undercharge vehicles due to unaccounted losses, resulting in lower energy sales and reduced utility revenue.

Energy-Efficiency-Aware Smart Charging Strategy Case Studies

This section examines additional case studies on other forms of energy-efficiency-aware smart charging strategies.

UNIVERSITY OF DELAWARE HIGH EFFICIENCY DISPATCH LABORATORY DEMONSTRATION

This analysis evaluated a high efficiency dispatch algorithm in a controlled lab setting. The simulation emulated a frequency regulation event implemented by a central aggregator, which received power setpoint signals ranging between -1 and 1 for each of the 10 bidirectional EVs in the participating fleet. The algorithm solved a constrained optimization problem to minimize power losses across the fleet, incorporating user-defined SoC limits and allowable thresholds for charging and discharging. It leveraged a 3D empirical model relating percentage power losses to AC current (A) and SoC, derived from component-level measurements in the test bed. Below, the empirical relationship is depicted in Figure 25, and a summary of the results is presented in Table 5.

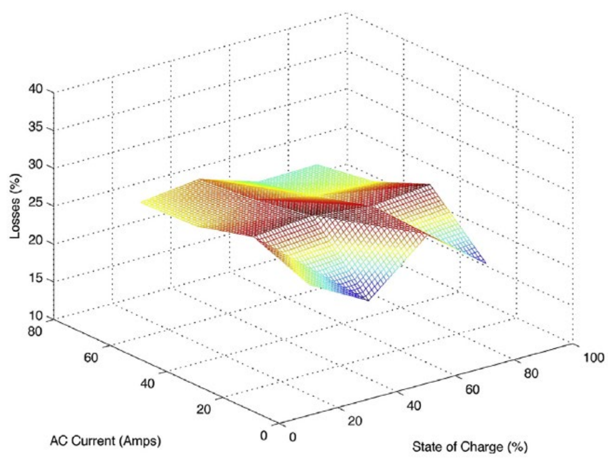

Fig. 3. Interpolation of round-trip losses (PEU and Battery).

Figure 25: Empirical relationship between system round-trip energy losses, AC current, and SoC.

Source: (E. Apostolaki-Iosifidou et al. 2017)

Table 5: Summary of efficiency-aware dispatch algorithm simulation results.

Test Variable	Naïve Dispatch Algorithm	High Efficiency Dispatch Algorithm
Duration of Simulated V2G Event (hrs.)	8 hours	8 hours
Number of V2G test EVs	10	10
Type of simulated grid service event	Frequency Regulation	Frequency Regulation
Average energy loss over event duration (kWh)	32.27 kWh	29.53 kWh
Computational resolution (s)	2 s	2 s
kWh loss reduction improvement (%)	N/A (Baseline)	9%

Source: (E. Apostolaki-Iosifidou et al. 2017)

The results indicate that the high efficiency dispatch algorithm was able to reduce energy loss by 8.5 percent without compromising on the provision of grid services. Although this demonstration did validate the efficacy and performance of an efficiency aware dispatch strategy, it was based on empirical data that was specific to the experimental set up. Scaling this approach may be difficult as it requires empirical data specific to the target system over a wide range of representative operating conditions (SoCs, power levels etc.). Although the study did not account for the variability in EV arrival and departure times, the results still serve as a strong foundation that can be refined in future demonstrations.

EVSE POWER CONVERSION EFFICIENCY AWARE V2G SIMULATION

This study investigated a decentralized[9] optimization approach for scheduling the charging operations of a simulated V2G environment with 100 EVSE 25-kW DC units equipped with a 100-kWp PV system and a 50-kW/150-kWh BESS (Jian-Tang Liao 2021).[10] The V2G-capable EV battery capacities ranged from 42 kWh to 100 kWh, which are representative of typical light- and medium-duty vehicle battery capacities.

An empirical relationship between load (kW) and EVSE power conversion efficiency was incorporated into the scheduling to prioritize efficiency while simultaneously charging in response to TOU price signals. A graphical representation of this relationship is shown in Figure 26 below.

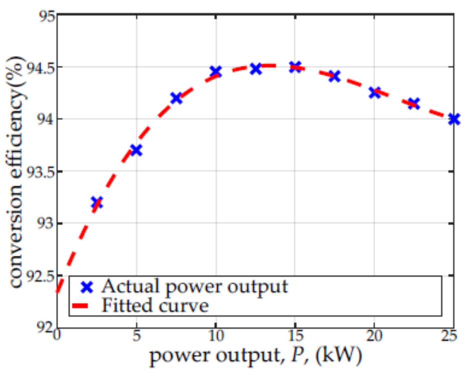

Figure 26: Empirical relationship between conversion efficiency and power output.

Source: (Jian-Tang Liao 2021)

Figure 27 validates the operation of the conversion efficiency-aware smart charging profile at the EVSE's best operating point, relative to a non-efficiency-aware profile.

[9] Decentralized approaches optimize EV charging behavior based on local conditions rather than at the distribution and bulk transmission levels and may provide better energy loss mitigation potential for individual V2X EV owners and fleet operators. See Appendix E for further comparison between centralized and decentralized approaches.

[10] EV arrival/departure times and SoC levels follow probabilistic distributions (Monte Carlo simulation). TOU pricing: Peak: $0.12/kWh (7:30 AM–10:30 PM) Off-peak: $0.051/kWh (10:30 PM–7:30 AM EV battery capacities: 42/62/100 kWh; rated power: 25 kW BESS: 50 kW / 150 kWh with 90% DC RTE.

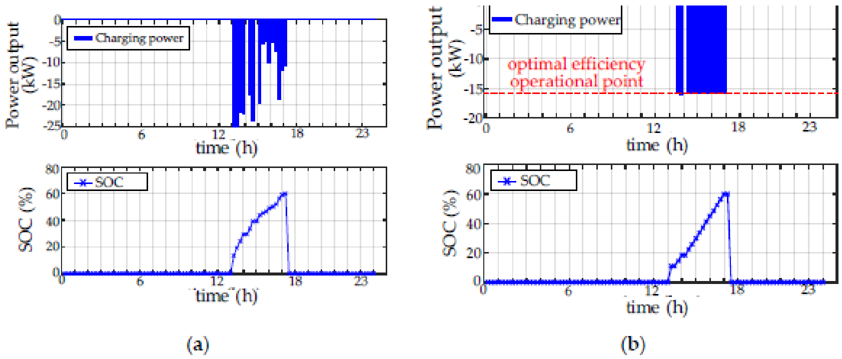

Figure 27: Daily scheduling results of EVs (a) without and (b) with the consideration of variable conversion efficiency.

Source: (Jian-Tang Liao 2021)

The bottom graphs show both approaches take an equivalent amount of time to fully charge despite the top graphs showing different patterns in charging behavior—the efficiency-aware strategy targets a specific power level while the other does not. Table 6 below provides a summary of these results.

Table 6: Summary of simulation results.

Cost Performance ($)	Scheduling Based on Grid TOU Tariff Only ($)	Conversion Efficiency Aware Scheduling with Grid TOU Tariff ($)
EV User Charging Fee (1)	264.93	265.1 (+0.06%)
Total cost caused by conversion loss (2)	17.2	8.63 (-49.83%)
BESS electricity cost (3)	-0.31	-0.32 (+3.32%)
Total profit of charging station (1-2-3)	248.04	256.79 (+3.53%)

Source: (Jian-Tang Liao 2021)

The findings indicated an approximate 50 percent reduction in total revenue losses due to improved conversion efficiency. Since this was the only variable altered between the two simulated scenarios, the recovered revenue can validly be attributed to avoided power conversion losses. By dividing the avoided revenue loss due to smart charging ($) by the assumed off-peak $/kWh, a conservative net energy (kWh) benefit of approximately 168 kWh—or 1.68 kWh per average charging session—can be attributed to this conversion efficiency-aware smart charging strategy.

These results are especially compelling as they demonstrate alignment between charging in response to TOU price signals, which primarily benefits the grid, and charging in response to EVSE power conversion efficiency, which primarily benefits the EVSE owner. This overlap creates a mutually beneficial outcome for the charge station owner and the utility under relatively representative real-world conditions and grid constraints. Additionally, the study accounted for the variability in EV arrival and departure times, which further supports the real-world viability of similar systems such as DC microgrids with integrated PV and BESS. It also highlighted reduced computational burden compared to a centralized control strategy, which presents a practical advantage from an implementation standpoint.

EVSE Sleep State Control

The operation of EVSE is subject to baseload idle energy consumption when in a standby state and not charging or discharging. Sleep state control is an energy saving feature that enables an EVSE that has exceeded a certain amount of time in idle mode to reduce or disable the energy consumption from certain non-essential functions. The EVSE normally consumes energy to support these non-essential functions—such as display light brightness or auxiliary systems that may include secondary cooling fans—under the assumption that it must maintain a fixed level of responsiveness to a potential grid service event signal. This capability could be valuable for EVSE that periodically undergoes relatively longer periods of non-utilization.

A more sophisticated EVSE may have several “deeper” sleep states with the capability to reduce more non-essential features in a tiered fashion. The efficacy of this capability can be enhanced by incorporating predictive algorithms that leverage artificial intelligence (AI) to forecast operational windows where the likelihood of participating in a grid service event is minimal and aligns the sleep mode reduction with these windows. However, it is important to ensure that this feature does not compromise the EV’s ability to participate in certain types of grid services like demand response or frequency regulation support.

Advanced sleep state control could eventually be recognized as an energy efficiency feature in novel bidirectional EVSE and could be specified as a minimum requirement by programs such as ENERGY STAR. ENERGY STAR currently specifies power allowance requirements for operational modes such as No-Vehicle Mode, Partial-On Mode and Idle-Mode for unidirectional EVSE (ENERGYSTAR 2023). A similar requirement could be developed for bidirectional EVSE.

There is limited knowledge and awareness on the energy efficiency benefits of optimized sleep state control in the current research. Based on stakeholder engagement and secondary research, no clear guidance has been developed to uniformly evaluate energy losses incurred during inefficient standby operational modes. However, an EPRI study reported that some V2X systems consume between 0.4 kW to 0.6 kW continuously during standby or idle operational modes (EPRI 2023). Assuming this corresponds to an EV in a corridor fast-charging environment that spends approximately one hour per day parked and charging, this could result in annual standby energy penalties of up to 219 kWh for the given V2X system.

Renewable Energy Aligned Smart Charging

This smart charging strategy prioritizes aligning EV charging windows with periods of high renewable energy generation based on real-time data or forecasts. Some V2X charging products may refer to this feature as “green mode” or “eco-mode.” EV owners with onsite PV can leverage these strategies to maximize self-consumption, and even without onsite generation, users can benefit by charging from the grid during periods of PV overgeneration to mitigate renewable curtailment. There are existing tariff structures that incentivize this charging behavior such as the PG&E BEV rate, which considers 9:00 a.m. to 2:00 p.m. as “super off-peak”—a time window that aligns with high solar generation.

Although this charging strategy does not specifically aim to minimize energy conversion losses like energy-efficiency-aware smart charging, it still contributes to reducing GHG emissions by prioritizing the use of clean, renewable energy over electricity with a higher carbon intensity. Key findings from case studies that demonstrate the energy impacts of V2X in renewable energy aligned smart charging are presented in the subsequent sections.

Case Study: Smart Microgrid with DC V2M and BTM Export

This case study examined the effectiveness of multiple control algorithms for managing the charging profile of two energy-export-capable EVs in a simulated microgrid modeled after a real European city. The microgrid includes a 31 kWp solar PV array and 24 kWh and 85 kWh EV batteries rated at 22 kW and 6.6 kW, each, for charging and discharging (Mart van der Kam 2015). The algorithms were evaluated based on their efficacy to maximize PV self-consumption and reduce peak demand. The real-time (RT) control algorithm adjusts the EV charging behavior dynamically in response to 15-minute weather data whereas the linear programming (LP) approach schedules EV charging based on day-ahead forecasted PV generation and grid load data. Besides specifying representative EV SoC and charging power constraints, the simulation restricted energy discharge to only occur behind-the-meter and when PV self-generation was unable to meet uncontrollable loads such as IT loads and households etc. The results are summarized in Table 7 below:

Table 7: Summary of simulation results of renewable energy aligned smart charging approaches.

