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Raising Awareness for Bidirectional Electric Vehicle Charging

CHALLENGES & OPPORTUNITIES

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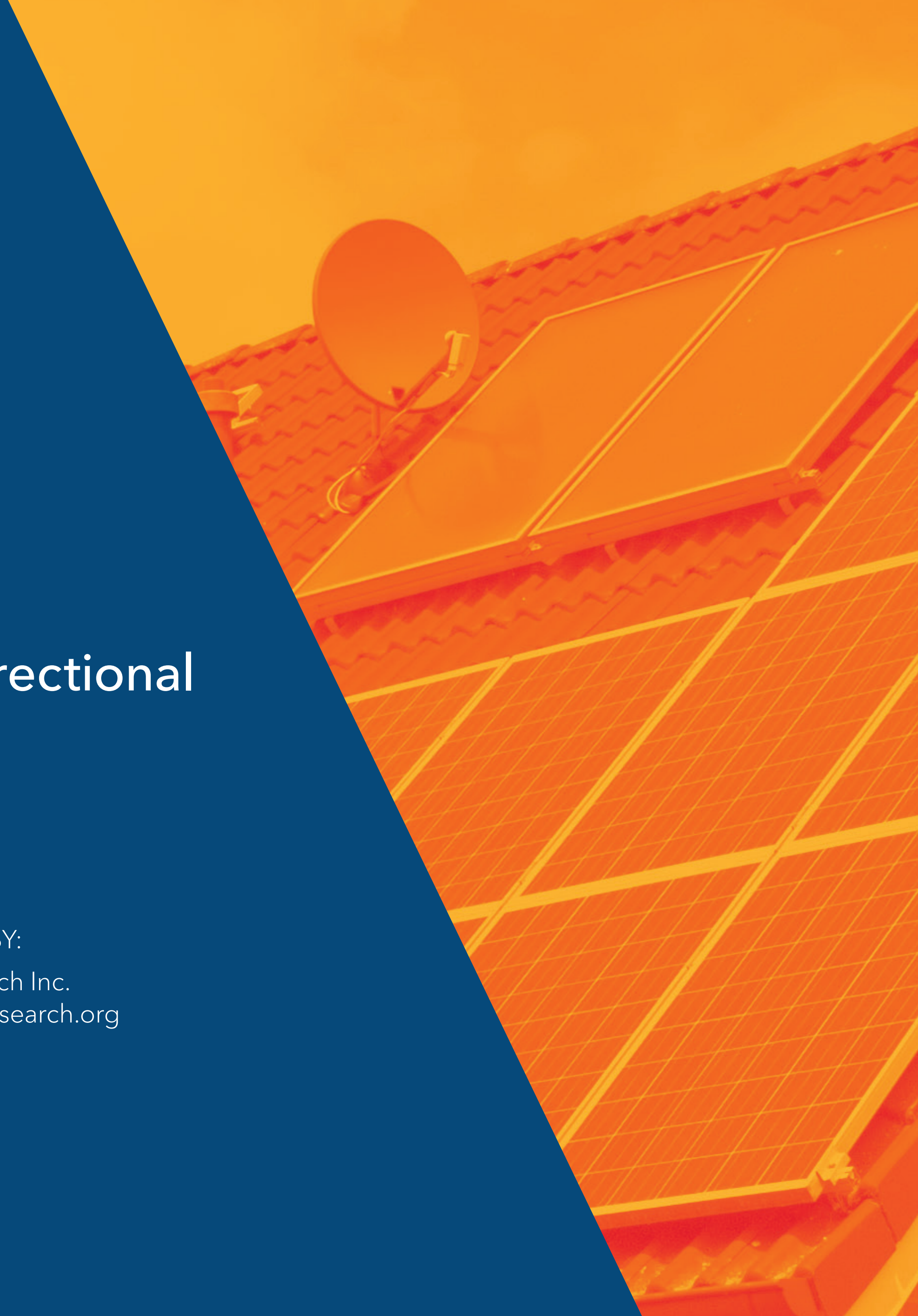

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The Project Team:

Volta Research Inc.: Volta was established as a not-for-profit to advance knowledge-based decision-making for low-carbon technologies. We do this by supporting and facilitating the research process and providing the analytical expertise to help our partners and clients maximize the technical, environmental, social, and market opportunities of low-carbon technologies.

Hero Energy & Engineering: Hero is a research and development company specializing in distributed energy and power systems to realize increased efficiency and resilience. Our mission is to "take the fight to climate change" by building flexible, intelligent solutions to harmonize the actions of resource owners, utilities, and regulators.

TABLE OF CONTENTS

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EXECUTIVE SUMMARY

This guide is produced as a part of Volta Research and Hero Engineering's project funded by the Natural Resource Canada program entitled Zero Emission Vehicle Awareness Initiative, which aims to raise awareness and public confidence with respect to the adoption of zero-emission vehicles. This guide focuses on raising awareness and demonstrating the ability of bidirectional electric vehicles to support the electrical load of homes, buildings, and the greater electric grid during outages or increased demand. While the primary target audience is utilities interested in understanding the barriers and opportunities with respect to this technology, the content may be of interest to municipalities, regulators, researchers, as well as current and prospective electric vehicle (EV) owners.

Bidirectional electric vehicles provide tremendous value for all energy stakeholders, whether in shifting peak electricity usage and reducing emissions, preventing outages during extreme weather events, and adding a revenue stream for owners interested in participating in energy markets. Although this technology has been explored over the past decade, publicly available data and lessons learned, specifically from a Canadian context, remain underrepresented. Bidirectional electric vehicles, with associated acronyms such as Vehicle to Everything (V2X) and Vehicle Grid Integration (VGI), can be a confusing landscape to navigate for energy stakeholders. Additionally, the technology and related standards continue to evolve rapidly, thus creating barriers to substantial uptake.

For these reasons, this guide takes a deep dive into the landscape of bidirectional charging, seeking to raise awareness with respect to its technological advancements to date, future opportunities, and barriers to success. The guide includes excerpts and survey results from over 100 vehicle owners and utility professionals, whose feedback was used to propose an example of a bidirectional charging program that utilities may use to pilot the technology.

To support the proposed program, the guide presents accompanying case studies on commercial and residential pilots that were conducted throughout the project, complete with interconnection plans, demonstration results for applications of demand response, arbitrage, and load-following, as well as lessons learned.

In summary, this guide is intended to serve as a launching pad for organizations, particularly utilities, to begin piloting bidirectional charging technology. The use of demonstrations has been heavily relied on to show the technology in action and increase public confidence in its uptake. Demonstration videos, including a short documentary, may also be viewed at https://www.youtube.com/@VoltaResearch.

1. INTRODUCTION TO BIDIRECTIONAL EV CHARGING

Bidirectional electric vehicle (EV) charging enables the onboard battery of the EV to be used both as a flexible load and as a generation source of electrical energy. This technology has many applications, particularly in its application with the electric grid in reducing peak demand, which can lead to reduced emissions and the deferral of expensive, time-consuming grid capacity upgrades that may be required by global mandates to electrify transportation [1].

A popular term for bidirectional EV charging is a Vehicle to Everything (V2X), where EVs can be used as a power source for directly connected loads (V2L), loads within homes or buildings (V2H/V2B), as well as the export of energy to the greater grid (V2G; Figure 1) [2]. This section of the guide aims to provide an example to contextualize these acronyms and explain their use.

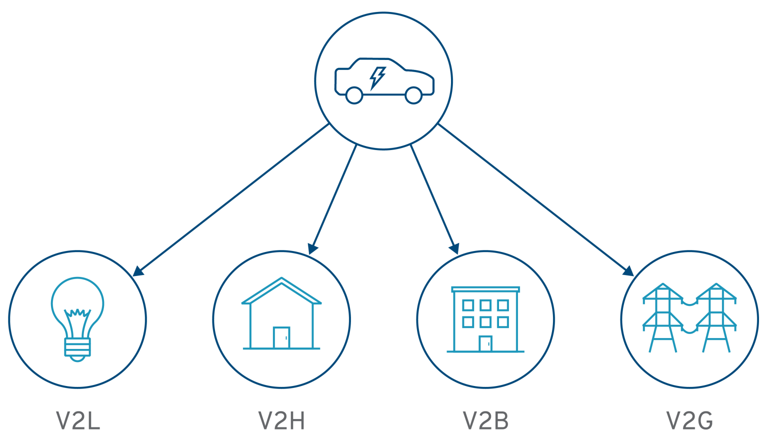

Figure 1. Types of bidirectional charging.

Example Scenario

One example of the components involved in bidirectional EV charging is shown (Figure 2) for a residential setting (V2H). When the EV discharges, the power flows through the bidirectional charger into the home's main panel and, subsequently, toward the house loads. If the generated power from the EV is greater than the local loads, the remaining power is exported to the grid.

- **EV:** Electric Vehicle
- **Bidirectional charger:** Level 3 (DC), enables bidirectional power flow between EV and the home. It has two subcomponents:
  - Bidirectional DC-DC Converter: Enables bidirectional power flow between the different DC voltage levels of the EV battery and bidirectional inverter.
  - Bidirectional inverter: Enables bidirectional power flow by (1) converting DC power from EV battery to AC when EV discharges, or (2) converting AC power from the grid to DC power when the EV charges.
- **Transfer switch:** An optional device used during power outages to isolate the home from the grid and use the EV to provide power. The transfer switch prevents back-feeding the grid during an outage. Otherwise, the bidirectional charger is certified to disconnect from the grid if no supply is present.

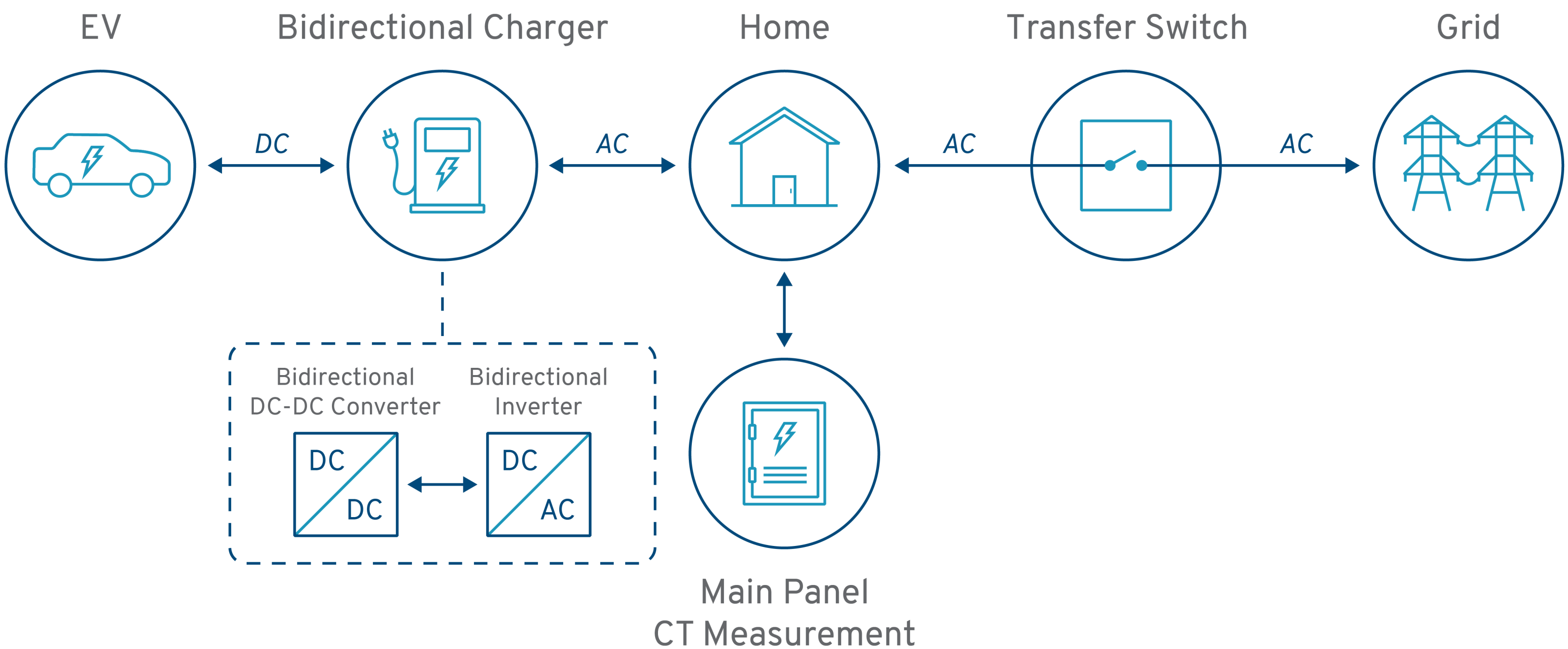

Figure 2. Schematic diagram for a V2H-based system.

