IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received 28 January 2023, accepted 9 February 2023, date of publication 13 February 2023, date of current version 23 February 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3244562

RESEARCH ARTICLE

A Techno-Social Approach to Unlocking Vehicle to Everything (V2X) Integration: A Real-World Demonstration

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This work was supported by the Independent Electricity System Operator (IESO) Grid Innovation Fund.

ABSTRACT The urgent transition towards electric vehicles (EVs) may potentially result in expensive capacity upgrades for power system operators (PSOs), however, the recent uptake in bidirectional EV charging, often referred to as ''Vehicle to Everything'' (V2X), may defer this need while simultaneously generating revenue for participating EV owners. Yet, there is a lack of real-world investigation to elicit (a) the willingness of EV owners to participate in V2X programs (b) the alignment of these programs within existing electricity markets, and (c) how V2X may be combined with other distributed energy resources (DERs) to realize maximum energy savings. As such, this paper proposes the design and implementation of a V2X program that is informed by the socio-technical preferences of EV owners, including convenience, revenue, and emissions savings. A survey is distributed to 124 EV owners to characterize their degree of willingness to participate in the program, which leads to the design of several EV session types that enable EV owners to arbitrage at their convenience, or participate in demand response (DR) events for higher revenue. Real-world tests at residential and commercial buildings in Ontario successfully demonstrate the facilitation of both arbitrage and DR, leading to increased revenue, decreased emissions, and the ability to participate in DR with other building DERs to reduce the building load by 30 kW. The proposed work contributes a novel attempt to demonstrate pathways to realize the potential offerings of V2X programs to benefit both EV owners, building owners, and PSOs.

INDEX TERMS Bidirectional charging, demand response, distributed energy resources, electric vehicles, grid services, microgrid, vehicle to everything, vehicle to grid, transactive energy.

I. INTRODUCTION

The urgency of transitioning towards electric vehicles (EV) has accelerated in recent times, with more than 20 countries mandating the exclusive sale of EVs by 2030 [1]. While this transition will significantly reduce tailpipe greenhouse gas emissions (GHGs), there is growing concern that the resultant rise in electrical demand may overburden power systems, leading to load congestion, voltage and frequency deviation, as well as extended power outages [2]. Of particular importance is the scenario where large numbers of EVs charge their batteries at the same time, which may coincide with pre-existing peak times of electricity, and would require expensive and time-consuming grid capacity upgrades inclusive of distribution transformers, feeders, and substations [3].

With the issue of rising peak load in mind, recent innovations in EV technology have aimed to turn the EV into a bidirectional source of energy that uses its on-board battery

The associate editor coordinating the review of this manuscript and approving it for publication was Akshay Kumar Saha.

as an auxiliary power source [4]. The pervasive outlook for this technology has led academia and industry to coin a new name, ''Vehicle to Everything-X'' (V2X), where power from the EV can be used by electrical loads directly plugged into the EV (V2L), by homes and buildings via a bidirectional EV charging station (V2H/V2B), as well as the greater electrical grid (V2G) [5]. Apart from peak load reduction, V2X can also provide other benefits at both the distribution and transmission level, including voltage/frequency regulation and renewable energy firming [6]. It is worthwhile to note that the term V2X is also commonly applied within communication paradigms involving vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) [7], however, without loss of generality, this manuscript will refer to V2X in its collective capacity to deliver energy within power grids, with specific mention of the destination of the energy flow described when appropriate, whether V2L, V2H, V2B, or V2G.

The topic of V2X has gained a great amount of interest in recent times, where researchers have made strong contributions. A tabular summary of recent research in this vein can be found in Table 1, while a more detailed discussion is presented hereunder.

The works in [6], [8], [9], [10], and [11] characterize EV owner preferences, such as anticipated departure time and discomfort caused by range anxiety, into parameters that define the total usable capacity of the EV for discharging purposes. In [6], an optimal scheduling algorithm is proposed for EVs to provide voltage and frequency support to the transmission system in consideration of battery degradation tolerance and anticipated time of departure. Furthermore, in [8], a deep reinforcement learning algorithm is proposed to consistently balance EV owner range anxiety and preferred charging location with financial gain under highly dynamic pricing. The work in [9] investigates the problem of V2G shifting peak load considering the randomness of EV owners arrival and departure times, and proposes a multi-objective satisfying platform that delivers appreciable load shifting and daily EV operation savings of over 30%. The authors in [10] develop a distribution system plan to minimize grid capacity upgrades in view of locational preferences for EV public charging and discharging, while in [11], the authors propose a distributed, multi-objective control solution to minimize battery degradation and maximize daily EV owner revenue under real time pricing incentives.

On the other hand, the research in [12], [13], [14], [15], and [16] focuses on integrating V2X with other DERs for optimizing power flow in behind the meter or off-grid applications. In [12], [13], and [15], optimal dispatch algorithms are proposed to aggregate wind, solar, and stationary energy storage systems with V2B to reduce the peak load of buildings and/or arbitrage according to electricity prices. The authors in [14] propose a cooperative power sharing strategy to shave peak load between four interconnected microgrids in concert with solar energy, leading to reductions of peak load between 67% and 90%. On the other hand, the work in [16] develops a V2H-enabled scheduling algorithm to minimize the time a home spends without power.

Building on the two previous criteria, the works in [17], [18], [19], [20], [21], and [22] explore the aggregation of V2G to provide grid services, including the modulation of reactive power for voltage regulation at the distribution level [18], [19], as well as active power modulation for frequency regulation at the transmission level. Similarly, the works in [17] and [20] use rolling-prediction based frameworks to estimate the total capacity that could be offered into capacity markets, finding that residential V2G could avoid capacity upgrades needed for full electrification of light-duty EVs. The authors in [21] utilize commercial EVs to provide load variance minimization and voltage regulation, which uses a fuzzy-decision-making predictive control strategy to target load variances and discharge EVs at strategic times. Furthermore, the work in [22] proposes a multi-market optimization model that enables EVs to participate simultaneously in both energy and ancillary markets, leading to increased revenue and decreased charging infrastructure costs.