Algorithm	Description	PV Self-Consumption (%)	Energy Exported to Microgrid (MWh/yr)	Relative Peak Reduction (%)
No Control	EVs charge at max capacity when connected.	49.0%	12.40	-
Real time (RT) Control	Real-time charging using excess PV power	62.0%	9.10	27.0%
RT Control + Energy Export	Discharges to support load demand	79.0%	4.80	43.0%
Linear Programming (LP)– 100% forecast accuracy	Linear programming with perfect forecasts	91.0%	2.00	75.0%
LP – 10% forecast deviation error	LP with forecast errors (10% deviation)	87.0%	3.40	67.0%

Source: (M. van der Kam, W. van Sark 2015)

The results showed that the LP approach with 100 percent simulated forecast accuracy resulted in the highest relative peak reduction and PV self-consumption. However, the RT algorithm that supported EV bidirectional export (i.e., RT Control + Energy Export) exhibited higher efficacy for both performance metrics compared to the RT and No Control scenarios, which did not allow the EVs to discharge.

Although the study did not quantify incremental energy efficiency impacts of each smart charging strategy, a rough estimate can be derived from the provided assumptions. The PV system reported an expected annual production of 25 MWh for a typical year assuming normal operation. The modeled increase in renewable self-consumption between RT and RT + Energy Export control strategies is 17% which is approximately 4.25 MWh of additional renewable energy, from a moderately sized microgrid, that would otherwise be curtailed or imported from the grid. However, this estimate is subject to uncertainty since the model assumed 90% conversion efficiency over all operational conditions – an assumption that may not fully represent real-world operation.

Temperature Controlled Smart Charging

Temperature-Controlled Smart Charging (TCSC) is an emerging energy management strategy for V2X systems operating in extreme thermal environments. As discussed earlier in the Ambient Temperature (°C) section, low ambient temperatures can significantly increase the internal resistance of EV batteries, leading to reduced driving range and greater energy losses during charging and discharging cycles. These effects are typically mitigated through thermal pre-conditioning, which relies on auxiliary heating provided by the vehicle's onboard Thermal Management System (TMS).

TCSC strategies optimize both charging power and auxiliary heating energy in a coordinated manner to satisfy driver mobility needs (i.e. SoC requirements), preserve battery health, and adhere to grid constraints—while minimizing unnecessary energy consumption by the TMS when possible.

While conventional thermal pre-conditioning is primarily aimed at maintaining baseline battery performance and mitigating cold-weather range degradation, advanced TCSC approaches integrate thermal management into the broader energy optimization workflow. This integration can improve energy efficiency compared to more basic temperature-controlled charging methods. It's important to note that the onboard heating system does not draw energy directly from the EV battery. However, it still requires power from the grid or an external power source. Therefore, reducing or avoiding auxiliary heating through advanced TCSC strategies offers a measurable energy efficiency benefit.

One recent study compared temperature-controlled smart charging strategies with two less advanced charging strategies (Grant Ruan 2025). Each charging strategy was evaluated based on its effectiveness to optimize EV charging costs and overhead heating energy use, while also meeting driver mobility needs and grid load constraints. The simulations were run for varying fleet sizes and used mostly realistic assumptions except for the unpredictable nature of real-world EV availability and fixed charging as well as heating system efficiency values.[11]

A comparison of the effectiveness of each charging strategy's ability to optimize charging cost and overhead heating energy usage is indicated in Figure 28 below:

[11] Simulations assume Level-2 AC charging for EVs with 37 kWh battery capacity and on-board thermal management systems (Positive temperature coefficient heating element or heat pump) controlled externally. Charging occurs on a day-ahead schedule with 15-minute resolution from 7am–10pm. Arrival SoC is uniformly sampled from [0.0, 0.4] and departure SoC is fixed at 0.9, with no stochastic modeling of arrival/departure times. Heating and charging efficiencies are set at 0.8 and 0.92 respectively. Solar PV and ambient temperature profiles used real data from ISO New England and ASOS weather stations. TOU electricity pricing reflects Boston rates: 12.48¢/kWh (off-peak), 17.22¢/kWh (mid-peak), and 22.09¢/kWh (on-peak), with a daily average of 17.50¢/kWh.

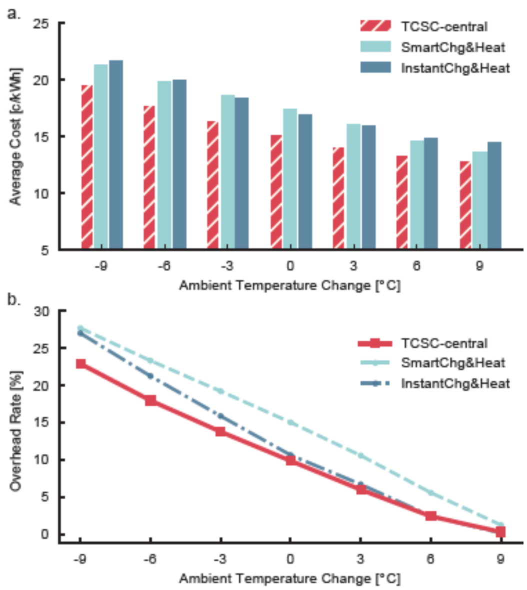

Figure 28: Comparison of TCSC smart charging strategies.

Source: (Grant Ruan 2025)

The results indicated that the TCSC strategy achieved lower average overhead heating energy usage rate—a 0.4 to 6.1% reduction—and a lower charging cost—a 17.7 to 18.4% reduction—per EV, compared to the less sophisticated temperature-controlled charging strategies such as "Smart Charge and Heat" and "Instant Charge and Heat."[12]

This experiment assumed a maximum on-board TMS nominal capacity of 3.0 kW with an 80 % heating system efficiency. It is reasonable to assume the system operates near full load during thermal pre-conditioning to maintain optimal temperature setpoint under low ambient temperatures. Using a conservative estimate of 2.5 kW TMS actual consumption and a one-hour average daily charging time—based on the partial charge of a typical 37 kWh EV charged via level 2 EVSE—the annual avoided overhead heating energy consumption per EV is approximately 913 kWh at very low ambient temperatures.

However, the interactive effects on the charging efficiency were not characterized in this study and would have to be considered for a more holistic understanding of net energy efficiency benefits of TCSC strategies.

[12] Smart Charge and Heat coordinates EV battery charging and heating over time to minimize energy use and cost, leveraging thermal inertia and solar availability. It schedules heating and charging jointly in a day-ahead optimization, assuming full control over on-board heaters and chargers, and uses temperature-sensitive constraints to avoid battery degradation. Instant Charge and Heat, by contrast, applies heating and charging immediately upon vehicle arrival without optimization. It assumes no coordination or flexibility, leading to higher peak loads and energy waste.

Research on Energy Efficiency Characterization of V2X Products

This research investigated the efficiency and design features of various commercially —or soon-to-be available—V2X products, including EVs and EVSE. The primary resources were specification sheets, OEM websites and existing databases; no quantitative data could be collected from equipment OEMs or independent research institutes due to privacy concerns. The goal was to identify industry standards in efficiency that could inform the integration of V2X equipment into the existing energy efficiency program landscape.

Parallel research reviewed existing guidance on V2X product characterization developed by industry working groups such as CharIN. It also examined best practices and frameworks for testing, certification, and characterization of V2X configurations and analogous systems—such as stationary energy storage and grid-tied PV inverters—developed by credible entities, including independent research institutes like Pacific Northwest National Laboratory (PNNL) and established demand-side management programs, such as California's Self-Generation Incentive Program (SGIP). This work was further supplemented by input from V2X industry stakeholders and standards organizations. Any recommendations based on findings will be synthesized in the Recommendations section at the end of this report.

V2X EV Research

The team reviewed specifications and databases of commercially available EVs with bidirectional power flow capabilities. We then catalogued key attributes relevant to energy efficiency or grid integration potential, based on available data. A sample of the findings is presented in Table 8 below while a more comprehensive list is available in Appendix E: V2X EV and EVSE Catalogued Product Specifications.

Table 8: Sample of commercially available V2X EV catalogued information.

	V2X LDEVs					
OEM	Ford	Ford	Genesis	Genesis	Genesis	GM
Model	F-150 Lightning (Extended Range)	F-150 Lightning (Standard Range)	G80 EV	GV60	GV70	Silverado EV RST
V2L Capable	x	x	x	x	x	x
V2G Capable	x	x	-	-	-	x
V2H/V2B Capable	x	x	-	-	-	x
V2V Capable	x	x	-	-	-	-
Battery Chemistry	Li-ion	Li-ion	Li-ion	Li-ion	Li-ion	Li-ion
Battery Size/Nominal Energy Capacity (kWh)	131	98	87.2	77.4	77.4	200
V2X Max Output Power (kW)	9.6	9.6	1.9	3.6	3.6	9.6
Battery RTE (%)	-	-	-	-	-	-

Sources: Manufacturer specification sheets and official OEM websites, (SEPA 2023)

The selected fields include parameters that influence overall efficiency and grid integration and were based on minimum reporting and eligibility requirements for batteries and integrated systems that qualify for the SGIP. This enables the evaluation of EV efficiency performance, regardless of the presence of an on-board inverter.

The findings reveal a significant lack of publicly available energy efficiency data and testing conditions that are commonly used to describe stationary BESS, inverters or integrated battery-inverter systems which have similar characteristics to V2X systems in function and design.

Gaps in reported V2X maximum output power (kW) across EVs were also noted. No clear information on the testing conditions such as ambient temperature or test duration could be determined from the research. Additionally, some of the reported maximum power output values correspond to the EV battery and on-board inverter equipment while other reported values assume operation with separate EVSE implying some values represent DC power while others represent AC power. This is consistent with an observed trend of frequent exclusive compatibility between certain EVs and EVSEs across the V2X product landscape.

Existing programs such as SGIP require stand-alone batteries to report DC RTE at standardized testing conditions, which include ambient temperature and SoC windows that are representative of the battery duty cycles. As V2X technology matures and interoperability challenges are resolved, product ecosystems are likely to become vendor-agnostic. To support full bidirectional grid integration, OEMs should report EV-specific efficiency performance metrics such as battery RTE and on-board inverter charging and discharging efficiencies to encourage a more modular, cross-compatible product ecosystem.

The importance of appropriately specifying energy efficiency boundaries is further highlighted when comparing different end-uses of an EV. The energy losses from the operation of the EV powertrain and drivetrain differ significantly from those incurred during discharging to external loads or the grid due to different power requirements and energy transfer pathways. Therefore, OEMs must clearly differentiate between energy efficiency metrics related to mobility and those related to V2X operation. This avoids misrepresenting the performance of EVs in stationary V2X applications.

V2X EVSE Research

The team reviewed specifications of commercially available bidirectional EVSE to identify trends in energy efficiency and related proxies. To support this effort, we engaged with industry subject matter experts responsible for the maintenance of the CEC V2G equipment list to assess the state of efficiency-related documentation. At the time of this study, the equipment list primarily catalogued EVSE attributes related to grid-integration and did not include any energy efficiency performance metrics.

The main parameters used to characterize EVSE efficiency are charging and discharging efficiency. Standby power consumption is another key factor that influences V2X operational efficiency which was specifically targeted for data collection. A sample of the findings is presented in Table 9 below while a more comprehensive list is available in Appendix E: V2X EV and EVSE Catalogued Product Specifications.

Table 9: Sample of commercially available V2X EVSE efficiency information.

OEM	Model	Charging Efficiency (%)	Discharging Efficiency (%)	Peak Efficiency (%)	Continuous Efficiency (%)	Standby Power (W)	System Round Trip Efficiency (%)	Operating Temperature Lower (°C)	Operating Temperature Upper (°C)
Rectifier Technologies	Highbury	96%	95%	-	-	-	-	-30	50
Enphase	IQ	-	-	98%	-	-	-	-30	55
Coritech	VGI-30	-	-	-	-	-	-	-29	49
Wallbox	Quasar 2	97%	97%	-	-	-	-	-29	40
dcbel	Ara	-	-	96%	98%	-	-	-	-
Wallbox	Quasar	-	-	-	-	-	-	-	-
Fermata	FE-15	95%	-	96%	-	-	-	-	-
Fermata	FE-20	-	-	95%	-	-	-	-30	50

Sources: Manufacturer specification sheets and official OEM websites.

