Harmonizing Standards to Unlock Vehicle-Grid Integration

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ABSTRACT

Vehicle-grid integration (VGI) enables electric vehicles (EVs) to evolve from a growing source of electrical demand into flexible assets that provide grid services and support building-level energy storage and management. While the potential is significant, several barriers must be addressed to enable widespread adoption.

One major barrier is a fragmented standards landscape related to VGI technology. While alignment efforts are underway, the gaps and overlaps in the standards landscape create uncertainty. Utilities, vehicle manufacturers, and aggregators face questions about which technologies, communications protocols, and standards to prioritize and how to ensure interoperability across EVs, chargers, aggregators, and the grid.

This paper will provide a comprehensive look at the VGI landscape and identify key opportunities for standardization. Drawing on extensive literature review and professional experience informed by stakeholder engagement with automakers, utilities, charging providers and regulators, our authors assessed the technical readiness, benefits, and limitations of four key VGI applications: unidirectional smart charging (V1G), vehicle-to-load (V2L), vehicle-to-building/home (V2B/V2H), and vehicle-to-grid (V2G).

The result includes the identification of five priority opportunities to advance standardization and enable reliable, interoperable, and scalable VGI deployment. Our paper will walk through these opportunities and discuss the challenges and benefits of each.

For utilities, the benefits of VGI are compelling. VGI can help shape load curves, integrate more renewable energy, and defer infrastructure upgrades, all while deepening customer relationships through new value streams. For customers, under-utilized vehicles can deliver value by offsetting home/building-level energy demand, optimizing electricity costs, and providing a source of backup power during grid outages.

Realizing VGI's potential will require targeted standardization efforts to help ensure safety, interoperability, and grid compatibility.

Introduction

Electrification of transportation is rapidly transforming electricity systems. Electric vehicle adoption is accelerating globally as governments, utilities, and automakers pursue decarbonization strategies and transportation electrification goals. In North America, EV sales have increased significantly in recent years and are expected to continue growing throughout the coming decade, fundamentally reshaping electricity demand patterns and infrastructure planning for power systems (Muratori et al 2025).

While EV adoption will increase electricity demand, EV batteries also represent a large and rapidly growing pool of distributed energy storage. EV batteries will collectively represent one of the largest sources of distributed storage on electricity systems in the coming decades

(Kempton and Tomic 2005; Xu et al. 2023). As EV adoption expands, the aggregate capacity of EV batteries will far surpass the scale of stationary battery storage deployed on electricity systems.

Vehicle-grid integration (VGI) refers to technologies that enable coordinated interaction between EVs, buildings, and electricity systems. These technologies allow EVs to function not only as transportation assets but also as flexible energy resources capable of supporting electricity system operations.

VGI includes a spectrum of capabilities, and falls into 2 main categories:

- **Managed one-directional charging (V1G)**, which optimizes charging schedules to align with co-located loads or grid conditions
- **Bidirectional charging (V2G)**, which enables EV batteries to supply power to a building (V2B/V2H) or to the grid (V2G)

These capabilities offer significant benefits to electricity systems and building operators.

Managed charging can reduce peak demand and improve load management, while bidirectional charging – allowing charged EV batteries to send power back to the building or grid – can provide resilience benefits and potential revenue streams from grid services that may offset a substantial share of EV operating costs.

Despite these opportunities, VGI deployment remains limited. One of the primary barriers is the fragmented standards landscape governing EV charging, equipment certification, grid interconnection, communication protocols, and utility program design (CSA Group 2025). The automotive and electricity sectors are both highly regulated industries with long histories and complex technical standards. However, these sectors have developed and operated largely independently for over a hundred years. VGI requires these industries to coordinate in new ways, introducing challenges related to interoperability, certification, and market frameworks.

This paper examines how harmonizing standards across the VGI ecosystem could accelerate deployment. It reviews the emerging standards landscape and identifies five priority opportunities to improve coordination among industry stakeholders.

The Opportunity

Vehicle-grid integration encompasses a broad set of technologies and operational strategies that enable EV charging infrastructure to interact dynamically with electricity systems. VGI includes all forms of managed or "smart" charging, where charging schedules are optimized in response to facility or grid conditions, as well as bidirectional charging, where EVs can provide power back to a building or the electricity grid.