Although prior research has contributed tremendously to the state-of-the-art in V2X, several aspects are preventing its improved uptake. While several works have considered EV owner preferences in the design of their proposed algorithms, these preferences have not been informed by real-world surveys or data, nor is it clear to which degree the preferences would affect the EV owner's participation in V2X. For example, the considered preferences focus mainly on monetary gain, and do not reflect environmental or societal benefits that could play a major role in the decision to participate in V2X [23]. Moreover, adequate steps have not been taken to reduce the complexity of V2X and improve its awareness for all parties, including power system operators (PSOs), EV owners, and energy aggregators, making it difficult to design programs that could maximize benefits for all in an intuitive manner [24]. In addition, V2X could play a significant role by being aggregated with other DERs and participating in grid services, however, its realistic alignment with current electricity market rules, including the governance and contracting between all parties, is left unclear [25]. This is an important oversight as PSOs begin to test the ability of mixed aggregations to perform in capacities as low as 100 kW [26]. Lastly, there is a lack of real-world V2X deployment and lessons learned to date, which is critical in establishing trust, market readiness and eventual uptake. It is worth noting that the papers described in Table 1 do not use real-world data sets within their work, thus speaking to the inaccessibility of this data.

As such, this paper proposes the design, development, and deployment of a V2X program that is tested at real-world residential and commercial buildings in Markham, Ontario. To investigate often neglected social aspects of V2X, a survey is distributed to 124 EV owners to characterize concerns, benefits, and criteria to V2X participation, thus establishing baseline preferences to design the V2X program. Specifically,

TABLE 1. Comparison table of related and proposed work.

Reference	Criteria #1 EV Owner Preferences	Criteria #2 Off-Grid DER Aggregation	Criteria #3 Grid Services	Criteria #4 Real-world Testing
[6], [10], [11]	✓		✓	
[8], [9]	✓			
[12]	✓	✓		
[13]–[16]		✓		
[17-18],[21-22]			✓	
[19], [20]	✓		✓	
Proposed paper	✓	✓	✓	✓

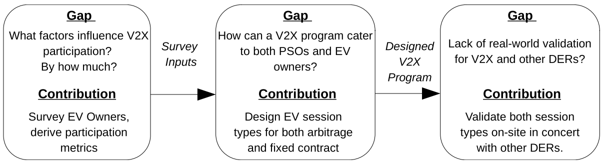

FIGURE 1. Contributions of proposed work.

the survey seeks to measure the financial, environmental, and societal incentives required to secure EV owner participation, combined with the willingness to leverage their EV for the provision of grid services such as demand response (DR). Based on the survey responses, a V2X program is developed to cater to the elicited preferences, which offer several EV session types that enable an EV owner to select between arbitrage or contracted grid support during DR events. The grid support mode is then aligned with the current DR market in Ontario, where contracting and governance between EV owners, building owners, and PSOs conforms with market rules for compliance. Both EV session types are tested with a 10 kW bidirectional EV charger at a commercial building, and paired with a 30 kW solar and storage system to demonstrate the mixed aggregation's ability to provide DR. Thus, as summarized by Figure 1, the main contributions of this paper are (a) the usage of survey data to define new parameters to characterize V2X preferences; (b) the design of a new V2X program with configurable EV session types that prioritizes the needs of both EV owners, building owners and PSOs; and (c) demonstration from real-world deployment and alignment with electricity markets to help accelerate the uptake of V2X.

The organization for the remainder of the paper is as follows. Section II provides an overview of the administered EV owner survey, including key takeaways that govern the design of the V2X program. Section III introduces the design of the proposed V2X program itself, while Section IV focuses on the software implementation of the program. Finally, section V presents real-world results, while Section VI is reserved for conclusions and future work.

II. OVERVIEW OF EV OWNER SURVEY

A. SURVEY DESIGN

The main objective of the EV owner survey is to capture their willingness to participate in V2X, comprising of environmental, societal, economic, and technical attributes.

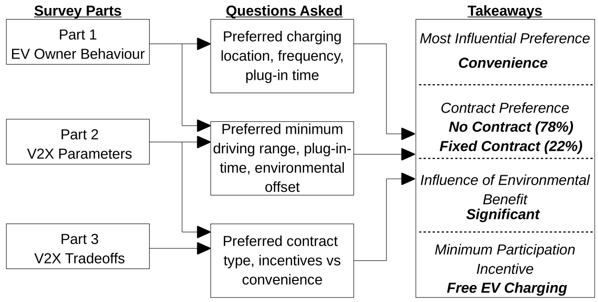

FIGURE 2. Summary of EV Owner survey.

These attributes are then parameterized into metrics that are useful in observing trends that establish preference heterogeneity and influence the overall willingness to participate, which informs the design of the proposed V2X program. As seen in Figure 2, the survey is divided into three sections that ascend in order of comprehension complexity due to the general unfamiliarity of EV owners with respect to V2X [23], [24]. The first section focuses on asking general questions that establish behavioral patterns of the EV owner, such as their preferred charging location, charging frequency per week, and estimated daily plug-in-time. The responses can be interpreted to ascertain the opportunity for EV owners to participate in V2X, and predict the aggregated capacity (kW) and energy (kWh) available to participate in DR.