The findings highlight a growing trend of evaluating EVSE efficiency separately over charging and discharging events. There were notable gaps observed in the reporting of clear standby power consumption metrics. A lack of uniformity in reported energy efficiency metrics across EVSE was also evident.

No information on the specific power level or duty testing conditions for the conversion efficiency metrics could be gathered from the researched sources or stakeholder engagement. However, the findings did indicate more consistency in the operational temperature limits for DC chargers capable of grid export, which suggests more uniformity in testing conditions for EVSE targeted for higher levels of grid integration.

There were also instances of commercially available EVSEs that had the capability to integrate with other DERs such as PV arrays. These types of charging solutions may be classified as hybrid systems (see Appendix B: V2X System Architectures for further details on hybrid systems). One residential EVSE that was researched features a hybrid inverter that can handle both solar input as well as imported grid electricity to charge the EV battery. These hybrid solutions have additional energy conversion pathways due to the different operational modes that they support (e.g. charging with solar or charging with grid power etc.). As such, it may be more practical to formally classify them as separate from AC V2X and DC V2X.

Research on Existing Guidance of V2X EVSE Efficiency Standardization

This section synthesizes findings from research on the current landscape of testing and certification requirements for V2X EVSE efficiency and related standardization efforts. The list of researched resources is provided below:

- CharIN white paper on power classes for DC bidirectional charging with CCS charging standard (CharIN 2023).
- ENERGY STAR® Program Requirements for Electric Vehicle Supply Equipment (ENERGY STAR 2023).

Findings

The findings revealed clearer guidance on proposed efficiency requirements for DC coupled V2X systems than AC V2X systems with on-board inverters. The industry working group CharIN has developed distinct power classes for DC EVSE that range from low power charging (LPC) to high power charging. Each power class is characterized by minimum and maximum operating power (kW) thresholds.

CharIN also proposed the concept of "relevant AC power points" for the different discharge power levels that correspond to the typical load (kW) requirements and duty cycles associated with specific bidirectional use cases, along with a framework to determine these power points based on real load data from metering infrastructure. An example of these relevant power points for some typical bidirectional use-cases is available in Table 10 below.

Table 10: Relevant power points for V2X implementation scenarios.

V2X Implementation Scenario	Use Case	LPC Relevant Power Point (kW)
V2H	Back Up Power	0.5[13]
V2G	Frequency Regulation	6.0[14]
V2B	Peak Shaving	6.0
V2G	Intra-day Trading/Arbitrage	6.0

Source: (CharIN 2023)

A three-tiered efficiency rating system based on operational ranges of discharge power levels was also proposed. Minimum discharging efficiency thresholds of 80% and 60% were recommended for normal operation and low-load operation. An example of the LPC power class is presented in Table 11 below. The proposed requirements for all the other power classes are presented in Appendix F.

Table 11: Sample of CharIN efficiency rating system.

Operational Mode	Normalized Power Range	Discharging Efficiency (%) and Efficiency Rating (A, B or C)
Very Low Power Range	Minimum OEM Power to 9% OEM Rated Power	Grade A: ≥ 73 Grade B: ≥70 Grade C: <70
Low Power Range	10% to 15% OEM Rated Power	Grade A: ≥ 93 Grade B: ≥90 Grade C: <90

Source: (CharIN 2023)

This framework could be a valid basis for uniformly evaluating V2X system performance and specifying minimum efficiency requirements. However, this guidance did not address the implications of standby power consumption on overall efficiency.

[13] The relevant power point was determined from data collected from a measurement campaign in Germany. Average residential per-house load demand data was divided by 8760 (hours per year).

[14] Relevant power point selection for V2G use-cases assumes that net benefits to the grid are garnered through the aggregation of several EVs and emphasizes the EV SoC requirements more stringently relative to other implementation scenarios. This is most likely because commercial fleets have stricter availability constraints than EVs in other sectors.

On the contrary, findings from the review of existing ENERGY STAR unidirectional EVSE testing and efficiency requirements indicated minimum standby-mode power (i.e., No-Vehicle Mode, Partial-On Mode, Idle Mode) and load-adjusted charging efficiency requirements for DC output EVSE load conditions—for example, 25% or 50% load. For the determination of load-adjusted efficiency, ambient temperature, testing conditions, and their relative weight adjustment factors were also explicitly specified. Similar requirements should eventually be formally developed for bidirectional EVSE.

However, care must be taken when specifying minimum standby consumption requirements for higher power (i.e. Level 3 charging infrastructure and higher) charging infrastructure. A V2G EVSE designer and aggregation software provider that was engaged during market outreach stated that high-power fleet and commercial chargers are subject to different operational parameters than residential EVSE. High power EVSE are inherently subject to higher standby consumption power levels as they must maintain a higher level of responsiveness to grid signals.

Research on Guidance for V2X Analogous Systems

This section synthesizes findings from parallel research on existing resources, case studies, frameworks, and guidance that offer sufficiently rigorous methodologies for efficiency testing and characterization. These resources pertain to technologies analogous to V2X systems in terms of design and functionality such as stationary BESS with PV generation.

Due to the limited availability of V2X-specific protocols—which reflects the current stage of technological maturity—methodologies developed for analogous systems can serve as a valid foundation for creating comparable frameworks for assessing the V2X system efficiency. A curated list of reviewed resources is provided below:

- The Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E TCP): Advancing the energy efficiency of home energy storage systems (HESS) (Langdon 2025).
- PNNL: Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems (PNNL 2016).
- Case Study: Efficiency characterization of 26 residential photovoltaic battery storage systems (al. 2023).
- Evaluation of the efficiency and resulting electrical and economic losses of photovoltaic home storage systems (Nina Munzke 2021).
- National Renewable Energy Laboratory (NREL): Battery Energy Storage System Evaluation Method (Walker 2023).
- Efficiency guideline for PV storage systems (BSW Solar 2019).

Findings

Findings from market assessments and case studies of analogous energy storage systems reveal well-established energy efficiency performance benchmarks and considerations for minimum efficiency requirements. These insights can be effectively leveraged to inform similar performance and efficiency requirements for V2X systems.

- Round-trip efficiency metrics, such as AC-AC RTE and DC-DC RTE, are key efficiency performance indicators for stationary energy storage systems.
- The reported RTE metrics of residential home energy storage systems (HESS) range between 80 percent to 98 percent, which could inform early benchmarking efforts for V2H systems.
- RTE was found to be strongly influenced by the inverter configuration within the HESS. AC-coupled systems reported slightly lower RTE values, ranging from 80 percent to 95 percent, compared to DC-coupled systems, which achieved higher efficiencies between 87 percent and 98 percent. These figures could inform early benchmarking efforts for V2X counterparts (i.e., AC V2X and DC V2X).
- RTE metrics are not uniformly reported or tested across energy storage product ecosystems. There were no clear signs of convergence towards a universal set of standardized efficiency performance metrics.
- Intrinsic design attributes, such as battery chemistry, inherently limit the maximum achievable efficiency regardless of operational optimizations. These inherent constraints should be considered when specifying minimum efficiency requirements for V2X systems.
- Uniform testing requirements are needed to facilitate valid benchmarking and comparison between key efficiency performance metrics. Performance metrics must be compared on a like-for-like basis (i.e., AC-AC RTE cannot be compared with DC-DC RTE).
- Test duty cycles, weather profiles, weighting factors, and SoC limits should reflect real-world operation.
- Hybrid systems with multiple energy conversion pathways will have specific pathway efficiencies (e.g., PV-feed-in-to-grid, PV-to-EV battery, etc.) associated with them that must be holistically accounted for to determine the overall system efficiency. Alternatively, the specific energy pathways relevant to V2X systems (e.g., PV-to-EV and EV-to-grid) should be isolated.

V2X Initiatives

This section describes research on relevant existing pilots, as well as regulatory and policy initiatives, that have been identified based on their implications for grid integration of V2X.

California Rule 21

California Rule 21 governs the interconnection of distributed energy resources (DERs) to the utility distribution grid. While not originally developed with mobile DERs in mind, Rule 21 has since been clarified to explicitly permit the interconnection of bidirectional EVSE, thereby enabling V2G-capable systems to legally export electricity to the grid under defined technical and procedural conditions. This clarification is essential for any V2X system seeking to operate under a grid-exporting configuration and ensures that V2X inverters meet the same smart inverter requirements (e.g., voltage and frequency ride-through, reactive power control) as stationary DERs.

Pacific Gas and Electric (PG&E) V2X Pilots

PG&E is currently implementing V2X residential, commercial, and microgrid pilots that aim to explore V2X impacts by incentivizing customer resilience—i.e., back-up power—and grid export. The incentives primarily subsidized installation and EVSE equipment costs and included an incremental subsidy for disadvantaged communities.

CEC GFO-24-302

In 2024, the California Energy Commission (CEC) released a targeted funding opportunity, GFO-24-302, to support field demonstrations of bidirectional EV charging technologies. The grant funding is estimated at $12.6 million and calls for project proposals that can demonstrate the following:

- Addressing VGI knowledge gaps
- Cost reduction of V2X enabling technology
- Submetering solutions to facilitate VGI

Barriers

This section highlights the key barriers to V2X adoption and implementation that were identified through secondary research and stakeholder engagement.

Interoperability

Interoperability refers to the seamless integration and communication between EVs, charging infrastructure, grid systems, and software platforms. Poor interoperability limits V2X adoption by negatively impacting scalability and market participation.

The main interoperability barriers are detailed in this section.

Fragmented Communication Standards

Bidirectional charging requires robust, real-time communication across multiple interfaces, such as EV-to-EVSE, EVSE-to-aggregator or VPP, and aggregator-to-grid or market operator. For example, the CHAdeMO charging standard port supports bidirectional charging but it is regionally limited and is not universally compatible with all EVs. The OCPP facilitates communication between EVSE and back-end systems, such as an aggregation platform managed by a VPP software provider; however, many OCPP implementations do not offer bidirectional support. This lack of harmonization of communication standards across the various component interfaces limits adoption, increases deployment costs, limits market access, and undermines the reliability of V2X services.

Closed Technology Ecosystems

During stakeholder engagement and product research, it became apparent that the current V2X product ecosystem is not universally vendor agnostic, with multiple instances of cross-vendor incompatibility between commercially available bidirectional EVs and EVSEs. This can create a negative consumer experience due to limited flexibility in selecting V2X products.

Lack of Streamlined Interconnection Processes

A major barrier to the deployment of V2X systems is the lack of standardized and streamlined interconnection processes across utilities and jurisdictions. As discussed in earlier sections, V2X systems have different levels of grid interaction. However, most utilities apply a one-size-fits-all approach to interconnection.

According to the VGIC, V2X systems fall into four categories: load-only (no grid export), islanded backup (disconnected from the grid during outages), parallel non-export (discharging to meet site load), and parallel export (discharging to the grid) (Vehicle Grid Integration Council (VGIC) 2022). Although each configuration is subject to varying degrees of risk and cost, utilities often indiscriminately route even small, non-exporting systems through complex generator interconnection processes designed for large-scale assets. This results in excessively long deployment timelines and potentially high permitting fees.

Cost

Cost remains one of the most significant and multifaceted barriers to the widespread adoption of V2X technologies. The high up-front equipment and installation costs, unclear market compensation mechanisms, and concerns around battery degradation have slowed market uptake.

High Upfront Costs

V2X equipment has a notably higher incremental cost relative to unidirectional equipment in general. An analysis of V2X deployments in Colorado found that V2H systems cost nearly $9,000 more than standard Level 2 chargers, with commercial V2B installations ranging from $28,000 to $43,000 per site, as indicated in Table 12 below.

Table 12: Upfront cost comparison of unidirectional and bidirectional equipment.

