STANDARDS RESEARCH

Charging Ahead: Unlocking Vehicle-Grid Integration in Canada

August 2025

Authors

Isabel Taylor, M.E,S., Dunsky Energy + Climate Advisors

Brendan McEwen, M.C.P., Dunsky Energy + Climate Advisors

Jeff Turner, M.Eng., Dunsky Energy + Climate Advisors

Manasi Goyal, B.A.Sc., Dunsky Energy + Climate Advisors

Project Advisory Panel

Adile Ajaja, EVLO Energy Storage, Inc.

Andrew Pride, Andrew Pride Consulting

Michael Hart, Tesla, Inc.

Nathalie Benoit, Hydro-Québec

Namat Elkouche, CSA Group

Olga L. Arevalo-Quintero, CSA Group

Tony Wong, CSA Group (Project Manager)

Acknowledgments

We thank all individuals and organizations whose contributions made this report possible. Special thanks to our interviewees for sharing their valuable insights and expertise.

Financial Support

CSA Group acknowledges that the development of this publication was made possible, in part, by the financial support of Natural Resources Canada.

Table of Contents

Executive Summary

The electrification of transportation is accelerating across Canada, with electric vehicles (EVs) expected to play an increasingly central role in reducing emissions, improving energy affordability, and enhancing grid flexibility. However, EVs also represent a substantial and growing source of electrical demand. If left unmanaged, this demand could pose significant challenges for existing electrical systems, including increased strain on grid infrastructure and higher costs.

To manage these impacts, vehicle-grid integration (VGI) is emerging as a powerful potential solution. VGI refers to a suite of technologies and strategies that enable EVs to interact with and support the electricity grid. When implemented effectively, VGI can unlock new value streams for consumers, utilities, and the broader energy system. This report provides a comprehensive assessment of the VGI landscape in Canada, focusing on four key applications: unidirectional smart charging (V1G), vehicle-to-load (V2L), vehicle-to-building/home (V2B/V2H), and vehicle-to-grid (V2G). It evaluates the technical readiness of each application, their respective benefits and limitations, and their implications for EV battery life and system performance. The research includes a review of existing literature, analysis of current standards and protocols, and insights from expert interviews across industry, utilities, and academia.

The VGI standards landscape in North America is diverse and evolving, spanning EV and electric vehicle supply equipment (EVSE) interfaces, grid interconnection, and communication protocols. Key standards, such as SAE J3072 and ISO 15118-20, support bidirectional power transfer and secure EV-charger communications. Grid interconnection is governed by IEEE 1547, UL 1741, and related Canadian standards, while protocols, such as IEEE 2030.5, Open Automated Demand Response (OpenADR), and Open Charge Point Protocol (OCPP), along with emerging frameworks like IEC 63110, facilitate coordination between EVs, utilities and system operators, and charging networks and third-party aggregators.

Despite this progress, several gaps and challenges in the standards landscape remain, including:

- **Fragmentation and overlap across standards,** creating uncertainty that can increase compliance costs, slow product rollout, and limit investment.
- **Proliferation of misaligned communication protocols,** reducing interoperability across the VGI delivery chain—from utilities and aggregators to EVs and EVSE.
- **Emerging standardization for V2G-AC (alternating current) systems,** including evaluating them using existing frameworks and navigating a lack of mature and/or widely adopted standards.
- **Inconsistent utility interconnection processes,** varying across jurisdictions and creating inefficiencies for original equipment manufacturers and service providers.

To address these challenges, this report identifies five priority opportunities for standardization:

- **Facilitate communications protocol alignment** by developing guidance to help interested parties, including automakers, charging networks and aggregators, and grid operators, navigate the growing VGI communications landscape and inform decisions about protocol adoption.
- **Harmonize Canadian standards with international best practices** to improve interoperability, streamline regulatory compliance, and enhance market access.
- **Support V2G-AC standardization** by establishing a certification pathway for evaluating grid performance of V2G-AC applications as distributed energy resource systems.
- **Provide a basis for verification that a technology stack will deliver VGI** to facilitate the deployment of systems that have been proven to work with the landscape of protocols and standards available today.
- **Develop best practices for utility interconnection** to provide utilities with clear guidance on integrating grid-connected VGI applications (e.g., V2G, grid-tied V2H/V2B) into their grid operations.

VGI offers transformative potential for Canada's electricity systems, but realizing this potential will require targeted standardization efforts to help ensure safety, interoperability, and grid compatibility. By advancing the standards landscape, Canada can better position itself to capture the economic, environmental, and resilience benefits of integrating EVs into its electricity systems.

List of Abbreviations

AC	Alternating current
AMI	Advanced Metering Infrastructure
CE	Canadian Electrical
CMS	Charging management systems
CSP	Communication service provider
DC	Direct current
DER	Distributed Energy Resource
DERMS	Distributed energy resource management system
DMS	Distribution management systems
DoD	Depth of discharge
DR	Demand response
DSO	Distribution system operator
EPS	Electric power system
EV	Electric vehicle
EVEMS	Electric vehicle energy management system
EVSE	Electric vehicle supply equipment
GO	Grid orchestration
EV	Electric vehicle
HVAC	Heating, ventilation and air conditioning
ICT	Information and communications technology
IEEE	Institute of Electrical and Electronics Engineers
ISE	Interconnection system equipment
ISO	Independent system operator
NEMA	National Electrical Manufacturers Association
OCA	Open Charge Alliance
OCPP	Open Charge Point Protocol
OEM	Original equipment manufacturer

OpenADR	Open Automated Demand Response
OSCP	Open Smart Charging Protocol
PCE	Power conversion equipment
PCS	Power Control System
PEL	Power Export Limiting
PIL	Power Import Limiting
SAE	Society of Automotive Engineers
SDO	Standard Development Organization
SoC	State of charge
TOU	Time-of-use
UI	User interface
UL	Underwriters Laboratories
V1G	Vehicle-one-grid
V2B/V2H	Vehicle-to-building/home
V2G	Vehicle-to-grid
V2L	Vehicle-to-load
V2X	Vehicle-to-everything
V2X-AC	Vehicle exporting AC power
V2X-DC	Vehicle exporting DC power
VGI	Vehicle-grid-integration

"EVs represent a substantial and growing source of electricity demand that, if left unmanaged, could strain existing grid infrastructure and drive up costs."

1 Introduction

1.1 Background

The adoption of electric vehicles (EVs) is increasing rapidly, driven by consumer demand, technological advancements, and supportive policies. Transportation electrification, and the broader energy transition, could reduce emissions and air pollution, make transportation more affordable, drive economic development, and improve Canadians' quality of life [1], [2].[1] At the same time, EVs represent a substantial and growing source of electricity demand that, if left unmanaged, could strain existing grid infrastructure and drive up costs.

An emerging area addressing EV-related grid impacts is vehicle-grid-integration (VGI), which refers to the suite of technologies, strategies, or policies designed to mitigate the impacts and costs of EV charging on the electric grid [3]. VGI enables EVs to function as flexible electrical grid assets by managing factors like charging times, power output, power flow direction, and charging locations. This flexibility can reduce costs and facilitate the integration of renewable energy resources, benefiting grid operators, utility ratepayers, and EV users alike. VGI encompasses a range of applications, including unidirectional managed charging (vehicle-one grid [V1G], a type of automated demand response [DR]), as well as bidirectional EV power transfer applications, including vehicle-to-load (V2L), vehicle-to-building/home (V2B/V2H), and vehicle-to-grid (V2G) technologies.

VGI's potential value, and the landscape of VGI technologies, services, and applications, have evolved significantly in recent years. Collectively, these applications can increase the value proposition of EVs by enabling services, such as energy arbitrage (charging when electricity is low cost and clean, discharging when it is expensive and emitting), non-wires alternatives (deferring upgrades in distribution and transmission system assets), ancillary services (e.g., balancing services, reserves, frequency, and voltage regulation), backup power, and utility bill optimization. By the 2030s, EVs are projected to represent one of the largest sources of utility DR [4].

Despite significant advancements, challenges remain, including the need for clear standards and regulatory frameworks to maintain safety, interoperability, and widespread adoption. Furthermore, understanding the technological readiness and performance implications of bidirectional EV power transfer, particularly its effect on battery life and grid reliability, is essential for advancing these applications. This report addresses these challenges by exploring the potential of VGI applications, assessing the current technological and

1 EVs have lower lifecycle greenhouse gas emissions than conventional vehicles, even in regions with higher carbon intensity in their electrical grids in Canada [2].

regulatory landscapes, and identifying pathways to advance standards to support broader adoption and realization of benefits.

1.2 Purpose

This research report explores opportunities to better enable VGI, focusing on applications, such as V1G, V2L, V2B/V2H, and V2G. The specific purpose of this research report is to:

1. Provide an overview of VGI applications.
2. Assess the technological readiness and performance impacts of VGI applications.
3. Identify key gaps and challenges in the current standards landscape.
4. Outline recommendations to advance standards that support VGI adoption and help improve interoperability, safety, and functionality.

Several related topics are considered outside the scope of this study. In particular, this report does not address:

- Recycled or second-life EV batteries, which introduce unique safety and coordination challenges that require separate consideration in standards development.
- Building-scale electric vehicle energy management system (EVEMS) designed to optimize facility-level electrical capacity and load management. EVEMS are covered extensively in a previous report for CSA Group [5]. Likewise, CSA Group will shortly publish CSA 22.2 No. 343, *Electric vehicle energy management systems,* a product standard including performance criteria [6]. Thus, this report does not focus on EVEMS functions or the standards landscape for these applications.
- Use of bidirectional EV power transfer to avoid inclusion of certain loads in Canadian Electrical (CE) Code Section 8 load calculations, a niche application with regulatory and logistical complexities.

2 Methods

The findings and recommendations outlined in this report are based on a review of the published literature regarding VGI applications, technologies and system components, performance and battery impacts, and related protocols and standards. The researchers also conducted interviews with experts and market actors from Canada and the US.

2.1 Literature Review

The literature review focused primarily on VGI applications and performance, and battery impacts of bidirectional EV power transfer. The research team consulted primarily two types of sources: industry and academic literature, and standards and regulations.

First, academic and industry publications were reviewed to gather insights on VGI technologies, use cases, and performance considerations. Sources included peer-reviewed journals, technical white papers, government reports, and publications from industry organizations and utilities. Searches were conducted using the ScienceDirect and Google Scholar databases, employing keyword queries, including "VGI," "V2G," "V2B," "V2H," "V2L," "V1G," "bidirectional charging," "EV battery degradation," "grid interconnection standards," and "EV communication protocols." In addition, all sources listed in the Vehicle-Grid Integration Council's resources page were reviewed. Searches were limited to English-language documents published between 2015 and 2025. Each document was screened for relevance based on its abstract and table of contents.

Second, relevant standards were reviewed to understand the regulatory and technical context for VGI implementation. These standards were sourced from CSA Group's internal database and other standards development organizations (SDOs), including the Society of Automotive Engineers (SAE), Underwriters Laboratories (UL), and Institute of Electrical and Electronics Engineers (IEEE). In several cases, specific standards were identified and prioritized through expert interviews, helping to focus the review on the most applicable frameworks and protocols.

2.2 Expert Interviews

To enrich our understanding of VGI applications, technologies, and opportunities for standardization, we conducted expert interviews to validate findings from the literature review and gather practical insights into emerging challenges and opportunities. Potential interviewees were invited via email, and those who expressed interest were contacted to arrange a 60-minute interview via Microsoft Teams. Before each interview, participants received background information on the project's objectives and the interview questions. The interviews covered topics, such as defining VGI applications, standards considerations, technology readiness, and performance and battery impacts. Participants included Canadian utilities, original equipment manufacturers (OEMs) of VGI technologies, engineers, industry associations, researchers, and academics. All interviews were recorded using a web conferencing application, transcribed, and conducted with informed consent. The full interview guide and list of organizations interviewed are presented in the Appendix.

3 Results and Discussions

3.1 Vehicle-Grid Integration (VGI) Applications

This section introduces key applications of VGI, focusing on how EVs can interact with the grid to provide energy-related services. It outlines the five primary VGI use cases, each of which is summarized by infrastructure, applicable standards, and key benefits and challenges, and then compares the applications across requirements (equipment/infrastructure, policy/programs).

3.1.1 Overview of VG1 Applications

VGI is a broad term that captures several applications that leverage EVs to deliver energy-related benefits, including grid services, backup power, and lower energy costs. These applications involve using EV batteries as a source of energy (through bidirectional EV power transfer) and managing EV battery charging to support upstream electrical systems, or both. This section outlines and compares the five primary VGI applications:

1. **V1G:** Automated signals from a utility grid operator influence the timing and rate of EV charging.
2. **V2L:** EV supplies power to a specific load, such as an appliance, tool, or circuit.
3. **Islanded V2B/V2H:** EV provides power to a building or home during a power outage while disconnected from the grid.
4. **Grid-tied V2B/V2H:** EV supplies power to a building or home that is connected to the grid without a net export of power to the grid.
5. **V2G:** EV exports power to the electrical grid.

Among these, V2L, V2H/V2B, and V2G fall under the broader category of vehicle-to-everything (V2X), which refers to bidirectional EV power transfer applications (Table 1).

V2X deployments may exist in one of two states:

- **Islanded:** The EV exports power to a load that is not connected to the grid. Configurations include islanded V2H/V2B (i.e., temporarily disconnected from the grid, typically during an outage) and V2L applications. As part of V2H/V2B applications, grid isolation devices (e.g., microgrid interconnect devices) ensure that power is only provided to on-site loads and does not back-feed into the grid.
- **Grid-tied:** The EV exports power to loads that are grid connected. It involves applications such as V2G and grid-tied V2H/V2B. A grid interconnection framework is required in these circumstances, similar to those for on-site solar photovoltaic (PV) and other behind-the-meter generators.

Table 1: VGI applications

Unidirectional	Bidirectional (V2X)			
V1G	V2L	Islanded V2H/V2B	Grid-tied V2H/V2B	V2G

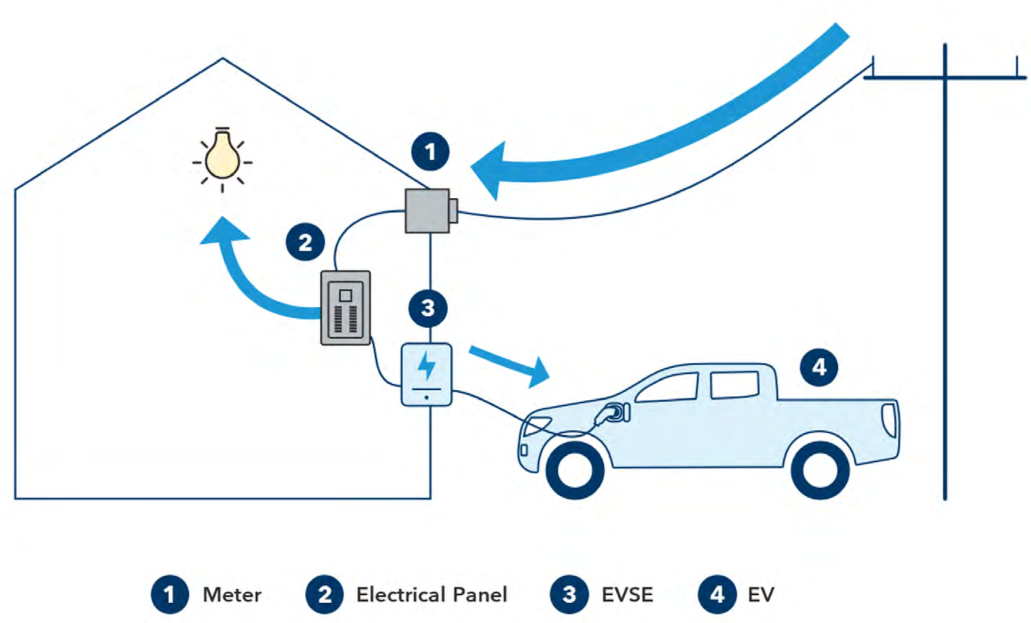
The applications described in this section are illustrative rather than exhaustive, highlighting the most common and impactful VGI use cases today. Each application is explored in terms of required infrastructure, relevant standards considerations, and high-level insights into feasibility, advantages, and limitations.