At its core, the concept is simple: an EV is a battery on wheels. The primary purpose of EVs is transportation, but a large proportion of vehicles have low utilization, spending much of their time stationary. U.S. Department of Transportation research shows that personal vehicles are parked approximately 95 percent of the time (U.S. DOE 2024), representing a large untapped opportunity to use EV batteries as flexible energy resources when they are not needed for driving. Unlike most electricity end uses which draw power instantaneously at their time of use, EVs draw power separately from when the vehicle is used – and as long as the battery has enough charge when it is needed for driving, the timing of charging has no inherent impact on the user. Some use cases need high speed, inflexible charging, such as highway fast charging and fleets with short dwell times – which are best suited to co-located stationary storage as a VGI strategy. However, the majority of charging takes place at home and at work with longer dwell times, and studies have consistently shown that EV charging demand is highly flexible when customers are given the option and incentivized to do so (SEPA 2023; IEA 2022). Studies of utility managed charging programs have demonstrated significant potential to shift EV charging away from peak demand periods while maintaining customer satisfaction and providing measurable grid benefits (SEPA 2024).

Similarly, electricity infrastructure is designed to meet peak demand that may occur only a small number of hours each year. Because electricity demand fluctuates by time of day and can increase dramatically during extreme temperatures, power systems must be built to ensure reliable supply even during rare peak demand events. As a result, generation, transmission, and distribution infrastructure often operates well below its maximum capacity during most hours of the year (Vanderhoof 2026).

VGI offers an opportunity to increase the utilization of both grid infrastructure and vehicles, and in so doing so increase the affordability of both. Additionally, VGI expands the decarbonization benefits of EVs. EVs reduce emissions by replacing internal combustion engine vehicles with electric drivetrains – EVs can provide the storage the grid needs to decarbonize other end uses by balancing variable renewable generation, charging when the wind is blowing or sun is shining, and discharging when the grid needs it. The International Energy Agency has estimated that by 2030 the global EV fleet could provide more than ten times the electricity system's short-duration storage requirements if bidirectional charging were enabled, highlighting the scale of the potential flexibility resource (IEA 2022).

The customer proposition for VGI is intuitively appealing. EV owners could earn revenue by allowing their vehicles to participate in grid services when parked, while also gaining additional resilience benefits through backup power capabilities. Just as modern smartphones evolved from single-purpose communication devices into multifunction digital platforms, EVs have the potential to evolve from transportation devices into multi-functional energy assets. Our own analysis described in this paper and several analyses in the literature indicate that the potential grid value of bidirectional EVs in some North American markets exceeds the annual cost of charging an EV, depending on compensation mechanisms and market participation models (Argonne National Laboratory 2021; VGIC 2022). Conceptually, in any jurisdiction where stationary storage is a cost-effective resource, V2G is also likely to be a cost-effective resource, and can be incentivized to participate in the same types of mechanisms and programs as stationary storage and other demand response. This offers the prospect of 'free' fuel for EV drivers, and potentially net revenue generation, if and when compensation mechanisms exist to enable it.

For automakers and charging providers, VGI capabilities can enhance product differentiation and create new business models and service offerings, and will accelerate sales if and when compensation mechanisms exist to pay for the grid benefits of VGI.

For utilities and grid operators, EV charging represents a growing revenue source and a flexible distributed energy resource. Managed charging programs can help utilities accommodate new EV load without increasing peak demand and help defer infrastructure investment needs, alleviating upward pressure on electricity rates. For example, EV load management has been demonstrated for peak reduction or managing infrastructure capacity constraints at multiple levels, and the optimization objective yields different aggregate load shapes – from managing load behind one specific meter, through to various distribution, transmission and bulk system levels (SEPA 2024). Bidirectional charging technologies can provide access to wide-spread distributed storage, at potentially significantly lower cost than stationary storage – put simply, if EVs are sitting in customers' driveways and parking lots, the battery capacity is already 'paid for', and the incremental cost to make that available to the grid is far less than the full cost of the battery capacity itself.

More broadly, vehicles and electricity infrastructure represent two of society's largest capital investments and historically operate at relatively low average utilization rates. Vehicle-grid integration offers an opportunity to increase the utilization of both asset classes, potentially reducing the overall cost of transportation, electricity systems, and decarbonization pathways.

The Problem

Despite this strong potential, VGI deployment remains limited (CSA Group 2025, SEPA 2024).