Deployment Cost Component ($)	V2B Deployment Commercial Level 2 EVSE	V1G Commercial Level 2 EVSE
Charger	$10,000	$4,900
Power Management Equipment + Installation	$18,000 - $33,000	$4,173
Deployment Total	$28,000 - $43,000	$9,073 - $11,383
V2B Premium	$16,617 - $33,927	-

Source: (SEPA 2023)

Uncertain Compensation and Value Recovery

Most utilities are still in the early stages of developing bidirectional charging programs, and few offer direct compensation for energy discharged from EVs. There is currently no standardized framework for compensating energy exported from bidirectional charging systems, and the classification of electricity exported from these systems remains ambiguous. Unlike solar generation, bidirectional EVs do not qualify for NEM tariffs, and unlike stationary batteries, they do not seamlessly integrate into existing demand response (DR) or energy storage compensation structures. This regulatory gap complicates their inclusion in prevailing rate designs and incentive programs. Existing programs, such as ConEd's Value of Distributed Energy Resources tariff, are limited in scope and often restricted to commercial or fleet applications. Although fleet operators typically face the lowest annual revenue requirement—estimated at approximately $470 per vehicle—to justify bidirectional operation, the absence of stable and predictable revenue recovery mechanisms presents a significant barrier that must be addressed to mitigate uncertainty in overall cost-effectiveness (SEPA 2023).

Battery Degradation Anxiety and OEM Warranty Limitations

Battery degradation remains a key source of hesitation for V2X adoption. While studies suggest that shallow cycling may have negligible impact or even extend battery life, OEMs have yet to broadly endorse V2X use under warranty. Most OEMs restrict bidirectional usage to V2H or V2L, citing insufficient real-world battery degradation data as the primary reason.

This uncertainty affects consumer behavior and EV procurement. Until OEMs provide standardized guidance and broader warranty coverage, battery degradation anxiety will continue to suppress demand and limit market growth.

Uncertainty in Energy Impacts

As mentioned earlier in this report, there is limited real-world performance data on commercially available V2X products and systems under representative conditions that clearly validate energy efficiency benefits. This is further exacerbated by the limited commercially available V2X EVs and EVSE.

The feasible measurement of energy transacted during V2X operations by leveraging the EV technology itself remains challenging. While many EVSE units incorporate dedicated metrology for revenue-grade metering, EV on-board telematics are not engineered to provide this level of measurement accuracy. This issue is further compounded by the absence of formal standards that specify data formats, nomenclature for reported parameters, and accuracy thresholds across platforms. Since EVs are mobile DERs that do not have a fixed PCC, they may interconnect to existing infrastructure in a variety of ways. For this reason, it may be difficult to disaggregate EV energy signatures from other loads, such as BTM DERs, by using existing AMI infrastructure. Thus, it is imperative to ensure that V2X telemetry data is sufficiently accurate for energy-metering purposes.

An EPRI independent validation of measurement accuracy across multiple EVs and EVSE units revealed notable deviations when compared to measurements from laboratory-grade instrumentation (EPRI 2024). Independent testing revealed notable discrepancies in energy measurement accuracy across various charging systems and EV telematics platforms. For AC Level 2 chargers, shorter test cycles of 5 minutes were associated with increased error, ranging from −2 percent to −17 percent, while a DC fast charger demonstrated a best-case deviation of −7 percent. EV telematics systems showed substantially higher inaccuracies, with errors between −16 percent and −60 percent, particularly during charging sessions involving auxiliary load usage. This uncertainty in measurement accuracy could limit the integration of EVs into performance-based incentive pathways.

Lack of Efficiency Standards for V2X

Currently, there are no universal industry standards that mandate minimum efficiency requirements for V2X bidirectional equipment. This is primarily due to the prioritization of other key barriers, such as cost, interoperability, and technology maturity. It is important to deliberately address this through collaborative efforts that involve relevant V2X stakeholders.

V2X Adoption Roadmap for Hard-to-Reach (HTR) and Disadvantaged Communities (DAC)

The development of a V2X adoption roadmap for hard-to-reach (HTR) and disadvantaged community (DAC) market segments was informed by researching case studies and relevant secondary literature, as well as engagement with a project developer with specialized expertise in all-electric housing solutions for socioeconomically underserved populations.

The team deemed the following key findings from the research relevant to advancing equitable V2X adoption in HTR and DAC market segments:

- Grid voltage disparities are correlated to disadvantaged designation, per the criteria specified for the Climate and Economic Justice Screening Tool (CJEST). Communities designated as disadvantaged based on the CJEST methodology were twice as likely to have low-voltage circuits (Interstate Renewable Energy Council 2025).
- Circuits in disadvantaged communities had 10.5 percent to 23 percent less normal and overload capacity. (Interstate Renewable Energy Council 2025).
- Carbon-intensive peaker plants are often located in or near underserved communities (DOE 2025).
- High upfront costs are a significant barrier.
- EV battery packs that have degraded to 70 percent to 80 percent of their original capacity are designated as second-life batteries, which are no longer suitable for vehicular usage (DOE 2025). Second-life batteries can be subsidized as cost-effective offerings for existing load flexibility and self-generation incentive programs that target underserved communities.
- Multifamily residential dwellings deal with inherent space restrictions that limit conventional on-site charging infrastructure options in many cases. Shared mobility business models, such as ridesharing, can be viable alternative solutions that are compatible with these constraints.
- Commercial fleets—e.g., buses, garbage trucks, etc.—are considered suitable first adopters of V2X due to their firm availability and predictable parking location costs (Gschwendtner, Sinsel and Stephan 2021)

Goal 1: Expand Access to V2X Infrastructure and Mobility Options

Strategy 1A: Enable Shared Mobility and Community-Based V2X Models

Due to the high upfront costs of V2X EVs and EVSE, shared mobility programs offer a practical and scalable pathway to electrified transportation in underserved communities. EV OEMs can utilize leasing business models to defer the upfront cost and avoid the risk of ownership. One V2X stakeholder proposed a creative agreement in which EV OEMs donate bidirectional EVs to municipality funded ridesharing initiatives in exchange for public relations benefits, such as promotional advertising on city transport.

Shared mobility programs can take advantage of various federal grants and initiatives that allocate funds to underserved communities, including the CARB Clean Cars 4 All initiative and the Clean

Mobility Options Voucher Program, the latter of which has invested more than $66 million in under-resourced communities and Tribes to address mobility gaps and reduce air pollution.

Strategy 1B: Expand Make-Ready Infrastructure Eligibility

Make-ready programs can subsidize the incremental cost of bidirectional EVSE and fund the infrastructure needed to install EV chargers—such as wiring, trenching, and electrical panel upgrades. However, the eligibility for this funding is usually restricted to "publicly accessible" chargers. This definition typically excludes bidirectional EVSE installed in multifamily housing, assigned parking spaces, or community-serving locations where chargers are not open to the public, which hampers V2X adoption in in DAC and HTR communities.

One V2X EVSE OEM and software provider suggested the following policy recommendations to address this funding inequity (Fermata Energy 2024):

- Modify "public access" definitions to include chargers that provide public grid value, even if physically located in private or assigned spaces.
- Explicitly allow V2X chargers in multifamily housing and underserved neighborhoods to qualify for make-ready infrastructure funding.
- Remove restrictions that disqualify chargers based on assigned parking or lack of shared access.

Goal 2: Enhance Local Resilience with V2X Technology

Strategy 2A: Integrate V2X with Resilience Investments

Since HTR and DAC communities are more likely to be served by old, low-voltage grid infrastructure, local resiliency should be prioritized in V2X implementation to ensure equitable access to electrification and clean energy benefits. An analysis of FirstEnergy's service territory found that CEJST-designated disadvantaged communities were twice as likely to have low-voltage circuits and had grid infrastructure that was 3.4 to 4.2 years older than in non-disadvantaged areas, with 10.55 percent to 23 percent less circuit capacity—conditions that limit hosting capacity for DERs and V2X technologies (Interstate Renewable Energy Council 2025).

To overcome these disparities, V2X deployment could be co-located with resilience investments, such as microgrids with on-site PV and battery storage. The Meridian at Corona Station project in Petaluma, California demonstrates this approach, featuring an all-electric multifamily development with bidirectional EVSE and a microgrid that powers the community for 95 percent of the year, along with a standby grid connection for emergencies (EPRI 2024). Additional financial subsidies for second-life batteries from EVs could be designed and implemented specifically for underserved communities.

Recommendations

Based on the study findings, the team synthesized the following recommendations for advancing implementation and adoption of V2X technology for key technology stakeholders.

Recommendations for Industry

Establish Feasible Cost-Recovery Mechanisms for Bidirectional Export

It is essential to establish clear cost-recovery mechanisms that adequately value the bidirectional capability of V2X. Currently, V2X EVs are subject to a lack of parity with stationary ESS, with which they compete with for the provision of equivalent services during stationary applications. This lack of parity is primarily due to regulatory and subsidy restrictions that hamper value stacking through the various cost-recovery and revenue-generation mechanisms that stationary ESS benefit from. For example, bidirectional EVs are unable to export to the grid under NEM tariff structures, thus limiting them exclusively to BTM or resilience-based use cases. As alluded to earlier, reliably modelling the cost of battery degradation due to bidirectional operation is still an emerging area of research that will require more empirical data of real V2X systems. As such, EV owners are not compensated uniformly for battery degradation impacts, if at all.

An example of a solution proposed by a V2G implementor involves adjusting the eligible EV battery storage capacity to reflect the actual amount of energy storage available for export (Fermata Energy 2024), which could be specified based on factors that are representative of the EV behavior specific to a given situation. Emerging research efforts present consolidated data, which reflects the impacts of several factors on available EV storage capacity. Below, Table 13 presents an example from a study that estimated seasonal impacts on energy consumption for two V2G use-cases from empirical data (Robert Alfie S. Pena 2025).

Table 13: V2G energy consumption after the morning drive phase of the passenger EV use case.

Use Case	Available capacity before V2G (kWh)	Remaining capacity after V2G (kWh)	New SoC after V2G (%)
Summer (Use Case 1)	15.75	7.75	29.8
Winter (Use Case 2)	12.92	4.92	18.9

Source: (Robert Alfie S. Pena 2025)

Similar data could be leveraged to establish fair criteria for specifying available V2X system battery firm capacity that is eligible for incentives.

Develop Consolidated Framework for Testing and Evaluating V2X Efficiency Parameters

A clear gap identified during this study was the lack of industry standard protocols and methodologies for uniformly evaluating and measuring V2X energy efficiency performance metrics, such as AC RTE, DC RTE, and standby power consumption.

Independent research institutes, such as PNNL, have developed protocols for stationary ESS, whose design and functionality closely overlaps with V2X systems in stationary use cases. These protocols can serve as a valid basis for the development of similar protocols for V2X systems. For example, the CEC utilizes a load-adjusted efficiency for PV inverters that acknowledges the time spent at representative operational points (Sandia National Laboratories n.d.). This procedure could be modified into a testing methodology for EV batteries.

An example of this approach could involve selecting specific battery C-rates that are representative of targeted use cases and testing them for RTE performance in accordance with established duty cycle testing requirements that correspond to the use-case. The C-rates could then be multiplied by appropriate weighting factors and consolidated into a DC RTE metric that corresponds to the expected V2X use case.

Recommendations for Utilities

Streamline Interconnection Process

To facilitate scalable deployment of V2X bidirectional charging systems, interconnection pathways should be streamlined by aligning them with existing DER processes, particularly for load-only and islanded configurations that warrant minimal review (Vehicle Grid Integration Council (VGIC) 2022). Regulators should permit flexible transitions between configurations post-installation, avoid routing small-scale V2X systems through large generator procedures, and establish interim approval mechanisms for AC V2X systems utilizing emerging standards (Vehicle Grid Integration Council (VGIC) 2022).

Performance Based Incentives

There are existing methodologies that specify protocols for evaluating efficiency of stationary BESS systems that leverage on real world operational data from metering infrastructure, including the Battery Energy Storage System Evaluation Method developed by NREL for the Federal Energy Management Program. This methodology uses the actual metered charge and discharge data to determine various RTE metrics. This approach would reflect real-world performance and efficacy of a V2X system and could facilitate the design and implementation of performance-based incentive programs for V2X systems. Eligibility criteria could be customized based on factors such as the market segment or targeted use cases. This can be implemented via existing AMI infrastructure and revenue-grade submetering, or by leveraging the capabilities of the V2X telematics.