The second section gently introduces the concept of V2X and describes the opportunity to earn incentives for participating in exchange for energy discharged and a commitment to plug-in to a charging station for a minimum duration. Participants are also educated about the environmental opportunity for V2X in offsetting energy generation from fossil fuel based power plants. Two important parameters are introduced to the EV owner at this stage, which are the minimum driving range (MDR), and minimum-plug-in-time (MPT) [27]. The MDR is the minimum level of range that is guaranteed to be left on the EV at all times to allow it to get to its next destination, while MPT is the minimum number of hours an EV owner would be required to plug in to a bidirectional charging station per month.

The third section focuses on using the MDR and MPT parameters to introduce two different V2X program types and assess their interest in each. The first program broadly resembles a ''pay as you go'' program based on energy arbitrage, where EV owners would charge their EV during times when electricity prices are relatively inexpensive (off-peak hours), and discharge their EV during times when electricity prices are comparatively expensive (peak hours). This form of arbitrage may also result in a lower carbon footprint for the EV owner, since generally, the fuel mix of electricity generated at off-peak hours is cleaner as compared to peak hours, where fossil-fuel based peaking power plants may be procured to meet additional demand [28]. This program type prioritizes the convenience of the EV owner over their potential to earn incentives, since the EV owner may choose

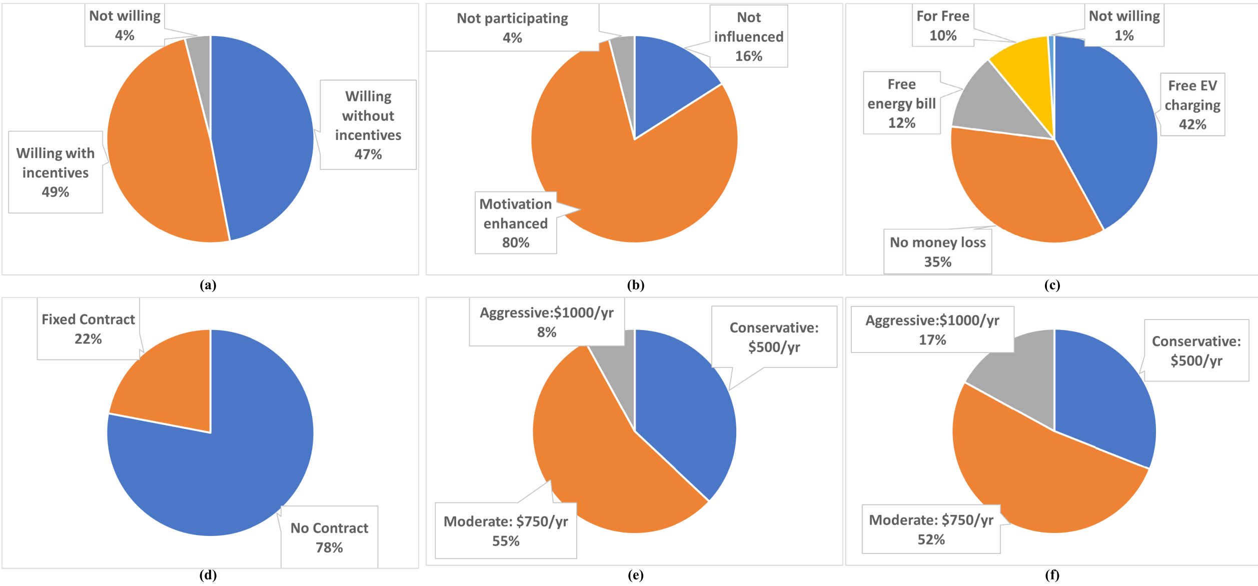

FIGURE 3. **EV Owner survey results showing (a) participation due to financial incentive, (b) participation due to environmental benefit, (c) minimum incentive to participate (d) preferred V2X program, (e) profiling based on MDR and (f) profiling based on enhanced MDR.**

to initiate and abort an EV session without any penalty, and does not need to commit to any sort of contract with an energy aggregator or PSO. The second program is based on a fixed contract, where the EV owner would commit to a MDR and MPT, and receive payments for energy discharged ($/kWh), as well as capacity payments for the time spent plugged in ($/kW). If a DR event is called, the EV owner is entitled to enhanced payment for energy discharged during the DR event. However, the EV owner forfeits all monthly incentives if they do not fulfill their level of MPT, or disconnects from the charging station for a certain period of time during a DR event.

To make the programs more intuitive to understand, three separate profiles are created to characterize ranges of preference for MDR and MPT, entitled conservative, moderate, and aggressive. Without loss of generality, it is assumed that a conservative EV owner sets the MDR as two times their daily commute and the MPT at 4 hours, a moderate EV owner sets the MDR as 1.5 times their daily commute and the MPT at 8 hours, while an aggressive EV owner sets the MDR at their daily commute and the MPT at 12 hours. Monetary amounts are attached to each of the profiles and varied to observe the trade-off between convenience and desire for incentives by determining if any of the EV owners changed their desired profile type.

B. DISCUSSION OF SURVEY RESULTS

The selection criteria to participate in the survey was for the participants to reside in Ontario, Canada, and to have driven an EV before conducting the survey. The survey was subsequently disseminated online to EV owners in the Canadian province of Ontario for a period of 9 months between March 2021 and December 2021, and garnered 124 responses. It is worthwhile to note that individual consent to use the survey responses for the purposes of knowledge dissemination within this paper was obtained during the survey process itself, where participants indicated their consent by having an option to opt-out of the dissemination activities.A total of 68% of EVs were from Tesla, Chevrolet, and Nissan, with Tesla accounting for 38% (models S, X, Y, 3), the Chevrolet Bolt at 19%, and the Nissan Leaf at 11%. Further observations from the survey results can be seen in Figure 3, and are discussed below.

