FIELD TESTING AND ECONOMIC ANALYSIS OF RESIDENTIAL VEHICLE-TO-GRID DEPLOYMENT

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Abstract

The development of Electric Vehicles (EVs) has surged in recent years, positioning them as direct replacements for fossil fuel-dependent internal combustion engines. However, the rise in EVs will place considerable strain on the grid, necessitating upgrades to the transmission and distribution infrastructure. In this regard, EVs equipped with bidirectional charging can act as independent energy storage, managing energy at home during normal and emergency conditions, feeding excess energy back into the grid to reduce its strain, and potentially generating revenue for their owners.

However, the high cost of Residential Bidirectional Chargers (RBC) and the limited availability of EVs that support bidirectional charging, particularly Vehicle-to-Home/Grid (V2H/G), remain significant barriers. Despite extensive theoretical research on bidirectional charging of EVs, there is a lack of real-world testing and comprehensive techno-economic analysis to assess the feasibility of the wide deployment of these technologies in residential areas.

This thesis aims to investigate the techno-economic viability for the wide deployment of RBC throughout the following:

1. **Field Testing for RBCs**: Conducting practical evaluations of RBCs to gather empirical data on their performance, efficiency, and reliability under real-world conditions.

2. **Identification of Policy and Regulatory Barriers**: Analyzing the legislative and regulatory frameworks in Ontario to identify obstacles that hinder the deploy-

ment of RBCs, and proposing solutions to overcome these barriers.

3. **Development of a Mathematical Model**: Creating a model to perform a regional-wide cost-benefit analysis for RBC deployment programs, considering three main stakeholders: local distribution companies, EV owners, and ratepayers.

By addressing these aspects, this research will provide a comprehensive understanding of the practical and economic implications of implementing RBC technologies, paving the way for its broader adoption and integration into the energy infrastructure.

Acknowledgements

"In the name of Allah who is the most beneficient and the most merciful."
And He honors whom He wills, and He disgraces whom He wills.

This thesis, bearing my name, is a testament to the invaluable mentorship and support of my supervisor, Dr. Hany Farag. He provided me with one of the most significant opportunities of my academic life by accepting me under his guidance. Despite the challenges I faced, his unwavering support was instrumental in successfully completing this study. Under his mentorship, I have grown personally and academically, and I am deeply grateful to him for making my Master's journey smooth and comfortable.

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I want to dedicate my thesis to my Father-in-Law **KHALIL UR REHMAN KHAN** and my Mother-in-Law **MUSARRAT FATIMA**. Thank you for always treating me like your own daughter.

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Chapter 1 - Introduction

1.1 Motivation

The unavoidable fact is that global warming is increasing rapidly. It is also certain that internal combustion engines (ICEs) play a significant role in greenhouse gas emissions (GHGs) [1]. The number of vehicles is increasing annually by 56% because of its usage. However, there is a phase shift in vehicle usage. The world is moving towards Electric Vehicles (EVs) as they do not depend on combustion engines and provide the same purpose with clean energy [2]. The number of EVs has increased 35% worldwide based on the statistics of 2023 [3]. It is also worth mentioning that these EVs can provide auxiliary services like Vehicle to Everything (V2X), which allows a vehicle to communicate information from its sensors, cameras, and internal systems with other cars, surrounding pedestrians, road infrastructure, and Smart City technologies via wireless data communication [4]. V2X also interacts with the grid by transferring power between the grid and the vehicle.

Although V2X can communicate between vehicles and the grid, it has advantages and disadvantages for EV owners regarding power transfer. The V2X can act as a backup power supply in case of blackout or power outages [5] improving reliability indices such as the customer average interruption duration index (CAIDI). Technically, the most crucial benefits of V2X are the low costs for utility grid operators, high potential power capacity, and the efficiency and fast response of storage

devices. [6]. V2X technology can also be utilized during peak hours when electricity rates are high. During these times, EVs can discharge and provide power, reducing the need to draw electricity from the grid. This bidirectional power flow allows EV owners to participate in the provision of grid services and, thus, receive incentives from distribution companies [7]. Also, EV owners will significantly reduce GHG emissions, which can be beneficial globally [1].

On the other hand, the installation and purchase of bidirectional meters for homes are relatively expensive, and not all EV owners can participate without first conducting a cost-benefit analysis [8]. It is noted, however, that while the initial cost of a bidirectional charging system is high, its operational costs are relatively low. Due to its high upfront cost, there is anxiety among EV owners to participate in providing V2X services [9]. Another disadvantage for EV owners is that they must be at home, plugging in their EV, to participate in V2X systems, which can disrupt their schedules. Consequently, EV owners may only occasionally be available to meet the requirements. [10]. Moreover, the EV's battery will degrade with time due to frequent charging/ discharging and other factors. Thus, replacing the battery is quite costly [11]. Another barrier is the data privacy of EV owners, as their schedule, vehicle information, location, and other related factors will be traceable by the aggregator [12].Functions such as V2G can significantly reduce GHG emissions, but their effectiveness largely depends on the source of the charging power. To achieve meaningful reductions in GHG emissions, this power must come from renewable energy sources rather than fossil fuel-fired power plants. Therefore, for EVs to maximize their environmental benefits, they must integrate with renewable energy sources [6], [12]. Finally, social acceptance of V2X technology is essential for its widespread adoption and success. The willingness of EV owners to participate in V2X systems considering several barriers is explored in details in [9].

For distribution companies, V2X can help provide backup power in case of any power outage or maintenance upgrade and thus improving the system reliability [7]. Moreover, with the increasing number of EVs and electrification of other sectors, the electricity demand also increases. In such cases, V2X could play a pivotal role in deferring the costs of upgrading and/or expanding the electricity system infrastructure via shifting toward decentralized system [13]. This can lead to avoiding peak energy costs when the electricity demand is high [14].

On the other hand, the incentive offered to EV owners are expected to be paid by local distribution companies, which is considered as additional costs on running the local electricity system [15]. Moreover, the cost of developing a V2X program is millions of dollars. This can be a risky investment without technical cost-analysis [14]. It is also worth noting that V2G can impact the ratepayers, people who do not have EVs and/or will not participate in V2X programs. The investment that distribution companies might make for V2X can result in an increasing amount of electricity or other factors that could affect non-EV participants [16].

Despite the pros and cons of V2X for EV owners, distribution companies, and ratepayers, various research studies have been conducted on its uptake. The V2X at the residential level is called Vehicle to Home/Grid (V2H/G), in which the EV owner can perform bidirectional charging by providing power back to the residential unit [17]. It is also worth noting that not all EVs can support bidirectional charging. The onboard charger of an EV requires specific synchronization for this purpose [18]. Similar is the case with chargers; most of the chargers available in the market are unidirectional. Very few bidirectional chargers are available, while the rest are in the production phase [19].

Furthermore, the usage of EV batteries depends on various environmental and technical parameters, precisely the specifications of an EV battery for V2X [20]. It

is essential to analyze the real-world implementation, which gives a clear picture of the importance of V2G in the region and future steps for its cost-benefit calculation.

1.2 Scope

The term V2X (Vehicle to Everything) refers to communication between vehicles and infrastructure [4]. However, V2X technology can also facilitate power transfer between vehicles, homes, electrical grids, and buildings [21]. While considerable research has demonstrated the potential of V2X for power transfer, significant barriers still hinder its adoption for residential bidirectional charging.to its uptake for residential bidirectional charging. The following is a description of the key challenges hinder the widespread adoption of bidirectional charging for Electric Vehicles (EVs).

- **High Cost of Residential Bidirectional Chargers (RBC)**: One of the primary obstacles is the high cost associated with Residential Bidirectional Chargers (RBC). These chargers, which enable the two-way flow of electricity between the vehicle and the home or grid, are significantly more expensive than traditional unidirectional chargers. The advanced technology required to manage this bidirectional energy flow, ensure safety, and maintain compatibility with various EV models contributes to these higher costs. Additionally, the installation of RBCs often requires upgrades to a home's electrical system, further increasing the overall expense for consumers.

- **Limited Availability of Supporting EVs**: Another significant barrier is the limited availability of EVs that support bidirectional charging, particularly Vehicle-to-Home (V2H) and Vehicle-to-Grid (V2G) systems. While the concept of using EVs as mobile energy storage units is gaining traction, only

a few models currently on the market are equipped with the necessary technology for bidirectional charging. This limited selection constrains consumer choice and slows the adoption of these systems. Moreover, automakers face challenges in standardizing bidirectional charging capabilities across different models, which further complicates the integration process.