Recommendations for V2X OEMs

Optimize Inverter Part-Load Efficiency

During this study, the team observed that certain V2X applications—particularly V2H and V2B—may experience operational inefficiencies due to misalignment between system performance characteristics and real-world constraints. For example, a study that analyzed actual residential home energy management system (HEMS) data from V2H systems found that discharging power levels were frequently limited by household demand, resulting in underutilization of available discharging capacity (Y. Iwafune and T. Kawai 2024). When the rated capacity of charging infrastructure significantly exceeds the average demand of the connected loads, the system operates at part-load conditions.

For stationary systems like BESS, designers can specify battery and inverter configurations with a high degree of modularity and flexibility to suit diverse service requirements. These systems often incorporate multiple batteries and inverters optimized for specific use cases, allowing dynamic switching and scaling based on grid demands. In contrast, V2X systems are inherently limited by the architecture of individual EVs, which typically feature a single fixed battery and, in some cases, an on-board inverter. Furthermore, an EV may interact with various EVSE during its lifetime due to mobility. This restricts the ability to reconfigure components or tailor performance to varying grid services. Additionally, the need to prioritize mobility imposes strict constraints on weight, space, and thermal design, further reducing flexibility.

These limitations highlight the need for continued optimization of inverter and battery efficiencies (AC RTE and DC RTE) across diverse operational modes without compromising vehicle functionality. To meet this challenge, OEMs must align inverter performance more closely with the characteristics of the loads they serve, particularly by improving bidirectional part-load efficiency for duty cycles representative of targeted V2X use cases.

Clarify Messaging on Battery Degradation and Warranties

EV OEMs should provide clear guidance on the implications of bidirectional charging for battery health and warranty coverage, particularly as V2X applications expand beyond V2L and V2H into grid-tied use cases such as V2G (SEPA 2023). While select OEMs have begun approving bidirectional operation under constrained conditions, a lack of standardized messaging remains prevalent across the industry.

To support market confidence and accelerate adoption, OEMs should delineate warranty parameters by V2X application type, disclose expected battery degradation profiles under typical cycling scenarios, and align product documentation with utility program requirements. This clarity is essential for enabling informed customer decision-making and for facilitating integration into utility-managed programs and virtual power plant platforms.

Address Gaps and Non-Uniformity in Reported V2X Efficiency Metrics

As observed during research of commercially available V2X products, there were frequent gaps in key efficiency metrics, such as DC RTE, AC RTE, and standby power consumption. The team also observed non-uniformity in the types of efficiency metrics reported across product classes, such as EVSEs. This lack of uniformity limited comparison between like-for-like products.

These gaps should be addressed to promote transparency of the representative efficiency performance capabilities of the products under standardized conditions, which will facilitate more accurate technoeconomic analysis of V2X system performance during stationary operation.

Recommendations for Standards Bodies

Establish Standardized EVSE and EV Telematics Data Requirements

Real-time data from V2X systems (e.g., SoC, kWh transacted, standby power, etc.) that facilitate the evaluation and verification of efficiency performance metrics should be standardized to comply with uniform nomenclature, accuracy, and data format requirements. This can mitigate uncertainty in energy impacts by enabling more streamlined data measurement and verification.

Establish Fair System Boundaries for V2X Efficiency Determination

There are no rigorous methodologies or frameworks that outline specific guidance on the uniform characterization and measurement of energy efficiency performance of V2X systems. Findings from a secondary literature review indicate recurring inconsistencies in the definition of energy efficiency boundaries for V2X systems.

Energy efficiency system boundaries should be defined to capture both the direct energy impacts of bidirectional use cases and their interactive effects on other systems. For applications like V2G, which may inherently involve high standby power consumption (a recognized proxy for energy efficiency under ENERGY STAR guidelines), stakeholders emphasized the need for a holistic approach. This approach should account not only for device-level efficiency but also for broader grid-level benefits enabled by bidirectional export.

Develop Performance Rating Systems for V2X

Standards bodies and industry working groups should collaborate to develop comprehensive performance rating systems that are fluid enough to adapt and adjust to the emerging technological capabilities of V2X. The Research on Existing Guidance of V2X EVSE Efficiency Standardization section offered an example of a rating system developed for DC V2X systems by CharIN, which rewarded better performance at part-load conditions but did not account for standby power consumption performance.

Another performance rating system that could inform the development of V2X efficiency rating systems is the system performance index (SPI), which was developed by the Solar Storage Systems Research Group for grid-tied PV systems with stationary energy storage (Weniger J 2024). SPI tests the performance of HESS according to a representative duty cycle and ranks them based on AC RTE within performance classes that range from A (highest tier) to G (lowest tier), as shown in Table 14 below.

Table 14: System performance index rating system.

Class	SPI (5 kW)	SPI (10 kW)
A	≥ 92.5%	≥ 94.5%
B	≥ 90.5%	≥ 93.5%
C	≥ 88.5%	≥ 92.5%
D	≥ 86.5%	≥ 91.5%
E	≥ 84.5%	≥ 90.5%
F	≥ 82.5%	≥ 89.5%
G	< 82.5%	< 89.5%

Source: (Weniger J 2024)

This incentivizes systems operating at higher power levels to perform more efficiently and accounts for the specific duty cycle. However, like the CharIN rating system, it does not account for standby energy losses.

Minimum Efficiency Requirements

Minimum energy performance standards can serve as an effective policy tool to enhance the energy efficiency of V2X systems. By establishing a baseline level of efficiency across the market, these standards help eliminate the lowest-performing technologies or compel them to improve, thereby raising the overall energy performance of available products.

Minimum energy efficiency performance standards may also be preferable over rating systems in contexts where the product is complex, or consumers are not expected to have the time, resources, or interests to choose products based on energy efficiency (Langdon 2025). There are several key considerations that apply when implementing a minimum energy efficiency performance standard:

- Minimum energy performance standards should be designed to accommodate inherent technical differences across system types and configurations. For example, variations in energy efficiency between different storage technologies—such as lead-acid and lithium-ion—may reflect fundamental design trade-offs rather than poor performance. To avoid unintentionally excluding emerging or evolving technologies, differentiated standards or performance tiers may be necessary to avoid stifling emerging innovation.
- Voluntary energy performance standards can serve as a practical first step toward market transformation, offering a faster and less resource-intensive pathway than mandatory standards. They allow for early implementation and impact assessment while minimizing disruption to R&D efforts. However, if the underlying technical data is robust and stakeholder consensus is strong, policymakers may opt to proceed directly with mandatory standards to accelerate adoption and ensure consistent performance across the market.
- Minimum energy efficiency performance standards are effective at improving the efficiency of the worst performing products. However, if the aim is to provide incentives or resources to improve best-practice standards, an alternative policy mechanism could be required.

Future Research Efforts

A key gap identified during this study was the lack of empirical performance data for V2X systems under representative conditions. It is imperative to conduct more comprehensive testing and empirical measurement of energy efficiency performance metrics—such as AC RTE, DC RTE, standby power consumption, and component energy losses—for commercially available V2X products under real-world conditions. These conditions should include parameters such as EV battery capacities, SoC requirements, grid load conditions, utility tariffs, and charging environments (such as fleet, workplace, and residential).

According to a recent Lawrence Berkeley National Laboratory (LBNL) survey of gaps in existing research on EV charge management, field demonstrations should quantify the technical performance of individual and aggregated charging events to characterize the resources. The survey also recommended demonstrations should evaluate the technical performance of smart charging management to each V2X stakeholder comprehensively (LBNL 2024).

Further research on the energy efficiency benefits—such as energy loss reduction potential—of optimized forms of V2X smart charging strategies—such as efficiency-aware dispatch—could address this gap and create novel pathways for integrating V2X technology into the existing landscape of energy efficiency programs.

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Appendix A: V2X Field Demonstrations in US Jurisdictions

This section summarizes the performance of key V2X field demonstrations.

North Boulder Recreation Center (NBRC)

In 2020, the City of Boulder initiated a vehicle-to-building (V2B) demonstration at the North Boulder Recreation Center (NBRC) in partnership with a V2X EVSE OEM. Site selection involved a citywide assessment of public facilities, prioritizing buildings with peak electrical loads exceeding 100 kW and access to a city fleet vehicle. The deployment utilized an EV and a DC bidirectional charger to enable behind-the-meter power export from the EV battery to the NBRC facility. This configuration supported targeted peak demand reduction by discharging stored energy during periods of high building load. A project summary is provided in Table 15 below. Figure 29 depicts the monthly average bill savings realized by the customer during the first year of operation.

Table 15: NBRC V2X pilot summary.

V2X Configuration	Grid Parallel, Non-Export (V2B)
Use Case 2	Demand Reduction
Summer Capacity Value ($/kW)	$23/kW
Winter Capacity Value ($/kW)	$17/kW
Average Monthly Demand Reduction Achieved (kW/month)	13 kW

Source: (SEPA 2023)

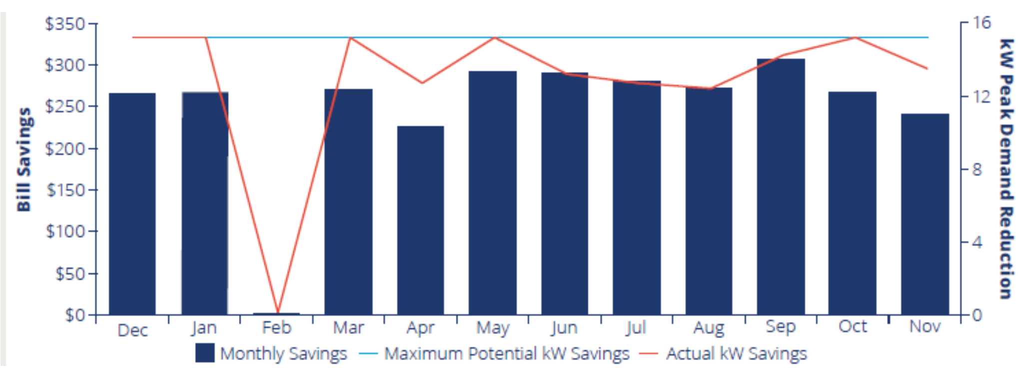

Figure 29: NBRC demand reduction and cost savings for year 1 (December 2020 – November 2021).

Source: (SEPA 2023)

Plymouth State University (PSU) and New Hampshire Electric Co-op (NHEC)

Plymouth State University (PSU), in collaboration with the New Hampshire Electric Co-op (NHEC), implemented a vehicle-to-building (V2B) demonstration using two EVs and a DC bidirectional charger. The project was integrated with NHEC's pilot Transactive Energy Rate (TER), a day-ahead electricity pricing structure. Real-time price signals were processed through an AI-enabled dispatch platform to identify economically optimal charge and discharge windows, i.e. energy arbitrage. PSU retained full discretion over EV dispatch, balancing grid services participation with vehicle availability for student transportation.

The system delivered over 1 MWh of energy across a six-month period, offsetting approximately 90 hours of building load and generating more than $1,300 in utility bill credits. The pilot also demonstrated cold-weather operational reliability and highlighted the potential of dynamic pricing frameworks to incentivize DER exports from bidirectional EV systems. A project summary is provided in Table 16 below:

Table 16: PSU and NHEC V2X pilot project summary.

V2X Configuration	Grid Exporting (V2G) and BTM Export (V2B)
Use Case 1	TOU Arbitrage
Use Case 2	Demand Reduction
Total Energy Exported (MWh)	1 MWh
Revenue Generated ($)	1300

Source: (SEPA 2023)

Revel Rideshare

In 2022, Revel launched a fleet-scale vehicle-to-grid (V2G) pilot at its Red Hook depot in Brooklyn, New York, in partnership with an EVSE OEM. The installation included three DC bidirectional chargers and three EVs, configured solely for grid export. The V2G system was interconnected to the Consolidated Edison (ConEd) grid under a modified stationary storage protocol, becoming the first bidirectional EV deployment to receive interconnection approval in the utility's service territory. The system participated in ConEd's Value of Distributed Energy Resources (VDER) tariff, discharging daily during the 2–6 PM window to earn revenue under Demand Reduction Value (DRV) and Installed Capacity (ICAP) provisions. In 2022, the pilot generated $6,000 under DRV and $4,500 under ICAP, with anticipated earnings of $10,000 for the 2023 summer season. The project demonstrated the technical feasibility of V2G operations in a dense urban environment while uncovering tradeoffs between fleet availability for core operations and grid service participation. A project summary is provided in Table 17 below:

Table 17: Revel Rideshare V2X pilot project summary.