3.1.2 Unidirectional Smart Charging (V1G)

Unidirectional smart charging, also known as active managed charging or V1G, allows for one-way control of EV loads based on the needs of the local electrical grid (Figure 1). V1G differs from other VGI applications in that power flow is unidirectional. The technology required for V1G includes an EV and/or electric vehicle supply equipment (EVSE) capable of responding to signals from utility grid operators or aggregators that control EV charging and, in turn, communicate with grid operators.

Under active management, the EV charging rate can be influenced by automated external signals from a utility grid operator. It is analogous to V2G in that EV loads can be controlled; however, it does not involve bidirectional power export to the grid. Grid operators deploying V1G will use software systems and communications networks to send signals to dynamically influence the EV charging rate. V1G signals can be sent to aggregators, who will then control EV loads either through remote communication with networked EVSE, or communications directly to EVs via telematics systems.

Figure 1: V1G: Grid-responsive control of the timing and rate of EV charging.
The timing and rate of unidirectional charging is controlled to provide value to the grid.



Effective deployment of V1G relies on communication and interoperability standards to enable seamless coordination between EVs, EVSE, and grid operators.

Key standards considerations for V1G include:

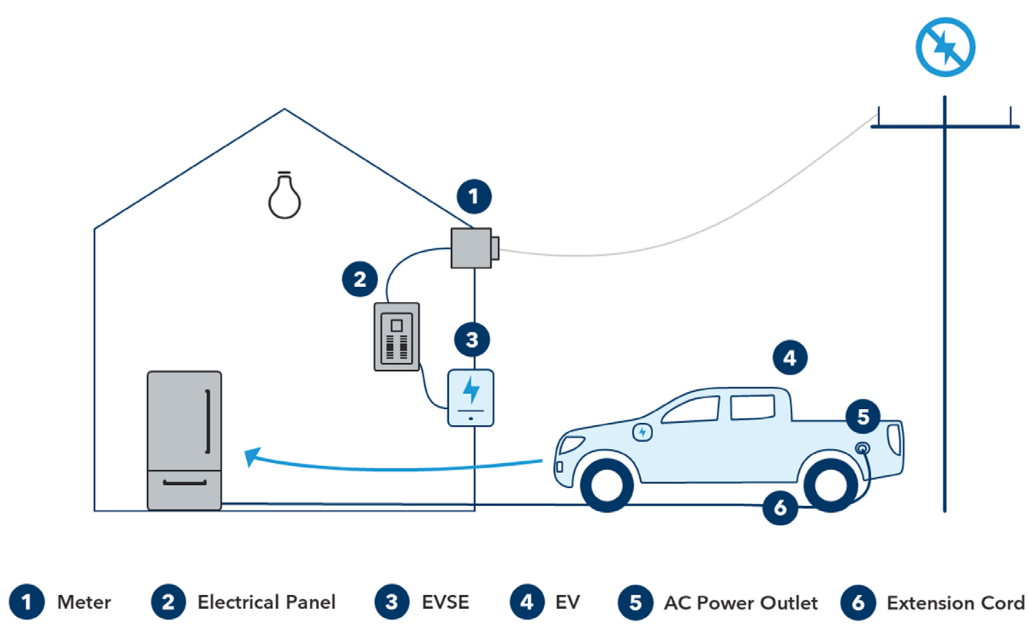
- **communications protocols** to ensure reliable and secure communication between charging infrastructure and utility systems;
- **grid compatibility standards** to facilitate integration with utility DR programs and ensure that V1G systems operate within the grid's technical limits; and
- **cybersecurity standards** to protect user privacy and grid operations through secure data exchange protocols.

3.1.3 Vehicle-to-Load (V2L)

V2L enables an EV to directly power external devices or auxiliary loads, such as construction tools, home appliances, or remote locations like campsites (Figure 2). Although this application involves a bidirectional EV power transfer, a bidirectional EVSE is not required because power flows from the vehicle battery to the electrical load via an electrical outlet or an on-board adapter [7]. Unlike V2G or V2H/V2B applications, which require bidirectional EVSE to facilitate power export back to the grid or home/building, V2L performs power export without using EVSE.

The two main ways a V2L-capable vehicle exports power are:

Figure 2: V2L (discharge mode) power port example.
The vehicle provides power to a specific load (e.g., appliance, tool), such as during a power outage or at a site without grid power.



- **Integrated power outlet (alternating current (AC) power outlets):** These are standard household-style power outlets (e.g., 120V or 240V in North America) located inside the cabin, cargo area, or even externally. They provide AC power directly to appliances, tools, or other electronic devices. Figure 2 illustrates this configuration.
- **V2L adapter via the charge port:** Some vehicles allow power output through the EV charge port using a special V2L adapter that includes a household-style power outlet.

Some vehicles offer both options for power export, as described above. In addition to being equipped with an electrical outlet or adapter, the vehicle must have an integrated on-board direct current (DC) to AC inverter to enable V2L. For more information on AC and DC power and their relevance for VGI applications, see Section 3.2.1.2.

From a standards perspective, V2L is relatively simple compared to other VGI applications, as it does not require a bidirectional EVSE (unlike V2H/V2B and V2G) or sophisticated communication infrastructure and control systems (unlike V1G and V2G). In this way, V2L is similar to a standard portable generator, with safety requirements focusing on basic electrical safety, grounding, and user instructions to maintain a safe level of operation during external power supply. While V2L has most commonly been used to power specific loads via an extension cord, the availability of EVs with 240V V2L capabilities introduces the possibility of powering a home subpanel through a generator inlet. Standardization efforts for V2L primarily revolve around ensuring compatibility with common devices, reliability of on-board inverters, and adherence to general safety protocols for portable power solutions.

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

V2B and V2H use an EV to provide supplementary power to a building whether connected to the grid (i.e., grid-tied) or not (i.e., islanded). While both configurations enable an EV to supply power to a home or building, they differ in infrastructure requirements (e.g., grid isolation devices for islanded systems compared to interconnection equipment for grid-tied systems) and standards considerations (e.g., anti-islanding protections compared to grid compatibility protocols).

3.1.4.1 Islanded V2H/V2B

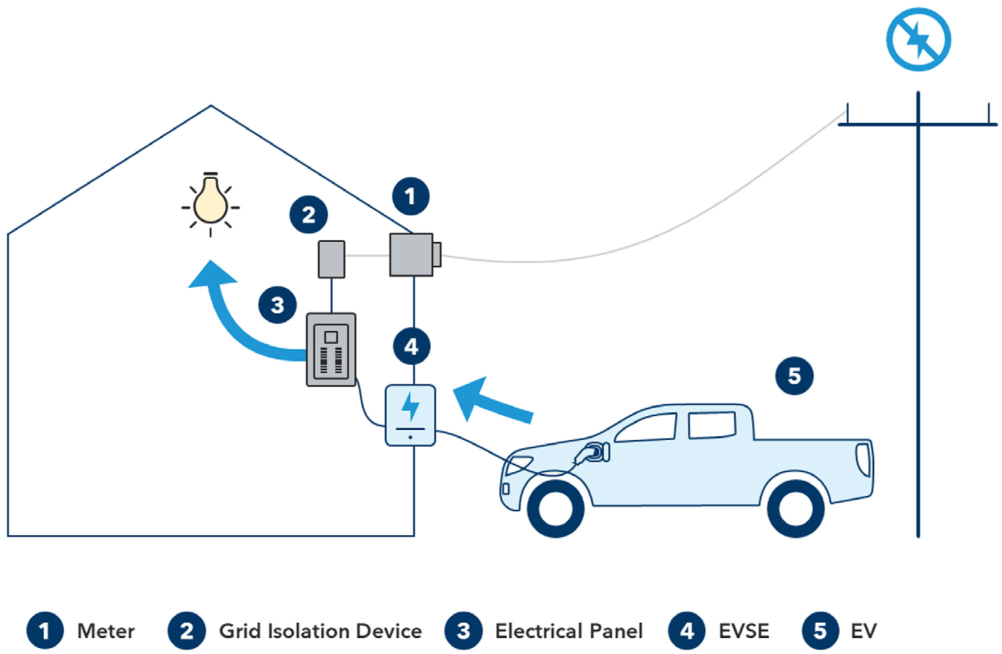
Islanded V2B/V2H systems allow EVs to supply electricity to a home or building to provide power backup during power outages (Figure 3). This functionality is typically accomplished using a bidirectional EVSE such that the vehicle can automatically provide backup power via the same electrical connection used for charging. Islanded V2B/V2H enhances resiliency by allowing homes or buildings to maintain power during outages, supporting critical systems, such as refrigeration, medical devices, or heating. Like V2L, islanded V2B/V2H can reduce reliance on fossil-fuel generators, while still providing backup power.[2]

During islanded V2B/V2H operations, the home or building must be disconnected from the grid to prevent back-feeding—when power flows from the building into the grid during an outage. Back-feeding poses significant risks, including potential harm to utility workers repairing the grid and damage to grid infrastructure. To mitigate these risks, a grid isolation device, such as a microgrid interconnect device, ensures that the EV supplies power only to the building's internal circuits and remains isolated from the grid until normal operations resume. This measure is critical for compliance with grid interconnection standards (see Section 3.3.2) and regulatory requirements.

In addition to safety and compliance, power delivery during islanded operation is also limited by system capacity. Depending on the power output capabilities of the EV and associated systems, it may only be possible to power a subset of the building's circuits during an outage. In such cases, load management

2 Islanded V2B/V2H reduces emissions assuming that the EV was charged by electricity with a lower emissions intensity of the fossil fuel generator it is replacing. This is the case everywhere in Canada, since diesel generators emit on average 900 gCO_2/kWh [8] and Nunavut, the province with the highest electricity carbon intensity, emits 840 g CO_2e/kWh [9].

Figure 3: Islanded V2B/V2H (discharge mode).
The vehicle provides power to a building or house during a power outage. The house or building must be isolated from the grid using a grid isolation device.



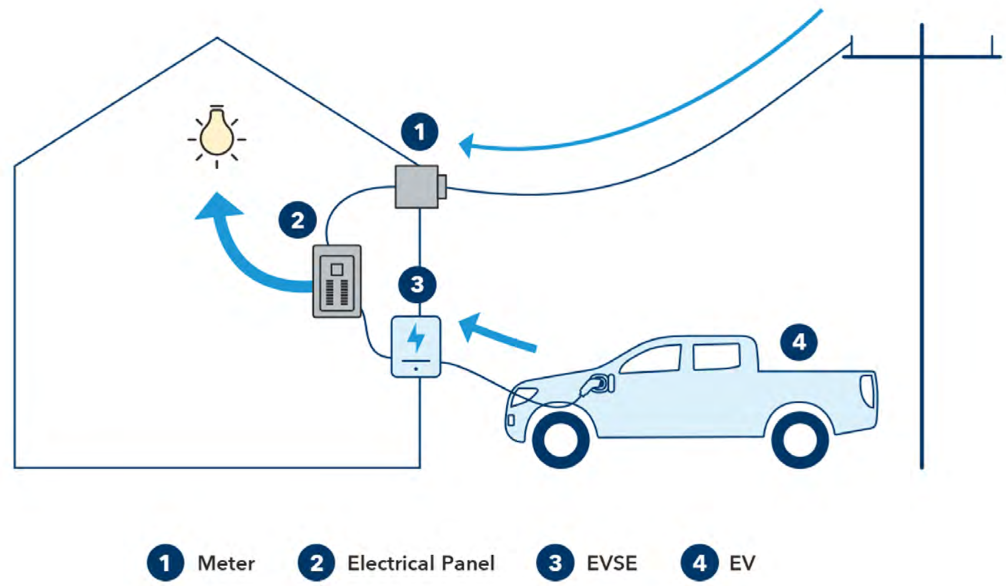
strategies, such as sub-panels for critical loads, smart panels that shut off non-essential circuits, or systems that automatically disable non-critical loads, can help to prioritize essential services (e.g., lighting, HVAC, and essential appliances). However, these strategies are not always required. V2H/V2B systems, which function similarly to multimode energy storage systems, are typically configured to supply individual loads as needed. Many are designed to shut down safely in the event of a temporary overload, reducing the need for precise load isolation under all circumstances. Although they do not offer the same inertial response of traditional generators, certified multimode inverters can manage dynamic load conditions while maintaining system safety.

3.1.4.2 Grid-Tied V2H/V2B

Grid-tied V2B/V2H enables a vehicle to supply energy to a home or building while remaining connected to the grid, but without exporting energy back to it (Figure 4). Hence, the power supplied by the EV is less than the power consumed locally by building loads. Grid-tied V2B/V2H can benefit the vehicle owner by reducing grid energy use during high electricity -price periods or by maximizing self-consumption of solar energy. For example, excess solar energy can be stored in the EV battery and used later to power building loads, rather than being exported to the grid.

This application aligns closely with the technical and regulatory requirements of V2G (see Section 3.1.5), particularly in terms of required communication protocols, interconnection standards, and grid compatibility. Indeed, grid-tied V2B/V2H is sometimes referred to as “V2G, non-export.” From a standards perspective, both grid-tied V2B/V2H and V2G require compliance with similar requirements. In both cases, the EV and associated equipment must be capable of

Figure 4: Grid-tied V2B/V2H (discharge mode).
The vehicle sends power to a building or house that is grid connected, offsetting overall demand from the grid but not delivering a net power export to the grid.



interacting with building energy systems and/or grid infrastructure in a controlled and predictable manner. However, since grid-tied V2B/V2H does not export power to the grid, the interconnection process and regulatory requirements could be simpler or faster than V2Gs, reducing barriers to implementation. For example, in California, under Rule 21, non-exporting systems are eligible for fast-tracked interconnection [10].

Grid-tied V2B/V2H systems may still require power export limiting (PEL) functionality to ensure that no energy is inadvertently exported to the grid. This functionality, also referred to as a zero-export power control system (PCS), enables systems to dynamically monitor and control power flows to remain within defined export limits. UL 3141, a forthcoming standard for PCSs, includes requirements to validate these capabilities (see Section 3.3.2.4 for more information on UL 3141). Even non-exporting configurations may need to demonstrate compliance with such standards to meet utility interconnection standards.

Like V2G, grid-tied V2H/V2B adoption generally depends on utility incentives or favourable rate structures. For example, time-of-use (TOU) rates or demand charges may make it economically attractive for EV owners to use stored energy from their vehicles during peak pricing periods. Utilities may also offer rebates for bidirectional EVSE or incentives for participating in programs that support grid stability or energy efficiency. Without such measures, the upfront costs and operational complexities of grid-tied V2H/V2B systems may limit widespread adoption.