- **Lack of Real-World Testing**: Despite extensive theoretical research on the potential benefits and mechanisms of bidirectional charging, there is a significant gap in real-world testing. Most studies to date have been conducted in controlled environments, which do not fully capture the complexities and variabilities of actual residential and grid conditions. Real-world testing is crucial to understanding how bidirectional charging systems perform over time, under different usage patterns, and in various environmental conditions. Without this data, it is difficult to address practical issues and optimize the technology for everyday use.

- **Comprehensive Techno-Economic Analysis**: In addition to the lack of real-world testing, there is also a scarcity of comprehensive techno-economic analyses. Such analyses are essential to evaluate the overall feasibility and economic viability of wide-scale deployment of bidirectional charging technologies. They involve assessing not only the upfront costs but also the long-term benefits, potential savings, and revenue generation from feeding energy back into the grid. This includes understanding the impact on energy bills, return on investment, and the broader economic implications for both consumers and utility providers. Without a thorough techno-economic analysis, stakeholders cannot make informed decisions about investing in and promoting these technologies.

In summary, the high cost of RBCs, the limited availability of supporting EVs, the lack of real-world testing, and the absence of comprehensive techno-economic analyses are significant challenges that need to be addressed to facilitate the widespread adoption of bidirectional charging technologies in residential areas.

1.3 Assumptions

To overcome the challenges faced in the adoption of bidirectional charging for Electric Vehicles. The major assumptions are mentioned below. The detailed assumptions will be mentioned in the respective analysis.

- In a real-world demonstration of residential bidirectional charging, the electric vehicle (EV) owner was not permitted to feed energy back into the grid. The experiment was conducted three times, and the average results from these trials were used for analysis. It's important to note that all results were independent of the home's load, meaning the same experiment can be performed in other residential units.

- From a single experiment, it was determined that the feasibility of vehicle-to-grid (V2G) technology in Ontario cannot be justified. Consequently, a detailed mathematical analysis was carried out regarding the residents of Ontario. This analysis could be conducted based on factors such as region, population, and types of residential units. However, in this specific analysis, the focus was on enhancing the impact of V2G for employed individuals and business owners to increase its overall effectiveness in Ontario.

- To overcome the limited availability of supporting EVs, all the EVs that are available in the market are considered with their specifications and market

share. This assumption for all stakeholders will enhance the benefit-to-cost ratio for the next twenty years with correct parameters.

1.4 Thesis Objective

This thesis aims to contribute towards the positive uptake of V2X at the residential level. Fig. 1.1 represents the three main objective of the thesis.

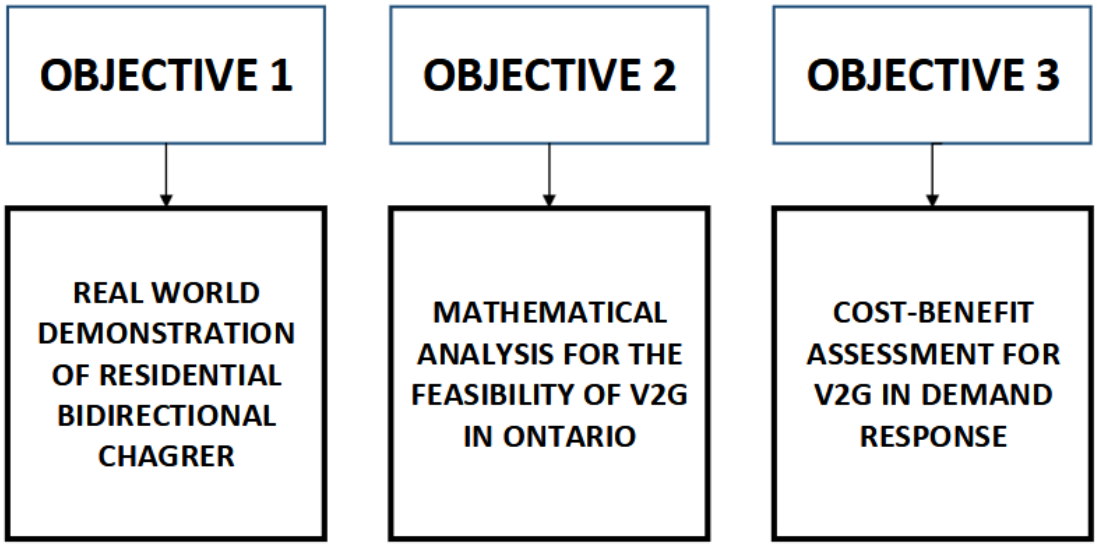


Figure 1.1: Layout of the thesis research objective

1.4.1 Objective (1): Real-World Demonstration of Residential Bidirectional Charger

It is evident that the number of EVs and chargers supporting bidirectional charging is currently limited. Consequently, there has been insufficient field testing of bidirectional charging stations at the residential level. This thesis aims to address

this gap by outlining the necessary steps, tests, and equipment required for implementing Vehicle-to-Grid (V2G) systems in a specific region. Additionally, it seeks to determine the extent to which a bidirectional charging setup can meet load demand and identify the barriers that need to be addressed in future experiments.

1.4.2 Objective (2): Mathematical Analysis for the Feasibility of V2G in Ontario

The second objective of this thesis centers on the mathematical analysis explaining the feasibility of V2G. Ontario, the most populated province in Canada, faces rising electricity demand and the challenges of global warming. [22]. Thus, it is essential to analyze the feasibility of V2G systems in Ontario. This analysis will help identify the necessary steps for implementing a bidirectional charging infrastructure in the province.

1.4.3 Objective (3): Cost-Benefit Assessment for V2G in Demand Response

The final objective of this thesis is to conduct a comprehensive cost-benefit assessment of Vehicle-to-Grid (V2G) participation at the residential level, considering all stakeholders involved. This analysis evaluates the technical parameters of residential V2G over a twenty-year period. By normalizing the costs for all stakeholders, the study aims to demonstrate the economic viability and encourage the positive adoption of V2G systems at the residential level.

1.5 Thesis Layout

The remainder of this thesis is organized as follows:

- **Chapter 2:** Gives a brief background of the terms used in this thesis. It also explains the policies and the rates that the government has regarding renewable and independent sources of energy.
- **Chapter 3:** Presents the literature survey on the topics related to the thesis. Then, it outlines the research gaps based on the survey and how it can be implemented on the thesis
- **Chapter 4:** Presents the field testing of the residential bidirectional charging system. Moreover, the steps involved in installing bidirectional charging stations at home.
- **Chapter 5:** Introduced the mathematical analysis neede for the feasibility studies of V2G in Ontario alongwith some recommendations for its positive uptake.
- **Chapter 6:** Presents the cost-benefit assessment of residential V2G participating in Demand Response. This chapter analyzes all the costs and expenses related to the stakeholders involved in Residential V2G.
- **Chapter 7:** This is dedicated to the conclusion and future recommendations needed to expand the work on this thesis further.

Chapter 2 - Background

This chapter provides the background of the terms, policies, and rates used in the thesis. The chapter is organized as follows: section 2.1 gives an overview about the Vehicle-to-Grid (VGI) interaction, section 2.2 presents in details the forms of VGI, while section 2.3 discusses the DER interconnection process in Ontario. Section 2.4 explains the types of electricity rates and finally, section 2.6 and 2.7 list all the EV chargers and EVs available in today's market with bidirectional capabilities.

2.1 Vehicle To Grid Interaction (VGI)

VGI is a dynamic process involving energy exchange between EV owners and an electric power grid. In this system, the EV battery acts as a flexible energy source, aiding in the balance of power flow within the grid [1]. VGI encompasses both unidirectional smart charging, where EVs reduce their charging power during peak electricity demand [2], and bidirectional charging, where EVs can generate power of their own [3]. The provision of VGI is beneficial for both power system operators (PSOs) and EV owners. EV owners can derive additional value from their EV battery. At the same time, it is parked, and PSOs gain an alternative resource to enhance the resiliency and sustainability of the power system [23].