The technical building blocks required to enable vehicle-grid integration are not new. Most chargers, or electric vehicle supply equipment (EVSE), are Wi-Fi enabled. Most EVs on the market today are equipped with vehicle telematics and software interfaces that also allow customers to control charging preferences. The resilience value of V2G was demonstrated in practice as early as 2011, when Nissan Leaf vehicles were deployed in Japan to provide backup power following the earthquake-triggered tsunami and Fukushima nuclear disaster, and Nissan launched a commercially available 'LEAF to Home' power system in Japan in 2012 (Nissan 2012). The enabling technologies for managed charging are the same as more mature forms of demand response such as smart thermostats. The enabling technologies for V2G are the same as back-up generators and distributed renewables, which have been around for decades – such as isolation switches, inverters and bidirectional meters.

However, realizing this opportunity requires coordination across multiple industries and regulatory frameworks. The benefits of VGI are distributed across automakers, utilities, charging providers, regulators, and consumers. No single stakeholder group has complete control over the ecosystem required to enable these technologies at scale.

The primary barrier is ecosystem fragmentation rather than technology. VGI faces a three-way chicken-and-egg problem:

- Utilities are waiting for technologies to reach the market
- Automakers and technology providers are waiting for customer demand
- Customers are waiting for clear incentive pathways and programs

This is not a technology problem – it is a coordination problem. As a result, progress toward large-scale VGI deployment has been slower than the underlying technological capabilities might suggest.

Vehicle-Grid Integration Applications

Vehicle-grid integration encompasses multiple technical applications that allow EV charging infrastructure to interact with buildings and electricity systems. The opportunity for VGI energy- and load-management can be split into four key categories.

Managed Charging (V1G)

Managed charging refers to the ability to control EV charging schedules in response to grid conditions (SEPA 2024). Charging can be shifted away from peak demand periods, aligned with renewable generation, or optimized to minimize system costs. This can include bulk system costs, as well as distribution system and facility-specific costs.

Utilities across North America are increasingly deploying managed charging programs as EV adoption grows. This includes passive managed charging, such as using time of use rates to encourage EV customers to shift their charging behaviour to off-peak times of day, as well as direct managed charging, where the utility or a third party sends a direct control signal to slow or stop charging during peak events or directly optimizes charging schedules within the customers' selected preferences. Studies have shown that managed charging can significantly reduce peak demand impacts and defer distribution system upgrades (SEPA 2024). Managed charging is particularly relevant for large electricity customers such as commercial buildings and industrial facilities. Smart charging infrastructure integrated with building energy management systems can coordinate EV charging with other building loads such as heating, cooling, and water heating – either to maintain building demand below a certain threshold, such as to avoid triggering capacity upgrade costs, or for dynamic co-optimization of facility electricity costs.

Vehicle-to-Load (V2L)

Bidirectional charging allows EV batteries to both draw power and provide power. Vehicle-to-load refers to a vehicle providing power to a single load, disconnected from any other system – such as the ability to power construction tools or camping equipment. This is the most common form of bidirectional charging enabled by EVs available in today's market.

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

Bidirectional charging allows EV batteries to discharge electricity back into buildings or homes. This can provide back-up power for resilience during outages. These systems include grid isolation devices in addition to bidirectional charging equipment, such as a transfer switch, similar to the system configuration for conventional back-up generators. In this paper, vehicle-to-home or vehicle-to-building (V2H/V2B) refers to systems which operate only whilst isolated from the grid, such as providing back-up power during grid outages. However, this label is sometimes used to refer to systems that also operate whilst grid connected, and which offset the load from a building while it is grid-connected but do not export power directly to the grid.

Residential V2H systems have been deployed in several pilot programs and commercial products, allowing EV batteries to provide backup power to homes during outages. Amongst the earliest and most well-known US examples include PG&E's vehicle-to-everything (V2X) pilot programs in California, which include a residential as well as commercial and micro-grid programs streams, launched in 2022; as of writing, the current V2H eligible products list for PG&E's program includes Ford, GM and Tesla products (PG&E 2026).

Vehicle-to-Grid (V2G)

Vehicle-to-grid systems enable EV batteries to provide power to the grid or to a building while grid-connected. These systems can be limited to offsetting a building's load with no net grid export, or can export power directly to the grid. These systems can provide the same benefits and grid services as a stationary battery systems, including peak demand reduction, ancillary services such as frequency regulation, and renewable energy integration (CSA Group 2025).