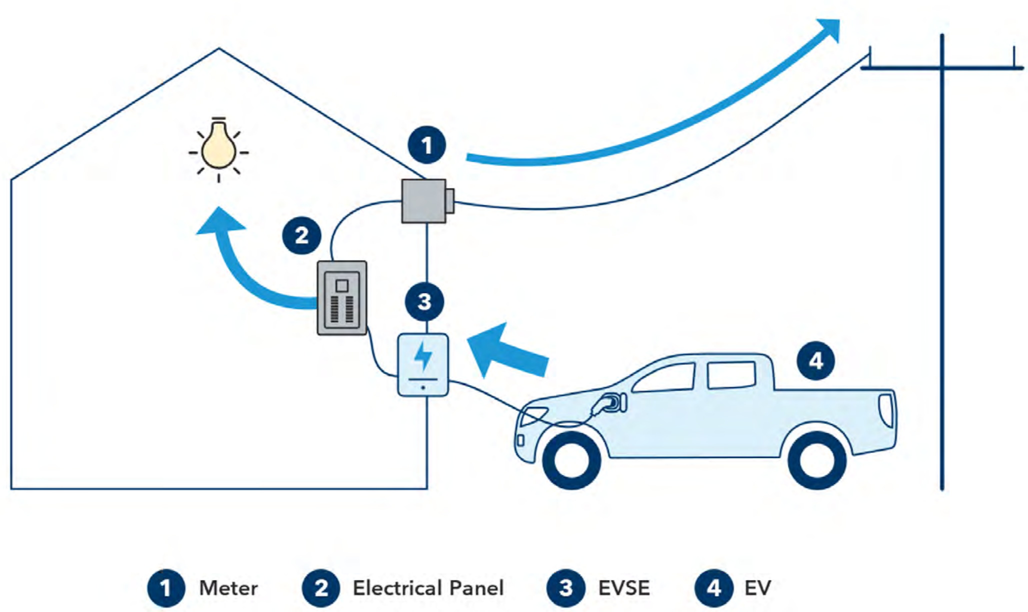
3.1.5 Vehicle-to-Grid (V2G)

V2G enables EVs to supply power back to the electricity grid, allowing them to function as energy storage resources that provide a range of services to grid operators (Figure 5). In a bidirectional exporting application, the vehicle operates as a two-way energy resource, capable of charging from and supplying energy back to the grid [11]. This requires compensation from the utility, either through a net-metering rate structure or via an advanced communications interface, such as a distributed energy resource management system (DERMS), that controls and measures the vehicle's output and provides appropriate compensation.

V2G is similar to V1G in that both are primarily intended to provide services to the grid. However, while V1G can only shift charging loads in time or adjust the rate of charging, bidirectional systems can both charge and discharge EV batteries. Therefore, V2G offers a **greater "depth"** of DR compared to V1G. Additionally, grid-connected bidirectional systems, including V2G and grid-tied V2H/V2B, allow EVs **to be available more consistently** to serve grid needs. As long as an EV is connected and has sufficient charge, it could theoretically export power. Conversely, V1G relies on a vehicle charging at the time that grid services are necessary.

As the most complex VGI application, V2G relies on advanced communication systems, robust grid compatibility standards, and bidirectional power flow infrastructure. Ensuring interoperability between EVs, EVSE, and grid management systems requires significant coordination. Standards related to power quality, cybersecurity, and system safety standards are also critical, as V2G systems involve the exchange of sensitive data and direct interaction with grid operations.

Figure 5: V2G (discharge mode).
The vehicle provides power to a building or house to completely offset the building/house power demand and deliver a net export of power to the grid.



3.1.6 Comparing VGI Applications

As detailed above, VGI applications vary significantly in terms of the equipment, infrastructure, and policies needed to support their functionality or adoption. Table 2 summarizes the key technical and regulatory requirements for each VGI application. This comparison underscores the importance of tailoring standards to the specific needs of each application to assist in maintaining safety, ensuring interoperability, and supporting scalability.

3.2 Technology Overview

This section presents VGI technology, including system components and the impacts of VGI on EV battery life. The first part outlines the key components of VGI systems, including EVs, EVSE, and other electrical distribution and conversion hardware, and communications infrastructure and control. Distinctions between AC and DC applications are also highlighted to clarify operational differences. The second part summarizes the factors influencing EV battery life,

Table 2: VGI requirements by application

Requirements		V1G	V2L	V2H/V2B islanded	V2H/V2B grid-tied	V2G
Equipment / infrastructure	EV	X	X	X	X	X
	Bidirectional EVSE		on-board outlet or adapter	X	X	X
	DC to AC inverter		X on-board	X on-board or off-board	X on-board or off-board	X on-board or off-board
	Grid isolation device			X		
	Anti-islanding[1]			X	X	X
	Communications infrastructure and controls[2]	X			X	X
Policy / programs	Utility approval / interconnection agreement			X sometimes	X	X
	Utility incentive/ compensation programs[3]	X			X	X always

1 For grid-tied inverters (e.g., grid-tied V2H/V2B and V2G), anti-islanding typically refers to the inverter's ability to detect a grid outage and automatically shut off to prevent back-feeding. A grid isolation device (e.g., a microgrid interconnect device) is additional equipment required to enable the inverter to operate independently during an outage, allowing for islanded V2H/V2B functionality.

2 Includes grid-level, EVSE and charging network, and vehicle-to-OEM (e.g., telematics).

3 While V1G, grid-tied V2H/V2B, and V2G could technically function without utility incentive or compensation programs, these applications are unlikely to be adopted without such programs. The primary benefit of these applications for vehicle owners is the cost savings and/or revenue potential associated with participation in utility programs, which helps offset potential downsides, such as battery degradation, increased capital costs, and complexity.

such as depth of charge/discharge, cycling frequency, charging voltage and rate, temperature, and calendar aging, and how various VGI applications affect battery performance and longevity. It also identifies strategies to mitigate these impacts.

3.2.1 Overview of VGI System Components

The three core components to VGI systems are as follows:

1. **EV that supports VGI functionality,** including either unidirectional (V1G) or bidirectional (e.g., V2G, V2H) operations.
2. Electrical conversion and distribution hardware, including:
   a. EVSE installed in the home, building, or other location that supplies power to the vehicle.
   b. Charger / inverter, which converts AC to DC power for charging, and, in bidirectional systems, DC to AC conversion for power export. This component is listed separately from the EVSE, as it can be on board the vehicle (AC charging) or part of the EVSE itself (DC charging).
3. **Communications infrastructure and controls** to exchange the information necessary for coordinating charging and power export.

The following sections provide further information about these system components.

3.2.1.1 Electric Vehicles (EVs)

All forms of VGI require some degree of compatibility with EVs and support from manufacturers. In its simplest form, V1G requires only that the EV be capable of responding to signals that start, stop, and control the speed of charging. All commercial EVs support this through the basic control interface between EV and EVSE; or, in some cases, through direct communication with the EV's control system via telematics.

By contrast, commercial deployment of bidirectional EV power transfer requires that EV manufacturers market and warranty their vehicles for this application. Use in V2X applications increases the frequency of charge and discharge cycles, which, all else being equal, can reduce EV battery range and service life (see Section 3.2.2 for more information on factors impacting EV battery life). However, battery and battery management system (BMS) technologies are improving rapidly, increasing affordability, energy density, charging speed, and lifespan. Several research efforts are underway to better determine the impacts of different V2X cycling profiles and to optimize V2X strategies for battery health [12]. Continued improvement in battery and BMS technologies will increasingly enable EV manufacturers to support V2X. For example, manufacturers are investigating advanced battery chemistries that could meet the demands of bidirectional charging [13]. Historically, only a few EV manufacturers have offered V2X capabilities, but several are now announcing that their new models will support this feature [14].

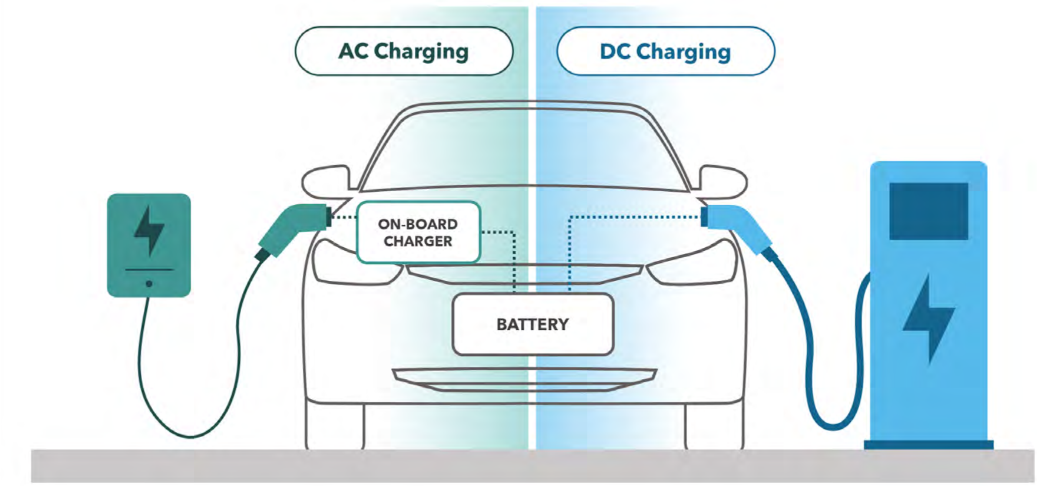
3.2.1.2 Electric Vehicle Supply Equipment (EVSE) and Other Electrical Distribution and Conversion Hardware

The electricity grid delivers AC power, which is used for most homes, businesses, and appliances. However, EV batteries charge and discharge DC power, which necessitates electrical conversion equipment to switch between AC and DC power.

Broadly, the two means to charge EVs (see Figure 6), each with different types of EVSE, are:

- **AC charging:** EVSE delivers AC power to the EV. An on-board charger converts AC to DC power, which is stored in the EV's battery. The SAE J1772 standard defines Level 1 (120V) and Level 2 (single-phase 208V or 240V) as AC charging levels. Level 1 and Level 2 are commonly used in home, workplace, fleet, and public applications.
- **DC charging:** EVSE includes the AC to DC converter. DC power is provided to the EV's battery, bypassing the vehicle's on-board charger. DC charging thereby allows for faster charging without requiring a higher capacity and more expensive converter in each vehicle. DC charging is most commonly used in fleet and public charging applications.

Figure 6: AC and DC charging.
AC charging (with an on-board charger/converter) and DC charging (with converter integrated into EVSE).



Likewise, exporting power from a vehicle for use by AC equipment requires an inverter to convert DC to AC. V2X can use an electrical inverter either built into the vehicle itself or into the EVSE:

- **Vehicle exporting AC power (V2X-AC)** involves the vehicle exporting AC power. The vehicle's on-board charger serves as the inverter when exporting AC power. Level 1 or Level 2 EVSE can be used, without the need for an EVSE with an integrated inverter.
- **Vehicle exporting DC power (V2X-DC)** involves the vehicle exporting DC power. In this case, the inverter is in the EVSE.

In V2X applications to date, **V2X-DC is the most common and commercially mature approach**. Many vehicles currently compatible with V2X, or announced by OEMs for future release, are designed to operate with V2X-DC. Because the inverter is integrated into an EVSE permanently installed at a fixed location, systems for certifying the inverter for grid interconnection are similar to those used for solar PV or stationary battery systems. Accordingly, the ecosystem of industry standards supporting V2X-DC is relatively well established, making it easier for utility grid operators to administer interconnection and certification processes. However, V2X-AC is growing in prevalence, and may ultimately be more cost-effective for lower power V2X applications. V2X-AC avoids the cost of an EVSE with an inverter. Instead, V2X-AC uses the on-board charger already located in every EV, exporting power to the Level 1 and Level 2 EVSE already commonly deployed in home, workplace and fleet charging. Table 3 summarizes the comparison of V2X-DC and V2X-AC.

3.2.1.2.1 V2X-AC and Split-Phase Power (120V/240V)

One additional challenge for V2X-AC in North American markets is to provide both 120-volt (V) and 240 V power in split-phase systems, which are common in residential contexts. While standard EV charging connectors can support either 120 V or 240 V charging/discharging, they cannot support both at the same time due to a limited number of pins in the connector. This means that for islanded V2H/V2B, the system must include a 240 V to 120 V transformer (e.g., integrated in the EVSE) in order to supply power to 120 V circuits in the home. This limitation does not apply to V2G or grid-tied V2B/V2H use cases, since both 120 V and 240 V circuits are energized by the grid and connected via the home's existing split-phase configuration. In this case, the EV supplies energy back to the grid or home at 240 V, but 120 V loads can still operate normally.

Table 3: Comparison of V2X-DC and V2X-AC

Requirements	V2X-DC	V2X-AC
Interconnection process	Certification and interconnection approval is simplified by having an inverter in a fixed location (analogous to other distributed energy resources (DERs), like solar photovoltaic systems).	Certification and interconnection approval processes are still being defined due to limited understanding of the V2G-AC interconnection.
Equipment	EV only requires a DC charge port and compatible software to enable V2X.	EVs' on-board chargers serve as inverters and must be certified for use in V2X applications or evaluated as part of a DER system.
Cost	EVSE is more expensive.	EVSE is less expensive.
Prevalence	Most common.	Less common today; bespoke.

3.2.1.3 Communications Infrastructure and Controls

Many VGI applications, including V1G, grid-tied V2H/V2B, and V2G, require robust controls software and information and communications technology (ICT) networks across which to exchange information. Implementing controls and ICT systems is one of the greatest challenges facing the deployment of VGI. Collectively, ICT and controls must enable secure and efficient exchange of information between EVs, EVSE, aggregators, and grid operators. Furthermore, control systems must ensure VGI charging and discharging occur with responsiveness to provide different VGI services. For example, energy arbitrage as part of V2G can add value despite lags on the seconds-to-minutes timeframe, whereas some V2G ancillary services and balancing loads as part of V2H/V2B require much faster response. The services V2X provide therefore impacts the nature of ICT technologies used.

In particular, V2G typically requires grid operators to communicate signals to either charge or discharge EVs batteries, except in certain cases such as net metering. These signals may be received by the EVSE; a facility-scale EV energy management system (EVEMS) that controls the EVSE; and/or the vehicle. Table 4 summarizes where this "smart" communications node function may be located. In addition to V2G-DC and V2G-AC, **V2G-AC split inverter** systems use a power converter integrated in the EV but shift some of the control functionality to the EVSE.

Figure 7 illustrates a simplified schematic of the basic categories of communications infrastructure necessary for V2G to operate, noting communications systems in black.

These communications systems include:

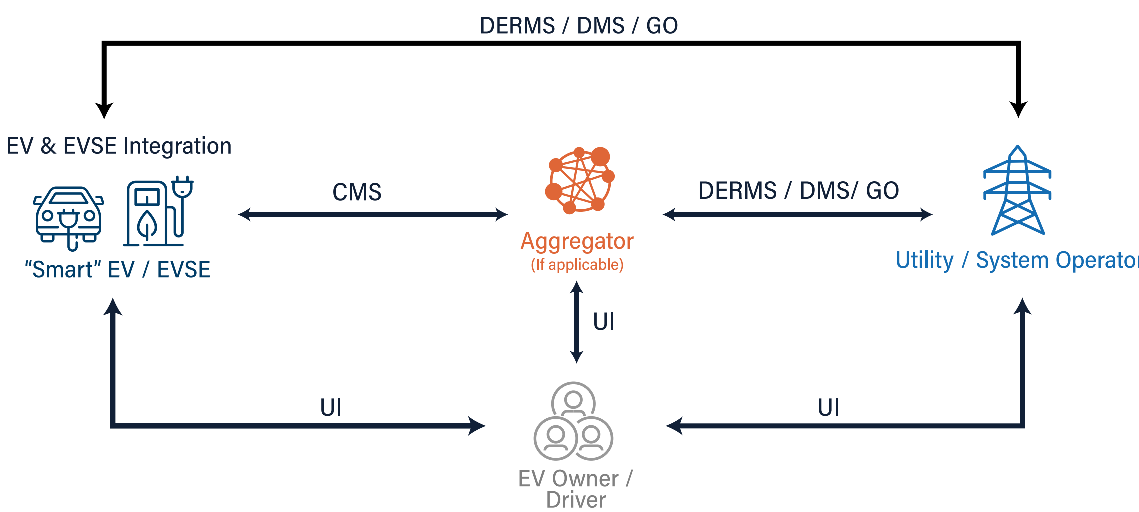
- **Utility grid operators' DERMS, distribution management systems (DMS), and/or grid orchestration (GO) platforms:** These systems provide means for utilities to coordinate V2X and other DERs on the grids. Typically, these systems signal to aggregators, which then control individual DERs, including V2X assets. However, DERMS/DMS/GO could also theoretically control individual V2X assets. Aggregators may include EV charging service providers and network operators, vehicle OEMs, and other actors.
- **Charging management systems (CMS):** Mediate EV charging by facilitating communication between aggregators and EVs,[3] EVSE, and/or facility-scale EVEMS. CMS platforms may send dispatch signals to charge/discharge EV batteries, transmit price signals, validate that EVs are certified to charge, and communicate other information necessary for V2G operation.