1) GENERAL WILLINGNESS TO TRIAL V2X PROGRAMS

As seen in Figure 3(a), there appears to be a general willingness to engage in a V2X program across respondents, with only 4% rejecting participation outright, 49% participating for a minimum incentive, and 47% participating regardless of incentives. When told that V2X had the potential to offset the use of fossil-fuel based generators, 80% of the respondents cited enhanced motivation to participate, as seen in Figure 3(b). Interestingly, when queried with respect to the minimum incentive required to participate in a V2X program, as seen in Figure 3(c), dominant responses included year-round free charging for their EV (42%), while 35% indicated that they would participate as long as they did not lose any money. Put together, the survey results indicate that the survey respondents possess a general willingness to trial V2X programs, strongly motivated by environmental benefits and financial incentives.

Qualitatively, participants were also asked the reasons they **would not** participate in a V2X program, where the top reason cited by 33% of participants was the fear of accelerated battery degradation due to frequent charging/discharging cycles, while 28% cited trust issues with the technology itself

Proposed EV Session Types

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

FIGURE 4. Summary of EV Session types.

and allowing PSOs to remotely control their EV. These concerns underscore the importance of designing and deploying real-world V2X programs to mitigate these concerns.

2) PREFERENCE FOR V2X PROGRAM TYPES

EV owners indicated a strong preference for a no contract type program as seen in Figure 3(d), with 78% voting for no contract, versus 22% voting for fixed contract. To further explore the motivation to participate as a function of MDR, EV owners were asked to choose between profile types of conservative, moderate, and aggressive, as discussed previously. As seen in Figure 3(e), 55% chose the moderate profile, while 37% chose the conservative profile, with only 8% choosing an aggressive profile. Next, financial incentives were attached to the profiles in two stages, where in the first stage, the annual payout for conservatives, moderates, and aggressives was $500, $750, and $1000 respectively, while in the second stage, the annual payouts were enhanced to $750, $1000, and $1500, respectively. At the first stage, the aggressive profile reported an increase of 4 EV owners, or 3.3% of the total respondents. In the second stage, shown in Figure 3(f), the trend was observed again, where the number of EV owners switching to the aggressive profile increased by 7 (or 6% of the total respondents). By increasing the annual payout for the aggressive profile by a factor of 1.5, the number of EV owners willing to lower their MDR and offer more capacity for grid services more than doubled, from 10 to 21.

In totality, it can be established that the most influential characteristic that drives an EV owner's willingness to participate in V2X is their convenience, as evidenced by the strong preference for the no contract option. However, the survey evidence also suggests that both environmental benefits and financial incentives do play a secondary role in establishing participation. Therefore, it follows that a V2X program must provide options that cater to these preferences in an intuitive manner, which includes facilitating both fixed contract and no contract options.

III. DESIGN OF PROPOSED V2X PROGRAM

This section introduces the design of EV session types within the proposed program that cater to the preferences garnered from the survey results discussed in the previous section, which are summarized in Figure 4 as a quick reference. First, the roles of participants in an EV session transaction are defined, including the EV owner, energy aggregator/building owner, and/or the PSO, followed by a detailed description of the logistics of the EV sessions themselves. Lastly, a subsection is dedicated to introducing how the proposed session types would integrate within the existing electricity market in Ontario, along with the governance and contracting required between the transaction participants.

A. EV TRANSACTION PARTICIPANTS

The intent of the proposed EV program is to provide the EV owner with flexibility to charge or discharge their EV at different locations, whether at home, work, or at a public charger. Depending on where the EV owner plugs in, the transaction participants will differ. If the EV owner utilizes a charger at home, then the transaction only involves the EV owner and the PSO, where it is assumed that the transaction price would equal the regular rate of electricity at that point in time, which EV owners would earn if discharging, and pay if charging. This transaction is most conducive to jurisdictions where electricity prices vary as a function of time, such as time-of-use. On the other hand, if the EV owner utilizes a charger at work or in public, the transaction participants are the EV owner and the building owner, with the transaction price being set by the building owner.

However, if a DR event is called by the PSO, they are included in the transaction as they are distributing incentives to the EV owners and building owners for participating in the event. As such, it is assumed that the building owner would act as an aggregator of EVs and other on-site DERs, and operate as the point of contact between EV owners and PSOs. This practice aligns with the direction of current and future electricity markets, where aggregators procure DERs that are behind the meter and sell capacity and energy to upstream markets [29]. Thus, incentives would flow from the PSO to the building owner (aggregator), and from the building owner to the EV owners. The contracting and governance of these transactions will be discussed later in this section, when alignment with electricity markets is discussed.

B. EV SESSION TYPES

Based on the preferences discovered from the survey that prioritize both EV owner convenience as well as opportunities to earn revenue via V2X, three types of EV sessions are proposed, which are Charge My EV, Quick Support and Extended Support (Figure 4). Charge My EV is provided for an EV owner that wishes to charge their EV as quickly as possible, and is designed to cater to those use cases where the EV owner is short of time, and may not be at their preferred charging location. As such, Charge My EV accepts a target battery level as a parameter and immediately dispatches the charger at the maximum acceptable power rate. Optionally, a departure time can be added as a parameter for those EV owners wishing to average their power consumption over a fixed duration of time. For discharging the EV, EV owners leverage the Quick Support or Extended Support session type. In Quick Support, the EV owner provides their MDR, and the charger is either dispatched at the maximum acceptable discharging rate, or at an average discharge rate if a departure time is provided. If a DR event is called during a Quick Support session, the EV owner may "opt-in" to the DR event, and they will receive an additional DR payment (in \$/kWh) from the PSO on top of the regular electricity rate. This use case caters to the dominant socio-economic preferences of EV owners found in the survey by (a) enabling revenue opportunities by discharging at peak electricity rates; (b) lowering carbon footprint by discharging to offset the use of peaking power plants; and (c) maximizing EV owner convenience by not enforcing a penalty for aborting their EV session. In the context of charging location and V2X scenarios, it is worth noting that the three session types encompass all forms of V2X within this paper, whether V2L, V2B, V2H, or V2G.