V2X Configuration	Strictly Grid Exporting (V2G)
Use Case 1	TOU Arbitrage
Use Case 2	Demand Reduction
kWh Incentive Rate ($/kWh)	0.854 $/kWh
kW Incentive Rate ($/kW-yr)	100 $/kW-yr
Total Revenue from Energy Transacted ($)	$6,000
Total Revenue from Demand Reduction ($)	$4,500

Source: (SEPA 2023)

Appendix B: V2X System Architectures

V2X Architectures

V2X systems may exhibit different characteristics depending on factors such as inverter configuration, the number of power conversion stages, and diversity of power conversion pathways. Although the following classification framework is not formally recognized by any existing standards, it was determined to be generally reflective of current market offerings. Therefore, it may serve as a useful basis for uniform comparisons between EVSE with similar design attributes.

DC V2X System

In the DC architecture (DC V2X), both the power conversion and smart inverter functions are located within the Electric Vehicle Supply Equipment (EVSE). The EVSE performs grid-interface responsibilities and effectively operates as a stationary smart inverter, capable of grid synchronization, bidirectional power flow, and grid services provision. DC configurations are widely agreed to be the most technologically mature V2X solution. Since the DC V2X architecture closely resembles conventional stationary energy storage systems, they typically qualify for a more streamlined certification and interconnection process under existing DER interconnection rules (e.g., CA Rule 21). A schematic of this system architecture is depicted in Figure 30 below.

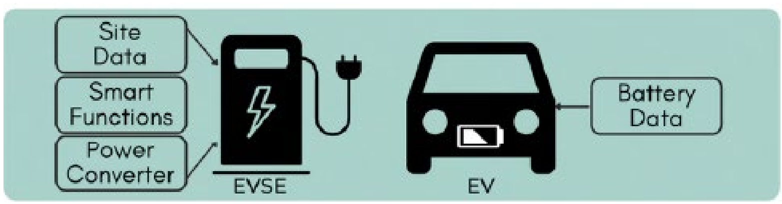

Figure 30: DC V2X system.

Source: (IREC 2022)

AC V2X System

In the AC architecture (AC V2X), the power conversion and smart inverter capabilities are embedded within the vehicle itself. The EV manages voltage synchronization, power quality, and communication protocols, functioning as a mobile smart inverter. AC coupled V2X systems are currently less mature than DC coupled systems. Although conceptually attractive due to the reduced hardware cost – namely, the elimination of an off-board bidirectional charger – widespread adoption remains limited. Key barriers include incomplete standardization and limited certification pathways. A schematic of this system architecture is depicted in Figure 31 below.

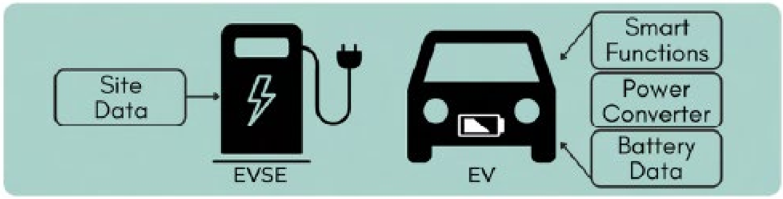

Figure 31: AC V2X system.

Source: (IREC 2022)

Hybrid V2X System

A hybrid V2X architecture supports both AC and DC interfaces. It exhibits characteristics of both AC and DC V2X systems and typically features alternative power conversion pathways. For example, a grid-parallel V2H system that is integrated with an on-site PV array may charge using imported power from the grid or electricity generated from the PV system. EPRI developed a prototype EVSE known as SPIN system that supports integration with other DERs (e.g. PV, hydrogen fuel cell etc.) via multiple ports. Thus, it allows for flexibility in charging options depending on PV availability. A schematic of the SPIN system is depicted in Figure 32 below.

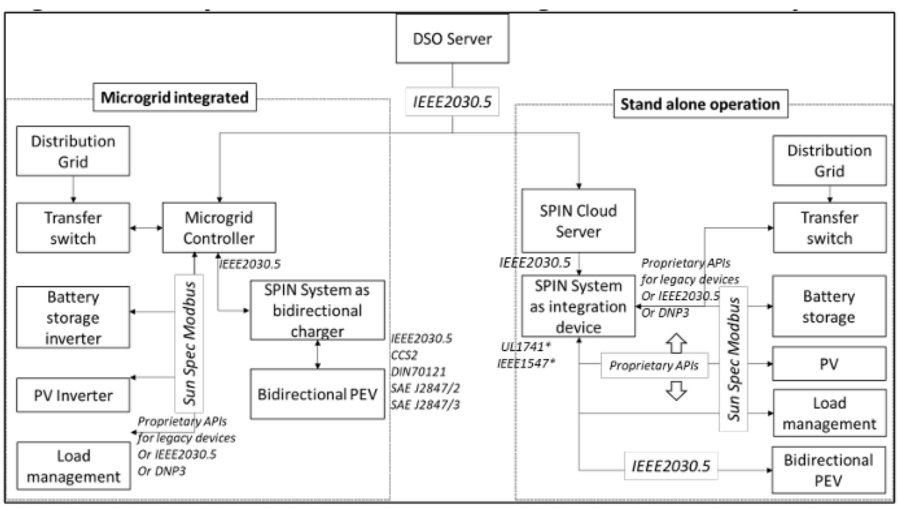

Figure 32: Schematic of SPIN system architecture configured as microgrid or stand-alone operation (example of hybrid V2X).

Source: (EPRI 2023)

For further clarity, Figure 33 below presents an example of how stationary energy storage systems—analogous in design to V2X stationary systems—can be characterized using the classification framework described above.

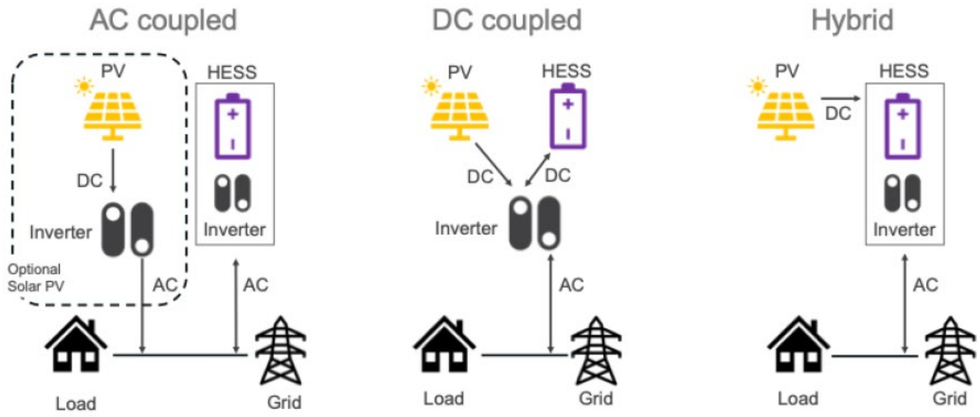

Figure 33: Classification of stationary energy storage systems.

Source: (N Orth 2023)

Appendix C: V2X Stakeholder Engagement Questionnaire

Proposed Interview Questions to V2X Industry SMEs

1. What V2X smart charging strategies have the highest potential for implementation at scale? What is the efficacy and readiness level of existing and emerging smart charging strategies and algorithms that are optimized for energy loss mitigation during typical V2X operations and aggregated dispatch events?

2. In your experience, what are the most effective strategies for minimizing round-trip losses during charging and discharging?

3. Are there efforts being made to standardize efficiency definitions as well as testing and reporting conditions for different V2X implementation scenarios (V2H, V2G, V2M) and use cases (Frequency regulation, TOU arbitrage)?

4. Are there any real-world examples where energy efficiency constraints have been hard-coded into V2X dispatch algorithms? If so, what was the outcome?

5. Are there consensus-building efforts among industry groups to align on RTE boundary conventions (e.g., AC-to-AC vs. DC-to-DC) across use cases?

6. Are there design attributes that make a V2X system more appealing for grid integration inherently result in efficiency penalties?

Proposed Interview Questions to V2X OEMs

1. How are bidirectional inverters in V2X applications being optimized for energy export?

2. How are system efficiency testing conditions being aligned with real world V2X use cases? Are there standard testing conditions for measuring V2X efficiency?

3. What use cases are commercially available V2X products and solutions offerings being optimized for?

4. Can your EVs support feedback control based on energy loss metrics (e.g., inverter temperature, voltage efficiency)? Is this part of current V2X product development roadmaps?

5. Is there coordination between OEMs and aggregators to enhance EV telematics data visibility? Are there efforts being made to include data on EV telematics dashboards and interfaces that gives users and fleets more visibility on the energy efficiency associated with their V2X system?

6. How should battery degradation effects on V2X system round trip efficiency be modelled?

7. Are you able and willing to provide any of the following types of datasets or similar ones to inform the independent characterization of V2X efficiency metrics assuming anonymity?

   - Empirical measurements of system RTE for different permutations of commercially available (or soon to be) V2X systems from laboratory test beds, V2X pilots under simulated conditions or real-world operation.

- Product performance datasets (e.g. EV battery, inverter) under varying conditions that have implications for energy efficiency or energy losses (e.g. Variations in temperature, power level etc.)

Proposed Interview Questions to Standards Bodies and Industry Working Groups

1. What efforts are being made to develop minimum efficiency requirements for V2X technology that have implications for energy losses during typical V2X use cases?
2. Are any working groups currently developing performance-based efficiency tiers (e.g., RTE > 80%) analogous to ENERGY STAR or similar labels for stationary DERs?
3. Is there opportunity to introduce minimum efficiency requirements for V2X products based on current levels of commercial readiness?
4. What is the rationale behind selecting specific test conditions (ambient temperature, SoC range, power levels) for proposed efficiency test protocols?

Proposed Interview Questions to V2X Pilot Program Implementers

1. How are the energy impacts of V2X EV quantified behind the meter?
2. Are V2X specific submetering approaches being explored to better characterize their energy efficiency performance when delivering their typical services?
3. What are the perceived risks or uncertainties for key elements of V2X pilot programs (i.e., technology performance, lack of customer uptake, integration challenges, lack of supported commercially available products)? How are they being mitigated to scale V2X?
4. Is there potential for system RTE to be accounted for in V2X program design and implementation?
5. Have any minimum efficiency requirements been discussed for V2X systems that are eligible for pilot program participation?
6. What kind of data and key performance indicators (KPIs) would you want to see on a V2X product catalogue to facilitate more optimal program design and implementation?
7. Have pilot participants expressed concerns about energy losses and battery degradation?
8. How is the adoption of V2X by disadvantaged communities (DAC) and hard-to-reach (HTR) market segments being addressed during program and pilot development?

Proposed Interview Questions to V2X Trade Allies/Installation Contractors

1. Are contractors receiving training or product documentation on energy efficiency characteristics of V2X inverters or EVSE?
2. Are there any challenges you have encountered during commissioning related to control settings or interconnection configurations that affect RTE?

3. Do system design choices (e.g., panel upgrades, wire gauge) meaningfully influence energy losses in practice?

Proposed Interview Questions to V2X Software Providers

1. What are the main software integration challenges associated with V2X EVs?
2. In prior V2X system deployments that you have served as the aggregator for, what kinds of energy loss mitigation dispatch schemes (if any) have you had success implementing under real world conditions? Do you feel that there is promise for this?
3. Are there any real-world examples where energy efficiency constraints have been hard-coded into V2X dispatch algorithms? If so, what was the outcome?
4. How do you envision energy loss-aware dispatch constraints being balanced against other objectives such as grid reliability or user mobility preferences?

Appendix D: Overview of V2X Control Strategies and Scheduling Approaches

This section provides background information on the classes of control strategies and EV dispatch scheduling approaches that typically form the basic framework more most V2X smart charging strategies.