The main actors and components of bidirectional EV charging are shown in Fig. 2.1. These are described as follows:

2.1.1 EV owner

The individual operating the EV and the primary decision maker regarding participation in VGI [24].

2.1.2 Power System

The physical system responsible for generating, transmitting, and distributing electricity to customers is operated by Public Service Organizations (PSOs), who seek to maintain the balance between electricity demand and supply in real-time and ensure that peak demand does not exceed system capacity [25]. Notably, this thesis focuses on electrical distribution systems, and henceforth, the term PSO will refer to distribution system operators [26].

2.1.3 PSO Meter

The PSOs use an energy meter to measure their customers' net energy consumption and calculate the final bill, including any credits/incentives due to VGI [27].

2.1.4 Charging Station

The device EV owners use to recharge their EVs, also known as electric vehicle supply equipment (EVSE). These may be found in municipal parking lots, retail shopping centers, or EV owners' homes, among other locations [28].

2.1.5 Aggregator

The aggregators are organizations that serve as intermediaries between electric vehicle (EV) owners and the grid. These aggregators receive control signals from

PSOs to gather information when vehicle-to-grid interaction (VGI) is required from EVs. This typically happens when there is high electrical demand that needs to be reduced [29]. The aggregator then either directly controls the EVs or asks the owners to follow the control request from the PSOs. In return, the EV owners receive a share of incentives, which serves as data for VGI [30].

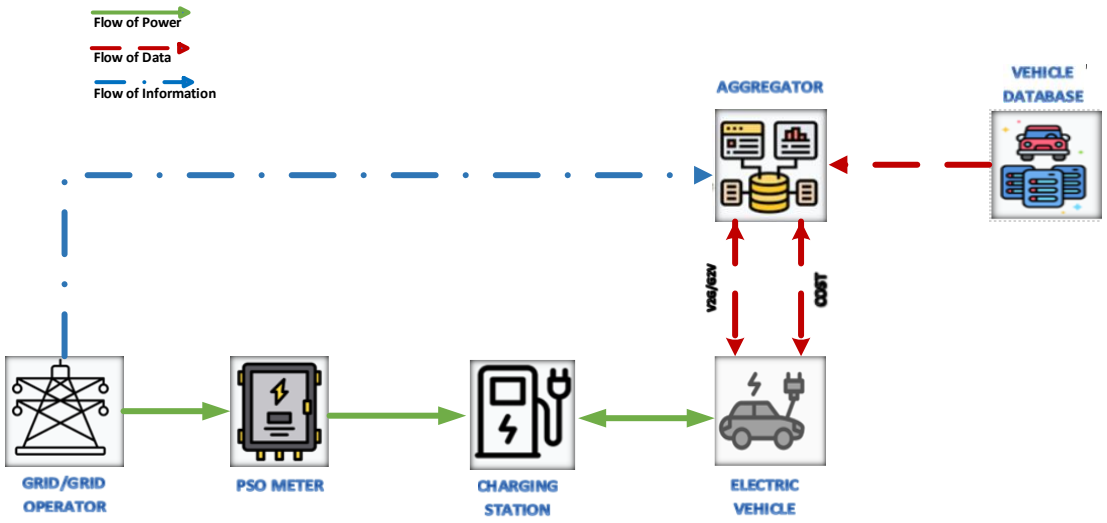


Figure 2.1: Main actors and components of VGI

2.2 Forms of Bidirectional Charging within VGI

A common term to describe bidirectional EV charging is Vehicle to Everything (V2X), where the "X" signifies the ability of the EV to supply power to directly connected loads, homes, or buildings, as well as the upstream power system [31]. The EV can generate power via an inverter, which converts the battery's direct current (DC) energy into alternating current (AC) energy to satisfy electrical demand [4]. The V2X can be further divided into four categories in terms of power, as shown in Fig. 2.2 and they are described in further details below.

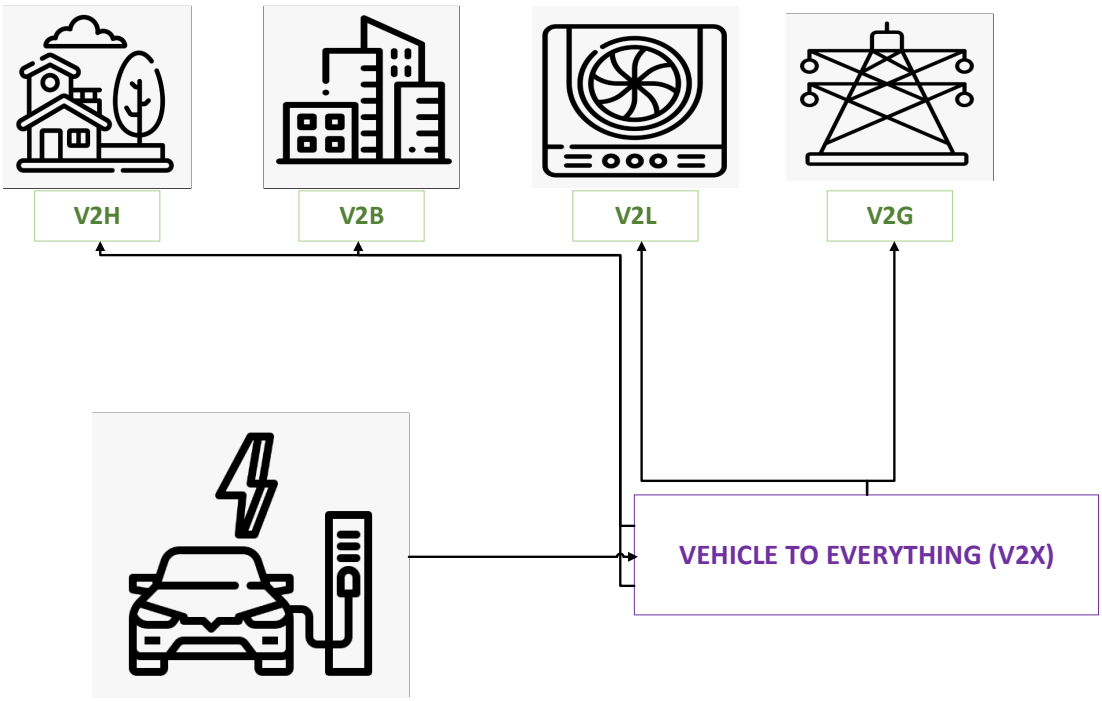


Figure 2.2: Vehicle to everything (V2X) types

2.2.1 V2L (Vehicle to Load)

The capability of an EV to supply AC power to directly connected loads. In some cases, an external inverter connects the load; however, more commonly, EVs are manufactured with bidirectional inverters inside the vehicle and 120/240V AC outlets are exposed from the vehicle body [17]. It is worth mentioning that EVs can directly charge other EVs in this way [32].

2.2.2 V2H (Vehicle to Home)

V2H is the ability of EVs to supply power to residential units, as shown in Fig. 2.3. Currently, V2H most commonly uses an external DC charging station with bidirectional capability. DC charging stations, or Level 3 charging stations, convert the

DC energy to AC energy by coupling with an inverter and housing a bidirectional charger. In North America, at the residential level, the grid supplies AC power of 240 V to the home, which interfaces with the bidirectional charging consisting of two converters: an AC-to-DC converter and a DC-to-DC converter [33], which converts AC voltage to the required DC voltage for the EV. Two additional devices are helpful but not mandatory in V2H operation. A transfer switch can isolate the home and charger if there is a power outage on the primary grid, while an energy meter measuring the net power consumption of the house can enable the EV to supply power to the home without exporting excess power to the grid [9].