- **CT Measurements (Meter):** The meter is an optional device that is placed at the point of interconnection between the home and the grid to measure the net power consumption (including the contribution of the EV). Based on these measurements, the EV can generate power to meet only the load of the home (load-following).

Figure 2 represents only one of the many scenarios within the V2X paradigm. For example, the home could be replaced with a larger facility or commercial building. The bidirectional charger could be wired to a sub-panel rather than a main panel to provide emergency power to critical loads only in a V2H/V2B scenario.

2. USE CASES OF BIDIRECTIONAL EV CHARGING

Bidirectional EV charging has the potential to unlock energy, emissions, and monetary savings for EV owners, EV network operators, and electric utilities. This section of the guide provides several use cases for bidirectional EV charging supported by real-world examples:

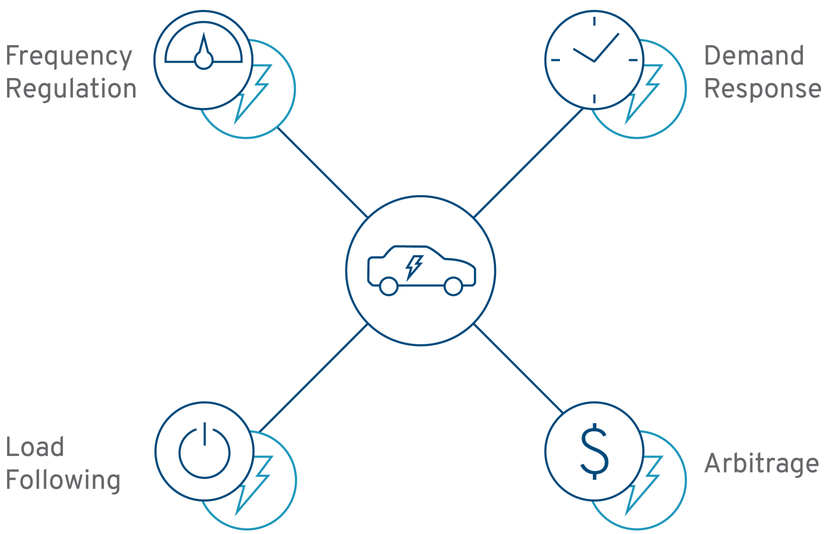

Figure 3. Bidirectional charging use cases.

1. **Load Following:** Mainly used in the capacity of V2H/V2B where the EV is used to provide power only to building loads without exporting to the upstream grid. This functionality also can provide an EV owner with emergency backup power for their building during power outages. When connected to the grid, the EV has the potential to offer bill reductions to the end user by minimizing electricity consumption or it can be directed to limit the electrical demand of a building, as seen by the utility.

   Pilot Example: In 2019, a V2H trial was conducted in a rural area of Auckland, New Zealand, where homeowners could use their EVs to power their internet router, fridge, lights, and phone chargers in case of a power outage [3].

2. **Arbitrage:** Mostly for jurisdictions where time of use (TOU) is in place (the price of electricity varies over time), bidirectional EV arbitrage involves charging the EV when prices are typically low (off-peak hours) and discharging the EV when prices are relatively higher (peak periods) to realize daily revenue. This use case often leads to greenhouse gas emissions (GHG) savings since utilities routinely use fossil-fuel-based, "peaking" power plants to satisfy electrical demand at peak times [4], which bidirectional EVs can displace. Jurisdictions could assign the intent of the optimization to either favour price or GHG reductions (or both).

Pilot Example: From 2012-2015, an 80-EV pilot in Maui, Hawaii, successfully reduced peak load during 18:00-21:00 by discharging their EVs and shifting their EV charging consumption between 00:00 - 06:00 [5].

3. **Demand Response/Peak Load Reduction:** This use case aims to ease congestion within power systems. EV discharging can reduce the load of the homes/buildings they are connected to or export excess power to the grid. Demand response usually requires some form of contracted commitment between the EV owner and utility, either directly or via an aggregator, where EV owners may be paid capacity payments (for the number of hours they remain plugged in), as well as payments for each kWh of energy exported during demand response events.

   Pilot Example: The University of Delaware earned approximately $1200 per EV by discharging during multiple demand response events in 2013 [6].

4. **Frequency Regulation:** Utilities enter into contracts with fast-acting resources to inject or withdraw energy quickly (2-6 seconds) to stabilize grid frequency. In this case, participating EV owners would allow their EV to be "remotely controlled" by the utility, where the EV would respond to quickly dispatch instructions to charge or discharge according to specific setpoints.

   Pilot Example: A 29 EV fleet located at a Los Angeles Air Force Base successfully demonstrated frequency regulation for 255 MWh regulation up and 118 MWh regulation down for 20 months in 2020 [7].

The residential and commercial case studies that follow in Sections 7 and 8 will demonstrate several of these use cases.

3. MARKET SCAN

This section provides a market scan for light-duty vehicles and charging stations compatible with bidirectional charging technology (as of August 2024), along with a look at future offerings.

Bidirectional charging until 2021: ChaDeMo dominant

Until 2021, only three commercial EVs were outfitted with the proper power electronics for bidirectional charging: the Nissan LEAF, Mitsubishi Outlander, and Kia Soul [8]–[10]. These EVs all use the Japanese CHAdeMO charging standard, which is DC-based and has supported bidirectional charging from its inception.

To accompany these EVs in delivering bidirectional power transfer, several CHAdeMO-compliant charging stations have been available in the North American market during the last decade. A summary of their capabilities is presented in Table 1.

It is worth noting that a Canadian-based company, dcbel, plans to offer a single-phase, CHAdeMO bidirectional charging solution in 2024 capable of discharging the EV at 7.6 kW [11].

2021 onwards: The case for bidirectional CCS

With the dominant charging standard in North America being CCS and CHAdeMO slowly on its way to being phased out [12], significant efforts have been made to enable the CCS standard to support bidirectional charging. The standards that have primarily governed this capability are DIN 70121 and ISO 15118 – Road vehicles – Vehicle to grid communication interface [13]. With ISO 15118-20 reaching the final draft international status in April 2022 [14], EV manufacturers can be expected to adopt the standard to enable the mainstream integration for CCS-based bidirectional charging by 2025 [15].

Pilots have already begun to validate the ability of CCS bidirectional charging. The Ford F-150 Lightning (98–131 kWh) can provide up to 9.6 kW of backup power to the home when paired with its proprietary charging station, the Ford Charge Station Pro [16]. The Kia EV9 (76.1–99.8 kWh) has been integrated with Wallbox's Quasar 2 to demonstrate V2H during grid outages [17].

On the other hand, several vendors are implementing DC charging stations that support bidirectional charging using CCS. The technical specifications provided publicly by some of these vendors and products due to enter the market in late 2024/early 2025 are provided in Table 2. It is worth noting that compatibility with EVs has yet to be made public at the time of publication.

Vendor	Model	Protocol	Frequency	Connection	Max. Power	Outage Protection	Standards
Ampere Technology	e-loop	CHAdeMO	50 Hz	1 Phase, 230V	+/- 6 kW	No	IEC 61851-1, IEC 61851-23, IEC 62196, IEC 62116 (EU)
Coritech	VGI-30-DC	CHAdeMO	60Hz	3 Phase, 480V	+/- 30 kW	No	UL 1741, IEEE 1547a, IEEE 62109-1.2
Fermata	FE-15	CHAdeMO	60Hz	3 Phase, 480V	+/- 15 kW	No	UL 9741
Fermata	FE-20	CHAdeMO	60Hz	3 Phase, 480V	+/- 20 kW	No	UL 1741
IKS	S06US010V	CHAdeMO	50 Hz, 60Hz	1 Phase, 240V	+/- 6 kW	Yes	UL 9741
Rectifier Technologies	Highbury	CHAdeMO	50 Hz, 60Hz	1 Phase, 220V–240V	+/- 7 kW	No	IEC 61851-1, IEC 61851-23, UL 1741, UL 9741
Rectifier Technologies	Highbury	CHAdeMO	50 Hz, 60Hz	3 Phase, 380V–415V	+/- 11 kW	No	IEC 61851-1, IEC 61851-23, UL 1741, UL 9741
Tellus Power Green	TP5-30-480-V2G-1	CCS	60 Hz	3 Phase, 480V	+/- 30 kW	No	UL-2202, UL 1741-SA, IEEE 1547.1:2005, CSA C22.2
Tellus Power Green	TP5-40-480-V2G-1	CCS	60 Hz	3 Phase, 480V	+/- 40 kW	No	UL-2202, UL 1741-SA, IEEE 1547.1:2005, CSA C22.2
Tellus Power Green	TP5-60-480-V2G-1	CCS	60 Hz	3 Phase, 480V	+/- 60 kW	No	UL-2202, UL 1741-SA, IEEE 1547.1:2005, CSA C22.2
Wallbox	Quasar 1	CHAdeMO	50 Hz	1 Phase, 230V	+/- 7.4 kW	No	UL 1741
Wallbox	Quasar 2	CCS	60 Hz	1 Phase, 240V	+/- 11.5 kW	Yes	UL 9741 in progress

Table 1. Existing DC bidirectional chargers in the market.

Vendor	Model	Protocol	Frequency	Connection	Max. Power	Outage Protection	Standards
BorgWarner	RES-DCVC60-480	CCS	60Hz	3 Phase, 480V	+/- 60 kW	No	UL 2202, CSA 22.2, IEEE 1547.1, UL 1741-SA
BorgWarner	RES-DCVC125-480	CCS	60Hz	3 Phase, 480V	+/- 125 kW	No	UL 2202, CSA 22.2, IEEE 1547.1, UL 1741-SA
dcbel	Ara	CHAdeMO or CSS	60Hz	1 Phase, 240V	+/- 7.6 kW	Yes	UL 9741, UL 2231-1, UL 2231-2
Delta	V2H11A-11	CHAdeMO	50 Hz, 60Hz	3 Phase, 400V	+/- 11 kW	No	European Standard CD, EVPS-006:2018
Delta	V2H11A-22	CHAdeMO	50 Hz, 60Hz	3 Phase, 400V	+/- 22 kW	No	European Standard CD, EVPS-006:2018
Emporia	V2X Bi-directional charger	CSS or NACS	60Hz	1 Phase, 240V	+/- 11.52 kW	Yes	unknown
Enphase	IQ	CHAdeMO or CSS	60Hz	1 Phase, 240V	unknown	Yes	in progress
Flex	Spin 10kW	CCS	60Hz	1 Phase, 240V	+/- 10 kW	Yes	UL 2202 & UL 1741-SA in progress

Table 2. Upcoming CCS-based bidirectional chargers to enter the market in 2024 (proposed).

Notable mentions: EVs with V2L capability

As the introduction explains, some EVs currently offer V2L capability, where the battery can directly power a load from electrical outlets within the car. Table 3 summarizes some of the current EVs with this capability [18]. Please note that some V2L-capable EVs listed require specific trim levels or optional packages to enable V2L functionality.