Conversely, Extended Support is contract oriented, where the EV owner would establish their constraints as per MDR and MPT, which can be updated monthly. For each session, two additional inputs are taken into consideration, which are a maximum battery level, and an expected departure time. The expected departure time indicates the availability of the EV to discharge should a DR 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 DR event to occur, where each hour plugged in to the station counts towards the monthly MPT. If a DR 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), 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 certain number of minutes during an DR event, all payments for the month are forfeited. This particular session type caters to those EV owners in the survey that aggressively seek revenue opportunities and do not mind fixing their schedule to realize them.

C. PROPOSED INTEGRATION WITH DEMAND RESPONSE MARKET IN ONTARIO

As discussed in the previous subsection, aggregators act as the point of contact between providers of DR and the PSO, and so within context of this paper, we assume the aggregator to be a building owner with a parking lot of bidirectional chargers, as well as on-site DERs. Thus, it follows that the building owner will bundle capacity from parked EVs in Extended Support mode alongside capacity from its on-site DERs to provide DR services within a PSO administered market. As seen in Figure 5, this would require contracting between EV owners and the building owner to establish the available capacity from the EV owners as a function of individual MDRs and MPTs, and a subsequent contract between the building owner and the PSO that culminates in a DR capacity bid that bundles the contracted EV capacity with other on-site DERs. As an example for the proposed integration, the market rules from Ontario's DR market are used hereunder.

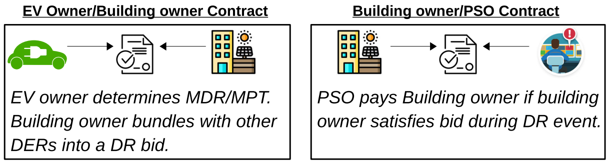

FIGURE 5. Participant contracting for demand response.

Ontario's transmission system operator, the Independent Electricity System Operator (IESO), administers a DR market that contracts market participants, including aggregators, to reduce energy consumption during periods of high demand in exchange for economic incentives [30]. Market participants bid into an annual capacity auction, committing to a specific reduction of energy consumption, in kW, for each applicable hour. With commitments in hand, the IESO issues a "stand by" notice to market participants by 7:00 on the morning of the day to begin preparing for a DR event, and further issues an activation notice at least 2 hours in advance of the event itself. In context of this paper, the formulation of the DR capacity bid relies heavily on the contracted capacity between the building owners and EV owners, along with the useable capacities of its on-site DERs. The average contracted capacity from EV owners opted-in to the Extended Support session type is analogous to the average useable capacity of the EV, in kW, as a function of MDR and MPT, and can be formulated as follows:

$$UCAP_j^{EV} = \frac{(STR_j^{EV} - MDR_j^{EV}) * CAP_j^{EV}}{MPT_j^{EV}/N_{WD,j}} \tag{1}$$

where, j is an iterator for the number of EVs assigned to the building and operating in Extended Support session type, $UCAP_j^{EV}$ is the average useable capacity of an EV in kW, STR_j^{EV} is the average starting range of the EV in % (typically at the beginning of a workday), MDR is the minimum driving range in %, CAP_j^{EV} is the capacity of the EV battery in kWh, MPT is the monthly minimum plug in time in hours, and $N_{WD,j}$ is the average number of workdays the EV is parked at the building per month. From (1), the building owner can obtain the DR bid as follows:

$$DR_i^{BID} = \sum_{j=1}^{N_{EV}} UCAP_{i,j}^{EV} + \sum_{k=1}^{N_{DER}} UCAP_{i,k}^{DER} \tag{2}$$

where, DR_i^{BID} is the cumulative DR bid, in kW, entered by the building owner into the DR market for market interval i, N_{EV} is the number of EVs, k is an iterator for the number of on-site DERs, N_{DER} is the total number of DERs, and $UCAP_{i,k}^{DER}$ is the useable capacity of the aforementioned DERs. It is worthwhile to note that the useable capacity of each DER is a function of each unique type of DER and its constraints, whether energy storage, intermittent renewable, or distributed generator. More information in this regard can be found in [29].

Building owners are subject to non-performance charges if the DR capacity is not delivered during DR events, where two important charges are the dispatch charge, and the capacity charge [30]. The dispatch charge states that the resources providing DR capacity must stay within a percentage tolerance of their set-point for each five-minute interval during a DR event, which can be formulated in our scenario as the following constraint:

$$(1-\alpha)DR_i^{BID} \leq P_i^{AGG} \leq (1+\alpha)DR_i^{BID} \tag{3}$$

where $P_{AGG,i}$ is the average aggregate power generated by the building owner, in kW, during interval i, and α is a percentage tolerance that is between 0 and 1. On the other hand, the capacity charge ensures that the committed DR capacity actually reduces the load of the building, and thus is a function of the hourly baseline load of the building [30]. The constraint for the capacity charge can be realized as follows:

$$BL_i - CON_i \leq \epsilon * DR_{BID,i} - SCH_i \tag{4}$$

where BL_i is the average baseline load of the building during interval i in kWh, CON is the averaged measured consumption of the building during interval i in kWh, ϵ is the percentage tolerance for the for the capacity charge between 0 and 1, and SCH is a scheduled real-time constraint signal issued by the IESO, in kW.