Several pilot projects have demonstrated the potential for EV fleets to provide grid services through V2G participation. Fleet vehicles – including school buses and delivery vehicles – are often early candidates due to predictable operating schedules and centralized charging infrastructure (Argonne National Laboratory 2021). However, personal vehicles offer the largest potential market for V2G value if they can be enabled and aggregated at scale, because they represent by far the largest segment of the vehicle market, have a relatively low utilization rate on average, and collectively provide a much larger pool of battery capacity than fleet vehicles if they can be enabled and aggregated at scale (Xu et al 2023, IEA 2022). It is also important to note that V2G has materially greater value to the grid than managed charging (V1G) per unit, it is not simply a 2x multiplier – this is because the grid value of V1G is limited to offsetting EV charging demand that otherwise would have occurred, which typically does not have a high coincidence factor with peak times, whilst V2G can be dispatched at any time the vehicle is connected up to the installed capacity (Guéret et al 2025). As an illustrative example, imagine a residential vehicle with an EVSE capable of charging or discharging at a rate of 7kW, and where the average coincident on-peak charging demand is 1kW – managed charging can offset up to 1kW of peak demand, while V2G could contribute an additional 7kW towards offsetting system peak. FERC Order 2222 requires all federally regulated US electricity grids to allow small distributed energy resources to participate in electricity markets through aggregation – which will enable EVs to participate in virtual power plants and compete against traditional fossil fuel resources (FERC 2020).

V2G DC versus AC

It is also worth noting that different equipment configurations are relevant for AC versus DC bidirectional charging. All bidirectional charging requires an inverter for a DC-AC conversion. The inverter can be inside the vehicle, or outside of the vehicle as part of the EVSE/installed system configuration. To date in North America, most bidirectional systems are DC, requiring an inverter outside of the vehicle – however, EVs that enable AC bidirectional charging may enable lower incremental customer costs or enable a greater proportion of EVSEs to provide V2G. As of writing, the first bidirectional AC-capable product available for purchase in the US is the Tesla Cybertruck (PG&E 2026).

Cautionary Note: 'Capable' versus 'Enabled' VGI Applications

It is important for all potential purchasers to be aware that buying a 'smart charging capable' or 'bidirectional-capable' vehicle or charger does not mean that if you buy that product, you can use its VGI capabilities – including those mentioned in this paper[1]. This applies to both smart charging and bidirectional charging. To enable any bidirectional use case requires a full technology stack with interoperable hardware, software and communications, as well as enabling utility rules and processes, and capable or certified installers – including but not limited to both a vehicle and an EVSE (charger) (CSA Group 2025). For example, an EVSE marketed as 'bidirectional-capable' may only be capable of bidirectional power flow if paired with an AC-V2G vehicle that isn't available in your region, and may not guarantee backward-compatibility in future – and similarly, while the V2G-DC-capable vehicles referenced above in PG&E's eligible equipment list are commercially available across North America, the compatible V2H charging systems are not, at the time of writing. There may also be warranty considerations. This is further discussed below.

The VGI Standards Ecosystem

Deploying VGI requires coordination across multiple technical systems that historically evolved independently.

Key sectors include:

- automotive technologies
- EV charging infrastructure
- building energy systems
- electricity grid operations

Each of these sectors is governed by its own standards organizations and technical protocols.

Major standards bodies involved in VGI include:

- **ISO**, which defines vehicle-charger communication protocols
- **IEEE**, which establishes distributed energy resource interconnection standards
- **UL**, which provides safety certification for electrical equipment
- **Open Charge Point Protocol (OCPP)**, which governs charger-network communication

These standards address different aspects of the VGI ecosystem, as depicted in Figure 1, including:

- communication between vehicles and chargers

[1] Please note that specific products are mentioned in this paper as examples for reference purposes only, and should not be interpreted as recommendations for any specific product nor brand by the authors.

- communication between chargers and grid operators
- safety certifications for charging equipment
- grid interconnection requirements

While many of these standards are evolving rapidly, lack of alignment across jurisdictions and industries creates uncertainty for technology providers and utilities.

Figure 1. Vehicle-grid integration ecosystem

Key Barriers to VGI Deployment

Based on the literature cited in this paper and the authors' professional experience in practice, several categories of barriers arise from the fragmented standards landscape. This is supported by stakeholder engagement across multiple previous and ongoing projects

Interoperability Uncertainty.