Vendor	Make/Model	Battery Size	Max. Output
Chevrolet	Equinox EV	85-200+ kWh *	3 kW *
Chevrolet	Silverado EV	200+ kWh	7.2 kW *
Ford	F-150 Lightning	98-131 kWh	9.6 kW
Ford	E-Transit	89 kWh	2.4 kW
Genesis	GV60	77.4 kWh	3.6 kW *
Genesis	Electrified GV70	77.4 kWh	3.6 kW *
Genesis	Electrified G80	87.2 kWh	1.9 kW
GMC	Hummer EV Pickup	170 or 212-246.8 kWh *	3 kW *
GMC	Hummer EV SUV	170 or 212-246.8 kWh *	3 kW *
Hyundai	Ioniq 5	58-77.4 kWh	3.6 kW
Hyundai	Ioniq 6	53-77.4 kWh	3.6 kW
Hyundai	Kona EV	48.6-64.8 kWh	3.6 kW
Jeep	Wrangler 4xe	17.3 kWh	3.6 kW *
Kia	EV6	58-77.4 kWh	3.6 kW
Kia	EV9	76.1-99.8 kWh	3.6 kW
Kia	Niro	64.8 kWh	3.6 kW
Mitsubishi	Outlander PHEV	20 kWh	1.5 kW
Tesla	Cybertruck	123 kWh	9.6 kW
Volvo	EX90	111 kWh	11 kW *

Table 3. Available V2L EVs as of August 2024.
* pending confirmation

4. CHALLENGES & OPPORTUNITIES

To gain a more diverse perspective concerning the challenges and opportunities of bidirectional EV charging, we interviewed over 42 individuals representing utilities, knowledge champions, researchers, regulators, and safety authorities across Canada. A summary of notable points is presented below.

Barriers to the Adoption of Bidirectional Charging

1. Lack of customer education and awareness

Unanimously, interviewees felt that the lack of customer education about the benefits and opportunities of bidirectional charging was the most significant barrier to mass adoption. Customer awareness is the cornerstone of adopting new practices, whether to motivate potential EV owners to buy EVs capable of bidirectional charging and to their subsequent participation in utility bidirectional charging programs. What further aggravates this concern is that it is unclear under whose purview the responsibility to educate the public lies, whether original equipment manufacturers (OEMs), utilities, or regulators. The education piece must be well thought out and coordinated for the energy sector to benefit from bidirectional charging.

2. Complexity of program design and incentive modeling

Interviewees raised concerns regarding the complexity of designing a bidirectional charging program that must balance the temporal and spatial needs of the power system with the varying preferences and constraints of EV owners, including plug-in time, commuting time, and responsiveness to environmental factors. The need for more techno-socioeconomic data than is currently available makes program design particularly challenging. It is unclear what level of incentives or characteristics would motivate EV owners to participate in a program. Without many active smaller pilots or demos where lessons can be learned and adoption can be estimated, the risk of launching a large pilot is a significant barrier.

3. Lack of clarity regarding accelerated battery degradation and warranty cancellation

EV OEMs apart from Nissan have not commented on whether the warranty for EV batteries will be affected when participating in bidirectional charging [19]. Without guaranteeing that the warranty will not be cancelled, there are significant risks to rolling out wide-scale programs involving bidirectional charging. Furthermore, EV owners may ask for additional incentives to compensate for the additional cycling of their EV battery; however, it is complex to calculate this incentive accurately, given other factors that degrade the battery, such as temperature, age, and kilometres driven [20].

4. Current energy regulations restrict the business case of bidirectional charging

For some regulated utilities, the core business model relies on earning a rate of return on existing infrastructure (poles, wires, assets). This is in direct contrast to the business case of bidirectional charging, which can help avoid building additional poles and wires. Regulatory oversight and guidance are needed to align these business models and unlock the full value of bidirectional charging. Furthermore, some jurisdictions do not allow customers with non-renewable energy resources (batteries, generators, EVs) to participate in net metering [21]. In the case of Ontario, a customer with only a bidirectional EV (no solar) might be moved to the tiered electricity rate structure that is not dependent on time and, thus, will not be able to take advantage of the new "ultra-low" overnight pricing plan that encourages EVs to charge with relatively inexpensive, clean electricity [22].

"The average EV owner doesn't have the slightest clue what bidirectional charging, or V2X even is. Even if they knew they probably wouldn't care. The only people that care are the techies in EV societies."

– EV knowledge champion

"If you build a pilot and think that people will come, you can forget it. This is about understanding human behavior and their response. It's not trivial, especially in the case of something as complex as V2G."

– Utility professional

"An EV would be a pretty big investment … and I'd like to make sure that it lasts as long as possible. If you could perhaps quantify that a battery has a certain number of charge cycles and you'll be using 25% of those up … I'd like to see at least 25% of the value back at some point."

– Utility professional

"There is an underlying issue with respect to fairness as well. If certain upgrades need to be made to the grid in order to accommodate bidirectional charging, current provisions put the financial burden of this on the early adopters. This may cause friction and decreased uptake."

– Regulator

Priorities for Overcoming Barriers to Adoption

1. Involve the customer early. Simulated demos, surveys, webinars, and general outreach

Efforts must be made to understand the human response to potential V2X modes of operation. What incentives will elicit the required participation? What other factors will drive or hinder adoption? Developing simulated applications and accompanying surveys, like a "try before you buy" approach, will help gauge customer responsiveness. Based on this data, small-scale pilots should be launched to gauge the interest of residential, commercial, and industrial utility customers in bidirectional charging.

2. Detailed business case modeling to prove benefits to all in the energy value chain

The complete business case for bidirectional charging should be developed before utilities and regulators will consider long-term investments. Specifically, what would the customer adoption rate be, what services and incentive models would be offered, and what incentives are needed for the business case to be feasible? The business case should include a complete list of costs to upgrade the grid for adopting V2X against a baseline scenario consisting mainly of unidirectional, managed charging. Direct evidence is required to convince regulators and utilities of the value of bidirectional charging before they will consider it a worthwhile exercise to spend time on.

3. Harmonize incentives for energy, grid services, and emissions to unlock full value of bidirectional charging

Often called "value-stacking," a bundled set of services EV owners can provide to the grid could unlock multiple value streams, such as energy efficiency, capacity deferral, demand response, and emissions reduction [23]. Bidirectional charging has the added benefit of mobility, and innovative cases could be implemented to provide location-specific services to ease grid congestion. Value stacking these services together in a simple, intuitive program that enables both utilities and EV owners a fair measure of commitment and control will spearhead the adoption of bidirectional charging.

4. Obtain transparency from auto OEMs regarding compatible EVs and warranty fears

While choices for EV makes and models continue to increase every year, many OEMs still need to provide commitments concerning compatibility for bidirectional charging. Further, if bidirectional compatibility is present in the EV, there needs to be more clarity regarding the parameters with which the battery can be used for bidirectional charging without impacting the warranty. Without committed timelines and guidelines for warranty management, bidirectional charging will remain a "niche" feature for EVs and provide only marginal results.

"We don't have time of use, and we don't have a direct way for behind-the-meter resources to aggregate and participate in markets. Value-stacking services is the only way I see bidirectional charging getting off the ground."

– Utility professional

"Utilities are still quite set in their ways with respect to deterministic modelling, which is not going to work for V2G, especially since the EV will move around. In the business case modelling, we might need to use probabilistic model to overcome the uncertainty of where we think the EV might be parked to provide maximum value to the grid."

– Utility professional

"Partnerships with OEMs are key, especially in the initial stages, and especially as work on the CCS bidirectional charging protocol is being completed. Without knowing what the market is, we can't quantify the benefits and can't achieve adoption."

– Regulator

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Proposed steps to building a bidirectional charging program

1. Measure responsiveness to different program types and commitments

Several program types can be offered to enable bidirectional charging, and interviewees feel that the programs would reflect a sliding scale of control from the EV owner. A suggestion from a utility professional was a "battery as a service" model, where utilities would buy the EV battery from the EV owner and operate it to the maximum benefit of the utility grid. This would ostensibly ease the complexity of computing appropriate incentives in exchange for forecasted battery degradation for the EV owner since the utility would be the battery owner. On the other hand, models are available based on arbitrage and TOU, which involve no commitment from EV owners on when to plug in but rely on the electricity price to shift charging/discharging behaviour. Measuring the responsiveness of program types at opposite ends of the control scale would be a way to find a feasible program design.

2. Implement the end-to-end control required to manage and optimize power flow and metering

Interviewees would like to see several small-scale pilots involving EV owners in aggregations of 10 or more, specifically focusing on how the controls and metering would fit within existing utility SCADA systems. Specific issues to be investigated are the added costs to upgrade the EV owner's home (panel capacity upgrade), interoperability between EVs and bidirectional charging stations, metering the true EV contribution when exporting to the grid, observing what interface is used to communicate pricing signals/events to the EV owner, and controls for reverse power flow management. The lessons learned from such pilots to evaluate the technical readiness for mass bidirectional charging adoption.

3. Partnership building with OEMs to determine their action plan over the next decade

Interviewees felt that it was important to build partnerships with OEMs for three reasons. First, the OEMs could help with the burden of customer education as they have direct access to the EV owner. Second, the OEMs could directly answer questions concerning battery degradation and warranty. Third, gauge the OEM's appetite to participate directly in energy markets. It needs to be clarified if OEMs will enable aggregators to operate the EVs and bundle them for the provision of grid services or restrict this capability and perform this service themselves.

"As an aggregator, we worry about enhancing our existing software to accommodate bidirectional charging. OEMs are entirely capable of using an over-the-air update to completely disable an aggregator's access to the EVs controls."

– System integration specialist

"Important to show value to EV owners in reducing energy bills and offsetting higher rate exposure before aggregating and providing services to the grid. It's better that those consumers see direct benefits first, especially at the beginning of a program."

– Utility professional

"I propose utilities to 'buy' EV batteries from customers. They don't need to worry about degradation since it's not theirs anymore. Any performance requirements are contracted from the very beginning. This means the customers are happy, compensated, adoption is increased, and the utility can start the program with a certain reliability."

– Utility professional

5. EXAMPLE BIDIRECTIONAL CHARGING PROGRAM

This section introduces an example of a bidirectional charging program that caters to EV owners' preferences while enabling electric utilities to secure commitments for EVs to participate in grid services, such as demand response. The program's design is based on survey responses from 124 Canadian EV owners, where preferences ranging from minimum plug-in time, fixed contract vs no-contract, and environmental factors were evaluated. The program was also developed into a simulated application and can be found at https://v2xhero.web.app.

Survey Design

The survey's main objective was to capture EV owners' willingness to participate as a function of environmental, societal, economic, and technical factors. As such, the survey consisted of general questions establishing the behavioural patterns of the EV owner, including their preferred charging location, charging frequency per week, and estimated daily plug-in-time, as well as questions that gauge the motivation of the EV owner to engage in bidirectional charging, whether for environmental or financial reasons.

The survey also aimed to introduce different program types to the EV owners to evaluate their priorities concerning time commitment. The first program is a no-contract, "pay as you go" style based mainly on arbitrage, where the operational model would motivate EV owners to charge at off-peak hours and discharge at on-peak hours, where the EV owner would earn revenue at a rate fixed by the utility. This program prioritizes the convenience of the EV owner since there is no contract with the utility.

The second program type is a fixed-contract commitment, where the EV owner would commit to a minimum plug-in-time (MPT) in hours per month and receive incentives for availability ($/kW) and energy discharged ($/kWh). The EV owner would also specify a minimum driving range (MDR) to ensure they would have enough range to get to their next destination. Suppose the EV owner is unable to fulfill their plug-in time commitment or disconnects from the charging station for a certain period during a demand response event. In that case, the EV owner will forfeit all incentives for the month. This program type prioritizes the ability to earn incentives over the convenience of the EV owner.

Survey Results

The results of the survey can be seen in Figure 4, and are summarized below.