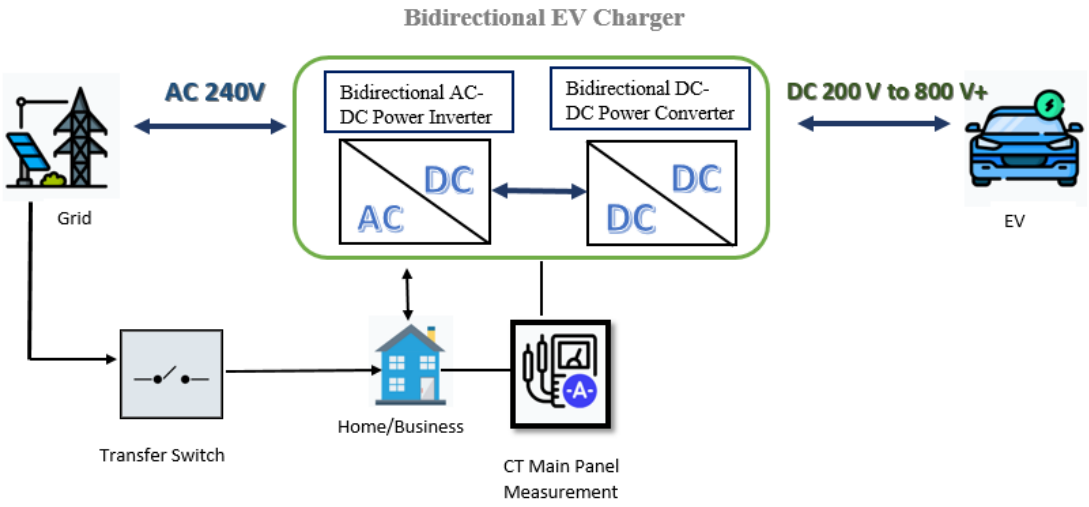


Figure 2.3: Components of bidirectional EV Charging

2.2.3 V2B (Vehicle to Building)

Similar to V2H, the EV supplies power to the building, mostly during peak demand [34]. In some cases, the power from EVs can be routed to a specific, critical sub-panel to keep essential loads alive, such as the internet or other universal power

supplies (UPS) [35].

2.2.4 V2G (Vehicle to Grid)

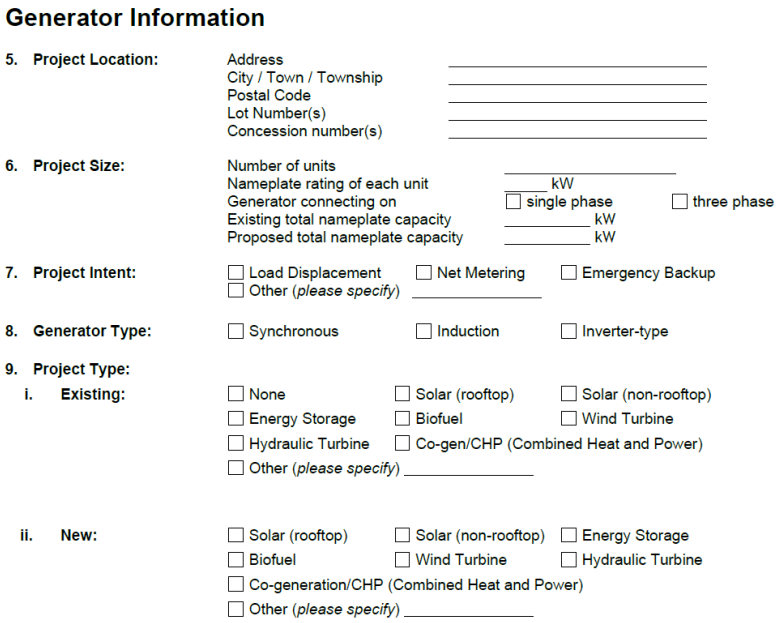
During V2G, an EV battery is discharged, and excess power is exported to the power grid [36]. V2G can also refer to the provision of ancillary services, such as voltage and frequency regulation.

2.3 Typical Interconnection Process for DERs

The interconnection process varies according to generation, capacity, and usage types [37]. The customers, utilities, and DER owners are not always on the same page. Therefore, some standards must be followed for DER installation [38].

There are various standards available in the world. However, the Institute of Electrical and Electronics Engineers (IEEE) standard 1547 has offered a foundation and unique document for the interconnection process of DERs [38]. IEEE 1547-2018 standard provided a uniform copy for the interconnection of DERs whose frequency is 60 Hz with electrical power systems while considering the performance, operations, testing, safety, and maintenance considerations [39]. According to this standard, the generation is divided into the following categories:

- Micro-generation: Power $\leq$ 10 kW
- Small generation: 10 kW $\leq$ Power $\leq$ 500kW
- Mid-sized generation: 500 kW $\leq$ Power $\leq$ 10MW
- Large generation: Power $\geq$ 10 MW



Generator Information

5. Project Location:
Address _____
City / Town / Township _____
Postal Code _____
Lot Number(s) _____
Concession number(s) _____

6. Project Size:
Number of units _____
Nameplate rating of each unit _____ kW
Generator connecting on ☐ single phase ☐ three phase
Existing total nameplate capacity _____ kW
Proposed total nameplate capacity _____ kW

7. Project Intent:
☐ Load Displacement ☐ Net Metering ☐ Emergency Backup
☐ Other (*please specify*) _____

8. Generator Type:
☐ Synchronous ☐ Induction ☐ Inverter-type

9. Project Type:

i. Existing:
☐ None ☐ Solar (rooftop) ☐ Solar (non-rooftop)
☐ Energy Storage ☐ Biofuel ☐ Wind Turbine
☐ Hydraulic Turbine ☐ Co-gen/CHP (Combined Heat and Power)
☐ Other (*please specify*) _____

ii. New:
☐ Solar (rooftop) ☐ Solar (non-rooftop) ☐ Energy Storage
☐ Biofuel ☐ Wind Turbine ☐ Hydraulic Turbine
☐ Co-generation/CHP (Combined Heat and Power)
☐ Other (*please specify*) _____

Figure 2.4: Preliminary Consultation Information Request (PCIR) Form

Here, residential units are considered where generation is less than 10 kW. The Ontario Energy Board (OEB) follows the IEEE-1547 standard for the interconnection process of DER. The OEB has given some means that all Local Distribution Companies (LDCs) in Ontario for the installation of DER [40]. LDCs usually provide a form for homeowners to specify the type of DER and other initial information for its structure as shown in Fig. 2.4. This form asks about general information: project information, which means the project's intent, project size, and its types; site information, which means the location for DER installation.

The whole DER Interconnection Process followed by OEB is shown in Fig 2.5 and the following are main actors in this process:

- Applicant
- LDCs

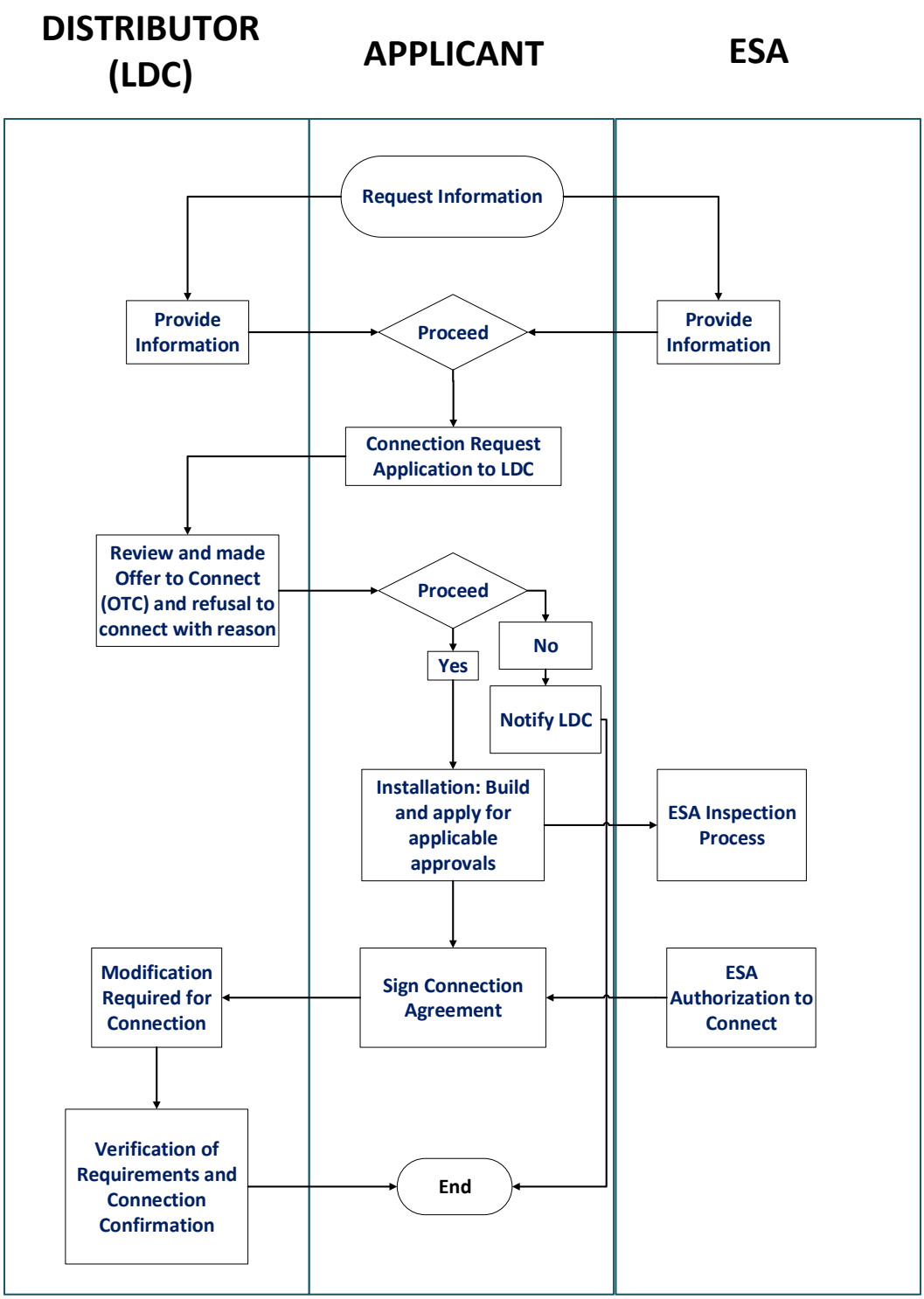


Figure 2.5: Flow Chart for the Interconnection Process of DERs in Ontario

- ESA
- Electrical Consultant
- Electrician

The step-by-step procedure for the installation of DERs in Ontario is given below:

Step 1: The applicant contacted LDCs to ask about installing a DER Connection in their home. The LDC provides the applicant a Preliminary Consultation Information Request (PCIR) [41]. In this form, LDC wants the initial information regarding the applicant's details, project information, site information, and if any other information is required.

Step 2: The applicant must also contact the Electrical Safety Authority (ESA) and provide information about installing the DER connection. They will do a safety check of all the equipment, functions, and associations according to Regulation of 22/04 [42].

Step 3: After collecting the information for the process, a project and installation plan is required. The project plan shows the detailed single-line diagram (SLD) of the unit where DER needs to be installed. The installation plan shows the project size, the purpose of its installation, and the type of DER. For this purpose, the applicant needs to hire an electrical consultant to provide all the required information.

Step 4: The customer submits these documents to their respective LDCs once all the information is collected. The LDC will review it and notify them within 15

calendar days whether to proceed with it or not. If the LDC approves the DER connection, they will offer to connect, typically including the cost, implementation timing, etc.

Step 5: Now, the applicant decides to proceed with this offer within 30 days. The applicant is responsible for monitoring the information from the ESA, distributor, and any other organization involved to prevent delays.

Step 6: If the applicant decides to proceed with this agreement, they need to build its installation with the help of an electrician. After installation, the whole setup must be sent to ESA for inspection.

Step 7: Once the ESA authorizes the agreement, the applicant can sign it and return it to LDC for further modifications.

Step 8: Last but not least is installing the whole setup by the electrician under the supervision of the applicant and the electrical consultant.

The Ontario government has given all the basic micro-generation steps, but these are for renewable energy resources; there is not any proper guidelines for independent energy sources. The number of EVs is taking an uptake, and consumers have started using EVs for V2H purposes. Below are some critical differences in generating power from independent energy sources compared to renewable energy sources.

1. Complex Program Design and impulse modeling:

   The design for a bidirectional charging system is complex, which is not high-

lighted by OEB. The bidirectional power via an EV varies from one customer to another. There is not any proper document that evaluates these complexities. Each EV owner has their own commuting time, plug-in time, and environmental factors, depending on their region and work hours. No significant and major pilot project or document motivates EV owners to adopt bidirectional charging and participate in these incentives.

2. Lacking of Battery Degradation and Warranty Cancellation Documents:

   EV battery degradation plays a significant role in bidirectional charging. It depends upon various factors like charging, discharging, driven range (km), Battery type, temperature, etc [43]. No EV Original Equipment Manufacturers (OEMs) have commented on the battery warranty when EVs are used for bidirectional charging except Nissan [44]. They also lack the requested customer incentive documentation while providing a bidirectional charging setup.

2.4 Electricity Pricing and Renewable Energy Policy

Time of Use (TOU) rates is an international perspective that is accepted globally for calculating the price of electricity [45]. TOU tariffs are the best way to meet the demand response of the electrical power systems. Many countries worldwide are taking advantage of this tariff to meet the needs of their customers while adjusting the peak demands in all seasons [46].

2.4.1 Types of Electricity Prices

By offering TOU rates, the utilities are giving control to the customers while providing variable rates and changing their rates according to the peak demand [45].

For example, in the United States, the electricity rate is high in summer due to the increased use of air conditioners. On the other hand, in Quebec, the electricity rate is high in Winter as the winter is extreme over there, and the number of running heaters will increase [47].

In Ontario, Canada, customers and small business owners can buy electricity whenever needed. They are usually categorized based on either the usage of electricity or time at which they are consuming electricity. The types of electricity rates are listed below [48].

a) **Time of Use (TOU)**: In Ontario, the electricity rates differ in summer and winter. It varies when electricity is being used. The TOU rates and times are listed below [48].

- The price during off-peak hours is 7.4 cents/kWh, and its duration is from 7 p.m. to 7 a.m. on weekdays, weekends, and all holidays in both summer and winter.

- The price during mid-peak hours is 10.2 cents/kWh, and its duration varies in summer and winter.

  1. Winter (November 1 - April 30): Weekdays are from 11 a.m. to 5 p.m..

  2. Summer (May 1 - October 31): the duration is 7 a.m. to 11 a.m. and 5 p.m. to 7 p.m. on weekdays.

- Lastly, the price during on-peak hours is 15.1 cents/kWh; its duration varies in summer and winter.

  1. Winter (November 1 - April 30): 7 a.m. to 11 a.m. and 5 p.m. to 7 p.m. on weekdays.

  2. Summer (May 1 - October 31): Weekdays are from 11 a.m. to 5 p.m..

b) **Ultra-Low Overnight (ULO) Rates**: The Ontario government is taking steps to reduce greenhouse gas emissions [49]. That's why they have introduced the new "ultra-low" overnight pricing plan encouraging EVs to charge with relatively inexpensive, clean electricity [50]. The ULO Rates are mentioned below [48].

- The ULO rate is 2.4 cents/kWh, and it's every day from 11 p.m. to 7 a.m.
- The off-peak rate is during weekends from 7 a.m. to 11 p.m.
- While mid-peak rate is 10.2 cents/kWh and its during weekdays from 7 a.m. to 4 p.m. and 9 p.m. to 11 p.m.
- On the other hand, the on-peak rate is 24 cents/kWh and its during weekdays from 4 p.m. to 9 p.m.

2.5 Net Metering

Net Metering is a policy introduced by the Congress Energy Policy Act 2005. The primary reason for this policy is to give prosumer (an individual who produces and consumes electricity) incentives by using net metering [51]. By using this policy, the customer can feed power back to the grid, which is now accepted by 70 countries worldwide [52].

In Ontario, OEB introduced a net metering rule for customers with renewable energy source power generation, such as solar installed at home. These customers are providing power back to the grid and receiving incentives from the government for this electricity [40]. The payment is calculated based on renewable energy credits (RECs), which can be carried for up to 12 months. They can start using the credit after the 8th month of the 12-period cycle, which will affect their bill, as the RECs can't be used after 12 months ends [53].

2.6 Electric Vehicle Chargers

The electric vehicle supply equipment (EVSE) plays a vital role in Vehicle Grid [54]. Many EVSEs are available in the market, but not all can provide bidirectional capabilities. The onboard charger on the EVSE must be capable of providing bidirectional charging, which requires synchronization with the grid [55]. The electric vehicle charging systems available in the market are listed below:

Table 2.1: Bidirectional EV chargers with their specifications

Name	**Charger Output Power**	**Efficiency**	**Cost**	**Warranty**
Enphase's	8 kW	98%	$13,000	Five years
GM Energy	24 kW	97%	$10,000	Three years
Wallbox Quasar 2	11.5 kW	97%	$6,000	Two years
Ford Charging Station Pro	11.3kW	98%	$12,878	Three years
Sigenergy SigenStor	12.5 kW or 25 kW	98.3%	$8,000	Ten years

Table 2.1 lists all the available bidirectional chargers released in 2024. Their price range is from $6,000 to $13,000. If the charger is low-priced, the warranty is for fewer years.