Centralized Control Strategies

Centralized approaches rely on a supervisory controller (e.g., aggregator, utility, or grid operator) to optimize and dispatch charging/discharging schedules based on global system conditions such as locational marginal prices, distribution grid congestion, and renewable generation forecasts.

Aggregated load profiles and price signals dictate the dispatch behavior of V2X EVs accordingly. These strategies enable large-scale participation in ancillary services, frequency regulation, and demand response (DR) programs by orchestrating fleets of EVs based on market participation criteria and forecasted system needs.

However, this approach may under-optimize individual EV round-trip efficiency due to generalized setpoints that do not reflect vehicle-specific physical parameters (e.g., inverter efficiency curves, SoC limits, temperature). Aggregator systems often rely on simplified or average efficiency assumptions, potentially leading to increased cumulative energy losses when implemented at utility scale.

Decentralized/Distributed/Local Control Strategies

Decentralized approaches shift the optimization burden to a more local node in the grid infrastructure such as the EVSE, EV, or energy management system (EMS), allowing decisions to be made based on local information (e.g., PV output, real-time SoC, temperature, or homeowner preferences).

Since decentralized approaches may optimize EV charging behavior based on local conditions rather than at the distribution and bulk transmission levels, they may provide better energy loss mitigation potential for individual V2X EV owners and fleet operators.

Resource Forecasting and Dispatch Scheduling Approaches

Forecasting and dispatch scheduling strategies form the operational backbone of V2X smart charging control systems. These approaches aim to coordinate EV charging and discharging behavior with grid conditions, price signals, and DER availability through pre-planned or dynamically updated control signals. Depending on the temporal granularity and forecasting horizon, V2X dispatch strategies are typically categorized into day-ahead scheduling and real-time or near-real-time dispatch optimization, each presenting distinct tradeoffs in RTE, operational flexibility, and computational intensity.

Day-Ahead Forecasting and Scheduling

Day-ahead scheduling relies on 24-hour forecasts of grid demand, time-of-use pricing, distributed generation (e.g., PV), and EV availability to generate baseline dispatch schedules. These strategies are widely used in aggregator-operated DR programs and ancillary service markets that require advance capacity commitments. The main advantage of day-ahead scheduling is its compatibility with existing ISO and regional transmission operator markets and DR program design, allowing aggregators to bid aggregated V2G capacity into markets such as CAISO's day-ahead ancillary services or resource adequacy structures.

However, the inherent uncertainty in EV driver behavior, fleet availability, and localized DER output can lead to suboptimal dispatch outcomes. This may result in increased reliance on corrective real-time dispatch or operational setpoints that diverge from optimal inverter efficiency zones. For instance, under-forecasted solar output or unexpected early vehicle departures may prompt mid-cycle discharges from low SoC levels, reducing round-trip efficiency due to elevated inverter and battery losses at these operating conditions. Studies leveraging predictive modeling approaches such as stochastic programming or ensemble learning have attempted to improve the robustness of day-ahead schedules. However, these often require access to high-quality telematics data, which may not be universally available in commercial deployments.

Real-Time and Near-Real-Time Optimization

Real-time dispatch approaches leverage hourly or more granular real-time data on grid load constraints, DER generation, EV SoC, ambient temperature, and network constraints. This class of control strategies is especially relevant for V2X implementations in microgrids, commercial fleet depots, or dynamic pricing pilot programs.

Appendix E: V2X EV and EVSE Catalogued Product Specifications

V2X EV Catalogued Data

Table 18: Catalogued V2X LDEVs

V2X LDEVs								
OEM	Ford	Ford	Genesis	Genesis	Genesis	GM	GM	Hyundai
Model	F-150 Lightning (Extended Range)	F-150 Lightning (Standard Range)	G80 EV	GV60	GV70	Silverado EV RST	Hummer EV Pickup	Ioniq 5
V2L Capable	x	x	x	x	x	x	x	x
V2G Capable	x	x	-	-	-	x	x	-
V2H/V2B Capable	x	x	-	-	-	x	x	-
V2V Capable	x	x	-	-	-	-	-	-
Battery Chemistry	Li-ion	Li-ion	Li-ion	Li-ion	Li-ion	Li-ion	Li-ion	Li-ion
Battery Size/Nominal Energy Capacity (kWh)	131	98	87.2	77.4	77.4	200	212	77.4
V2X Max Output Power (kW)	9.6	9.6	1.9	3.6	3.6	9.6	6	3.6
Battery RTE (%)	-	-	-	-	-	-	-	-

Source: OEM specification sheets.

Table 19: Catalogued V2X MDEVs and HDEVs.

V2X MDEVs and HDEVs								
Manufacturer	Blue Bird	Blue Bird	BYD	BYD	Lion Electric	Lion Electric	Lion Electric	Thomas Built Buses
Model	Vision Electric	All American RE Electric	BYD Type A	BYD Type D	Lion Electric LionA	Lion Electric LionC	Lion Electric LionD	Saf-T-Liner C2 Jouley
V2L Capable	-	-	-	-	-	-	-	-
V2G Capable	x	x	x	x	x	x	x	x
V2H/V2B Capable	x	x	x	x	x	x	x	x
V2V Capable	-	-	-	-	-	-	-	-
Battery Size (kWh)	155	155	156	255	168	168	210	226
Battery Chemistry	Li-ion	Li-ion	Li-ion	Li-ion	Li-ion	Li-ion	Li-ion	Li-ion
Battery RTE (%)	-	-	-	-	-	-	-	-
V2X Max Output Power (kW)	-	-	-	-	-	-	60	60

Source: OEM specification sheets.

V2X EVSE Catalogued Data

Table 20: Catalogued V2X EVSE

OEM	Model	AC V2X	DC V2X	Charging Efficiency (%)	Discharging Efficiency (%)	Peak Efficiency (%)	Continuous Efficiency (%)	Standby Power (W)	Round Trip Efficiency (%)	Operating Temperature Lower (°C)	Operating Temperature Upper (°C)
Rectifier	Highbury	-	x	96%	95%	-	-	-	-	-30	50
Enphase	IQ	x	x	-	-	98%	-	-	-	-30	55
Coritech	VGI-30	-	x	-	-	-	-	-	-	-18	-18
Wallbox	Quasar 2	-	x	97%	97%	-	-	-	-	-18	-18
dcbel	Ara	x	-	-	-	96%	98%	-	-	-	-
Fermata	FE-15	-	x	95%	-	96%	-	-	-	-	-
Fermata	FE-20	-	x	-	-	95%	-	-	-	-30	50
GM	Powershift Energy Inverter e1.11	x	-	96%	96%	-	-	8	0.975	-40	50
InCharge Energy	ICE-44 V2X	-	x	-	-	-	-	-	-	-20	70
Delta	LF_V2X_10kW	x	x	96%	96%	-	-	-	-	-30	50
Autel	Maxicharger V2X	-	x	-	-	96%	-	-	-	-25	50
Nuvve	RES-HD60-V2G	-	x	95%	-	-	-	-	-	-20	45
Nuvve	RES-HD125-V2G	-	x	95%	-	-	-	-	-	-20	45
Nuvve	EVSE-B-P3-T2-H1-A063	-	x	-	-	-	-	3.11	-	-30	40
Tellus Power Green	TP5-30-480-V2G-1	-	x	-	-	94%	-	-	-	-30	55
Tellus Power Green	TP5-40-480-V2G-1	-	x	-	-	94%	-	-	-	-30	55
Tellus Power Green	TP5-60-480-V2G-1	-	x	-	-	94%	-	-	-	-30	55
Heliox	HE9823009-01	-	x	-	-	95%	-	-	-	-18	-18
Ford	Charge Station Pro	x	-	-	-	-	-	-	-	-	-
Lucid	Home Charging Station	x	-	-	-	-	-	-	-	-	-

Source: OEM specification sheets.

Appendix F: CharIN Efficiency Rating System for DC V2X

Table 21: LPC class discharging efficiency proposed rating thresholds[15].

Power Range Designation	Power Range	Efficiency (Battery: 330V ± 30V)	Efficiency (Battery: 680V ± 30V)
Very low power range	P_{min} to 9% P_{ref}	Grade A: ≥73% Grade B: ≥70% Grade C: <70%	Grade A: ≥73% Grade B: ≥70% Grade C: <70%
Low power range	10% to 15% P_{ref}	Grade A: ≥93% Grade B: ≥90% Grade C: <90%	Grade A: ≥93% Grade B: ≥90% Grade C: <90%
Low power range	16% to 20% P_{ref}	Grade A: ≥95% Grade B: ≥92% Grade C: <92%	Grade A: ≥95% Grade B: ≥92% Grade C: <92%
Low power range	21% to 25% P_{ref}	Grade A: ≥96% Grade B: ≥92% Grade C: <92%	Grade A: ≥96% Grade B: ≥92% Grade C: <92%
Medium power range	26% to 50% P_{ref}	Grade A: ≥96% Grade B: ≥92% Grade C: <92%	Grade A: ≥96% Grade B: ≥92% Grade C: <92%
Medium power range	51% to 75% P_{ref}	Grade A: ≥96% Grade B: ≥92% Grade C: <92%	Grade A: ≥96% Grade B: ≥92% Grade C: <92%
High power range	76% to 100% P_{ref}	Grade A: ≥96% Grade B: ≥92% Grade C: <92%	Grade A: ≥96% Grade B: ≥92% Grade C: <92%

Source: (CharIN 2023)

Table 22: Fast charging, ultra-fast charging, and high-power charging class discharging efficiency proposed rating thresholds.

Power Range Designation	Power Range	Efficiency (Battery: 330V ± 30V)	Efficiency (Battery: 680V ± 30V)
Very low power range	P_{min} to 9% P_{ref}	Grade A: ≥72% Grade B: ≥69% Grade C: <69%	Grade A: ≥72% Grade B: ≥69% Grade C: <69%
Low power range	10% to 15% P_{ref}	Grade A: ≥92% Grade B: ≥88% Grade C: <88%	Grade A: ≥92% Grade B: ≥88% Grade C: <88%
Low power range	16% to 20% P_{ref}	Grade A: ≥94% Grade B: ≥91% Grade C: <91%	Grade A: ≥94% Grade B: ≥91% Grade C: <91%
Low power range	21% to 25% P_{ref}	Grade A: ≥95% Grade B: ≥91% Grade C: <91%	Grade A: ≥95% Grade B: ≥91% Grade C: <91%
Medium power range	26% to 50% P_{ref}	Grade A: ≥95% Grade B: ≥91% Grade C: <91%	Grade A: ≥95% Grade B: ≥91% Grade C: <91%
Medium power range	51% to 75% P_{ref}	Grade A: ≥95% Grade B: ≥91% Grade C: <91%	Grade A: ≥95% Grade B: ≥91% Grade C: <91%
High power range	76% to 100% P_{ref}	Grade A: ≥95% Grade B: ≥91% Grade C: <91%	Grade A: ≥95% Grade B: ≥91% Grade C: <91%

Source: (CharIN 2023)

15 P_{min} is the OEM specified lower limit for the EVSE operating power. P_{Ref} is the OEM specified upper limit for the EVSE operating power.

Appendix G: Empirical Efficiency Relationships

This section provides examples of empirical relationships between energy efficiency (or efficiency proxies such as power loss) and various parameters that were found during secondary research. This is not intended to be an exhaustive list. Rather, it is intended to provide high level awareness of practical ways of predicting energy efficiency behavior under changing conditions.

The relationship in Figure 34 below models the conversion losses (kWh) incurred during charging as a function of energy input (kWh) to the EV. It was developed from empirical data gathered from actual integrated home energy management systems (HEMS) in V2H deployments in Japan.

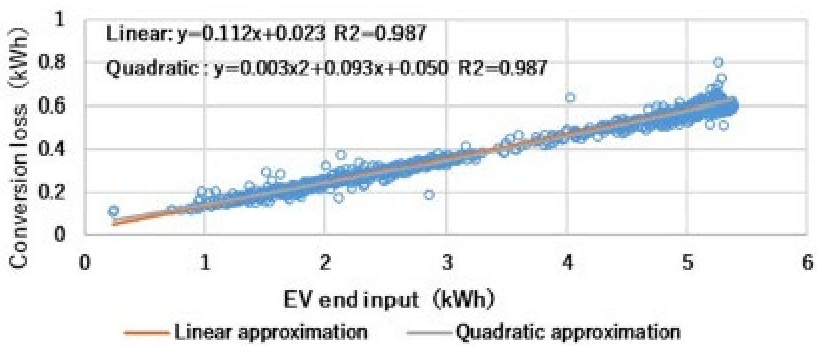

Figure 34: Power conversion loss for V2H charge.