3 If V2X/V2G signals are sent to EVs, then this CMS function is usually part of broader telematics systems.

Table 4: V2G inverter and ICT communications nodes configurations. Source: Smart Electric Power Alliance 2023 [15]

	V1G		V2L		V2H/V2B grid-tied	
	EV	EVSE	EV	EVSE	EV	EVSE
Site data		X		X		X
Battery data	X		X		X	
Smart functions		X	X			X
Power converter		X	X		X	

Figure 7: Communications systems required in V2G.



- **EV and EVSE integration:** Communication between the EV and EVSE helps ensure safe charging and discharging, reception of external signals, coordination of user-facing information, and other functions. Either the EV or the EVSE can serve as the primary node for external communication, relaying information and directions to the other device as necessary.
- **User interface (UI):** For a user-friendly experience, interfaces and management platforms allow EV owners and operators to interact with the V2X system. Through mobile apps or web portals, users can set preferences, schedule charging or discharging sessions, "opt-out" of V2X events, view transaction histories, and more.

3.2.2 Implications of VGI for Battery Life and Performance

This section discusses the various factors that can impact EV battery life, including voltage and rate of charge/discharge, depth of charge/discharge (DoD) and state of charge (SoC), cycling, temperature, and calendar aging. It also explores how various VGI applications affect these factors and strategies to mitigate their impact. Battery life is a complex subject influenced by numerous variables. This overview provides a high-level summary of key factors affecting battery life, which, like charging and driving, are dependent on usage patterns and vehicle design.

3.2.2.1 Voltage and Rate of Charge/Discharge

Battery longevity is impacted by both the voltage at which the battery is charged and the rate of charging. Higher charge voltages, commonly associated with fast charging, increase internal resistance, which in turn generates excess heat [61]. High temperatures accelerate chemical reactions within the battery, potentially leading to faster degradation and reduced lifespan. Charging at slower rates, particularly at moderate temperatures, is less damaging and can help to extend battery life. Accordingly, charging and driving behaviours can significantly impact battery health. Frequent use of fast charging may contribute to electrochemical degradation of the battery. Similarly, driving habits, such as aggressive acceleration and high speeds, increase the energy demand on the battery, intensifying charge/discharge cycles and placing strain on the system [17]. Using lower voltage and avoiding high charge/discharge rates can preserve battery health; **moderating these rates**, especially by avoiding rapid charging or discharging, reduces thermal stress and wear, contributing to longer-term battery performance.

3.2.2.2 Depth of Charge/Discharge (DoD) and State of Charge (SoC)

Frequent cycling between high and low SoC, known as deep cycling or characterized by high DoD, can accelerate battery wear and degradation, particularly in lithium-ion batteries, which are more sensitive to deep cycles than lead acid or nickel-based systems [18], [19], [20]. Deep cycles, where the battery is discharged near 0% or charged to 100%, place stress on internal battery components, shortening lifespan. To mitigate this stress, maintaining a moderate SoC range, typically between 20% and 80%, is recommended to limit stress and extend battery life [21]. While V2X systems can involve frequent **SoC fluctuations**, certain VGI applications, such as V1G, grid-tied V2H/V2B, and V2G, can be used to help maintain the battery within this SoC range and support battery longevity.

3.2.2.3 Cycling

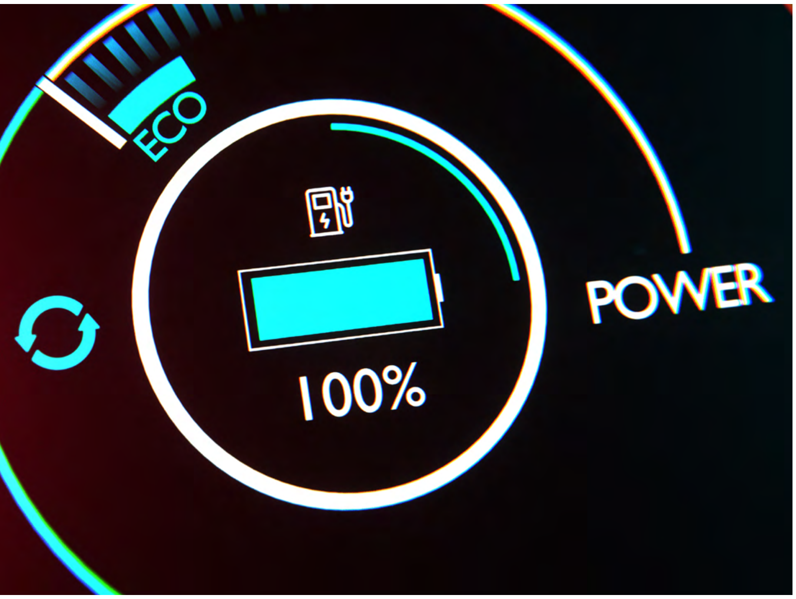
The frequency and number of charge-discharge cycles also significantly impact battery life, as batteries have a limited number of effective cycles before degradation begins to affect performance. Frequent cycling increases wear on the battery's internal components, leading to faster capacity loss over time [22]. The extent to which cycling impacts battery life depends to an extent on the depth of cycling, as well as the rate of charge/discharge, as noted above.

Building on this, V2X applications inherently increase the frequency of battery cycles by requiring additional discharge events beyond those needed for regular driving. This increase in cycling can accelerate battery degradation, depending on the specific V2X use case. For example, V2G driven by TOU rates to provide grid services is more likely to involve frequent and deep cycling, which may impose more strain on the battery compared to islanded V2H/V2B use cases, which might involve fewer, shallower cycles during backup power events. The overall impact on battery life depends on the intensity and frequency of these additional cycles.

3.2.2.4 Temperature

In addition to cycling, temperature is another key factor affecting battery degradation. Exposure to high temperatures can significantly impact an EV battery's chemistry and overall performance. High temperatures accelerate the degradation of the battery by increasing the rate of chemical reactions within the cell, which can lead to the breakdown of its materials and a reduction in lifespan [16]. Conversely, low temperatures temporarily reduce the battery’s performance by decreasing its efficiency and capacity. Additionally, cold temperatures increase internal resistance, which can make the battery more difficult to charge and place added stress on its components during the charging process. Both high and low temperatures pose risks to long-term battery health [18].

Similar to charging and driving, V2X applications can lead to operational temperature fluctuations if not managed appropriately. However, these temperature fluctuations are an inherent consideration in the design of the EV and are typically regulated by the BMS. BMS helps maintain optimal temperature control to prevent accelerated degradation, including in V2X applications, by limiting charge and discharge rates if battery temperatures are too high or too low.



"Calendar aging is especially accelerated by factors, such as prolonged storage at high SoC and exposure to high temperatures."

3.2.2.5 Calendar Aging

Batteries also naturally lose capacity over time due to a process known as calendar aging, which occurs even if the battery is not in use. This form of degradation is caused by chemical reactions within the battery that occur as it ages. Calendar aging is especially accelerated by factors, such as prolonged storage at high SoC and exposure to high temperatures. Keeping a battery stored in conditions that are too hot (i.e., at or above 50°C) or at a full charge for extended periods will speed up this degradation process, ultimately reducing its overall capacity and effectiveness [23].

While calendar aging is an inevitable process, certain V2X applications may help mitigate its effects. By engaging the battery in applications, such as grid support (i.e., grid-tied V2H/V2B, V2G) or backup power (i.e., V2L, islanded V2H/V2B), V2X can keep the battery in active use, which may help prevent or slow the degradation caused by prolonged inactivity. As previously noted, V2X systems can help maintain the battery within an optimal SoC range (e.g., 20–80%), reducing the stress associated with long periods of high SoC storage. The benefits of V2X in mitigating calendar aging depend on careful management of cycling frequency, depth of discharge, and operational conditions to ensure that additional wear from active use does not outweigh the benefits of reducing calendar aging.

Still, the effectiveness of these benefits depends on careful optimization of battery use to avoid undermining the advantages with additional wear. In the context of a finite calendar life, V2X may represent an opportunity to maximize the value of EV batteries that are otherwise underutilized. If a vehicle is not driven often, performing V2X functions may allow an EV owner to derive more value out of their vehicle before the battery reaches its end of life due to calendar aging. However, while V2X applications can offer opportunities to mitigate calendar aging, the effectiveness of these benefits depends on careful management and optimization of the battery's use.

3.2.2.6 Summary of VGI's Impact on Battery Life

The impact of VGI on battery longevity will vary significantly depending on the specific use case. Table 5 categorizes VGI applications into three broad groups: unidirectional (i.e., V1G), occasional bidirectional, and frequent bidirectional. These categories are compared based on factors including cycling frequency, SoC, voltage and rate of charge/discharge, which collectively influence impact battery longevity.

Overall, unidirectional applications (i.e., V1G) do not lead to an increase in cycling frequency and can even enhance battery longevity compared to unmanaged charging by optimizing rate and depth of charge to prevent degradation. Occasional use of bidirectional EV

Table 5: Impacts of VGI on battery life relative to baseline battery degradation

Factor influencing battery life	Unidirectional (e.g., V1G)	Bidirectional, occasional (e.g., V2L and Islanded V2H/V2B for backup power, V2G for DR events	Bidirectional, frequent (e.g., grid-tied V2H/V2B and V2G for daily grid services / utility bill minimization)
Cycling frequency	**No impact**	**Low** Slight increase	**Med to high** Significant increase
DoD and SoC	**No impact** Controlled by user	**Low to high** Low during emergency use; could be mitigated; ultimately controlled by user	**Low to med** Controlled by user; design of programs to maintain optimal SoC to limit degradation
Voltage and rate of charge/discharge	**No impact** Could be used to control rate of charge to prevent degradation	**Low to med** Elevated during emergencies; mitigated through control programs	**Low to med** Controllable through program design to limit degradation
Battery temperature	**Variable** Depends on cycling frequency, voltage, and rate of charge/discharge		
Calendar aging	**No impact**		
Impact on battery life	**None or positive**	**Low to med**	**Low to high**

power transfer functionality, such as for backup power, resilience, or infrequent utility DR events like Critical Peak Pricing, or Emergency Load Reduction Program in the United States, may have a minor negative impact on battery longevity, but this can be minimized by controlling the depth and rate of discharge. Frequent bidirectional power transfer, such as daily cycling driven by TOU rates, may lead to more significant battery degradation; however, the extent depends on the depth of discharge and the cycling rate. Overall impacts vary from negligible to significant, highlighting the complexity of battery health in relation to user behaviour.

Looking ahead, advances in battery technology and declining EV costs [24] are improving the value proposition of VGI for customers. Recent analysis suggests battery degradation may be occurring more slowly than previously anticipated [25], [26], which could reduce concerns over battery as a barrier to VGI adoption.

3.3 Review of Standards Landscape

This section provides an overview of the key standards governing VGI, including EV and EVSE standards that define vehicle- and charger-side requirements; grid interconnection standards that establish safety and performance criteria for connecting EVs to the grid; and communications standards and protocols that facilitate real-time coordination between EVs, chargers, utilities, and grid operators.

3.3.1 Electric Vehicle (EV) and Electric Vehicle Service Equipment (EVSE) Standards

The following section examines key standards governing EV-EVSE interactions, including requirements for on-board components and bidirectional EV power transfer capabilities. Table 6 presents an overview of the most relevant EV and EVSE standards for VGI in North America. Among these, SAE J3072 and ISO 15118-20[4] are particularly significant, given their widespread adoption and relevance for bidirectional power transfer.

4 Note: In this report, "ISO" refers to independent system operator; references to standards such as ISO 15118-20 refer to the International Organization for Standardization.

Table 6: EV and EVSE standards or frameworks

Standard or framework	Category	Description
SAE J1772	Safety / performance	*Electric vehicle and plug-in hybrid electric vehicle conductive charge coupler.* Outlines "the general physical, electrical, functional, and performance requirements to facilitate conductive charging of [electric and plug-in hybrid] vehicles in North America" [27].
SAE J3072	Safety / performance	*Interconnection requirements for onboard, grid support inverter systems.* Establishes "requirements for a grid support inverter system function ... integrated into [an EV]." Additionally specifies the communication protocol between the EV and the EVSE necessary for configuring and authorizing the on-board inverter function [28].
SAE J3068/2	Performance / communication	*Control of bidirectional power for AC conductive charging.* Published in January 2024, this standard is designed to enable V2X-AC by providing any compliant EV with a unique digital identifier, allowing grid operators to confirm it is certified for power export, understand the vehicle's location on the grid, and coordinate EV charging via dispatch and price signals [29].
SAE J2847/2	Communication	*Communication between plug-in vehicles and off-board DC chargers.* Establishes "requirements and specifications for communication between [an EV] and the DC off-board charger ... for conductive charging" (i.e., using a physical cable). This recommended practice transforms the use cases for DC charging communications outlined in SAE J2836/2 into signals and messages [30].
ISO 15118-1	Communication	*Road vehicles — vehicle to grid communication interface,* Part 1: General information and use-case definition. Outlines communication standards between EVs and EVSE. Supports V2G, V2H and V2L, and promotes compatibility between different EVs and EVSE [31].
ISO 15118-20	Communication	*Road vehicles — Vehicle to grid communication interface, Part 20: 2nd generation network layer and application layer requirements.* Specifies the communication between the EV and EVSE in application layer messages. It outlines the requirements for bidirectional power transfer, covering both conductive and wireless charging. The standard also details the communication protocols necessary for automatic connection devices and information services related to charging and control status [32].
CSA C22.2 No. 348:23 / UL 9741	Safety	*Electric vehicle power export equipment (EVPE) (binational standard with UL 9741).* Applies to "off-board unidirectional and bidirectional equipment ... that transfers electrical energy between an [EV] and off board loads" [33].
CSA SPE-343:21	Safety	*Electric vehicle energy management systems.* Provides guidance for design, manufacture, and testing of "electrical equipment that form part of an" EVEMS to reduce the load contribution of EVSEs [34].
NEMA EVSE 40011-2023	Communication	*EVSE power export standard.* Defines the technical parameters for EVSE to enable bidirectional power transfer. This allows EVs to act as mobile energy storage units, transferring power back to the grid or to buildings and homes. The standard covers key areas such as electrical characteristics, communication protocols, and cybersecurity measures to ensure safe and efficient power export between an EVSE and an electric power system [35].

3.3.1.1 SAE J3072

SAE J3072 is a key standard for VGI applications—it establishes interconnection requirements for on-board grid support inverter systems in bidirectional EVs [28]. This standard specifies how an EV's on-board inverter can be safely configured and authorized by bidirectional EVSE, ensuring compliance with grid interconnection and safety requirements. It primarily applies to V2G-AC systems, where the inverter is integrated into the EV rather than the EVSE. SAE J3072 defines the communication framework needed to establish grid authorization, ensuring that the on-board inverter functions properly and meets utility requirements for grid interaction. Revision of the standard is expected in 2025 to align with UL 1741-SC (see Section 3.3.2.2), which will provide a more structured framework for certifying on-board inverters used in V2G-AC applications [36].