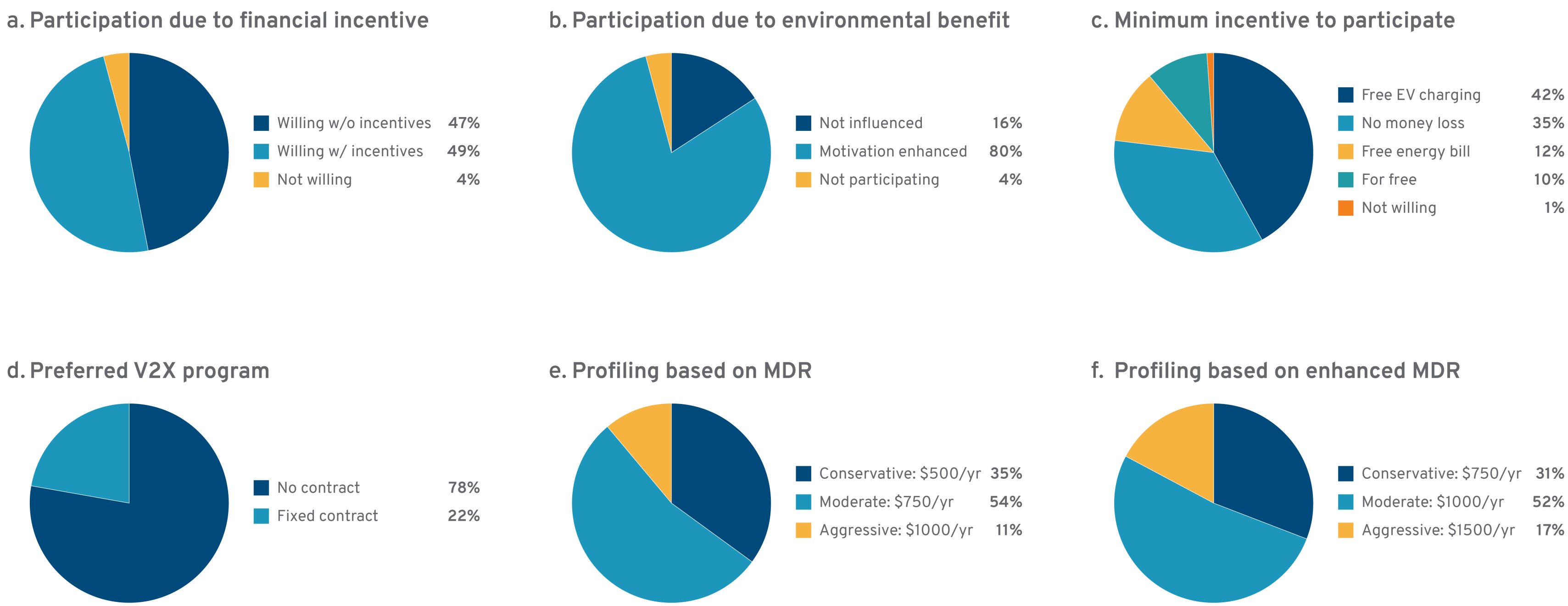

Figure 4. EV Owner survey results showing a) participation due to financial incentive, b) participation due to environmental benefit, c) minimum incentive to participate, d) preferred V2X program, e) profiling based on MDR, and (f) profiling based on enhanced MDR.

- Overall, respondents showed a strong willingness to participate in bidirectional charging, as seen in Figure 4a, with 49% of respondents willing to participate with incentives and 47% willing to participate without incentives. The possibility of leveraging bidirectional charging to directly offset fossil-fuel generation also enhanced the motivation of 80% of respondents in the survey, as seen in Figure 4b.
- With respect to the minimum incentive to participate in the program, Figure 4c shows that the majority expectation from EV owners was the possibility of free year-round EV charging (42%), followed by a guarantee of no financial loss (35%). Only 12% of respondents expected a relatively higher incentive to participate, a free annual energy bill estimated at approximately $2000, while 10% expected no incentive.

- When choosing between the two program types, the no-contract option captured the majority vote with 78% (Figure 4d).
- Exploring the fixed contract option (Figures 4e and 4f), three different profiles were introduced to the EV owner as a function of increasing MDR and incentives, with "Conservatives" setting their MDR to twice their commute distance, "Moderates" setting their MDR to 1.5x their commute distance, and "Aggressive" setting their MDR to exactly their commute distance. As seen in Figure 4e, the majority vote went to the "Moderates" (54%), with 35% of respondents preferring the "Conservative" profile and only 11% choosing the "Aggressive" profile.
- However, when the incentives were enhanced by a factor of 1.5 (Figure 4f), a total of 7 respondents chose to change their profile to "Aggressive," with the following result showing the majority to "Moderates" (52%), "Conservatives" at 31%, and "Aggressive" at 17%.

In summary, the major takeaway from the survey results is that while there is a general willingness to participate in bidirectional charging programs, the style of engagement is critical for adoption. Even though most respondents chose the no-contract option to prioritize their convenience over incentives, a portion of the population would still respond to a fixed contract program type.

Program Design and EV Session Types

Based on the survey results, the sample program proposes three different "EV session" types that facilitate both no-contract and fixed-contract options. The session types are illustrated and summarized below:

- **Charge My EV:** Provided for an EV owner that wishes to charge their EV as quickly as possible and is usually preferred when the EV owner may be short on time and/or not at their preferred charging station. There is no contract for this session type. The only session configuration is a maximum driving range (or target battery level), which the charging station aims to reach by delivering the maximum charging power.
- **Quick Support:** This option enables an EV owner to discharge their EV to earn incentives at a rate fixed by either the charge point operator (CPO) or the utility. Like the "Charge My EV" option, this option has no contract and enables an EV owner to stop discharging at their convenience or when their minimum driving range (target battery level) has been reached. Additionally, if a DR event is called during a Quick Support session, the EV owner may "opt-in" and receive an additional DR payment (in $/kWh). The combination of "Charge My EV" and "Quick Support" enable the arbitrage use case, allowing EV owners to earn incentives at their convenience without the threat of penalties.

- **Extended Support:** This option is contract-oriented, where the EV owner and utility agree to a minimum plug-in time and minimum driving range. The utility operates the EV battery as per its requirements when the EV is plugged in. For each session, two additional parameters are established: a maximum battery level and expected departure time, which indicates to the utility the amount of time the current session is expected to last should a demand response event occur. In a typical Extended Support session, the EV would be charged to the prescribed maximum battery level and sit idle, waiting for a demand response event to occur. Each hour plugged into the station counts towards the monthly MPT. If an event occurs, the EV discharges until its MDR is reached. In this case, the EV owner receives capacity payments for the entire time plugged in ($/kW-day), on top of enhanced DR payments for the energy discharged during the session ($/kWh). However, if the EV owner aborts the session and remains disconnected for a certain number of minutes during a DR event, all payments for the month are forfeited. This session type caters to those EV owners in the survey that aggressively seek revenue opportunities and are okay with fixing their schedule to realize them.

Simulated Application Demonstrating Bidirectional Charging Program

The proposed program has been implemented in the following case studies. It is also available as a simulated web application which can be found at https://v2xhero.web.app.

	Charge my EV	Quick Support	Extended Support
Use When	Short on time or not preferred charger	Short on time or not preferred charger	Adequate time and opportunity to plug in
Contract	No Contract	No Contract	Fixed Contract
Transaction Participants	EV pays CPO or EV pays Grid	CPO pays EV or Grid pays EV	CPO pays EV or Grid pays EV
Revenue	Regular Rate	Regular Rate	Regular Rate + DR + Capacity Payment
Penalty	None	None	Revenue forfeit if plug out during DR event

** CPO - Charge Point Operator*

Figure 5. Summary of EV session types.

6. THE INTERCONNECTION PROCESS – FAQ

This section serves as an education piece targeted toward utility customers that may be interested in engaging in bidirectional EV charging, particularly on the residential side.

I'm interested in bidirectional charging for my home but don't know where to start. What does the process entail?

1. Confirm that your EV is capable of bidirectional charging and that there are no associated warranty issues for this purpose.
2. Research the available bidirectional charging stations on the market and ensure their compatibility with your EV (Section 3 provides a list of current and upcoming chargers at the time of publication).
3. Ensure that the charger has the appropriate certifications for your jurisdiction for grid interconnection (CSA 22.2 No. 107.1 and CSA 22.3 No. 9-2020, or UL 1741–2016 or later).
4. Contact your local utility for a consultation, providing details of the intended charger capacity (in kW) and a line diagram of the proposed connection. The utility will check to ensure there is sufficient capacity within their power system to accommodate your proposed charger. If there is sufficient capacity, a formal connection application is made, and your utility will issue paperwork to connect the charging station officially.
5. Procure the charger, and have a licensed electrician deploy it at your home. The electrician will arrange for a permit and inspection for the charger installation and, if successful, will send a connection authorization to the utility. The electrician will also complete a commissioning process whereby the safe operation of the charger will be tested. **Note:** If your application requires an emergency power outage, your utility may require coordination to conduct appropriate testing.
6. The utility will generate a connection agreement specifying any billing plan changes and, once signed, will install a bidirectional meter at the home. Bidirectional charging can now begin.

How long will it take for the entire interconnection process to be complete?

This will depend on your local electric utility, their ability to process interconnection requests, and your local electrical safety authority to conduct the inspection. For our residential demonstration, the entire approval process took approximately ten months. However, three months were lost due to troubleshooting issues with the charger.

How similar is the interconnection process between bidirectional and standard EV charging stations?

The process is quite different. The bidirectional charging station involves more physical components. It is similar to a stationary battery installation, requiring an external disconnect, optional components of an automatic transfer switch for outage protection, and metering infrastructure. Both the bidirectional and standard EV charging stations require permits from the local electrical safety authority. However, the bidirectional charging station will require an additional step where the safety authority must sign off on a connection authorization form and send it directly to the presiding electric utility before interconnection approval. This step is not necessary for standard EV charging stations.

Lastly, a line diagram of the charger (including other energy resources, if applicable) must be printed on a limacoid and displayed near the utility meter. Again, this is not necessary for standard EV charging stations.

What upgrades will I need to make to my home for bidirectional EV charging?

The charging station will need a 240V connection, which may require you to position the charger where 240V service is available or work with your electrician to provide 240V service at your desired location. Secondly, an external disconnect will be required for the charger and placed near the utility meter.

Other upgrades are optional depending on the application, existing loads of the home, and the outlook of adding additional energy generation sources to the home.

In some cases, an upgrade of the capacity of the main electrical panel may be required or desired. For example, according to the Canadian Electrical Code 64-112 (4) for homes, the panel busbar capacity can only be exceeded by 125% when connecting parallel generation sources. For our residential demonstration, the home had a panel busbar capacity of 125 A, making for a total allowable capacity of 156 A. With 100 A service from the grid and 32 A from the bidirectional charger, this leaves only 24 A capacity for future additional generation sources. With the loading of the home being relatively light and the outlook on adding generation sources unclear, the homeowner chose not to upgrade the panel to 200 A at this time. However, the decision will be highly dependent on the unique circumstances of the homeowner.

If you are interested in load following and restricting the back-feed of power to the grid, metering will be required at the electrical panel to measure the net power consumption of the home. Note that some chargers support load following applications out of the box, **but with supported meters only** [24]. If you choose an unsupported meter, customer software will be required to enable the load following.

If you are interested in outage protection, a transfer switch will be required, which may be included as an add-on piece with the charger. For example, the Ford F-150 Lightning offers a "Home Integration System" as an add-on piece with its charging system, which includes the transfer switch to allow the EV to power the home in case of an outage [25]. Additionally, depending on the home's loads and the battery's capacity, you may choose to add a subpanel near the main electrical panel that consists of outlets for critical loads only (heating, cooling, internet).

What is the total cost for me to get set up for bidirectional charging?

This is very difficult to estimate because the price of the majority of residential bidirectional charging stations has not been set yet, apart from the Ford F-150 Lightning, whose charging station retails for USD 1,310, with an additional USD 3,895 required for the Home Integration System if outage protection is required [26]. Early estimates for other stations include the Wallbox Quasar 2 at USD 4,000 and the Emporia EMV2X1 at USD 1,500 [27].

In terms of the cost of installation for our demo, the individual line items (inclusive of tax) are summarized in Table 4.

Bidirectional charger	$8,000.00 (est.)
Electrician installation (including adding 240V service in garage, disconnect, and safety inspection)	$2,025.00
Energy Meter	$1293.98
Utility fees (Offer to connect)	$437.41
TOTAL	**$11,756.39**

Table 4. Residential V2G demo installation costs.

How does my electricity pricing get affected because of bidirectional charging?

This is a question that is highly dependent on jurisdiction and provincial laws. In Ontario, for example, customers adding generation sources to their premises are switched to a tiered rate instead of TOU (if not already on the tiered rate). **However, energy solely exported from the vehicle to the grid is not applicable for net-metering credits**, although it may be eligible for credits if paired with a renewable energy source [21].

This will change as bidirectional charging, and specifically, its integration with utility programs, matures.