Source: (Y. Iwafune and T. Kawai 2024)

This relationship in Figure 35 below models the conversion loss (kW) during charging as a function of EVSE AC-side power (kW). It was developed from empirical data that measured power losses across various components in a simulated V2G experiment under a variety of operating conditions.

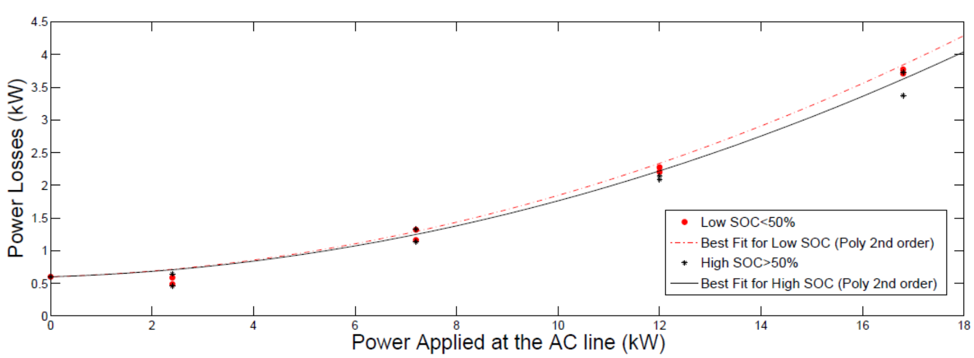

Figure 35: Round-trip EV losses against AC power.

Source: (E. Apostolaki-Iosifidou et al. 2017)

Appendix H: Efficiency-Aware Smart Charging Rule Setting Procedure

This section details a procedure for rule setting for EV scheduling and charging constraints. It is intended to be used as a resource for the development and validation of energy efficiency aware smart charging strategies for future demonstrations.

An example of scheduling for the PEV charging problem is Fixed-Rate First-Come-First Served (FR-FCFS) (Francesco A. Amoroso 2012). In this approach, if grid power is available, the charging process of each PEV connected to the grid is performed at a fixed rate and starts as soon as the PEV is plugged in, otherwise the request is added to a queue and sorted based on the arrival times of the users in the system. This way the charging behavior is optimized per the equipment's efficiency curve.

An alternative approach involves prioritizing charging EVs which will disconnect first from the grid. This prioritization can be refined by considering both the remaining time before the user departure and the energy still required. This approach may be implemented by defining a simple user priority index based on some relevant input parameters as seen in the formula below:

$$G(t) = \frac{E_R(t)}{P_{AVMAX} \times T_R(t)};$$

Source: (Francesco A. Amoroso 2012)

Where:

$G(t)$ is the user priority index
$E_R(t)$ is the remaining energy required at time instant t to complete the charging process.
P_{AVMAX} is the maximum available power from the grid.
$T_R(t)$ is the time still available before the user leaves.

This index can now be computed for each individual EV participating in a charging event to enable sorting based on the EV prioritization in the queue and subsequently be leveraged to schedule the charging of an arbitrary number of EVs. The independent variables that are used to determine the index can be selected and accounted for in different ways on a case-by-case basis based on specific needs.

The next step would require defining a charge rate adjustment rule to vary the rate at which the EV consumes or exports energy from the grid. A general framework for implementing charge rate adjustment logic is depicted in Figure 36 below. Once again, the level of sophistication of the logic that governs charging rate adjustment can be specified based on the degrees of freedom available in each situation.

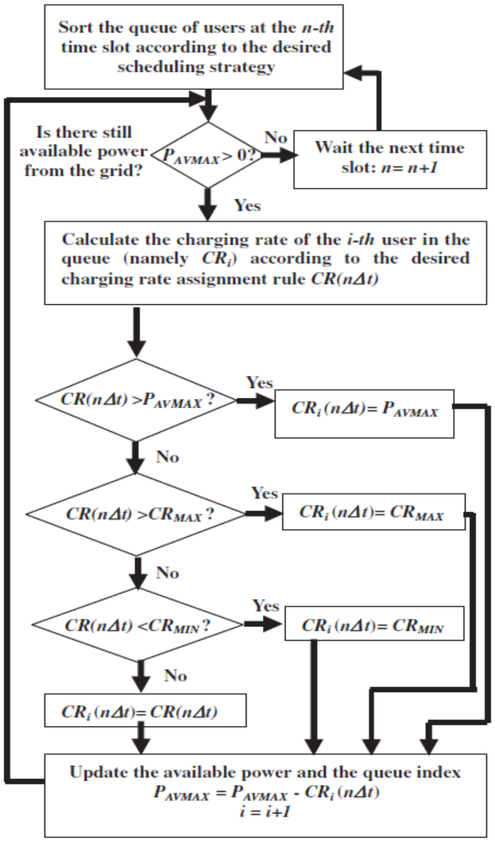

Figure 36: Basic operation of a smart variable-rate-based EV dispatching strategy.

Source: (Francesco A. Amoroso 2012)

The charge rate at a given time can be formulated as a function of energy still required by the EV as indicated below:

$$CR(t) = f[E_R(t)]$$

Source: (Francesco A. Amoroso 2012)

Where:

$CR(t)$ is the instantaneous charge rate.
$E_R(t)$ is the instantaneous remaining energy requirement of the EV to complete the charge event.

The remaining energy requirement at any arbitrary point during the charging process can be expressed according to the relationship below:

$$E_R(n\Delta t) = E_{R0} - \sum_{i}^{n-1} C_R(i\Delta t) \times \Delta t$$

Source: (Francesco A. Amoroso 2012)

The specific relationship between instantaneous charge rate and remaining energy requirement can now be customized. For example, an approach known as Variable-Rate Concentrated-Energy (VRCE) sets the charge rate to complete the charging event over a specific time increment Δt. It is expressed via the relationship below:

$$CR(t) = \frac{E_R(t)}{\Delta t}$$

Source: (Francesco A. Amoroso 2012)

Another approach known as Variable-Rate Spread-Energy (VRSE) involves spreading the energy required by the EV over the entire remaining period available. It is expressed via the relationship below:

$$CR(t) = \frac{E_R(t)}{T_R(t)}$$

Source: (Francesco A. Amoroso 2012)

For both the above approaches, a maximum and minimum available charge rate would need to be specified to reflect the grid and local system (EV battery, EVSE and/or local distribution panel) constraints.

The VRCE and VRSE approaches can be modified into their energy efficiency-aware counterparts by charging efficiency as an optimization variable to adjust the charge rate. The charging efficiency itself is a function of the charge rate as expressed via the formula below:

$$\eta(t) = f[CR(t)]$$

Source: (Francesco A. Amoroso 2012)

Where $\eta(t)$ is the instantaneous charging efficiency.

The modified expression for energy required by the EV at an arbitrary time slot after charging is initiated is now expressed as:

$$E_R(n\Delta t) = E_{R0} - \sum_{i}^{n-1} \eta[C_R(i\Delta t)] \times C_R(i\Delta t) \times \Delta t$$

Source: (Francesco A. Amoroso 2012)

Similarly, Efficiency-Aware Variable-Rate Concentrated Energy (EA-VRCE) is expressed recursively as:

$$CR(t) = \frac{E_R(t)}{\Delta t} \times \frac{1}{\eta[CR(t)]}$$

Source: (Francesco A. Amoroso 2012)

Efficiency-Aware Variable-Rate Spread Energy (EA-VRSE) is expressed recursively as:

$$CR(t) = \frac{E_R(t)}{T_R(t)} \times \frac{1}{\eta[CR(t)]}$$

Source: (Francesco A. Amoroso 2012)

Appendix I: Battery Degradation Mechanisms

Calendar Aging

Calendar aging refers to the progressive decline in battery performance due to time-dependent electrochemical reactions, independent of usage cycles. Elevated temperature and long dwell times at extreme state-of-charge (SoC) levels are principal accelerants of this degradation mechanism. Accelerated lab test data from NREL and EPRI on plug-in hybrid EVs held at a constant 30°C indicate that baseline degradation without V2G use was ~1.5% annually (EPRI 2023). This suggests that even outside of active cycling, V2X-capable EVs must contend with time-induced degradation, especially in climates or duty cycles that lead to elevated average battery temperature or extended dwell times at high or low SoC levels.

Cycle Aging

Cycle aging results from charge-discharge cycling and is influenced by depth of discharge (DoD), charging rates, and thermal conditions. V2X applications, particularly those providing frequent grid services such as frequency regulation or load shifting, significantly increase the number of shallow or deep cycles. An EPRI study observed that the addition of daily bidirectional V2G cycling (discharging approximately 43% of the battery's nominal energy capacity per day) added ~1.8% of incremental degradation annually. Over a 10-year period, this compounded to a total of ~33% capacity loss compared to 15% under mobility-only conditions. Despite this, the energy throughput accessed for grid services was 67% greater than that used under driving-only scenarios, reflecting a net gain in system utilization, albeit with faster degradation (EPRI 2023)

Capacity Fade

Capacity fade is the gradual reduction in usable energy capacity of the battery and is a composite result of both calendar and cycle aging. In V2X contexts, this reduction affects how much energy can be injected or absorbed per dispatch event. As capacity fades it diminishes the adequacy of the V2X asset for throughput dependent use cases such as energy arbitrage.

Laboratory testing results that simulated V2G operation on a commercially available 17.6 kWh plug-in hybrid EV pack indicate that capacity faded from 100% to ~67% of original capacity over a simulated 10-year V2G deployment, versus ~85% under standard mobility use (EPRI 2023). This dynamic has direct implications for V2X RTE. As capacity drops, idle energy losses can become a larger contributor to total losses.

Power Fade

Power fade denotes the reduction in maximum deliverable current or power output of a battery over time. While capacity fade directly limits energy throughput, power fade constrains peak dispatch ability, which may be critical for high-power V2X applications such as grid contingency support or fast-response ancillary services.

Experimental results from the U.S. DOE-supported testbeds indicate that although most battery degradation modeling emphasizes capacity, power fade becomes particularly relevant in later battery life stages or under high-rate cycling scenarios common in commercial or fleet V2G use cases. As internal resistance builds, energy losses increase during both charging and discharging events, which subsequently erodes RTE, especially under aggressive cycling profiles.

Appendix J: Supplemental Efficiency Definitions

Coulombic Efficiency/Faradaic Efficiency

Coulombic efficiency (also referred to as Faradaic efficiency) is a measure of the ratio of total electric charge extracted from a battery during discharge to the total charge put into the battery during the preceding charge cycle. Coulombic efficiency isolates electrochemical performance and is fundamentally concerned with charge conservation within the battery cell, exclusive of external power electronics and thermal losses. It can be expressed formulaically as:

$$\eta_{Coulombic} = \frac{Q_{discharge}}{Q_{charge}} \times 100\%$$

Where:

Q_{charge} : Total charge (Ah) supplied to the battery during charging.

$Q_{discharge}$: Total charge (Ah) extracted from the battery during discharging.

The measurement points are typically on the input and output terminals of the battery which ignore losses on any other connected equipment. This efficiency metric characterizes the total charge loss due to battery degradation mechanisms over the operational lifecycle such as lithium plating and SEI (Solid Electrolyte Interphase) layer growth.

Voltage Efficiency

Voltage efficiency is the ratio between the average voltage during battery discharge and the average voltage during battery charging. It reflects the energy lost due to internal resistance and polarization effects within the battery, which manifest as voltage drops during discharge and overvoltage during charge. Unlike Coulombic efficiency, which tracks the conservation of charge (Ah), voltage efficiency captures energy-related losses at the cell level. It can be expressed formulaically as:

$$\eta_{Voltage} = \frac{V_{avg,discharge}}{V_{avg,charge}} \times 100\%$$

Where:

$V_{avg,discharge}$: Average terminal voltage during the discharge cycle.

$V_{avg,charge}$: Average terminal voltage during the charge cycle.