2.7 Electric Vehicles

Numerous EVs are available in the market, but not all can provide bidirectional charging capabilities. Like charging stations, EVs have onboard chargers, which

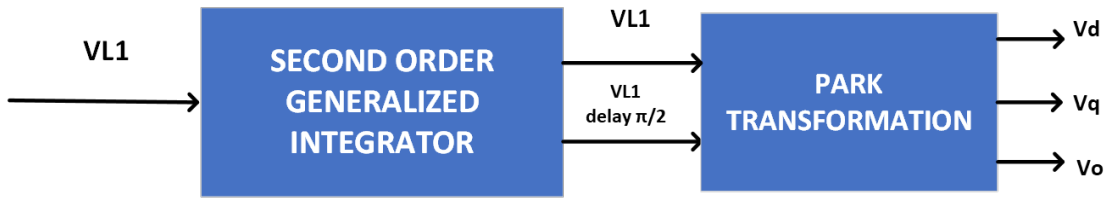


Figure 2.6: The basic configuration of an onboard charger for an EV for V2L

must be capable of bidirectional charging [56]. This bidirectional charging capability in EVs is of two types:

1. The EVs that can do bidirectional charging but only V2L because of the unavailability of synchronization with the grid [57]. As shown in Fig. 2.6 The line voltage is integrated into the alpha-beta frame, followed by the park's transformation. To convert the sinusoidal signal into DC components. The mentioned diagram is the basic configuration; there are some control mechanisms also involved after this conversion [58].

2. Conversely, the EVs that can participate in V2G have onboard chargers with synchronization configurations. As shown in Fig. 2.7 the line voltage is phase-locked by a PLL for synchronization with the grid voltage. Then, it is converted into the dq0 frame. Furthermore, a PQ controller is also installed for V2G to maintain the active and reactive power [58].

Table 2.2 This shows all the EVs available for bidirectional charging. It is worth noting that only a couple of EVs, the Ford F-150 Lightning, and Nissan Leaf, are available for V2G/V2H purposes, which can negatively impact the deployment of V2G/V2H.

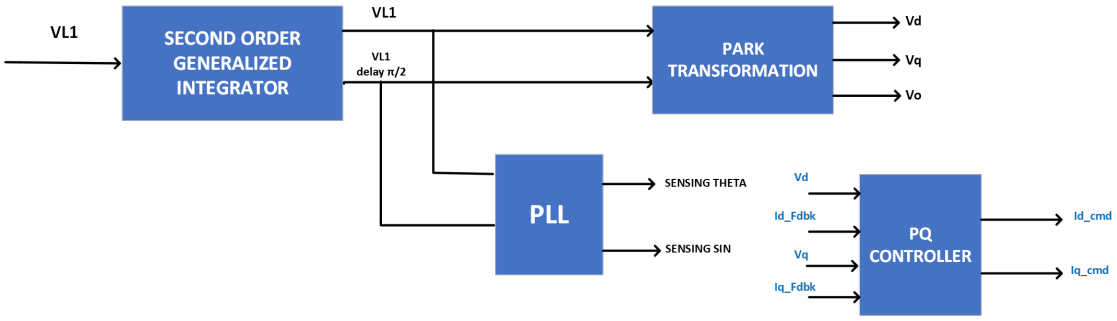


Figure 2.7: Basic configuration for the onboard charger of an EV for V2G

Table 2.2: Electric Vehicles Available with Bidirectional Capabilities

Electric Vehicles (EVs)	**V2X Capability**	**PHEV or BEV**	**Battery Capacity (kWh)**
Ford F-150 Lightning	V2G	BEV	98
Genesis GV60	V2L	BEV	77.4
Hyundai Ioniq 6	V2L	BEV	77.4
Kia EV6	V2L	BEV	77.4
Kia Niro	V2L	PHEV	64.8
Mitsubishi Outlander	V2L	PHEV	16.1
Nissan Leaf	V2H, V2G	BEV	40
Kia EV9	V2H, V2G	BEV	98

Chapter 3 - Literature Survey

This chapter includes a brief overview of the current state of V2G applications and the research conducted on policies and cost-benefit assessments. V2G has various applications, but this thesis primarily focuses on peak shaving and demand response. Substantial research has been conducted in these areas, which is discussed in section 3.1. Section 3.2 covers studies analyzing the impact of V2G in reducing greenhouse gas emissions, while section 3.3 discusses field tests conducted to analyze V2G. Section 3.4 encompasses all the research related to bidirectional charging policies. On the other hand, section 3.5 presents all the research on the economic analysis of V2G. Finally, section 3.6 addresses the research gaps in the aforementioned works and the thesis's contribution.

3.1 Applications of V2G in Power Systems

V2G has various applications. But, in this section, only peak shaving and demand response will be discussed, along with the kind of work that has been published related to those applications in the past. Moreover, the work that has been done is related to V2G policies, bidirectional chargers, and the cost-benefit assessment for V2G.

3.1.1 Peak Shaving

Peak shaving, a crucial aspect of managing a power system's peak demand, is the focus of our discussion. Its significance lies in maintaining grid stability and its potential impact on power procurement costs [59]. In many jurisdictions, consumer electricity prices are set based on their maximum peak demand, making understanding peak shaving strategies a practical necessity. This is because system capacity planning must accommodate the peak load, and any increase in peak load would generally require expensive and time-consuming upgrades [60].

3.1.1.1 How Peak Shaving Can be Reduced Using V2G/V2H

In [61], EVs are utilized for peak shaving by V2G application. It is concluded that EVs are idle 90% of the time. As such, there is potential to use EVs for demand response as electricity demand continues to increase over time. While in [62] the authors mentioned that EVs can be used for peak shaving, but the availability of the EVs at the right place and time is one of the primary factors for using EVs for V2G purposes. The authors in [63] have designed and simulated a control algorithm for peak shaving using V2G. They considered the EV parking schedule as a constraint of a specific parking lot on a short, modified-short, and long-term basis. The paper concluded that EVs designated on a long-term basis could reduce peak demands by 20% more than those on a short and modified-short term basis. Nevertheless, the papers [61], [62] and [63] have discussed in detail that EVs can be used for peak shaving applications on both long and short-term basis. However, various algorithms and controls are involved in its implementation, which are not mentioned in the work.

Therefore, [64] and [65] discussed the operation and the region where peak shav-

ing can be applied for V2G. Reference [64] developed a centralized, decentralized, user-oriented V2G scheme with multiple operation modes in Shenzhen, China. A hierarchical control structure for the V2G operation mode was developed to make the operation more effective based on Time of Use (TOU). The paper concludes that using the suggested strategy reduces peak demand by 5.89% for the modest case. In [65], V2G is used for peak shaving to unlock the integration of distributed heat pumps in Swedish neighborhoods. The objective was to shave the peak caused by heat pumps while enabling bi-directional flow. The paper concludes that the proposed solution can eliminate overloading up to 50% with 100% EV penetration.

The papers [66] - [67] discussed the algorithms and control of power that are involved in peak shaving. Paper [66] discussed Dynamic Economic/Emission Dispatch (DEED), which consideres battery degradation cost and usage of power flow constraints. The study analyzed the potential of peak shaving and valley filling using PEVs, considering the impact caused by V2G/ G2V. The simulation results were promising, indicating that using PEVs provides an innovative method for increasing peak load, leading to emission reduction and savings on peak load plants. While the authors in [68] proposed a Multi-agent Reinforcement Learning (MARL) mechanism that schedules the day-ahead EV battery discharging process to optimize the electric grid's peak shaving performance. The agents were trained centrally to flatten the peak load curve for the future Intelligent Transportation System (ITS). Moreover, in [69] a multi-objective optimization task was implemented to reduce peak shaving using the V2G service. A modified Dijkstra algorithm was formulated to implement this on a DC microgrid with distributed generators. For a 24-hour simulation, 4.4% and 13.9% of system losses were reduced in commercial and residential scenarios, respectively. The authors in [70], compared the users' expected and actual parking times. A multi-objective function is formed and solved

by the modified Quantum Particle Swarm Optimization (QPSO) Algorithm. This will predict the load demand and simulation results have shown that this can reduce the peak valley difference and the load demand curve. In [67] the authors have combined the alternating direction method of multipliers (ADMM) and distribution line power flow models (DistFlow). It consists of a single loop, three-layer hierarchal framework with three components. The proposed method on the IEEE-13 bus model reduced the cost and controlled the peak shaving and voltage regulation.