3.3.1.2 ISO 15118-20

ISO 15118 is the primary international standard governing EV-to-EVSE communication for bidirectional power transfer [36]. However, propriety communications between the EV and EVSE are permitted and remain common in practice. ISO 15118 consists of several parts, with the most recent being ISO 15118-20, published in 2022. This update outlines second-generation network and application layer requirements to facilitate secure and automated charging interactions between EVs, chargers, and the grid. ISO 15118-20 introduces bidirectional power transfer, enhanced cybersecurity measures, and improved communication protocols for wireless and conductive charging. Adoption of ISO 15118-20 has been slow, as testing protocols and industry uptake continue to evolve. In the interim, SAE J2847/2 may serve as a bridge solution for DC charging communications, providing an alternative framework for EV-EVSE interactions until ISO 15118-20 gains wider adoption [36].

3.3.2 Grid Interconnection Standards

This section focuses on how EVs and EVSE interconnect with the grid and meet safety and interconnection requirements for bidirectional power flow in V2G and grid-tied V2H/V2B applications. These standards (see Table 7) are not relevant for islanded VGI applications, such as V2L or islanded V2H/V2B, as there is no parallel operation with the utility's grid. However, for V2G and grid-connected V2H/V2B, compliance with interconnection standards is essential to help provide grid stability, safety, and interoperability.

Table 7: Grid interconnection standards or frameworks

Standard or framework	Category	Description
IEEE 1547	Performance	*Interconnection and interoperability of distributed energy resources with associated electric power systems interfaces.* Interconnecting DERs, including V2G-enabled EVs, with the electric grid. It defines requirements for voltage regulation, response to abnormal grid conditions, power quality, and islanding prevention [37].
UL 1741 (SA/SB/SC)	Performance / safety	*Inverters, converters, controllers and interconnection system equipment for use with distributed energy resources.* These requirements cover inverters, converters, charge controllers, and ISE to be operated in parallel with an EPS to supply power. For interactive equipment, this is intended to be used with IEEE 1547 and 1547.1 [38].
CSA C22.3 No. 9-2020	Performance	*Interconnection of distributed energy resources and electricity supply systems.* Provides technical requirements for the interconnection of DERs and distribution systems up to 50 kV. This standard is the Canadian equivalent to UL 1741-SA, specifying grid interconnection requirements for DERs, including bidirectional EVSE and vehicle power export systems [39].

Standard or framework	Category	Description
CAN/CSA-C22.2 No. 257	Safety	*Interconnecting inverter-based micro-distributed resources to distribution systems.* Specifies requirements for safe interconnection of inverter-based micro-DR to low-voltage systems (maximum 600 V) connected to distribution systems. CSA C22.2 No. 257 is the Canadian equivalent to UL 1741-SB and relevant for V2G-capable inverters [40].
CSA C22.2 No. 107.1	Safety	*Power conversion equipment.* Applies to AC and DC PCE that does not exceed 1500 V. It does not apply to automotive and nonautomotive chargers, as covered by CAN/CSA-C22.2 No. 107.2. Corresponds to UL 1741 [41].
CSA C22.2 No. 107.2	Performance / safety	*Battery chargers.* Outlines the requirements for safety and performance criteria for battery chargers [42].
UL 3141	Safety	*Outline of investigation for power control systems.* Covers PCSs used in DER systems which include one or more power sources in addition to the utility grid. The PCS limits power to stay within defined limits and may operate autonomously or respond to external commands. Does not cover specific communication protocols for transmitting commands. May be applicable for validating PEL functionality for grid-tied V2H/V2B systems that are not listed or approved for power export to the grid (i.e., V2G) [43].
CSA C22.2 No. 178 / UL 1008	Safety	*Transfer switch equipment (trinational standard with NMX-J-674-ANCE and UL 1008).* Safety standard for automatic and manual transfer switch equipment. Relevant for some islanded V2H/V2B systems [44].
UL 1008B	Safety	*Outline of investigation for source interconnection switches.* Once published, this standard will apply to source interconnection switches intended for interconnection of sources and/or loads in a DER system, sometimes referred to as a microgrid, or other similar applications [45].

IEEE 1547

IEEE 1547 is the foundational standard for interconnecting DERs, including grid-connected VGI applications, with the electric grid [37]. It defines technical requirements for voltage regulation, frequency response, anti-islanding, and interoperability to help ensure safe and reliable grid integration. IEEE 1547 has undergone several revisions to address evolving grid needs:

- IEEE 1547-2003: Established the baseline for DER interconnection, focusing on unidirectional power flow and strict anti-islanding requirements, limiting DERs' ability to support the grid [46].
- IEEE 1547a-2014: Introduced ride-through capabilities, allowing DERs to temporarily remain online during voltage and frequency disturbances [46].
- IEEE 1547-2018: A major update requiring DERs, including bidirectional EVSE, to support grid stability through voltage and frequency regulation, reactive power support, and advanced interoperability via standardized communication protocols (e.g., IEEE 2030.5, SunSpec Modbus) [46].

IEEE 1547 adoption is widespread, serving as the basis for UL 1741 and its supplements (see Section 3.3.2.2), CSA C22.3 No. 9-2020, CAN/CSA C22.2 No. 257, and other national interconnection standards.

3.3.2.1 UL 1741

UL 1741 is a key safety and interconnection standard for DERs, including bidirectional EV charging systems used in grid-connected VGI applications [38]. It establishes testing and certification requirements for grid-supporting inverters, converters, and ISE, ensuring compliance with relevant IEEE 1547 standards. In North America, EVs that export power to the grid use an inverter certified to UL 1741 (IEEE 1547 compliance).

UL 1741 is third-party certified in the US and widely referenced by Canadian utilities for VGI interconnection. It has evolved to include three different testing supplements—SA, SB, and SC—each aligning with specific versions of IEEE 1547 to ensure grid interoperability, advanced functionality, and safety requirements:

- UL 1741-SA (Supplement A): Developed to align with IEEE 1547-2003, UL 1741-SA introduced grid support functionality for smart inverters, particularly for voltage and frequency ride-through, reactive power support, and communication-enabled responses. Although it was widely adopted in early DER interconnection standards, UL-1741 SA is now superseded by UL-1741 SB, as described below.
- UL 1741-SB (Supplement B): UL 1741-SB covers grid performance for utility interactive inverters, converters, and ISE to ensure compliance with IEEE 1547-2018. It applies to V2X-DC configurations, as well as V2X-AC split inverter DER systems. IEEE 1547-2018 introduced advanced inverter functionalities, including: dynamic voltage and frequency regulation; grid-forming capabilities for DERs, including bidirectional EVSE; communication interoperability (with protocols like IEEE 2030.5 and SunSpec Modbus). UL 1741-SB certification for DER interconnection is increasingly mandated across Canada and the United States—a trend expected to continue as IEEE 1547-2018 adoption increases.
- UL1741-SC (Supplement C): UL 1741-SC is currently under development to establish a standard for V2G-AC systems, where the bidirectional inverter is located on board the vehicle rather than in the external charger. The supplement will specifically address SAE J3072-compliant inverters paired with a UL 1741 SC listed oversite device, which ensures the inverter operates in accordance with site-specific grid performance requirements.

The corresponding Canadian standards for UL 1741-SA and UL 1741-SB are CSA C22.3 No. 9-2020 and CAN/CSA-C22.2 No. 257, respectively. However, experts interviewed for this study report that most **Canadian utilities still default to UL 1741** for interconnection compliance, with some referencing both standards. This inconsistency among utilities underscores the need for clear national guidance or harmonization efforts to ensure a more uniform and predictable approach to VGI interconnection.

3.3.2.2 UL QIKP and DER System Certification

V2X-AC systems – where the inverter is located on board the vehicle – can be evaluated for safety and grid performance as a DER systems under existing standards. Key components in these systems include an on-board inverter, EVSE, and in some cases, a grid isolation device. Together, they form a DER system, which can be evaluated for grid performance at the point of interconnection to existing applicable standards, such as UL 1741 SA/SB, IEEE 1547-2018, and IEEE 1547.1-2020. At the same time, off-board ISE components are evaluated according to their governing safety standards (e.g., UL 9741, UL 1741).

UL's 1741 **QIKP certification program** exemplifies how V2G-AC systems can be evaluated as DERs for grid performance. Though not a standard itself, QIKP provides a framework for testing and validating the performance of grid-interactive equipment and systems to UL 1741 SA or SB. Under this program, each combination of the DER system must be evaluated together, including on-board and off-board components.

It is important to distinguish DER system certification (e.g., through UL's QIKP program) from the forthcoming UL 1741-SC. Under UL 1741-SC, SAE J3072-compliant inverters are self-evaluated by OEMs and paired with a UL 1741-SC listed oversite device to ensure conformance with site-specific grid performance requirements. As the market for on-board inverter-based systems matures, further formalization or endorsement of analogous evaluation pathways in Canada could support consistent utility interconnection practices and increase confidence in system-level certification.

3.3.2.3 UL 3141

UL 3141 is a forthcoming system standard for PCS, designed to help ensure the safe and efficient integration of DERs, including bidirectional grid-connected VGI applications [43]. Its primary function is to prevent electrical overload by limiting or controlling current or power to stay within defined limits. Currently, an Outline of Investigation, UL 3141 is expected to replace UL 1741 PCS-CRD upon its final publication, anticipated in 2025 or early 2026. UL 3141 has a broader scope than UL 1741-SB, as it defines device-level and system-level control functionalities for managing bidirectional power exchange between EVSE, the grid, and behind-the-meter loads. In the context of VGI, UL 3141 is particularly relevant for PEL (also known as zero-export PCS), which is a critical requirement for grid-tied V2H/V2B systems that operate in parallel with the grid but are not approved for exporting power (i.e., not V2G-capable). These systems must ensure that EV discharging remains within local site limits and does not result in unintended back-feed to the grid. UL 3141 provides a standardized framework for such functionality and may be used to manage overload protection at multiple levels, including the utility interface, service panel, feeders, branch circuits, and building loads or sources.

Beyond VGI, UL 3141 will apply to any systems designed to integrate, control, and optimize DERs, such as solar PV systems, energy storage, and DR assets. The standard will ensure that PCS can manage grid-connected and islanded operation modes while maintaining system stability and safety. Given UL 3141's anticipated role in governing power control functions for a broad range of DER systems, including VGI, the standard presents an opportunity for proactive Canadian engagement and harmonization. Early alignment could reduce future integration barriers for V2H/V2B and related zero-export configurations, while supporting consistent enforcement of export-limiting requirements. According to experts interviewed for this study, it is anticipated that UL 3141 will be adopted as a binational standard in both Canada and the US, once published.

3.3.2.4 UL 1741 PCS-CRD—Interim Certification for Power Control Systems

UL 1741 PCS-CRD is a temporary framework developed to certify PCS for managing power import and export in DER applications, including V2G and bidirectional EV charging systems [3]. It was introduced to address **power import limiting (PIL) and PEL** requirements before a formal PCS standard was established. It is primarily used in California and select US markets to certify **V2G-DC EVSE**, allowing bidirectional chargers to **energize in charge-only mode** while ensuring compliance with grid safety protocols. This interim certification framework is expected to be replaced by UL 3141, a formal, consensus-based PCS standard, anticipated for publication in 2025 [36] or early 2026.

3.3.3 Communications Standards and Protocols

This section summarizes the landscape of communications standards and protocols that relate to EVs' interaction with the grid. Figure 8 outlines several relevant application layer protocols and standards used in managing EV charging, and with the entities, systems, and equipment (represented by black boxes) between which they communicate information. Below, we first summarize the entities and systems involved, followed by an overview of the most relevant protocols and standards within each category.

The entities and systems reflected in Figure 8 include:

- **Distribution System Operators (DSOs, i.e., electrical utilities) and Independent System Operators (ISOs):** DSOs are responsible for managing the electricity distribution system and providing electricity to their final customers. ISOs are organizations which coordinate the operation of the wholesale electrical power system. To provide reliable electricity at affordable costs, DSOs increasingly seek to influence the timing and load profile of EV charging. Likewise, ISOs may enable aggregators of EV DR resources (and in the future vehicle to grid, V2G, resources) to bid into wholesale capacity and energy markets. DSOs' influence on EV loads can be done passively through dynamic utility rates (e.g., TOU rates) and/or other prices signals. Another way of passively influencing EV loads is through incentive program requirements that encourage designs that inherently shape facilities' load profiles in advantageous ways. Additionally, DSOs may establish active managed charging initiatives (i.e., V1G), sending real-time price signals or directly controlling EV loads at facilities. As noted in

Figure 8: Relevant application communications protocols and standards for EV charging.

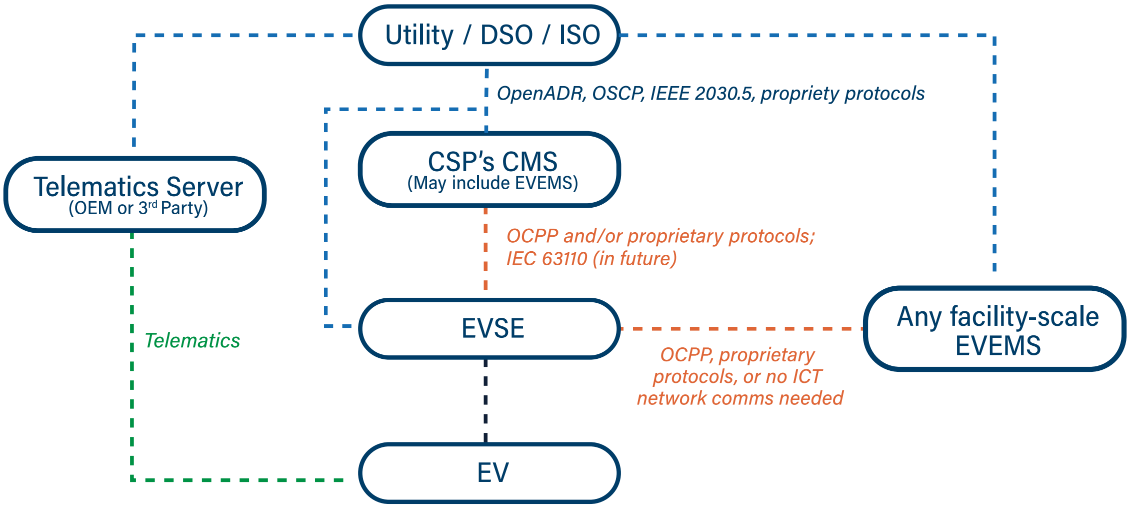


Figure 8 and explored further below, these signals can be communicated through a range of different standards and protocols to either charging service providers (CSP) serving as aggregators, or directly to EVSE. Furthermore, vehicle telematics can be used to have EVs respond directly to utility signals. Utilities' systems to support active management of various different end uses are often called DERMS.

- **CSPs:** Supply EV chargers, software, and support services for multi-unit residential buildings, workplaces, and other facilities. They offer a range of services, including: EVSE installations, managing user access controls, apps and dashboards for drivers and administrators, payment processing, and data security and customer support. CSPs also handle operations, maintenance, warranties, and managed charging initiatives, and may assist building owners in monetizing carbon credits under various provincial and federal programs.
- **CMS:** CSPs deliver many of the services noted above via CMS. CMS are enterprise software systems that support information processing and communications between EVSE, EVs, drivers, DSOs, and other interested parties. Some CMS are proprietary, while others adhere to the Open Charge Point Protocol (OCPP), summarized further below.
- **EVEMS:** The CE Code defines EVEMS as "a means used to control electric vehicle supply equipment loads through the process of connecting, disconnecting, increasing, or reducing electric power to the loads and consisting of any of the following: a monitor(s), communications equipment, a controller(s), a timer(s), and other applicable device(s)" [47]. EVEMS can be a component of CSP's CMSs. Alternately, they may operate independently of a CSP's CMS; operating independently of a CMS entails controlling EVSE loads at the scale of a facility, either through communications with EVSE to reduce their loads, or by switching circuits to EVSE on and off.