For the building owner to avoid capacity and dispatch charges, the building owner would need to dispatch the EVs and on-site DERs according to control rules that satisfy the aforementioned constraints for every market interval. This begins with the calculation of the target aggregate dispatch setpoint (P_i^{TAR}):

$$P_i^{TAR} = DR_i^{BID} - (BL_i - CON_i - SCH_i) \tag{5}$$

The building owner may then attempt to meet the target setpoint by dispatching all EVs operating in Extended Support mode as follows:

$$SP_{i,j}^{EV} = \frac{(CR_{i,j}^{EV} - MDR_{i,j}^{EV}) * CAP_{i,j}^{EV}}{L_{DR}} \tag{6}$$

where $SP_{i,j}^{EV}$ is the setpoint for every EV during each interval i, CR is the current range, in %, and L_{DR} is the length of the DR event remaining in hours. If the sum of the available EV capacity ($SP_{i,j}^{EV}$) is less than the target aggregate dispatch setpoint, other DERs will have to be dispatched to make up the difference.

After the DR event is complete, the building owner may validate the performance of every connected EV operating in Extended Support mode using similar logic to the dispatch charge that the PSO uses to evaluate the building owner, which can be formulated as follows:

$$(1-\alpha)SP_{i,j}^{EV} \leq P_{i,j}^{EV} \leq (1+\alpha)SP_{i,j}^{EV} \tag{7}$$

where $P_{i,j}^{EV}$ is the average measured power from each EV at each interval, in kW. If the measured power from each EV violates this constraint, the building owner may levy a penalty on the EV owner by forfeiting all expected revenue during the EV session (capacity payment and energy payment).

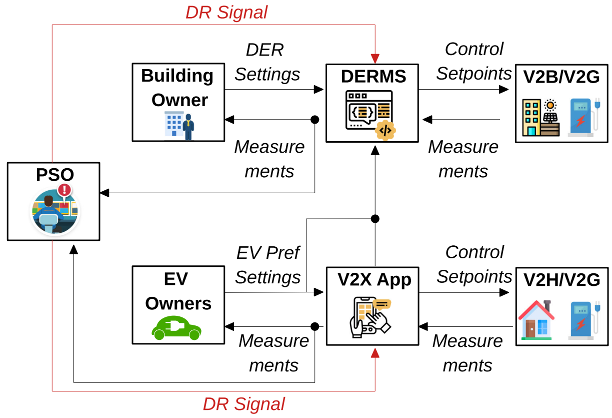

FIGURE 6. Block diagram of implemented V2X program.

IV. IMPLEMENTATION OF PROPOSED V2X PROGRAM

This section discusses the implementation of the proposed V2X program in context of the EV session types and integration with DR event handling discussed in the previous section, supported by a block diagram that shows the participants and dataflow in Figure 6. Central to the V2X program is a V2X application, referred to as the V2X App, which acts as the main interface between an EV owner and all other transaction participants. EV owners utilize this app to configure preferences, including session type and session configuration, and view measurements of their session in real-time. When at home, the V2X app interfaces directly with the bidirectional charger and dispatches the EV with control setpoints according to the EV session configuration, while receiving measurements from the charger and transmitting them back to the EV owner. The measurements provide details on the current battery level of the EV, setpoint (charging or discharging), electricity price, and approximate time left in the session. A PSO is able to signal a DR event by sending a notification to the V2X app, which, in turn, requests the EV owner to remain plugged into the charger for the duration of the event. Depending on the response and the session configuration, the V2X app will adjust the control setpoints to begin discharging the EV appropriately.

On the other hand, for building owners hosting bidirectional chargers and on-site DERs, a DER management system (DERMS) is used for all DER control and coordination. An EV owner still utilizes the V2X app to configure preferences and session settings, however, these settings are transmitted to the DERMS, which in turn, carries out the local control appropriately. During a DR event, the PSO can send the DR signal to the building DERMS, which will then dispatch all EVs in Extended Support mode and on-site DERs as per the methodology discussed in the previous section.

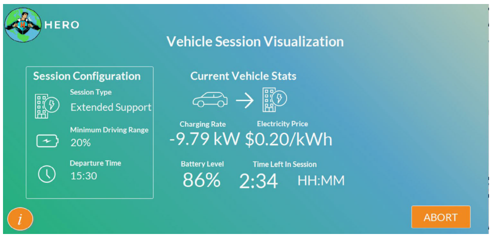

FIGURE 7. EV session visualization for grid support.

FIGURE 8. Photo of commercial building with BESS (left), solar (top), and Nissan Leaf with bi-directional charger (right).

The V2X app is implemented as both a remote mobile/web application, as well as a standalone application on a tablet that is meant to be hosted locally, near the charging station. An example screenshot from the V2X app is seen in Figure 7, where the EV is currently operating in Extended Support mode, with a configured MDR of 20% and departure time of 15:30. Real-time values from the bi-directional charger can also be seen on the screen, with the EV discharging at nearly 10 kW, earning revenue at $0.20/kWh, currently at a battery level of 86%, and with 2 hours and 34 minutes left until the session is complete.