Manufacturers and charging providers must navigate multiple evolving communication standards, including ISO 15118 and OCPP. Lack of alignment across standards can create uncertainty around which technologies will achieve long-term interoperability.

Certification Barriers.

Certification requirements for bidirectional charging equipment can delay market entry. These standards for bidirectional chargers are still evolving, and certification pathways may vary across jurisdictions.

Utility Interconnection Processes.

Utilities often lack standardized processes for approving bidirectional charging installations. Existing interconnection rules were developed primarily for renewable generation and stationary distributed energy resources and may not fully accommodate mobile resources such as EVs. Existing interconnection processes were also developed primarily for larger resources, which warrant custom engineering and system design attention, and may not be suitable to enable mass-market adoption of VGI applications.

Market Value Uncertainty.

Automakers and technology providers require clear market signals identifying the types of grid services that EVs can provide, and how customers will be compensated for providing those services. The value to the grid of VGI is material in the context of vehicle economics, and would provide a clear value proposition if customers could monetize this value. However, without clear compensation mechanisms, the business cases for VGI remain uncertain. Automakers are multinational companies with long product development lead times. The market size influenced by an individual electric utility is not sufficiently large to cover the costs of custom product development and equipment certifications – EVs and EVSEs are designed for global and North America-wide markets. As a result, individual utilities and jurisdictions have a limited ability to influence the market alone, but have significant purchasing power or market influence together.

These barriers create a classic "chicken-and-egg" problem, as illustrated in Figure 2. Automakers hesitate to enable V2G capabilities without a clear customer value proposition, while utilities hesitate to develop programs until compatible vehicles and chargers become more widely available. Customers will not adopt VGI unless the technology is readily accessible, and they are incentivized to use it in a way that provides benefits to the grid.

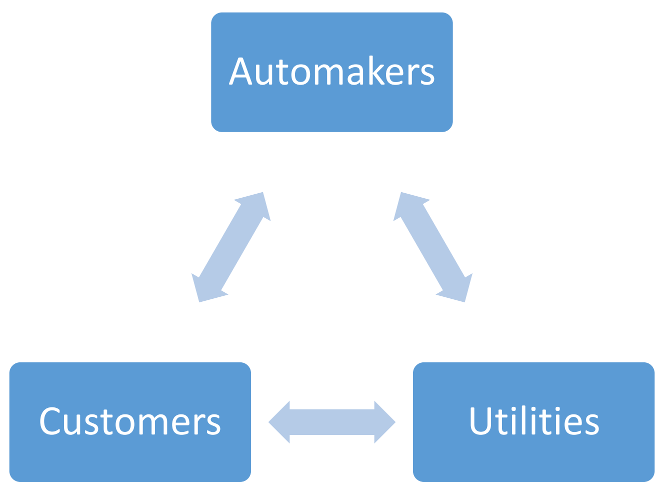

Figure 2. The VGI deployment "chicken and egg" coordination challenge

Five Opportunities to Harmonize the VGI Ecosystem

Our experience across recent VGI and broader grid advisory projects, supported by multiple reports published by our clients and partners (including CSA Group and VGIC) in addition to independent literature cited in this paper, suggests five key opportunities for harmonizing the VGI ecosystem. These opportunities have been informed by stakeholder engagement with automakers, utilities, charging providers and regulators across multiple previous and ongoing projects (reports are cited where public).

1. Harmonized Communication Standards and Certification Pathways

Interoperability between EVs, chargers, and grid systems requires alignment across communication protocols such as ISO 15118 vehicle-to-charger communication protocols and Open Charge Point Protocol (OCPP) standards used by charging networks (CSA Group 2025; VGIC 2022). Harmonizing certification processes can reduce the costs and reduce delays in bringing bidirectional charging equipment to market. Some jurisdictions have mitigated this barrier by allowing temporary exceptions, matching their requirements with other jurisdictions, or developing specific authorized equipment lists, allowing technologies to reach the market while broader industry standards and certification pathways continue to evolve. Examples include California and New York (VGIC 2025).

This mirrors the path of EVSE charging standards and one-directional charging interoperability overall – EVs first came to market with multiple different charging connectors and communication protocols, and the North American market has gradually standardized around harmonized protocols through ongoing multi-stakeholder coordination work.