It is worth noting that [66] - [67] have tremendously contributed to the applications, control, and algorithm of V2G when applied to peak shaving. However, a few factors of EVs are degrading over time while using EVs for V2G applications, such as battery degradation. Battery degradation is one of the primary factors in EVs. Specifically, when EVs are used for power system applications, there is a high probability that their battery will degrade over time. Due to this, the authors in [71] have developed an optimization model that provides an economical and efficient scheme for quantifying vehicle life loss and Battery Energy Storage Systems (BESS). The performance is validated on a V2G simulation system for peak shaving and a plug-in hybrid electric vehicle (PHEV). An integrated battery life loss modeling and anti-aging energy management (IBLEM) method was compared to other conventional methods like the Energy Management System (EMS) and Model Predictive Control (MPC). It is observed that IBLEM can improve the economy by 20.2% and 4.7% as compared to EMS and MPC, respectively. Meanwhile, the authors [72] have developed a two-stage BESS aging quantification and health-aware battery energy management method for reducing vehicle battery aging costs. A case study is done in an aggregated EV peak-shaving scenario using a PHEV with an engine-battery hybrid powertrain to demonstrate the developed method's effectiveness in reducing 16.9% of battery aging costs and improving the total vehicle

economy. In [73] EV is utilized in V2G and G2V modes of operation for 24 hours. The article proposes a smart charging model for EVs, estimates the off-load and peak load times over a while, and allocates charging and discharging based on the state of charge (SoC), power, and intermittent load demand constraints. A standardized IEEE 33-node DS integrated with an EV charging station (EVCS) and DGs is used to reduce the losses and improve the voltage profile of the proposed system.

3.1.1.2 How Peak Shaving Can be Reduced Using V2B

Peak shaving can be applied on commercial buildings, too. Like in [74], the authors have developed a machine learning model for a scheduled EV parking lot with minimum State of Charge (SOC) values to shave the peak during peak hours. While the authors in [75] have developed an optimization problem based on the different driving scenarios of EV users but with a fixed range of SOC. The authors in [74] and [75] were able to reduce the peak by 36% and 10%, respectively.

3.1.2 Demand Response

Demand response refers to the adjustment of energy consumption in order to meet specific objectives of the electrical grid. This could involve reducing the overall system load in case of a power plant failure, preventing high marginal prices, or easing the burden on a nearby distribution transformer [76]. Numerous studies and projects have explored the concept of demand response, which will be discussed further below.

The demand response is one of the important applications in power system applications. Meeting the grid demand is crucial and depends on various factors, such as the demand time and how the service provider will pay the price to a specific

EV owner. Therefore, the authors in [77] have created a robust model by utilizing available EVs in the market for demand response applications for V2G. While, the authors in [78] have proposed a mixed integer linear programming model for a residential house with shiftable and non-shiftable loads with EV. The simulation has shown how EVs can be used for V2H by utilizing the EVs in demand response. The authors in [79] have applied demand response to reduce the loads in on-peak time duration or shift them to off-peak times. The microgrid is optimized regarding EV scheduling and demand response program to obtain a 14.67% cost profile reduction compared to no optimization. While the authors in [80] have proposed a demand response strategy for charging/discharging EVs with V2G and V2H functionalities. They developed a Q-learning from the Reinforcement learning technique, and based on their simulation, grid demands were reduced by 23% in the morning and 15% in the evening.

It is also worth noting that the pricing scheme for applying demand response plays a significant role in its participation. Thus, the authors in [81] have considered the aggregators of EVs participating in demand response and other balancing services to prepare a pricing strategy for V2G participation. They have used the Stackleburg game theory with multiple entities for this strategy and observed that the pricing depends upon the viability of the suggested model and the relationship between the unpredictability of driving behavior and the market share of EV groups, the distribution system's loading level, V2G tactics, and DR capabilities. The authors in [82] have considered EVs' diversity in usage patterns and storage capabilities. They did real-time (RT) pricing for the day-ahead scheduling for a specific retailer. If the proposed algorithm is applied for retailer bidding and the suggested electricity market, the overall cost savings will be up to $151,407 annually. While, the authors in [83] have designed an optimal scheduling algorithm for EV

owners, aggregators, and distribution systems. The objective function maximizes an aggregator's benefit under the constraints of EV users' minimum satisfaction with SOCs and the minimum load-shifting capability required by the distribution network.

As the growth in energy demand for microgrids is increasing, it is becoming difficult for distribution systems to maintain the demand for EV and non-EV loads and other energy resources. Thus, the authors in [84] have created an optimization model that includes novel incentive-based DR program aggregators for EV and non-EV loads. The work includes an interface between the operator and DR participants to maximize the incentive offered to DR participants. For a day-ahead operation, the energy reliance of a microgrid on the utility grid and conventional energy source is found to decrease by 9.62% and 29.06%, respectively. But, the authors in [85] proposed an energy management approach with a novel energy credit mechanism (ECM) for EV fleets and households separately. To minimize the total energy cost, an optimization problem is formulated to provide V2G or V2H. Moreover, the authors in [86] proposed a Peer-to-Peer (P2P) energy trading scheme between the EVs and the Service Providers. Both parties will engage in an online transaction using a blockchain-based scheme. This will allow them to reduce grid demand with safe transactions.

Now, the point arises: If EV owners are participating in DR applications, how does it affect their net electricity bills? However, EV owners' conditions will differ based on their consumption and appliances. But, there must be some estimates for this perspective. Therefore, the authors in [87] have proposed a real-time pricing (RTP) based demand response to effectively utilize renewable-based distributed generation (DGs), batteries, and electric vehicles and reduce grid dependency by using the Binary Particle Swarm Optimization (BPSO) algorithm. The simulation

results show a reduction in grid dependency by 9.636 kW with a profit of 13.046. It is also worth noting that the EV owner should be available and capable of providing the demand response during the required time. The paper [88] focused on the emergency demand response (EDR) programs by creating an algorithm that will credit EV owners for providing power with an available deadline. It is also worth noticing that during emergencies, the EV owner may not be available at the right place, affecting the microgrid.

3.1.3 Home Load Following and V2G

When utilized in the V2H capacity, the EV powers the household's loads, whether linked to the grid or not. The primary goal in a grid-connected situation would be to use the EV to lower power costs, especially while operating energy-intensive loads like washing machines, dryers, and stovetops. The EV would power critical loads like the fridge, internet, and heating source in an off-grid situation or during a power outage. EV needs to follow the curve of the appliances for participation in V2H. In this regard, the authors in [89] have observed the charging behaviors of 215 EV owners in the U.K. to evaluate the applicability of EVs to following load demand. They have developed a data-driven approach based on two stages: clustering the customers according to their time-varying charging patterns and estimating the charging load of all EVs using the measured data. It is concluded that most of the representative results in less than 12% error in the estimation of charging load. Reference [90] developed a novel algorithm for the V2H system and then extended it to vehicles to homes (Vs2Hs). The simulation shows that the EV could provide sufficient backup power for household appliances.

3.2 V2G and Carbon Emission Reduction

It is a certain fact that Battery Electric Vehicles (BEVs) will reduce greenhouse gas emissions. The work in [91] focuses on the synergistic optimization control of EVs for V2G. The case study is based on the real load data and concluded that by 2025 EVs can reduce 138,783.799 tons of carbon. But the reduction of greenhouse gas emission depends upon the source of electricity for charging an EV. The wind and solar are considered as clean source of energy, if V2G will combine with the production power mix then the reduction of carbon emission will reduce to 2.95% by 2030 as discussed in China [92]. Moreover, the work in [93] discusses the economic and carbon reduction potential assessment of V2G development in Guangdong province. The authors considered the number of BEVs in the region, their annual mileage, carbon emission reduction and how if effect the Guangdong region from 2021-2060. They also discussed that how it can be implemented in photovoltaic charging-discharging scenario. Paper [94] presents the literature work for the positive uptake of residential V2G when combine with the correct form of electricity production. They also mentioned that battery degradation is one of the main concern for the V2G participants and one of the most expensive component of the EV battery. However, none of the work have considered its impact by considering the population of the whole region which can be beneficial in implementation of the policy for V2G, except the literature work in [94].