V. RESULTS

This section discusses the results of two case studies that demonstrate the proposed V2X program operating across all three session types. The first case study demonstrates arbitrage in using a combination of Charge My EV and Quick Support, while the second case study demonstrates the provision of DR using the EV in Extended Support mode in aggregation with solar and battery energy storage system (BESS). In the first case study, the EV is charged at a residential building using standard Level 2 AC charging (maximum of 6.6 kW), and is discharged at a commercial building using a Level 3 DC bidirectional EV charger (maximum of 30 kW, but derated to 10 kW due to building constraints). The EV used is a Nissan Leaf 2019 SV with a battery capacity of 40 kWh, while the bidirectional EV charger is manufactured by Coritech. The impact of the DC Level 3 charger enables far more power to be discharged from the EV, as compared to

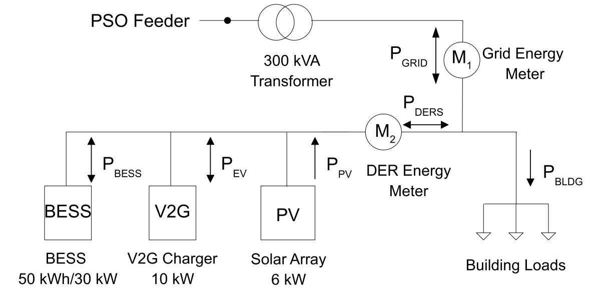

FIGURE 9. Single line diagram of building under test.

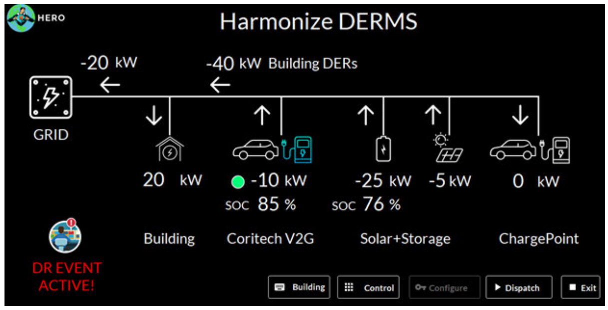

FIGURE 10. Snapshot of Hero DERMS dispatching DERs during DR event.

the standard AC Level 2 power transfer of the Nissan Leaf at 6.6 kW [31]. For the second case study, the experiments are conducted at the same commercial building, which additionally has a 6 kW solar array and 50 kWh BESS manufactured by TROES Corp, as seen in Figure 8.

A single line diagram of the commercial building is shown in Figure 9, where in addition to the aforementioned DERs, two smart energy meters are deployed. The energy meters are manufactured by Acuvim, with the model number being Acuvim-II, which is revenue-grade and samples measurements less than every 20 milliseconds. One meter is deployed at the building's point of interconnection to the PSO-administered grid to measure the net power flow, while one meter is deployed in front of all building DERs to measure the DER net power flow. This way, the true building load can be calculated by subtracting these two measurements from each other.

The DERMS platform used to control the building's DERs is entitled Harmonize, developed by Hero Energy and Engineering, which interacts with the DERs and energy meters using the Modbus protocol, as seen in Figure 10. The DERMS also listens for simulated DR Event signals from the PSO, which defines the event start time, end time, and values for the load that the building is expected to reduce based on its DR bid.

A. CASE STUDY 1: ARBITRAGE USING HOME CHARGING AND V2B

In Ontario, residential electricity prices follow a time-of-use based schedule, with the summer off-peak periods being from 19:00 to 7:00 at 8.2c/kWh, the mid-peak periods being from

TABLE 2. Energy, emissions and cost metrics for arbitrage test.

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	31.6	-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	12.98	25.61
Net	**7.7**		**3.62**		**12.63**	

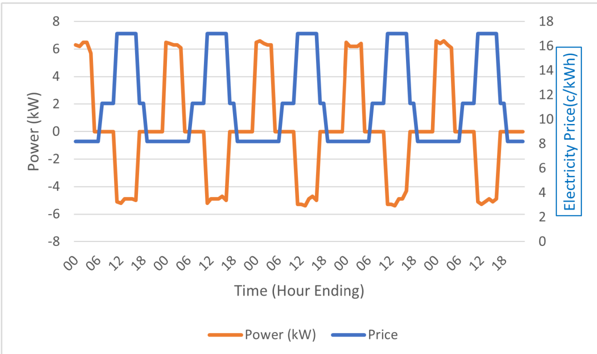

FIGURE 11. Power vs price in V2B arbitrage test.

FIGURE 12. Power vs emissions in V2B arbitrage test.

7:00-11:00 and 17:00-19:00 at 11.3c/kWh, and the on-peak periods being from 11:00-17:00 at 7.0c/kWh. Correspondingly, the emission factor of the Ontario grid is significantly higher during the on-peak periods, as the Ontario IESO utilizes gas-fired generators to meet the increased demand [32]. As such, this five day case study uses the Charge My EV session to charge between the off-peak hours of 00:00-5:00, and uses the Quick Support session to engage in V2B by discharging during the on-peak hours of 11:00-17:00. The results can be seen in Figures 11 and 12, which plots the EV power transfer against the electricity price ($/kWh) and hourly annual emission factor (gCO2eq/kWh) of the Ontario electricity grid [32], respectively. In both figures, it can be seen that the EV charges at approximately 6 kW when both the electricity price and emission factor are at their lowest, while on the other hand, the EV discharges at approximately 5 kW when both the electricity price and emission factor are at their highest.

The daily metrics are summarized in Table 2, where, negative entries in the table indicate energy discharged, emissions avoided, and revenue accrued. As seen in the table, over the course of 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 V2X without financial incentives attached, and 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 case study. Furthermore, the environmental advantages, especially at scale, are promising due to the ability of V2X to discharge at on-peak periods, which again aligns with the survey data as 80% of EV owners cited enhanced motivation to participate due to this very fact.