2. Standardized Installation and Grid Interconnection Frameworks

Utilities require clear processes for approving bidirectional charging installations. One of the key learnings from utility programs for renewables and stationary storage was that developing standardized and streamlined interconnection frameworks is key to reduce administrative barriers, approval delays, and provide clarity for customers and project developers (US DOE 2026).

Simplified single line diagrams, installation configurations, and interconnection frameworks would provide clear implementation standards for VGI. This in turn would help technology providers develop the relevant capabilities; would help customers and their enablers, such as electricians, understand what they need to purchase and install to enable VGI; and would help utilities with program design (CSA Group 2025).

3. Grid Services Dispatch and Operational Models

Grid operators have an opportunity to define how EVs can participate in electricity markets and demand response programs. Clear dispatch models are needed to integrate EVs alongside other distributed energy resources. Harnessing the potential of VGI will require operational frameworks for aggregating EV fleets, grid operator visibility and control requirements, and dispatch models for flexibility services.

Harmonizing these standards would enable technology providers to develop products to meet those needs, and would allow grid stakeholders to evaluate the ability of products to provide those services, and collect comparable data to incorporate in integrated resource planning and program design. For example, Ontario's IESO developed DER Test Cases to collect data and evaluate different DER technologies on an apples-to-apples basis (IESO 2023). Identifying grid services needs and operational models would also enable the development of testing standards for specific technology stacks, without requiring full interoperability – for example, for combinations of vehicles, chargers and software systems that are capable of collectively enabling the dispatch of grid services (CSA Group 2025).

4. Market Signals and Compensation Mechanisms

Customers and automakers need clear economic incentives for participating in VGI programs. Transparent compensation mechanisms for grid services can help establish viable business models. While EV charging is an inherently flexible load, customers need to be incentivized to participate in utility programs.

The EV market is expanding rapidly, and EV and EVSE manufacturers focus development efforts on the features that customers care most about and are most likely to drive sales. To date, other features have been perceived as higher priority to customers than VGI, as evidenced by market developments and features available to today's consumers – for example, paying for charging through multiple apps became a pain point for customers, and the industry has since made strides in rolling out integrations and one-touch payment to solve this need. The theoretical value of VGI to the grid is material in the context of vehicle economics and customer motivations – as noted above, the value to the grid of V2G could offset a customer's entire annual cost of charging a vehicle, if that value could be monetized by the customer. However, in order to motivate customers and technology providers to bring these technologies to market, clear compensation mechanisms and incentives are needed at scale.

5. Cross-Sector Coordination Mechanisms

Finally, effective coordination between utilities, automakers, regulators, and standards bodies is essential to align technical requirements and market frameworks, and develop real-world pilot program data.

Industry forums and collaborative initiatives can play an important role in facilitating this coordination. VGI technologies have been demonstrated at lab scale and demonstration project scale in multiple jurisdictions and use cases, both globally and in North America. The theoretical potential value to the grid is clear, and has been well studied (Argonne National Laboratory 2021; VGIC 2025; Xu et al. 2023). However, real-world pilot programs are needed to understand the customer experience and to collect data on performance, participation, and program design considerations. These are the data that will be needed to develop products that provide compelling value to customers, and that will enable utilities to prove the cost-effectiveness of VGI as a grid investment to obtain regulator approvals and unlock utility investments at scale.

Conclusion

Vehicle-grid integration represents a major opportunity to transform EVs into flexible grid resources capable of supporting electricity system affordability, reliability and decarbonization. For utilities and building energy professionals, VGI represents a new opportunity to integrate transportation electrification with demand-side management strategies and introduce new revenue-generating opportunities.

Managed charging programs can help utilities reduce peak demand impacts from EV adoption while enabling customers to benefit from time-of-use pricing or demand response incentives. Commercial buildings and fleet operators may benefit from integrating EV charging infrastructure with building energy management systems. Bidirectional charging technologies provide new revenue opportunities that could more than offset the cost of charging EVs, and can also enhance building resilience and provide backup power during outages.

However, achieving this potential requires coordination across multiple industries and standards ecosystems. Harmonizing communication protocols, certification pathways, interconnection processes, market frameworks and scalable pilot programs can significantly accelerate VGI deployment. As EV adoption continues to grow, aligning these standards will be critical to unlocking the full value of EVs as assets for electricity systems and customers.

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AI-assisted tools used: ChatGPT

Used for: synthesizing original authored content, summarizing, drafting.

Extent: drafting sections of text.
Human review: The authors reviewed and verified all content, calculations, and citations.