7. CASE STUDY I: RESIDENTIAL BIDIRECTIONAL CHARGING

This section of the guide discusses the findings of the residential bidirectional charging pilot, from the interconnection process and timeline to performance testing, as well as a summary of lessons learned. It is worth noting that initially, this pilot aimed to deploy three bidirectional chargers in three homes; however, due to technical issues with two chargers, only one demonstration was successful. Due to non-disclosure agreements with the vendors of the chargers, the make/model of the chargers used in the pilot are not disclosed.

Three chargers were procured for this pilot, with their technical specifications provided in Table 5. The experimental results will be derived from "Charger #3, which is shown in Figure 6.

Charger	Protocol	Connection	Max. Power	Max. Current	Outage Protection
Charger #1	ChaDeMo	Split Phase, 240V	+/- 6 kW	+/- 25 A	Yes
Charger #2	ChaDeMo	Split Phase, 240V	+/- 6 kW	+/- 25 A	Yes
Charger #3	ChaDeMo	Split Phase, 240V	+/- 7.4 kW	+/- 32 A	Yes

Table 5. Bidirectional charger specifications for residential pilot.

Figure 6. Deployment of residential bidirectional charger.

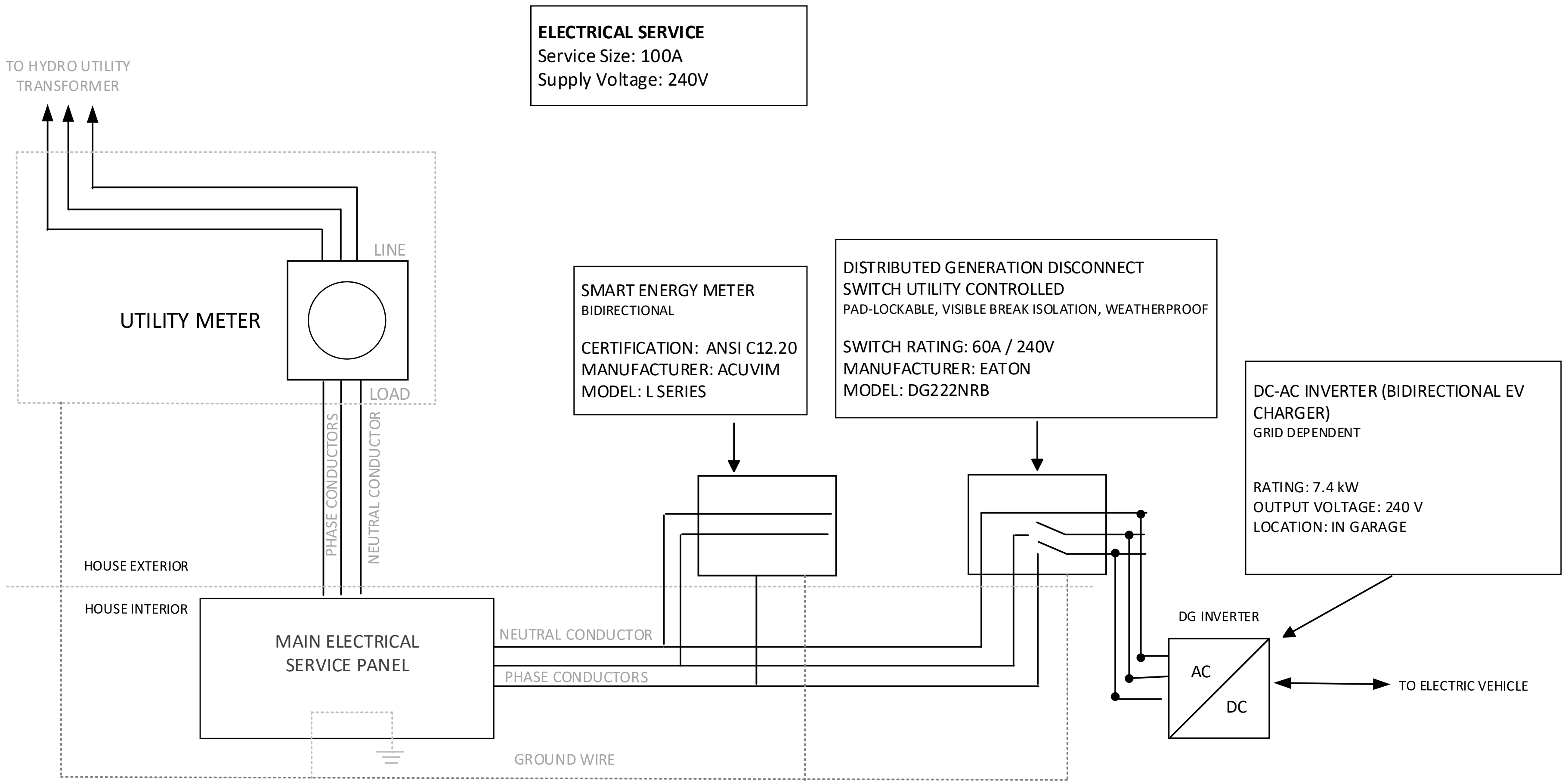

Figure 7. Single line diagram of residential deployment for V2X.

Interconnection Steps & Timeline

Days	Action
1-3	**Preliminary consultation approved.** Local utility checks network capacity constraints in anticipation of deployment of charger #1 (6 kW).
4-109	**Formal utility approval for charger #1 approved.** Multiple rounds of clarity were sought regarding project classification type (micro-load displacement), generator type (bidirectional charger not listed in approved types), and single-line diagram. Major concern regarding back-feeding the grid, considering the deployment home has no renewable energy source and does not qualify for net metering credits. After much technical discussion, a software-based, "zero-export" solution is agreed to for trial purposes, where control software would be developed to continuously monitor the net power consumption of the home and dispatch the charger to generate the requisite power in real time.
110-130	**Charger #1 installation complete.** Difficulties finding electrical contractors willing to take on the project results in a 10-day delay. Eventually, a suitable contractor is found with knowledge of both standard EV chargers and stationary battery storage systems.
131-186	**Charger #1 commissioning fails.** Charger powers on but fails to communicate with the EV. Power transfer is not possible. Charger #2 exhibits similar behavior.
187-200	**Update formal application with utility for anticipated deployment of Charger #3.** Updates to the line diagram are made, capacity constraints are rechecked due to the increased capacity of Charger #3.
201-207	**Charger #3 commissioning successful.** Charger is able to communicate with EV. Charger is able to charge/discharge the EV via mobile application, as well as by receiving remote commands via Modbus protocol.
208-221	**Electrical inspection successful.** Electrical authority satisfied with project intent and associated safety risks.
222-243	**Connection authorization approved.** Utility receives connection authorization approval directly from local safety authority. Finalized connection agreement with homeowner.
244-303	**Connection agreement signed.** Project testing can begin.

Table 6. Residential demo interconnection steps and timeline.

Use Case Experimentation

The data from this section is associated with charger #3 in Table 5, with a maximum power transfer capability of 7.4 kW and 32 A, while the EV is the Nissan Leaf SV 2019. Charger #3 exposes a remote communication method following the Modbus protocol, allowing an external controller to dispatch the charger by setting setpoints for power transfer in units of kW. To control the charger, an existing distributed energy resource management system (DERMS) was extended to interoperate with the charger. A block diagram of the experimental setup is seen in Figure 8. The DERMS obtains measurements regarding the net power consumption of the home from the smart energy meter, as well as the current EV power contribution from the charger every second. Subtracting these measurements from each other returns the actual load of the home, which becomes the setpoint sent to the charger for the next second to attempt to ensure zero export (back-feed) to the utility grid. A slight offset (or tolerance), in the range of 0.1-0.5 kW, can be added to the setpoint to mitigate further scenarios where the EV back-feeds the grid. An example of the DERMS solution in action can be seen in Figure 9, where the EV is discharging 5.86 kW to the home, and the net power measurement is 0.328 kW, which is aligned with the tolerance factor set at 0.3 kW.

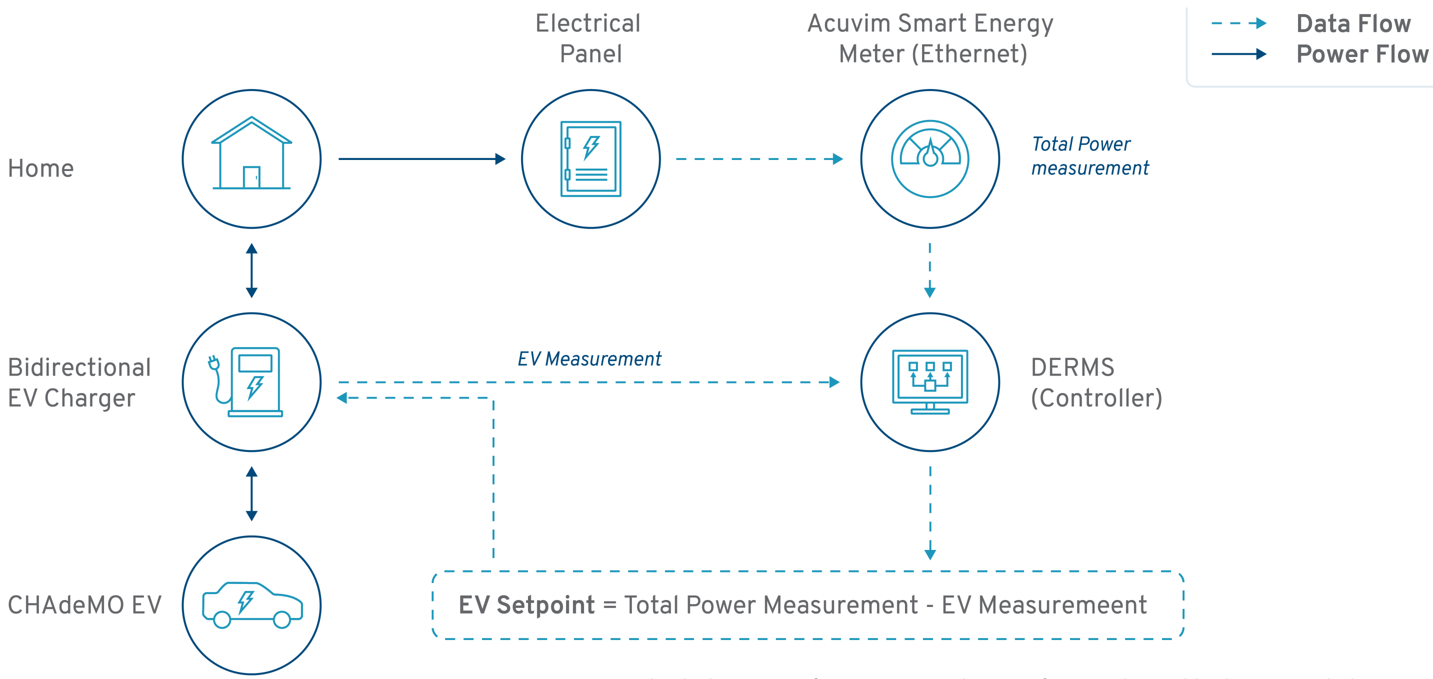

Figure 8. Block diagram of experimental setup for residential bidirectional charging.