B. CASE STUDY 2: V2B AGGREGATION WITH BUILDING DERs

This case study involves validating the ability of the building to deliver contracted DR capacity of 30 kW over a 2 hour duration, with percentage tolerances for dispatch and capacity compliance set to 15% and 90%, respectively, as per [30]. The MDR for the EV is set to 20% of the battery state of charge (SOC), while the minimum and maximum SOC levels for the BESS are 5% and 95%, respectively. The DERMS follows the priority dispatch discussed in Section III-C, where first, EVs operating in Extended Mode (and engaging in V2B) are dispatched, followed by other DERs. In this scenario, the solar array is not dispatchable, so the BESS is set to dispatch the remainder of the DER target after accounting for the production of the EVs and solar array. In terms of revenue, in addition to the electricity rate during the test $0.17/kWh, the EV owner would receive an enhanced rate of $2/kWh as per [33].

The results of the test can be seen in Figures 13, 14, and 15. As shown in Figure 13, the building load stays fairly consistent throughout the test period, oscillating between 125 kW and 136 kW. The building load is also consistent with the building's baseline consumption as seen in Figure 13, which is approximately 131 kW. The DER contribution reacts accordingly, averaging 30.4 kW of load reduction during the 2 hour period, and reducing the actual consumption of the building by 60.7 kWh. The contribution of each DER can be seen in Figure 14, with solar providing between 3 and 5 kW of production, the EV providing approximately 10 kW, and the BESS making up the rest to satisfy the DR capacity. In terms of meeting dispatch compliance, the dispatch tolerance of 15% necessitates that the DER contribution during each 5 minute interval of the test must be greater than 25.5 kW, which was successfully achieved as seen in Figure 14. Meanwhile, the capacity tolerance of 90% necessitated that the average of the difference between the baseline and actual consumption throughout the event be more than 27 kW, which

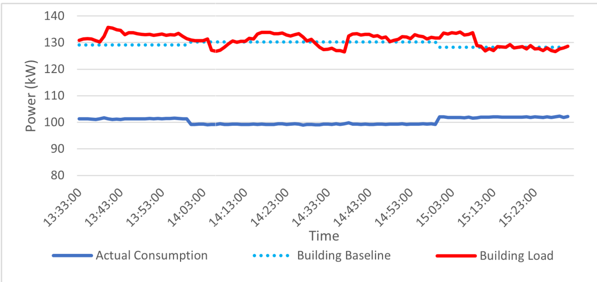

FIGURE 13. Metered values in 30kW/2HRS DR test.

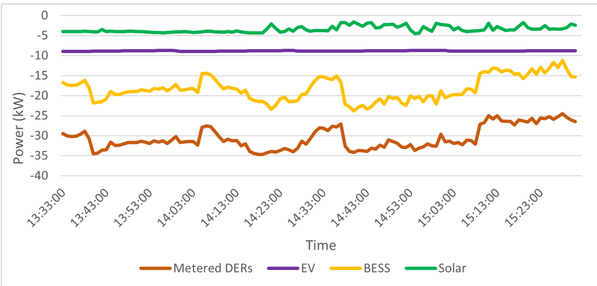

FIGURE 14. DER contribution in 30kW/2HRS DR test.

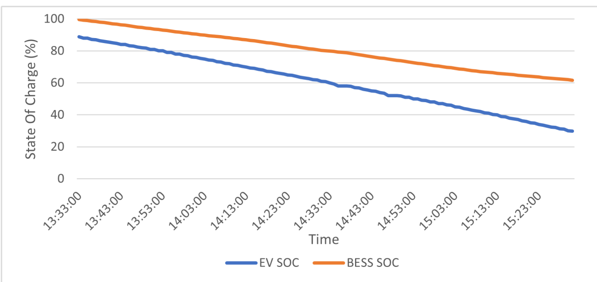

FIGURE 15. State of Charge of EV and BESS during 30 kW/2HRS DR test.

was also successfully achieved as seen in Figure 13, for an average reduction of 29.04 kW. It is worthwhile to note that the EV generated power at its maximum capacity of 10 kW throughout the test, and ended with a final SOC of 29%, which is well clear of the 20% MDR preference, as seen in Figure 15. With the EV having discharged 19.71 kWh during the event, the EV owner earns $2.17/kWh as a combination of the regular and enhanced rate, for a total of $42.8.

VI. CONCLUSION AND FUTURE WORK

This paper proposed a V2X program designed to cater to the socio-technical preferences of EV owners, while also being able to be aggregated with other DERs and participate in DR. To characterize the willingness of EV owners to participate in V2X, a survey was designed and delivered to elicit preferences with respect to MDR, environmental benefits, and economic reward. Two different types of programs were proposed in the survey, with a no contract option and a fixed contract option, and from the results of 124 respondents, both programs received a significant amount of interest for participation. Using the survey results, the V2X program was outfitted with three different EV Session types, enabling an EV owner to arbitrage at their convenience, or fix a contract with their PSO and building owner to provide DR with a MPT and MDR. The Extended Support EV session type was further aligned with the market rules for Ontario's existing DR program, with added consideration for aggregation with other DERs. All three EV session types were validated at real-world residential and commercial buildings, demonstrating the ability of the V2X program to deliver a 3.6 kg reduction of GHG emissions, EV owner revenue while arbitraging, and participating in a DR event in concert with other DERs.

While the proposed V2X program can be generalized to other regions and countries due to its flexibility in offering multiple EV session types that facilitate vehicle-grid integration from home or public charging infrastructure, recommendations for future work revolve around the financial feasibility of the program as it relates to electricity pricing. Different regions of the world have different pricing types, whether fixed, location-dependent, time-dependent, or both [34]. With evidence from experimental results in this paper suggesting that EV power generation can be reliable and constant, the revenue received as a function of electricity pricing will be variable depending on the region. As such, it is recommended that future work considers a feasibility assessment for V2X within different worldwide regions to determine the revenue pool available for EV owners to access, which will eventually inform new pricing models for the uptake s of V2X.

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