3.3.3.1 Grid-Level Communications

This section outlines key communication standards and protocols that enable utilities and grid operators to manage EV charging and energy export. These standards, summarized in Table 8, include IEEE 2030.5 for smart energy management, Open Automated Demand Response (OpenADR) 3.0 for automated DR, Open Smart Charging Protocol (OSCP) for grid capacity forecasting, and SAE J2847/3 for V2G interactions. At the grid-level, such protocols facilitate interactions between utilities, DSOs, ISOs, and key actors, including automakers (OEMs), CSPs, aggregators, and facility-scale energy management systems (EVEMS). They support real-time coordination of EV charging, pricing signals, and bidirectional energy flow, helping EVs contribute to grid efficiency while meeting driver needs.

3.3.3.1.1 IEEE 2030.5

IEEE 2030.5 facilitates management of the end user energy environment, including DR, direct load control, and price communication [48]. Like OpenADR and OSCP, IEEE 2030.5 is a software application protocol that establishes a standardized means of communicating information over the internet.

3.3.3.1.2 OpenADR 3.0

OpenADR is an open protocol intended to enable interoperable information exchange between DSOs and control systems to facilitate automated DR [49]. OpenADR offers a standardized and open method for Virtual Top Nodes, such as DSOs and ISOs, to communicate with different Virtual End Nodes, including aggregators, EV charging network operators, EVSE. This communication occurs over any IP-based network using a unified language. Originally developed to streamline and automate DR by using dynamic pricing and reliability signals, OpenADR enables end users to adjust their consumption habits while offering DSOs a consistent way to communicate with load aggregators or directly with end-use equipment. Protocols like OpenADR can also be integrated with other communication protocols, such as those between a charging station and a network operator (e.g., OCPP; see below). The OpenADR Alliance was formed in 2010 by industry actors, including electronics OEMs, EV CSPs, utilities and others, to support development and testing of applications enabled by OpenADR.

3.3.3.1.3 OSCP

The OSCP facilitates communication between a DSO and a CMS or EVSE [50]. It can also be used to communicate between facilities' energy management systems and the CMS. OSCP is administered by the OCA, an industry stakeholder-based non-profit that administers several open protocols relating to EV charging.

3.3.3.1.4 SAE J2847/3

This standard establishes communication protocols for plug-in electric vehicles (PEVs) equipped with on-board inverters [51], specifically addressing PEVs using the IEEE 2030.5-2018 protocol, also known as

Table 8: Grid-level communications standards and protocols

Standard or framework	Description
IEEE 2030.5	*Smart energy profile application protocol.* Defines an application layer and "Internet layers to enable utility management of the end user energy environment, including [DR], load control, time of day pricing, management of distributed generation," and so forth. Also defines mechanisms for exchanging application messages, exact messages, and security features to protect them [48].
OpenADR 3.0	*Open automated demand response.* Provides a non-proprietary, open, standardized and secure DR interface to allow electricity providers to communicate DR signals directly to existing customers using the internet [49].
OSCP	*Open smart charging protocol.* Facilitates the smart charging of EVs. Developed by the OCA, it enables communication between the charge spot operator and the DSO to forecast the available electricity grid capacity for the next 24 hours. This helps in optimizing the charging schedules of EVs to avoid overloading the grid and to make efficient use of available capacity [50].
SAE J2847/3	*Communication for plug-in vehicles as a distributed energy source.* Provides non-comprehensive framework for using V2G communication between EV and grid, for plug-in vehicles that communicate using the IEEE 2030.5-2018 protocol, also known as SEP2. The standard includes instructions for the SEP2 flow reservation function set, ensuring efficient and reliable communication between the vehicle and the grid during discharging [51].

SEP2. It supplements the SEP2 standard to support use cases defined by SAE J2836/3. It offers guidance on implementing the SEP2 DER function set, enabling PEVs to function as distributed energy sources by discharging electricity back to the grid. This capability is crucial for providing valuable grid services, such as DR and load balancing. SAE International is a leading global body that develops standards for mobility and transportation technologies.

3.3.3.2 EVSE and Charging Network Communications

This section highlights key EVSE communication standards, including OCPP, which standardizes interactions between charging stations and network management systems, and IEC 63110, which defines communication protocols for charging and discharging infrastructure management (see Table 9). These communication standards facilitate effective communication between EVSEs and network management systems (e.g., CSPs, facility-scale EVEMSs, and aggregators) to monitor, control, and optimize charging.

3.3.3.2.1 OCPP

The OCA developed this free, open-source, vendor-independent protocol [52]. It is an application protocol for communication between EVSE and a CMS. The intent of OCPP is to minimize the risk of networked EV charging infrastructure investments, by allowing interoperability with various EVSE models/manufacturers and different CSPs' CMS. Likewise, it can allow CSPs to be agnostic to the EVSE they support. Many EVSE vendors and CSPs have adopted OCPP. For consumers, OCPP supports greater network compatibility, improved charger reliability, and a more consistent user experience across different charging stations.

Multiple versions of OCPP are currently available [54]. These include:

- **OCPP 1.6:** Released in 2015, this widely adopted version remains the most widely used version of the OCPP standard [55]. It provides basic functionalities, such as starting and stopping charging, retrieving charging station information, and updating firmware. OCPP 1.6 is backward compatible with earlier versions like OCPP 1.5.
- **OCPP 2.0.1:** Released in 2020, this version introduced enhanced functionalities, including ISO 15118-20 integration for plug-and-charge capabilities, enhanced security, and improved smart charging feature [54]. OCPP 2.0.1 ed3 was approved as IEC standard IEC 63584 in 2024 [55], [56]. OCPP 2.0.1 is not backward compatible with OCPP 1.6. Upgrading to OCPP 2.0.1 requires updating both CMS and charger firmware.
- **OCPP 2.1:** Released in 2025, this version is an extension of OCPP 2.0.1 and introduces support for ISO 15118-20 bidirectional power transfer, enabling V2X applications [54]. It also includes improved smart charging capabilities, expanded transaction options (fixed costs, energy- or time-based billing), and support for battery swapping stations. Additionally, OCPP 2.1 introduces local cost calculation, new authorization options, such as prepaid charge cards, ad hoc payments via credit/debit cards, and secure dynamic QR codes for authentication and payments.

Table 9: EVSE and charging network communications standards and protocols

Standard or framework	Description
OCPP	*Communication standard for EVSE-to-network interactions.* Standardizes the interaction between EVSE and CMS. It allows interoperability with any management software and reduces dependency on specific vendors, promoting a more competitive and innovative market [52].
IEC 63110	*Protocol for management of electric vehicles charging and discharging infrastructures.* Defines the communication protocols necessary for interactions between EVs, charging stations, and the grid, ensuring efficient data exchange and interoperability among different e-mobility actors [53].

The OCA provides a certification program for EVSE and CMS, ensuring that the OCPP implementation has been verified for compliance with OCPP specifications by an accredited independent test laboratory. This verification process better ensures that OCPP EVSE and CMSs are interoperable.

Expert interviews report that the certification process for OCPP compliance is lengthy. Many CSPs and equipment vendors, particularly in North America, note that their EVSE and/or CMS are OCPP compliant, but have not yet been formally certified. Some equipment systems only partially implement OCPP, supporting certain functions or profiles but not others. Additionally, it is possible for OCPP implementation to be insufficient for interoperability, but for vendors to still claim their CMS or EVSE as "compliant"; indeed, several CMS vendors report testing EVSE for compatibility before offering them to their clients. It is also important to note that OCPP covers only the application layer: fully open systems require compatible transport protocols, hardware integration, and also compatible commands. Despite the potential issues and shortcomings noted above, it is generally acknowledged that OCPP EVSE and CMS can significantly reduce the risks of stranded assets.

3.3.3.2.2 IEC 63110

IEC 63110 covers many of the same functions as OCPP and is informed by the OCA [57]. IEC 63110 also allows bidirectional charging (V2G) and fast frequency response services, among other improvements in functionality on OCPP. As an international standard, as opposed to OCPP, which is fundamentally a voluntary protocol, it is hoped that IEC 63110 can better ensure interoperability. It is unclear whether IEC 63110 will be backward compatible with any version of OCPP; however, efforts are reportedly underway to enable coexistence between the two protocols.

3.3.3.2.3 IEC 61850

IEC 61850 is an international standard for power system communication, originally developed for substation automation but now applied to DERs, including VGI. While not a communication protocol itself, IEC 61850 is a **semantic model** that defines a structured data model and standardized communication framework to enable interoperability between grid operators, DER systems, and energy management platforms. In VGI applications, it supports real-time data exchange between EV charging infrastructure, aggregators, and utility control centres. The standard provides a common standardized nomenclature for power system components, and has been adopted, or is in the process of being adopted, by select VGI communication protocols, including ISO 15118-20, OCPP, and IEEE 2030.5, to enhance compatibility across different systems.

3.3.3.3 Vehicle-to-OEM Communications (Proprietary Telematics)

In the context of EV charging, telematics refers to the communication of data and commands between an EV and a remote platform, typically a telematics server [58]. Telematics systems are cloud-based EV communication for DR and fleet optimization. Vehicle OEMs may offer telematics services, and third-party service providers may also develop telematics controls for either individual or multiple vehicle brands, provided they coordinate with vehicle OEMs to prevent safety and coordination issues. Such proprietary telematics platforms typically bypass EVSE communication standards like OCPP and ISO 15118-20. Instead of communicating with chargers, they directly influence vehicles charging patterns. Vehicle telematics can be used for some communications functions instead of networked EVSE or EVEMS. For example, the status of a charger could be communicated by vehicles connected to it. By aggregating DR resources for DSOs, telematics systems can provide active managed charging at utility-scale.

3.3.3.3.1 ChargeScape: An OEM-Led Effort to Improve VGI Interoperability

ChargeScape is a joint venture between four large automakers aimed at enhancing interoperability between EVs and the power grid [59] by creating a common platform for managed charging and energy services. As noted in interviews, fragmentation of telematics and charging communication protocols across different automakers has been a key challenge in VG1. ChargeScape aims to streamline data sharing between EVs, utilities, and grid operators to enable more efficient load management and participation in grid services [59]. By aggregating EV charging data

"By contrast, grid interconnection standards are evolving rapidly, with several emerging standards still in development."

and coordinating with utilities, ChargeScape could reduce the burden on grid operators while providing standardized participation pathways for EV owners in managed charging and grid services programs. Interviewees noted that ChargeScape may simplify utility integration with multiple OEMs, reducing the need for custom solutions and one-off agreements with individual automakers. While it does not replace existing VGI protocols, such as IEEE 2030.5 or OpenADR, ChargeScape represents a shift toward more centralized coordination between automakers, utilities, and energy markets, potentially accelerating VGI adoption.

3.3.4 Summary

Overall, standards governing interactions between EVs and EVSE are relatively well established. While these standards continue to evolve, such as the anticipated update to SAE J3072 to align with UL 1741-SC, the foundational standards for governing EV-EVSE interactions are largely in place. However, adoption of newer standards designed to support bidirectional applications, such as ISO 15118-20, has been limited to date. Proprietary communication systems between EVs and EVSE also remain common, contributing to variability in implementation across the market.

By contrast, grid interconnection standards are evolving rapidly, with several emerging standards still in development. As V2X-AC applications gain momentum, UL 1741-SC is under development to provide a dedicated framework for V2G-AC systems, specifically addressing SAE J3072-compliant inverters paired with UL 1741-SC listed oversite devices. New DER system certification pathways, such as UL QIKP, are emerging to support grid performance evaluation for on-board inverter systems, though awareness and adoption remain limited. Meanwhile, UL 3141—an upcoming standard focused on PCSs—aims to provide a comprehensive framework for managing import/export limits and overload protection in bidirectional grid-connected DERs, including EV-based systems.

Communication protocols for VGI remain a significant area of fragmentation. A mix of proprietary and open protocols is used across OEMs, CSPs, utilities, and aggregators, with adoption varying widely by actor and jurisdiction. Experts interviewed for this study consistently identified inconsistent implementation and interoperability challenges as key barriers to effective VGI deployment. These conditions underscore the need for improved coordination, clearer guidance, and targeted standardization efforts to support scalable and interoperable VGI solutions.

3.4 Key Challenges and Opportunities

3.4.1 Key Challenges and Gaps

This section outlines four key challenges that currently limit the scalable deployment of VGI in grid-connected applications. These issues primarily apply to grid-tied configurations, including V2G, grid-tied V2H/V2B, and to a lesser extent V1G. By contrast, no major challenges were identified for V2L or islanded V2H/V2B systems, which do not interact with the grid and therefore avoid many regulatory and interoperability hurdles. While the North American standards landscape for VGI is robust and expanding, the review in Section 3.3 highlights several areas where misalignment, limited adoption, and evolving protocols have created barriers to scale.

Challenge #1: Fragmentation and Overlap of Standards

A key challenge in enabling VGI is the complexity created by the fragmentation and overlap of existing standards. Interested parties must navigate a growing list of safety, performance, and communication standards, many of which overlap or are evolving in parallel.

Key gaps include:

- **Lack of clarity for OEMs and industry:** The range of overlapping standards, detailed throughout Section 3.3, makes it difficult for key participants, including utilities, automakers, and charger manufacturers, to determine which standards best support interoperability and long-term market development. OEMs often face uncertainty regarding which standards are required for interconnection, as different utilities have varying requirements (see Challenge #4).
- **Slow adoption of new standards:** Adoption of evolving standards does not always keep pace with technological advancements, which can slow the market's ability to scale effectively. For example, delays in widespread adoption of newer standards (e.g., UL 1741 SB, and the forthcoming UL-1741 SC) can leave manufacturers uncertain about future compliance expectations. Additionally, many industry players have already invested in legacy standards, which can lead to hesitancy in adopting alternatives, even when those offer potential long-term benefits. As a result, older and newer standards coexist, reinforcing fragmentation and inconsistency across technologies and jurisdictions.
- **Misalignment between Canadian and** international standards: In Canada, CSA standards tailored to the Canadian context, alongside UL standards, provide valuable guidance for different regulatory and market needs. However, aligning these with international standards remains an ongoing challenge, as parallel requirements can sometimes lead to inefficiencies or uncertainty for manufacturers and grid operators. Divergent requirements can create inefficiencies, such as duplicative testing or certification, which in turn can raise costs, delay deployment timelines, and create barriers to market entry in Canada.

The net effect of this fragmentation is a lack of regulatory clarity that increases compliance costs, slows product rollout, and limits investment in VGI technologies.

Challenge #2: Proliferation of Misaligned Communications Protocols

While fragmentation of standards is a broader challenge (see Challenge #1), the lack of alignment across a growing list of communication protocols stands out as a critical barrier to VGI implementation. Currently, communication standards are fragmented across different segments of the delivery chain, ranging from utilities and third-party aggregators to EVs and EVSE. Key gaps and areas of fragmentation include:

- **OEM-to-utility interface:** This interface remains unstandardized, making interoperability between EVs and the grid particularly challenging. IEEE 1547 references multiple communication protocols, including IEEE 2030.5, SunSpec Modbus, and DNP3, but harmonization is incomplete.
- **Vehicle-to-OEM (telematics):** Proprietary telematics-based solutions used by major automakers limit cross-manufacturer compatibility, restricting open communication pathways within the VGI ecosystem. However, some interviewees noted arguments in favour of enabling proprietary communication between EV and EVSE/ISE for compatibility, safety, and security.
- **Grid-level communication:** Although OpenADR and IEEE 2030.5 are widely adopted for grid communication, uptake and implementation of these protocols varies across utilities, creating further barriers to interoperability.