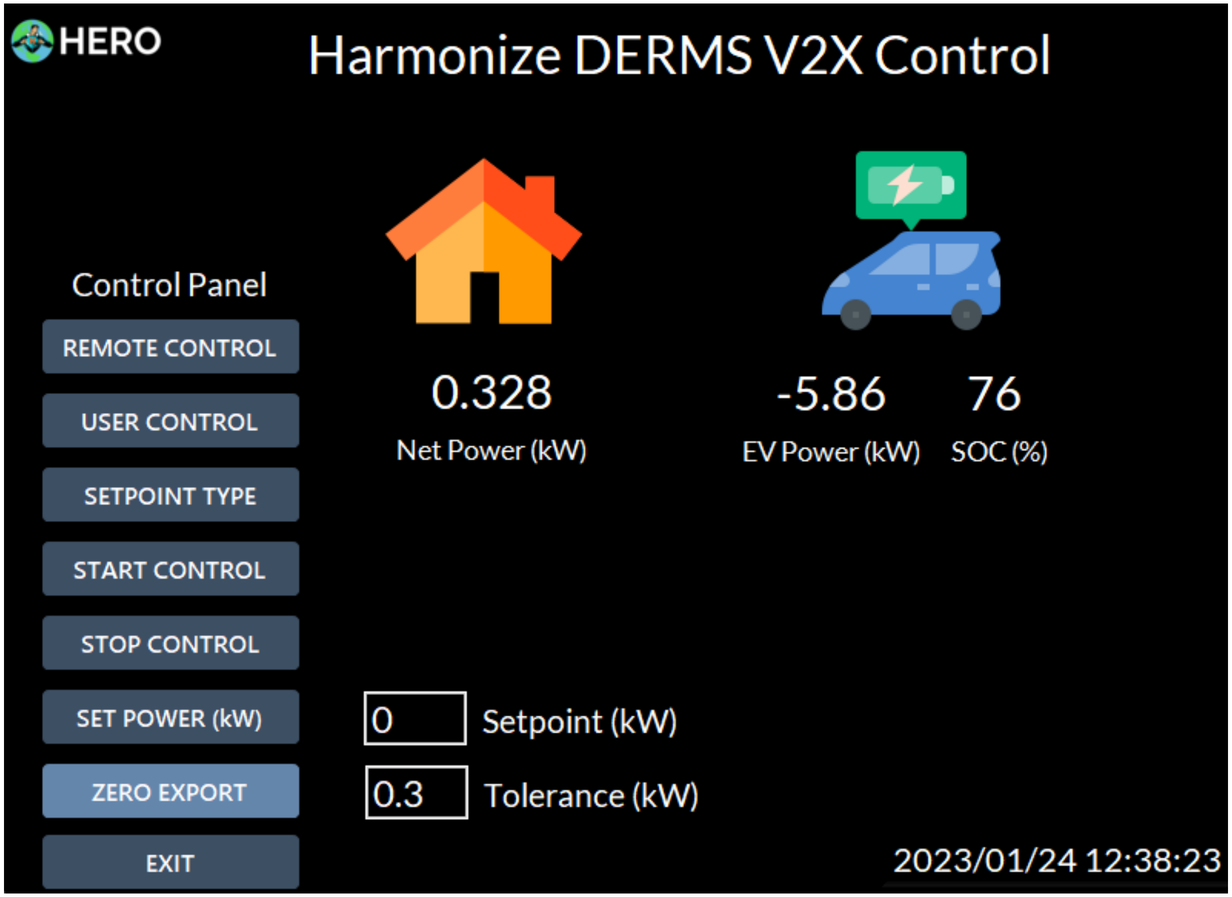

Figure 9. Screenshot of DERMS platform using an EV to perform load following.

Step and Sweep

The step test involves setting setpoints on the charger in steps of 1 kW to evaluate its speed and accuracy. In this test, the sampling data acquisition rate from the meter and charger was set at 5 Hz, and setpoints were set in decrements of 1 kW every minute (or 300 timesteps). The response speed is calculated as the duration between the time the setpoint command was sent and the first occurrence of the EV power measurement reaching the setpoint. In contrast, the accuracy is calculated as the percentage difference between the set-point and the average of EV power when the setpoint is stably reached. Three trials were repeated for this test; the average set of results can be seen in Table 7 and Figure 10.

Setpoint (kW)	EV Power (kW)	Time (s)	Error (%)
7 (START)	6.29	109.32	10.10
6	5.98	5.07	0.18
5	4.98	6.20	0.24
4	3.99	7.25	0.25
3	2.99	6.94	0.18
2	1.99	7.42	0.28
1	0.99	6.24	0.47
0	0.00	3.15	0.00
-1	-0.99	6.78	0.11
-2	-2.00	6.75	0.04
-3	-3.00	7.10	0.00
-4	-3.99	7.13	0.04
-5	-4.99	6.55	0.04
-6	-5.99	6.49	0.07
-7	-6.05	2.79	13.51

Table 7. Tabular residential step test results.

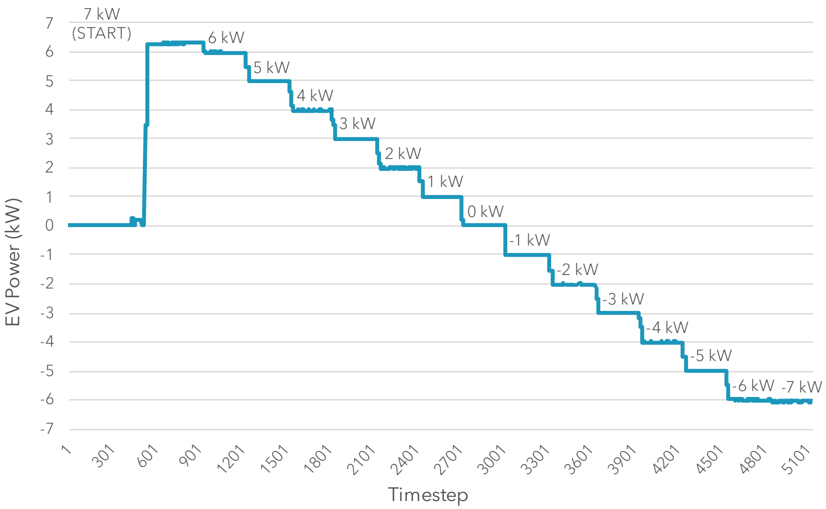

Figure 10. Visual step test results for residential bidirectional charging.

Three main observations can be made from the step test:

- The starting setpoint takes a significant amount of time to reach when compared to other setpoints, with the starting setpoint being reached at 109 s versus an average of 6 s for the rest of the setpoints. This is presumably due to the initial negotiations between the charger and EV, which occur on the first connection and subsequent charging request [28].
- The charger has a maximum power transfer of +/- 6.3 kW when attempting to set setpoints at +/- 7 kW despite the nameplate claiming +/- 7.4 kW. The maximum power transfer is a function of the maximum current output, in DC, of the charger (17A), as well as the DC voltage of the EV battery. With the average observable battery voltage of the 2019 Nissan Leaf SV being around 375V during the test, this would explain the limited power transfer (375V * 17A = 6.29 kW).
- The accuracy of the charger is relatively high when removing the samples of the +/- 7 kW setpoint, with an average error of less than 0.15 %. The step results indicate that the charger may work well for power system applications with less stringent timing requirements, such as demand response and arbitrage.

The sweep test is executed similarly to the step test; instead of step setpoints, the setpoints sweep through the entire allowable range. Thus, knowing that the charger does not provide power transfer beyond +/- 6 kW, the sweep test is conducted in three trials between this range. As seen in the results shown in Table 8 and Figure 11, the setpoint accuracy provided by the charger is extremely high, with an average error of less than 0.1%. However, moving through the entire allowable range takes an average of 8.74 s. On average, the frequency regulation signal can be between 2-6 s [29], and as such, improvements in response time are required before this charger can provide this service.

Setpoint (kW)	EV Power (kW)	Time (s)	Error (%)
-6	-5.99	8.74	0.07
6	5.98	7.32	0.18
-6	-5.99	8.40	0.07
6	5.99	9.52	0.07
-6	-5.99	8.90	0.07
6	5.99	9.54	0.07

Table 8. Tabular residential sweep test results.

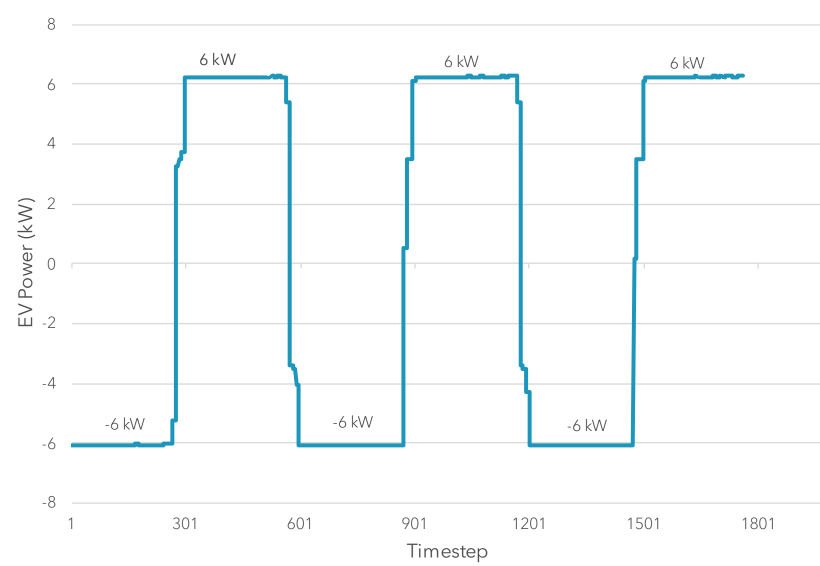

Figure 11. Visual sweep test results for residential bidirectional charging.

Load Following with Zero Export

In the load-following test, the EV is dispatched to follow the loads of the home. To this end, several common household appliances, such as the dishwasher, dryer, and washing machine, are turned on for approximately five hours to test the responsiveness of the EV and charger in load following. To minimize back-feeding the grid, a tolerance of 0.1 kW is set within the DERMS solution, while all other loads within the homes are turned off, leaving a base load of approximately 0.13 kW throughout the test.

The results from the test can be seen in Table 9, as well as Figures 12 and 13. Figure 12 shows how the dispatched EV power mirrors the overall house load, while the net power of the home hovers close to the 0.1 kW mark during a significant portion of the test, except for periods when the dryer is on. This is because the dryer's power consumption changes very quickly, within 1-2 seconds, while the average response time of the EV is around 6 seconds (as found in the step test). Thus, as seen in Figure 12, the plot of the EV power lags behind the plot of the net house power when the dryer is on, resulting in periods where the EV cannot account for all house loads. As such, the EV can supply 4.37 kWh to the house, out of a total consumption of 6.91 kWh during the test. Since the tolerance factor accounts for 0.505 kWh of load that the EV was not meant to generate energy for, this translates to the EV accounting for 68% of the total consumption during the test. A plot of the SOC of the EV is also shown in Figure 13, where the SOC drops from 85 to 66 during the test, with most of the decline occurring when the dryer is on.

Item	Duration (min)	Energy (kWh)
Kettle	4	0.07
Washing Machine	57	0.25
Dryer	80	4.35
Microwave	2	0.02
Dishwasher	83	1.08
Base Load	303	0.65
Tolerance	303	0.505
	TOTAL	**6.91**
EV	303	-4.37
Net House	303	2.53
House Load	303	6.91

Table 9. Tabular results of load following experiment.

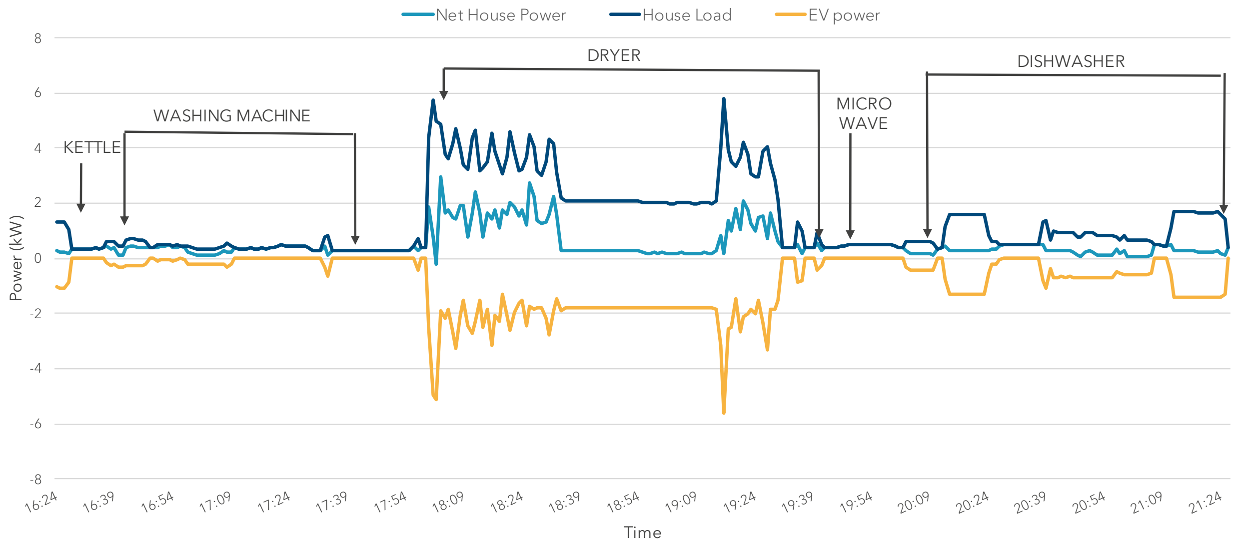

Figure 12. Time series plot of EV being discharged to follow the load of the home.

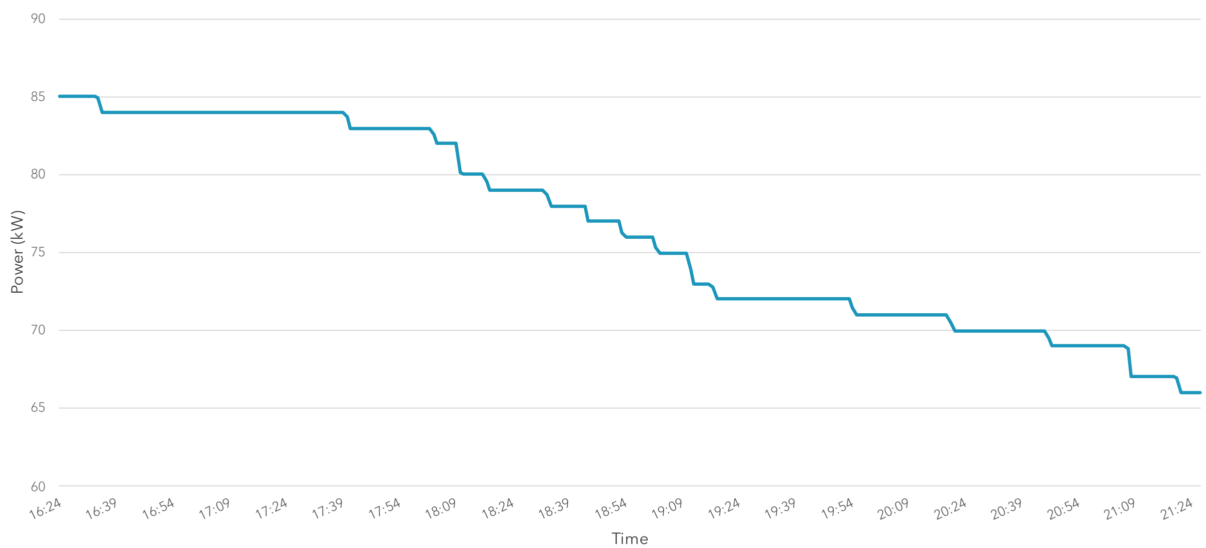

Figure 13. State of charge decline during load following test.

Time-Based Arbitrage

The arbitrage test involves charging the EV at off-peak hours and discharging the EV at on-peak hours. In Ontario, the 2022 retail electricity tariffs are $0.082/kWh for off-peak and $0.17/kWh for on-peak, where the off-peak summer hours are between 19:00 and 7:00, while the on-peak hours are between 11:00 and 17:00. Correspondingly, the emission factor of the Ontario grid is significantly higher during the on-peak periods, as the Ontario system operator utilizes gas-fired generators to meet the increased demand [30]. As such, this five-day experiment charges the EV between the off-peak hours of 00:00-5:00 and discharges the EV during the on-peak hours of 11:00-17:00. The results can be seen in Figures 14 and 15, which plot the EV power transfer against the electricity price ($/kWh) and hourly annual emission factor (gCO2eq/kWh) of the Ontario electricity grid [30], respectively. Both figures show that the EV charges at approximately 6 kW when both the electricity price and emission factor are at their lowest. On the other hand, the EV discharges at about 5 kW when the electricity price and emission factor are at their highest.

The daily metrics are summarized in Table 10, where negative entries indicate energy discharged, emissions avoided, and revenue accrued. As seen in the table, over the five days, the EV owner had a net energy balance of 7.7 kWh and contributed a net emissions savings of 3.6 kgCO2eq while earning a total of $12.63 and shifting 150.7 kWh of electricity consumption from the grid at on-peak hours. While the earnings may seem relatively insignificant, recall that 47% of EV owners from the survey data were willing to engage in bidirectional charging without financial incentives attached. A further 49% of EV owners' participation depended on a minimum incentive, of which the most popular answer was free EV charging, which was achieved during the test. Furthermore, the environmental advantages, especially at scale, are promising due to the ability of EVs to discharge at on-peak periods, which aligns with the survey data as 80% of EV owners cited enhanced motivation to participate due to this very fact.

Day	Energy (kWh)		Emissions (kgCO2eq)		Cost ($)	
	CHG	DCHG	CHG	DCHG	CHG	DCHG
1	31.2	-30.0	0.46	-1.19	2.56	-5.10
2	32.6	-29.6	0.47	-1.17	2.59	-5.03
3	32.1	-30.6	0.48	-1.22	2.63	-5.20
4	31.5	-30.1	0.47	-1.19	2.58	-5.11
5	32.0	-30.4	0.48	-1.21	2.62	-5.17
Sum	158.4	150.7	2.36	5.98	1298	25.61
Net	**7.7**		**3.62**		**12.63**	

Table 10. Energy, emission, and cost metrics for arbitrage test.

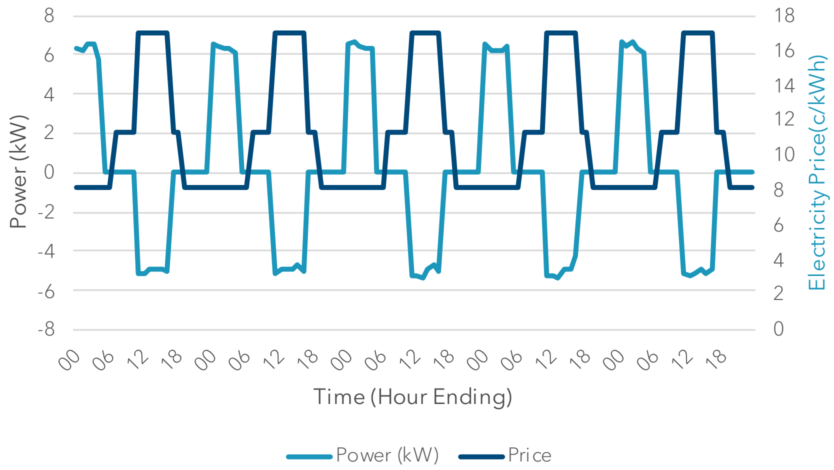

Figure 14. Power transfer against electricity prices for arbitrage test.

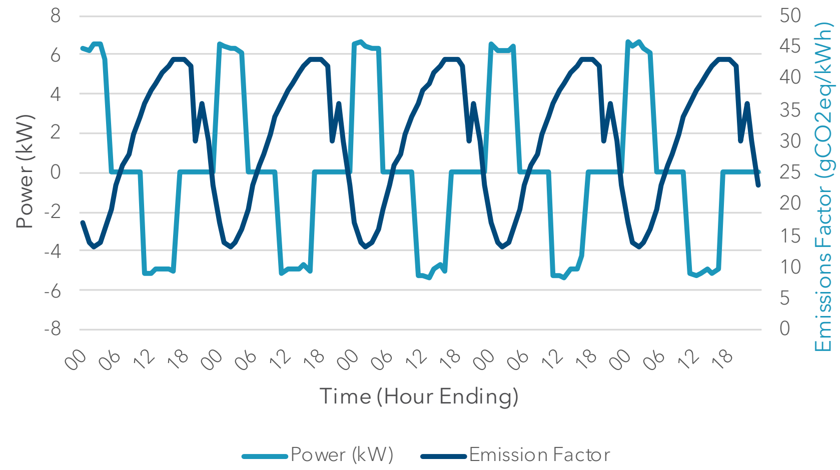

Figure 15. Power transfer against emissions for arbitrage test.

Lessons Learned

Awareness and education needed across the board in the energy value chain

As noted by stakeholders in this guide, the lack of awareness concerning bidirectional charging (specifically vehicle compatibility, control methods, and alignment with current interconnection practices) led to several long delays during the pilot. The initial outreach to recruit EV owners for the pilot gained an excellent response, with over 30 responses within ten days. However, over half of the responders had EVs that did not support bidirectional charging.

Additionally, for current energy resource interconnection processes, it is worth noting that bidirectional charging does not appear as a "type" of resource, whether in utility interconnection or safety authority permit forms. The lack of these options led to confusion during the safety approval process. The project team selected the resource type as a standard EV charger while adding that the charger was bidirectional in the "notes" section. The resultant safety inspection was unsuitable for generating the connection authorization needed for the project to move forward, thus causing an additional three-week delay.

Lastly, there was general difficulty recruiting an electrical contractor with sufficient knowledge to understand the project motivation, act as a liaison between the project team and the safety authority, and commission the charger at a reasonable cost. Out of fifteen electrical contractors approached, only five returned with valid quotations for the installation. Electrical contractors will play an integral role in the future adoption of bidirectional charging. Training materials are suggested to help them understand the products and services bidirectional charging offers.

Current response times limit efficacy for load-following and frequency regulation

As seen in the sweep and step tests, the average response time for the charger to reach setpoint ranges between 6-9 seconds, which may not be suitable for frequency response and load-following applications. In particular, the charger had significant difficulty keeping up with dynamic loads, such as the dryer, resulting in the generation of EV power lagging behind the dryer consumption. More testing is required across different makes and models of charging stations and EVs to determine the suitableness of bidirectional charging used in these applications.

Failure of power electronics

All three chargers faced significant periods of time in an inoperable state, with power electronics issues related to circuit boards, heat sinks, and transformer replacements. The reliability of the overall unit, particularly mission-critical power electronics, must be improved to ensure the uptime needed for bidirectional charging technology to obtain market trust.

8. CASE STUDY II: COMMERCIAL BIDIRECTIONAL CHARGING

This case study tested the ability of commercial bidirectional charging to integrate with other building energy resources, including solar and a battery energy storage system (BESS), to participate in simulated demand response tests. A single-line diagram of the building and its connected energy resources can be seen in Figure 18, while a picture of the infrastructure can be seen in Figure 21. The bidirectional charger used in this case study was the Coritech VGI-30-DC, as described in Table 1. It is worth noting that although the bidirectional charger has a capacity of +/- 30 kW, this was rate-limited to +/- 10 kW due to a cable capacity limit in terms of the maximum allowable amperage.

Use Case Experimentation

Step and Sweep

Similar to the test done on the residential charger, the results of the step and sweep test are shown below (Figures 16 and 17, and Tables 11 and 12, respectively), with accompanying observations.

- Like the residential charger, starting an EV session takes much longer than moving from setpoint to setpoint. Starting the EV session takes approximately 27.5 s to reach its intended setpoint of -10 kW, while, on average, moving from setpoints in 5 kW increments takes an average of 3.05 s.
- The sweep test elicits similar response times and error rates as the step test, suggesting that a range of 20 kW can be covered in approximately 3 seconds.
- Stopping the EV session takes much less time than starting an EV session (3.6 seconds vs 27.5 seconds).
- Compared to the residential charger (covering a range of 12.5 kW in approximately 9 seconds), the commercial charger shows superior response time.

Setpoint	Time to Setpoint (s)	Average Measurement (kW)	Error (kW)	Error (%)
Start (-10 kW)	27.46	-10.68	0.68	6.81
-5 kW	2.60	-5.70	0.70	13.90
0 kW	3.41	-0.16	0.16	N/A
5 kW	3.81	4.74	0.26	5.29
10 kW	3.41	9.24	0.76	7.63
Stop (0 kW)	3.6	-0.11	-0.11	N/A

Table 11. Tabular V2G test results for step-wise dispatch.

Setpoint	Time to Setpoint (s)	Average Measurement (kW)	Error (kW)	Error (%)
-10 kW	N/A	-10.57	0.57	5.74
10 kW	2.21	9.30	0.70	6.97
-10 kW	2.00	-10.67	0.67	6.68
10 kW	3.41	9.30	0.70	6.98
-10 kW	2.60	-10.69	0.69	6.89
10 kW	3.20	9.30	0.70	6.99

Table 12. Tabular V2G test results for range-wise dispatch.