- **DERMS and Advanced Metering Infrastructure (AMI):** The role of DERMS and AMI 2.0 in supporting VGI is not yet standardized. Emerging standards like UL 3141 provide a foundation for system-level control and PEL, but their integration with DERMS and AMI signalling pathways remains unclear. This lack of alignment limits the ability of VGI systems' participation in real-time grid services, such as DR or local load balancing, highlighting the need for clearer standards and guidance at the utility interface.
- **Lack of third-party certification:** The automotive industry's lack of standardized third-party certification processes makes aligning protocols with utilities and grid operators particularly difficult.

This fragmented standards environment creates uncertainty over which communication pathways will be widely adopted (see Challenge #1). Such uncertainty can deter investment in VGI-enabling technologies, as OEMs must navigate multiple protocols and integration requirements without clear return on effort [60]. Interviewees consistently emphasized the need for more streamlined, harmonized bidirectional communication protocols among EVs, EVSEs, charging networks, utilities, and system operators to maintain safe and interoperable VGI.

Challenge #3: Emerging Standardization for V2G-AC

While VGI technology is advancing, the standardization of V2G using alternating current (V2G-AC) remains relatively nascent compared to direct current (V2G-DC). As noted in Section 3.2.1.2, many automakers currently favour V2G-DC, where the inverter is located off-board in the charging infrastructure. However, V2G-AC, which utilizes an on-board inverter, is gaining traction due to lower costs and relative ease of installation. Despite growing interest, the lack of understanding regarding how to evaluate V2G-AC systems using existing standards, as well as a relative lack of mature, and/or widely adopted standards for V2G-AC has slowed deployment.

Key gaps include:

- **Limited understanding of available certification pathways:** UL 1741-SB is published and provides a clear certification and interconnection pathway for V2G-DC. While UL-1741 SB can also be used to certify V2G-AC systems as DER systems, this approach is less widespread and not well understood.
- **Lack of mature or widely adopted standards:** UL 1741-SC, intended to address V2G-AC with SAE J3072 inverters and UL 1741 SC listed oversite devices, is still under development and not yet finalized. As a result, utilities and automakers remain uncertain about how these requirements will affect interoperability, compliance, and deployment strategies.

Successful standardization of V2G-AC grid interconnection will depend on both completing and aligning industry around emerging standards like UL 1741-SC, as well as increased acceptance and formalization of DER system grid performance certification approaches using existing standards, such as UL 1741 SA and SB and Canadian equivalents CSA C22.3 No. 9-2020 and CAN/CSA-C22.2 No. 257. Advancing these efforts will be essential for providing regulatory clarity, reducing certification barriers, and accelerating the deployment of V2G-AC technologies. Continued collaboration among automakers, utilities, SDOs, and regulators will be critical to establishing a robust and flexible framework that supports both V2G-DC and V2G-AC.

Challenge #4: Inconsistent Utility Interconnection Processes

Interconnection processes for V2G and grid-tied V2H/V2B remain highly inconsistent across utilities and jurisdictions, creating deployment barriers.

Key gaps include:

- **Varied interconnection processes:** Utilities operate under varied frameworks, making it difficult for automakers, charger manufacturers, and EV owners to navigate interconnection requirements. In Canada, provincial interconnection standards differ significantly from those in the US, complicating market entry for manufacturers seeking to deploy V2G solutions across North America. Interconnection processes also vary significantly within Canada, further complicating adoption.
- **Lack of guidance for grid isolation devices:** Requirements for grid isolation devices in V2H/V2B

applications vary widely. No widely adopted standards exist for microgrid isolation devices. Although UL 1008B is being developed to address this gap, it is not yet published. Additionally, UL 1741 Multimode CRD provides requirements to help ensure multimode systems safely isolate from the grid before providing backup power; however, this is a temporary framework, and not a published, consensus-based standard. Without standardized guidance, some utilities require two separate utility connections for grid-tied and islanded operation, even within a single installation.

- **Limited utility programs or incentives:** The lack of financial incentives for EV owners (i.e. utility programs) limits real-world V2G deployment and opportunities to refine interconnection processes. Ideally, interconnection processes, utility programs, and rate structures should be technology-agnostic, supporting a broad range of DERs, including bidirectional EVs, under a cohesive framework. Treating technologies like solar PV, stationary energy storage, and V2G systems consistently can simplify the interconnection process, reduce administrative burden, and clarify participation pathways.

Inconsistent interconnection requirements significantly increase inefficiency and administrative burden, particularly for OEMs tasked with helping customers navigate varied utility requirements across jurisdictions. These inconsistencies can also negatively affect the customer experience, as EV owners interested in V2G or grid-tied V2H/V2B may face unclear, lengthy, or costly interconnection processes, discouraging adoption.

3.4.2 Opportunities for Standardization

Facilitate Communications Protocol Alignment

There is a need to develop guidance on key considerations for communication protocol alignment in VGI applications. This could include recommendations for interoperability between existing communication protocols, considerations for certification and testing processes, and insights into the needs of Canadian utilities and grid operators. Such guidance could help interested parties, including utilities, automakers, and charger manufacturers, navigate the evolving VGI communications landscape and make informed decisions about protocol adoption. By fostering greater alignment between protocols used for VGI applications, these efforts could support a more interoperable and scalable VGI ecosystem in Canada. In parallel, advancing the integration of VGI with utility-side systems, such as DERMS and AMI 2.0, is essential. This includes clarifying how evolving VGI-related standards can interface with DERMS and AMI signals. In particular, integration should support system responsiveness to signals, such as dynamic pricing and DR, while also ensuring timely and consistent functional control in response to AMI signals, to prevent overcurrent conditions at the customer or feeder level.

To address these needs, it is recommended to convene key industry actors (utilities, automakers, charger manufacturers) to address these issues. The convened group could be tasked with developing specifications for the “stack” of communications protocols and technologies to enable utilities to implement each of V1G and V2G. This collaborative process could help identify specific incompatibilities, or required communications formats between different protocols, and serve as a model for VGI deployments in Canada. It will also be important to engage with other efforts to rationalize standards, ensuring that this work complements rather than duplicates existing initiatives and accelerates the creation of a harmonized communications protocol landscape in Canada.

Harmonize Canadian Standards with International Best Practices

Aligning Canadian VGI standards with US and international frameworks will help improve interoperability, streamline regulatory compliance, and support market expansion. Greater harmonization can reduce complexity for manufacturers, utilities, and grid operators, while ensuring consistency in certification and deployment processes.

One potential approach is to pursue formal alignment or mutual recognition of corresponding standards where feasible. For example, the Canadian equivalents of UL 1741-SA and UL 1741-SB are CSA C22.3 No. 9-2020 and CAN/CSA-C22.2 No. 257, respectively. Ensuring greater harmonization between these standards across jurisdictions can reduce market

"By fostering greater alignment between protocols used for VGI applications, these efforts could support a more interoperable and scalable VGI ecosystem in Canada."

fragmentation and improve clarity for the parties involved. Similarly, as UL 1741-SC evolve, aligning a Canadian equivalent standard once it is published would help support the growing V2G-AC ecosystem. The same approach could apply to UL 3141, which is currently in development.

Harmonization efforts, particularly binational standards, can provide multiple benefits: improved interoperability between EVs, EVSEs, and grid systems; improved market access for manufacturers; and reduced compliance costs by minimizing duplicative testing or certification processes.

Support DER System Grid Performance Evaluation for V2G-AC Systems

To align with international best practices, it is also recommended to support the standardization of DER system grid performance evaluation for V2G-AC systems, using Canadian equivalents of UL 1741 SA and SB (i.e., CSA C22.3 No. 9-2020 and CAN/CSA-C22.2 No. 257). As discussed in Section 3.3.2, V2G-AC systems, with the bidirectional inverter located on board the vehicle, can be evaluated as DER systems at the point of interconnection. This ensures that the complete system, including the on-board inverter and off-board ISE, operates safely and in compliance with grid performance requirements.

Nationally recognized testing laboratories, such as UL, already offer this alternative pathway for certification through internal programs (e.g., UL 1741 QIKP), which assess the grid performance of DER systems against UL 1741 SA or SB. While QIKP itself is not a certifiable standard, it sets a precedent for validating V2G-AC systems. Formalizing a similar evaluation process in Canadian—potentially through additional guidance or clarification on testing procedures—could help specify how EV and EVSE interoperability is validated. This would reduce ambiguity for manufacturers, better align domestic practices with emerging international approaches, and facilitate the deployment of V2G-AC technologies.

Provide a Basis for Verification that a Technology Stack Will Deliver VGI

As noted above, the landscape of standards for VGI is incomplete, fragmented and overlapping, resulting in uncertainty for industry players (see challenges #1 and #2 in Section 3.4.1); this is particularly true for communication standards between EVs, EVSEs, aggregators, and utility grid operators. At the same time, V1G deployments are increasingly common, and V2G pilots are growing rapidly. V1G and V2G are possible today, even given the imperfect standards landscape. While there is a need to move toward a more consistent, open, and interoperable landscape of standards for VGI, there is also value in enabling the timely deployment of systems already proven to work with existing protocols and emerging standards available.

To reduce the need for bespoke oversight and piloting, utility grid operators could benefit from third-party assurances that different "technology stacks" (combinations of standards, industry protocols, and/or proprietary systems) work for particular VGI applications. For example, confirming that an OpenADR-based signal will successfully be transmitted and can achieve the appropriate response from EV charging systems. This could involve establishing the basis for verification that a system is ready to be implemented and then validating a growing list of deployments.

It is recommended to establish an initiative that will verify VGI technology stack; this initiative could be housed at a certified testing lab or potentially another non-biased entity. This program would provide certification of VGI technology stacks and specifications, enabling the VGI implementations beyond pilot projects. This effort could complement industry convening noted in the "Facilitate standardized Communications Protocols" discussion above.

Develop Best Practices for Utility Interconnection

The development of best practices for V2G and grid-tied V2H/V2B interconnection would provide utilities with clear guidance on integrating bidirectional EV power transfer into their grid operations. Standardizing key interconnection requirements, clarifying certification expectations, and outlining best practices for utility implementation would help streamline the process and reduce uncertainty for key actors. This could include establishing a basis for certification that an "end-to-end technology stack" for different VGI applications functions effectively. Developing these best practices can promote greater consistency across Canadian jurisdictions while ensuring alignment with evolving international standards. This initiative would support utilities in managing V2G resources more effectively, accelerating adoption, and maximizing grid benefits while reducing barriers for manufacturers and EV owners.

4 Conclusions

VGI represents a critical opportunity to enhance the flexibility, resilience, and efficiency of Canada's electricity systems as EV adoption accelerates. By enabling EVs to serve not only as transportation assets but also as DERs, VGI can support demand management, grid stabilization, backup power, and increased uptake of renewable energy.

Although VGI holds significant promise, several key challenges must be addressed to support its widespread and effective deployment. Chief among these is the lack of standardized, interoperable communication protocols across the VGI ecosystem. In addition, the fragmentation and overlap of existing standards create uncertainty for actors navigating certification and compliance. Standardization for V2G-AC systems also remains less developed than for V2G-DC, with incomplete certification pathways and limited understanding of evaluation approaches such as DER systems. Finally, utility interconnection processes vary widely across regions, with inconsistent requirements for grid isolation, a lack of harmonized practices, and limited financial incentives—all of which add cost and complexity for customers and slow deployment.

Despite these challenges, important opportunities exist to advance the role of standards in enabling VGI. First, developing guidance on aligning communication protocols, including integration with DERMS and AMI, would improve interoperability and enable real-time grid coordination. Second, harmonizing Canadian standards with international frameworks, such as UL 1741 and UL 3141, could reduce regulatory complexity and streamline access for manufacturers and utilities. Third, formalizing the evaluation of V2G-AC systems as DERs would clarify certification pathways and support safe, scalable deployment. Fourth, establishing a basis for verifying end-to-end "technology stacks" could give utilities confidence in deploying proven VGI configurations, even amid evolving standards. Finally, developing best practices for utility interconnection would help standardize requirements, streamline implementation, and reduce adoption barriers across jurisdictions. These initiatives collectively offer a pathway to a more consistent, interoperable, and future-ready VGI ecosystem—unlocking the full potential of EVs as dynamic grid assets.

References

[1] Clean Energy Canada, "The true cost," Vancouver, BC, Canada, Mar. 30, 2022. [Online]. Available: https://cleanenergycanada.org/wp-content/uploads/2022/03/Report_TheTrueCost.pdf

[2] M. Kannangara, F. Bensebaa, and M. Vasudev, "An adaptable life cycle greenhouse gas emissions assessment framework for electric, hybrid, fuel cell and conventional vehicles: Effect of electricity mix, mileage, battery capacity and battery chemistry in the context of Canada," *Journal of Cleaner Production,* Vol. 317, Oct. 1, 2021, doi.org/10.1016/j.jclepro.2021.128394

[3] Z. Woogen, "Relevant technical standards for bidirectional charging," Vehicle Grid Integration Council (VGIC), Mar. 28, 2024. Accessed: Jul. 12, 2025. [Online]. Available: https://static1.squarespace.com/static/5dcde7af8ed96b403d8aeb70/t/660c2dcb81d1e50d49850756/1712074188541/2024-03-28+VGIC+Presentation+on+V2X+Standards.pdf

[4] Smart Electric Power Alliance, "2024 SEPA Snapshot Series – Transportation," 2024. [Online]. Available: https://sepapower.org/resource/2024-sepa-snapshots-series-transportation

[5] C. Howey, K. Carmichael, and M. Shariat-zadeh, "Electric vehicle energy management systems," Canadian Standards Association, Toronto, ON, Canada, May 2019. [Online]. Available: https://www.csagroup.org/wp-content/uploads/CSA-RR_ElectricVehicle_WebRes.pdf

[6] CSA Group, "Electric vehicle energy management systems," Notice of Intent, CSA C22.2 No. 232, Standards Council of Canada, Feb. 8, 2019. [Online]. Available: https://scc-ccn.ca/standards/notices-of-intent/csa-group/electric-vehicle-energy-management-systems

[7] EVBoosters, "Vehicle-to-Load (V2L)." Accessed Aug. 18, 2025. [Online]. Available: https://evboosters.com/ev-charging-academy/ev-charging-vocabulary/vehicle-to-load/

[8] Utility Smarts, "How to calculate emissions from diesel generator?" Accessed Feb. 18, 2025. [Online]. Available: https://www.utilitysmarts.com/automobile/diesel/how-to-calculate-emissions-from-diesel-generator

[9] Environment and Climate Change Canada, "Emission factors and reference values," May 10, 2024. [Online]. Available: https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/output-based-pricing-system/federal-greenhouse-gas-offset-system/emission-factors-reference-values.html

[10] Southern California Edison, "Interconnecting generation under Rule 21." Accessed May 18, 2025. [Online]. Available: https://www.sce.com/business/generating-your-own-power/Grid-Interconnections/Interconnecting-Generation-under-Rule-21

[11] B. Blair and G. Fitzgerald, "The state of managed charging in 2024," Smart Electric Power Alliance (SEPA), Washington, DC, USA, 2024. [Online]. Available: https://sepapower.org/resource/state-of-managed-charging-in-2024

[12] K. Darcovich, T. Laurent, and H. Ribberink, "Improved prospects for V2X with longer range 2nd generation electric vehicles," *eTransportation,* vol. 6, no. C, Nov. 2020, Art. no.100085, https://doi.org/10.1016/j.etran.2020.100085.