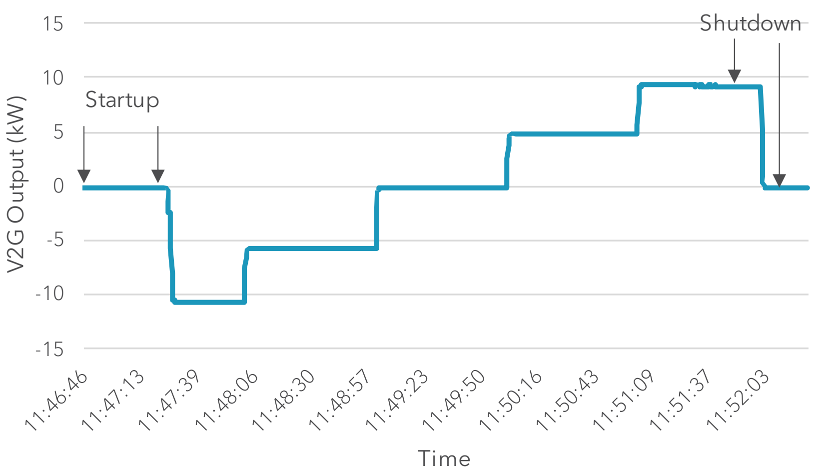

Figure 16. Time-series V2G test results for step-wise dispatch.

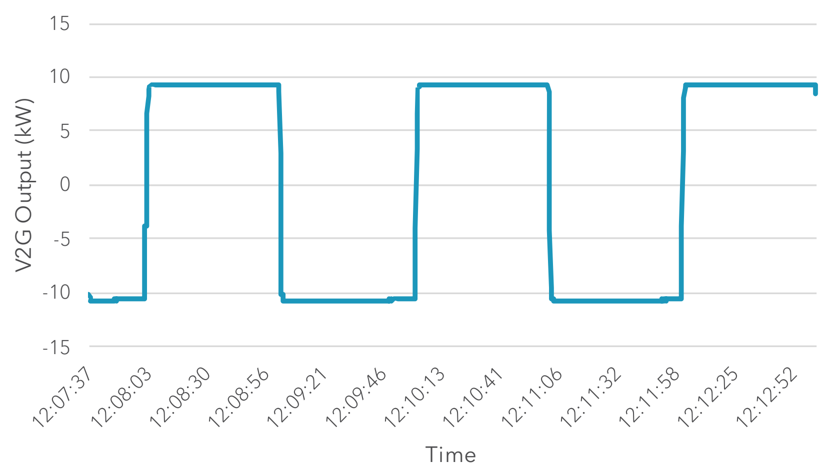

Figure 17. Time-series V2G test results for range-wise dispatch.

Demand Response

A sample test result for a load reduction commitment of 30 kW for 2 hours can be seen in Figures 19 and 20, where the building successfully reduces 30 kW of its load via the generation sources of solar, bidirectional charging, and energy storage [31]. In particular, the plot in Figure 20 shows steady performance of the EV, which is able to discharge 10 kW of the 30 kW commitment steadily over the 2-hour test.

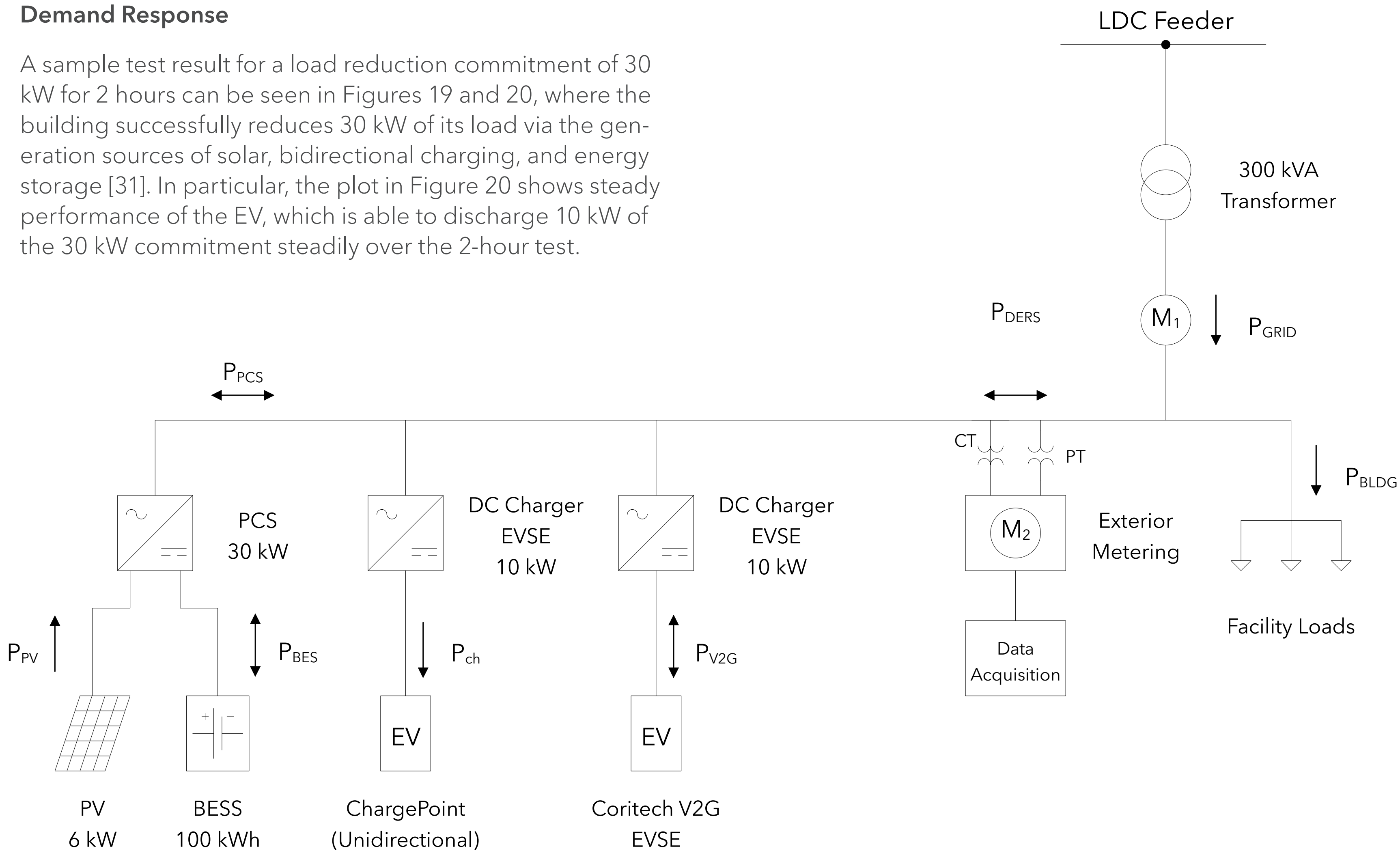

Figure 18. Single line diagram of commercial building with bidirectional charger, solar, and storage.

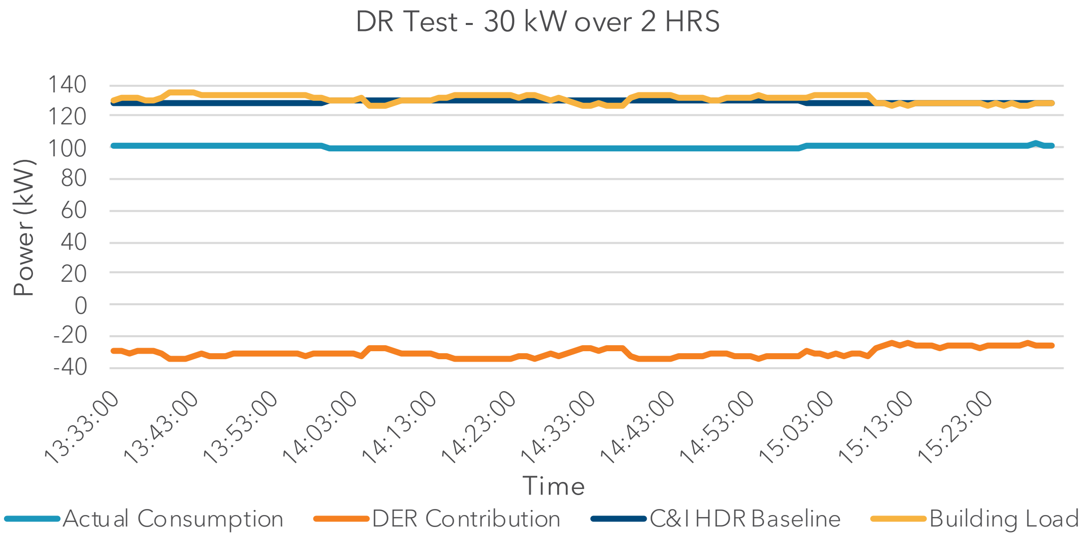

Figure 19. Load reduction of building compared to baseline.

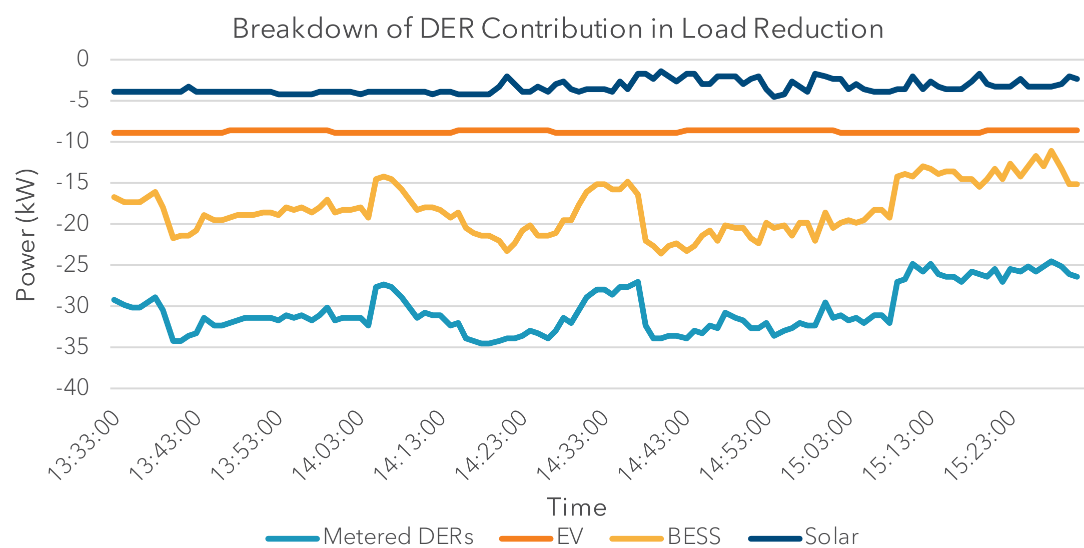

Figure 20. Contribution of each energy resource towards load reduction.

Lessons Learned

Power transfer efficiency is poor when discharging at smaller setpoints

It was observed that at setpoints less than 3 kW, the efficiency of the charger (converting DC energy to AC energy) dipped below 80% consistently, while on the other hand, higher setpoints in the range of 10 kW featured efficiency near 90%. As such, for peak shifting, it may be advantageous to dispatch the EV at higher setpoints in shorter bursts of time to increase the energy exported to the grid.

Power electronics failure due to lack of sealing

Transistors within the bidirectional charger did not receive the proper ventilation as the door to the bidirectional charging station was not sealed tightly shut, resulting in overheating and permanent damage. This led to a delay of six months in the project commissioning.

Location matters

The proposed program design considers an abstract set of plug-in hours, without considering the location of where these hours will be spent. However, given that EVs are a mobile resource, there is currently no consideration given to the fact that congestion occurs in different parts of the grid, which is a function of time and location. Future directions could involve the consideration of location and time since only a time-based approach may not be helpful if the EV owner plugs in only at off-peak hours and in locations that do not have congestion.

Figure 21. Deployment of residential bidirectional charger.

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