[13] Electric Vehicle Association of Alberta, "The current state of bidirectional EV charging in Canada," September 24, 2024. [Online]. Available: https://albertaev.ca/bidirectional-ev-charging-in-canada

[14] A. Brewer, "Industry leader unveils new tech that could revolutionize electric vehicle charging: 'Generational leap'," The Cool Down, May 14, 2025. Accessed May 18, 2025. [Online]. Available: https://www.thecooldown.com/green-tech/chargepoint-ev-chargers-v2x-technology

[15] [B. Blair and G. Fitzgerald,"The state of bidirectional charging in 2023," Smart Electric Power Alliance (SEPA), Washington, DC, USA, 2023. [Online]. Available: https://sepapower.org/resource/the-state-of-bidirectional-charging-in-2023

[16] F. Adegbohun, A. von Jouanne, E. Agamloh and A. Yokochi, "A review of bidirectional charging grid support applications and battery degradation considerations," *Energies,* vol. 17, no. 6, p. 1320, Mar. 2024, doi.org/10.3390/en17061320. [Online]. Available: https://www.mdpi.com/1996-1073/17/6/1320

[17] L. D. Vroey, C. Stuckens, N. Omar, Y. Oualmakran, R. Jahn, and J. V. Mierlo, "Is vehicle-to-home or vehicle-to-grid suitable for the electric vehicle user? Discussion from a one year intensive experience," in *Proc. 29th Intl. Electric Vehicle Symp.,* Montreal, QC, Canada, Jun. 2016, pp. 771–782.

[18] K. Uddin, T. Jackson, W. D. Widanage, G. Chouchelamane, P. A. Jennings, and J. Marco, "On the possibility of extending the lifetime of lithium-ion batteries through optimal V2G facilitated by an integrated vehicle and smart-grid system," *Energy,* vol. 133, Aug. 15, 2017, doi.org/10.1016/j.energy.2017.04.116.

[19] E. Gibson, "Can a battery discharge completely? Harmful effects on lithium-ion, lead acid, and NiMH," Powering Autos, Dec. 7, 2024. Accessed Feb. 18, 2025. [Online]. Available: https://poweringautos.com/can-a-battery-discharge-completely

[20] E. Gibson, "Lead acid battery discharge levels: How far down can you safely go?," Powering Autos, Dec. 20, 2024. Accessed Feb XX, 2025. [Online]. Available: https://poweringautos.com/how-far-down-can-you-discharge-a-lad-battery/

[21] M. Yakub, "EV batteries are likely to outlive vehicles they're in, finds latest Geotab data," Electric Autonomy, Sep. 18, 2024. [Online]. Available: https://electricautonomy.ca/ev-supply-chain/batteries/2024-09-18/ev-batteries-longevity-geotab-data

[22] D. Wang, J. Coignard, T. Zeng, C. Zhang, and S. Saxena, "Quantifying electric vehicle battery degradation from driving vs. vehicle-to-grid services," *Journal of Power Sources,* vol. 332, pp. 193–203, Nov. 2016, doi.org/10.1016/j.jpowsour.2016.09.116.

[23] A. Thingvad and M. Marinelli, "Influence of V2G frequency services and driving on electric vehicles battery degradation in the Nordic countries," in *Proc. of EVS 31 & EVTeC 2018,* 2019. [Online]. Available: https://orbit.dtu.dk/files/151021034/EVS31_V2G_service_battery_degradation_final_postprint.pdf

[24] D. McCarthy, "Chart: Lithium-ion battery prices fall yet again," Dec. 13, 2024. Accessed Feb. 18, 2025. [Online]. Available: https://www.canarymedia.com/articles/batteries/chart-lithium-ion-battery-prices-fall-yet-again

[25] C. Argue, "How long do electric car batteries last? What analyzing 10,000 EVs tells us...," Jan. 20, 2025. Accessed Apr. 4, 2025. [Online]. Available: https://www.geotab.com/blog/ev-battery-health

[26] S. Report, "Existing EV batteries may last up to 40% longer than expected," Dec. 9, 2024. Accessed Apr. 1, 2025. [Online]. Available: https://news.stanford.edu/stories/2024/12/existing-ev-batteries-may-last-up-to-40-longer-than-expected?utm_source=chatgpt.com

[27] *SAE Electric Vehicle and Plug-in Hybrid Electric Vehicle Conductive Charge Coupler,* SAE J1772_201710, SAE International, Warrendale, PA, US, Jan. 22, 2024. [Online]. Available: https://www.sae.org/standards/content/j1772_202401

[28] *Interconnection Requirements for Onboard, Grid Support Inverter Systems,* SAE J3072_202406, SAE International, Warrendale, PA, US, Jun. 10, 2024. [Online]. Available: https://www.sae.org/standards/content/j3072_202406

[29] *Control of Bidirectional Power for AC Conductive Charging,* SAE J3068/2, SAE International, Warrendale, PA, US, Jan. 2024. [Online]. Available: https://img.antpedia.com/standard/files/pdfs_ora/20250305/J3068_2_202401.pdf

[30] *Communication Between Plug-in Vehicles and Off-Board DC Chargers,* SAE J2847/2_202309, SAE International, Warrendale, PA, US, Sep. 6, 2023. [Online]. Available: https://www.sae.org/standards/content/j2847/2_202309

[31] *Road Vehicles – Vehicle to Grid Communication Interface, Part 1: General Information and Use-case Definition,* ISO 15118-1:2019, International Organization for Standardization, Geneva, Switzerland, Apr. 2019. [Online]. Available: https://www.iso.org/standard/69113.html

[32] *Road Vehicles – Vehicle to Grid Communication Interface, Part 20: 2nd Generation Network Layer and Application Layer Requirements,* ISO 15118-20:2022, International Organization for Standardization, Geneva, Switzerland, 2022. [Online]. Available: https://www.iso.org/standard/77845.html

[33] *Electric Vehicle Power Export Equipment (EVPE) (Binational Standard with UL 9741),* CSA C22.2 No. 348:23, Canadian Standards Association, 2023. [Online]. Available: https://www.csagroup.org/store/product/2430454

[34] *Electric Vehicle Energy Management Systems,* CSA SPE-343:21, Canadian Standards Association, Toronto, ON, Canada, 2021. [Online]. Available: https://www.csagroup.org/store/product/CSA%20SPE-343%3A21/

[35] *EVSE Power Export Standard,* National Electrical Manufacturers Association (NEMA), Rosslyn, VA, US, Jan. 16, 2025. [Online]. Available: https://www.nema.org/standards/view/evse-power-export-standard

[36] Z. Woogen, "Relevant technical standards for bidirectional charging," Vehicle-Grid Integration Council, Mar. 28, 2024. [Online]. Available: https://static1.squarespace.com/static/5dcde7af8ed96b403d8aeb70/t/660c2dcb81d1e50d49850756/1712074188541/2024-03-28+VGIC+Presentation+on+V2X+Standards.pdf

[37] *Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces,* IEEE 1547-2018, IEEE Standards Association, Piscataway, NJ, US, Apr. 6, 2018. [Online]. Available: https://standards.ieee.org/ieee/1547/5915

[38] *Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources,* UL 1741, UL Standards and Engagement, Northbrook, IL, US, Apr. 22, 2025. [Online]. Available: https://www.shopulstandards.com/ProductDetail.aspx?productId=UL1741_3_S_20210928

[39] *Interconnection of Distributed Energy Resources and Electricity Supply Systems,* CSA C22.3 No. 9:20, Canadian Standards Association, Toronto, ON, Canada, 2021. [Online]. Available: https://www.csagroup.org/store/product/CSA%20C22.3%20NO.%209%3A20/

[40] *Interconnecting Inverter-Based Micro-Distributed Resources to Distribution Systems,* CAN/CSA-C22.2 No. 257-06 (R2015), Canadian Standards Association, Toronto, ON, Canada, 2015. [Online]. Available: https://www.csagroup.org/store/product/2417965

[41] *Power Conversion Equipment,* CSA C22.2 No. 107.1:16 (R2021), Canadian Standards Association, Toronto, ON, Canada, 2021. [Online]. Available: https://www.csagroup.org/store/product/2424478

[42] *Battery Chargers,* CAN/CSA-C22.2 No. 107.2-01 (R2021), Canadian Standards Association, Toronto, ON, Canada, 2021. [Online]. Available: https://www.csagroup.org/store/product/CAN-CSA-C22.2%20NO.%20107.2-01/?srsltid=AfmBOooswyU7aWoV3Mshu1Av_zhMfKMFT2JsdZxw56sefBag25JosvD4

[43] *Outline of Investigation for Power Control Systems,* UL 3141, UL Standards and Engagement, Northbrook, IL, US, Oct. 9, 2024. [Online]. Available: https://www.shopulstandards.com/ProductDetail.aspx?UniqueKey=47260

[44] *Transfer Switch Equipment (Trinational Standard with NMX-J-674-ANCE and UL 1008),* CSA C22.2 No. 178.1:22, Canadian Standards Association, Toronto, ON, Canada, 2022. [Online]. Available: https://www.csagroup.org/store/product/CSA%20C22.2%20NO.%20178.1%3A22

[45] *UL LLC Outline of Investigation for Source Interconnection Switches,* UL 1008B, UL Standards and Engagement, Northbrook, IL, US, Mar. 13, 2025. [Online]. Available: https://www.shopulstandards.com/ProductDetail.aspx?UniqueKey=48024

[46] IEEE SA, "IEEE standards for the evolving distributed energy resources (DER) ecosystem," Nov. 9, 2021. [Online]. Available: https://standards.ieee.org/beyond-standards/ieee-standards-for-the-evolving-distributed-energy-resources-der-ecosystem

[47] A. Tsisserev, "Electric vehicle energy management system (EVMS)—Clarifying 'mystery' on this subject," IAEI Magazine, Oct. 28, 2021. [Online]. Available: https://iaeimagazine.org/columns/canadian/electric-vehicle-energy-management-system-evems-clarifying-mystery-on-this-subject

[48] *Smart Energy Profile Application Protocol,* IEEE 2030.5-2018, IEEE Standards Association, Piscataway, NJ, US, Dec. 21, 2018. [Online]. Available: https://standards.ieee.org/ieee/2030.5/5897

[49] Open ADR Alliance, "OpenADR 2.0 and 3.0 specifications download." Accessed Feb. 12, 2025. [Online]. Available: https://www.openadr.org/specification

[50] Open Charge Alliance, "Open smart charging protocol 2.0," 2020. Accessed Feb. 14, 2025. [Online]. Available: https://openchargealliance.org/protocols/open-smart-charging-protocol

[51] *Communication for Plug-in Vehicles as a Distributed Energy Source,* SAE J2847/3_202311, SAE International, Warrendale, PA, US, Nov. 6, 2023. [Online]. Available: https://www.sae.org/standards/content/j2847/3_202311

[52] Open Charge Alliance, "Open charge point protocol 2.1," 2025. Accessed Feb. 14, 2025. [Online]. Available: https://openchargealliance.org/protocols/open-charge-point-protocol

[53] Protocol for Management of Electric Vehicles Charging and Discharging Infrastructures, IEC 63110, International Electrotechnical Commission, Geneva, Switzerland, Jul. 29, 2022. [Online]. Available: https://webstore.iec.ch/en/publication/60000

[54] Open Charge Alliance, "Open charge point protocol." Accessed Feb. 14, 2025. [Online]. Available: https://openchargealliance.org/protocols/open-charge-point-protocol

[55] Open Charge Alliance, "Certified product." Accessed Feb. 14, 2025. [Online]. Available: https://openchargealliance.org/certified-companies

[56] Open Charge Alliance, "OCPP on fast track to an IEC international standard," Jun. 10, 2024. [Online]. Available: https://openchargealliance.org/ocpp-on-fast-track-to-an-iec-international-standard

[57] Environmental Coalition on Standards and Regulatory Assistance Project, "Standards for EV smart charging: A guide for local authorities," Dec. 2022. [Online]. Available: https://ecostandard.org/wp-content/uploads/2022/12/ECOS-RAP-Standards-for-EV-smart-charging.pdf

[58] Electric Autonomy Canada, "An introduction to telematics." Accessed May 24, 2025. [Online]. Available: https://evfleets.electricautonomy.ca/topics/an-introduction-to-telematics

[59] Chargescape, "Chargescape: A global vehicle-grid integration platform." Accessed Mar. 9, 2025. [Online]. Available: https://chargescape.com

[60] D. Black et al., "Survey and gap prioritization of US electric vehicle charge management deployments," Lawrence Berkeley National Laboratory, Berkeley, CA, US, Jun. 2024. [Online]. Available: https://eta-publications.lbl.gov/sites/default/files/scm_gap_analysis_.pdf

[61] T. Liu, S. Ge, X.-G. Yang, and C.-Y. Wang, "Effect of thermal environments on fast charging Li-ion batteries," *Journal of Power Sources,* vol. 511, 230466, Sep. 2021. [Online]. Available: https://doi.org/10.1016/j.jpowsour.2021.230466

Appendix A

Table A1: Organizations interviewed

Type of Organization	Number of Interviews
OEMs	3
Industry Association	3
Researcher / Academic	3
Utilities	3
Engineers	3

Table A2: Interview topics and questions

Research Topics	Interview Questions
Introductions	1. Before we get started, do you have any questions about our research? 2. Please tell us a bit about your role in your organization.
Defining VGI Applications	3. Which VGI applications (e.g., V2B/V2H, V2G, V1G) represent the most significant opportunities for utilities and customers moving forward? Why or why not? 4. What are the main advantages and limitations of each application from your perspective? 5. How prevalent is each of these applications currently, and how do you anticipate their adoption evolving in the future?
Standards	6. What are the primary standards considerations for VGI, and how do these considerations differ across applications? 7. What specific standards (either Canadian or international) are most relevant for VGI deployment? 8. What are the most pressing challenges and gaps in the current standards landscape for VGI, either in Canada or internationally? Where do you see existing standards falling short? 9. Are you aware of recent or ongoing developments in VGI standardization or certification, in Canada or internationally, that could significantly impact adoption? Are there international standards or best practices you believe Canada should emulate?
Technology Readiness	10. What is your assessment of the current technological readiness of the different bidirectional charging system components, including EVs, EVSEs and other electrical conversion and distribution hardware, and software and controls? To what extent does market and technical readiness vary by application? 11. While a number of automakers support bidirectional charging via off-board inverters (V2G-DC), to what extent are automakers developing EVs with on-board bidirectional chargers to support V2G-AC? Are there specific challenges for V2G-AC in terms of technology readiness and standards considerations? 12. Are you aware of any recent or ongoing advancements in the technology readiness of any key system components? What developments do you anticipate over the next few years?

Research Topics	Interview Questions
Performance and Battery Impacts	13. How does bidirectional charging affect EV battery longevity? Are there known challenges or solutions to mitigate these impacts? 14. What are the biggest performance considerations for different VGI applications? 15. What role can standards and performance criteria play in addressing battery longevity and other performance impacts associated with VGI?
Conclusion	16. Is there anything we haven't covered today that you'd like to add?

CSA Group Research

In order to encourage the use of consensus-based standards solutions to promote safety and encourage innovation, CSA Group supports and conducts research in areas that address new or emerging industries, as well as topics and issues that impact a broad base of current and potential stakeholders. The output of our research programs will support the development of future standards solutions, provide interim guidance to industries on the development and adoption of new technologies, and help to demonstrate our on-going commitment to building a better, safer, more sustainable world.

CSA GROUP™