3.3 Field Tests for V2G

There are various simulation studies for V2G, but real field tests are minimal. For V2G, the field tests of chargers that support bidirectional charging are essential. In [95], authors have tested and modelled commercial V2G CHAdeMO charger to

assess its capabilities for grid Services. They tested the up-down time, efficiency, response time, and set point linearity. It is observed that CHAdeMO was able to perform grid operations, and it is also modeled by simulation of the designed EV charger model. While the authors in [17] have designed a novel universal magnetic power plug to facilitate the lab's Vehicle to Everything (V2X) connectivity. They designed a universal power connector (UPC) and did its control test for EVs, efficiency, and response time for all the charging standards, such as SAE J1772, SAE Combo, or CHAdeMO. The results show that the proposed connector can provide all the bidirectional capabilities with the connected EV.

3.4 Policies for Bidirectional Charging

One important factor for implementing the vehicle to everything (V2X) is implementing a proper policy that gives EV owners a proper estimate of the expense and the incentive they will receive after participation in V2G. Some standards include IEEE-1547 [96] and net metering for renewable energy resources [53]. Although V2H is receiving significant interest in literature and real-world applications [97], several challenges impede its positive uptake. Like the early adoption of unidirectional electric vehicle charging stations [98], [99], [100], [101], there is a lack of standards for compatible EVs and certified bidirectional chargers available in the market [102]. Currently, a handful of EVs that support V2H, such as the Mitsubishi Outlander and Nissan Leaf [44], [103]. This shows that there needs to be awareness of pilot projects among people for V2H.

To those ends, policy-level works are being developed to promote EVs and bidirectional charging in general and raise awareness for challenges in increasing their adoption. The work in [99], [104], and [105] discusses the challenges and policies for buying EVs. The paper [99] divides the policy into three major categories:

financial incentives, which are to reduce the finances and provide subsidies to the customers who are buying EVs; information provision, which means to provide sufficient information to the customers on how it is helpful for the environment perspective, and lastly, convenience policy, which tells customers the feasibility of HOV lanes, etc. The combined theoretical result of these three policies changes the intention of 227 survey participants to buy EVs. Meanwhile, the work in [104] considers the psych impact of EV buyers by utilizing the Technology Acceptance Model (TAM), concluding that EV owners with more knowledge are more likely to be early adopters and take risks by purchasing EVs, and, as such, increasing customer awareness is a high priority. On the other hand, [105] considered fuel engines, Plug-in Hybrid Electric Vehicles (PHEVs), and EVs to compare the costs, applications, and subsidies the Government of China provided. After collecting the required data from all vehicles, they implemented a willingness-to-pay model, which encourages customers in China to move towards EVs. The work in [106] and [107] focused on vehicle-to-grid (V2G) policy, recommendations, and challenges. In [106], around 257 people from Nordic countries were interviewed to determine how many have in-depth knowledge about vehicle-to-grid technologies. These 257 people belong to academia, industries, or electricity-related fields. But unfortunately, not everyone knows about V2G in depth. A policy is implemented to briefly review vehicle-to-grid technology, its implementations, advantages, and challenges. Meanwhile, [107] presents a policy for V2G pricing, which uses a hierarchical approach to benefit the customer and operator's profit. The results obtained from this work play a vital role in EV charging management and power pricing policies. They are trying to tune the EV discharging price, which helps reduce peak loads and balance the energy demand from the user's side. But there is a lack of real-world implementation related to EVs and Vehicle to Everything (V2X) or Vehicle to Grid

except in [9], which gives a real-world performance for the promotion of Vehicle to Everything (V2X) by proposing a flexible charging/discharging policy that caters to the convenience and timing of EV owners to improve their participation rates in bidirectional charging programs.

3.5 Economic Analysis of V2G

Integrating bidirectional chargers for V2G is a big investment for Local Distribution Companies (LDCs) and EV owners. The works in [108], [109] and [110] discussed the economic analysis of V2G. The work in [108] discussed the economic success of V2G by considering the Plug-in Electric Vehicles (PEVs) used for V2G in 340 cases published between 2010 and 2018. In this study, they used meta-analysis to review these case studies. They concluded that EV owners will get 10% more profit than grid operators by providing V2G for load leveling and frequency regulation applications. The authors in [109] developed an optimization model to make more profit for EV owners by participating in V2G for peak shaving or load leveling applications. They compared the results for two cities in China with different electricity price rates. They concluded that instead of having 66% lower electricity rates in Chengdu compared to Shanghai, EV owners in Shanghai were still able to make 32% profit for ancillary services such as peak shaving. Moreover, the work in [110] discussed the benefit-to-cost ratios (BCRs) for all the stakeholders involved in V2G based on the Korean framework. There is no implemented policy for V2G in Korea, but based on their model, without subsidy, the EV owners were at a loss of 20%, while with the proposed subsidy, they can get a profit of 70% based on the recent framework. The work in [111], has done a cost-benefit analysis for the V2G implementation of an Electric Vehicle regarding the active and Reactive power Dispatch in the Distribution System. They considered the cost-benefit assessment

of EV owners and Distribution System operators (DSOs); the simulation is done on a 33-bus distribution system feeder. After the strategies they implemented, the improvement was 0.02% and 0.22%, respectively. While, the authors in [112] have developed an economic model without power from the microgrid to provide demand response with location privacy. The controller could mitigate the demand response and provide good performance concerning social welfare, satisfaction ratio, computational and communication overhead, and privacy leakage.

With the economic analysis for V2G, some technical parameters are involved in its deployment. The works in [113], [114] and [115] discussed the techno-economic analysis of V2G over specific years by considering multiple parameters such as battery degradation, temperature, and driving patterns of EV owners. EV owners can level the storage cost based on calculations of these technical parameters. EV owners might be able to make a profit after ten years. While, the authors in [116], discussed V2G participation for load leveling purposes in Indonesia. They considered different cases depending on the availability and schedule of EV owners. After their studies, they observed that EVs owned by business entities as operating vehicles show the highest feasibility of ancillary services and cost reduction by up to 60.15%.

3.6 Research Gaps

The research gaps for this thesis are based on the following criteria. While the tabular representation of the literature survey is shown in Table 3.3.

3.6.1 V2G and peak shaving

The work in [61] - [75], [91]- [93] and [109] have discussed in detail that how peak shaving can fill the valley by applying V2G. However, all of them are based on simulations and do not take into account the Time of Use (TOU).

3.6.2 V2G and TOU

The papers [64] - [65], [91], [93] and [109] have examined the time of use for charging and discharging of an EV. These studies also suggested that EV owners could receive incentives from the government by utilizing the correct charging times. Additionally, the schedule and availability of EV owners play a crucial role in Vehicle-to-Grid (V2G) systems, which need to be taken into account in the aforementioned works.be considered in the works mentioned above.

3.6.3 EVs Schedule and Availability for V2G

The authors in [66] - [67], [74] - [75], [83] - [88], [93] and [116] have emphasized the importance of scheduling electric vehicle (EV) availability at the right time and place. However, it's important to note that vehicle-to-grid (V2G) technology can impact EV battery life, leading to degradation over time. Considering battery degradation is crucial, as the battery is the most expensive component of an EV.

3.6.4 V2G and Battery Degradation

The study in [71], [72], [73], and [91] examined the battery degradation of electric vehicles (EVs) in relation to peak shaving applications to fill power demand gaps. The study also analyzed factors that could minimize battery fading. However, the number of charging cycles significantly affects battery degradation, and

participating in vehicle-to-grid (V2G) activities will increase the number of charging/discharging cycles, thus potentially requiring battery replacement every ten years.

3.6.5 V2G and Demand Response

V2G can be used for various power system applications, including demand response, necessary whenever peak demand occurs, regardless of the time. As a result, the papers [61], [77] - [88], [108] and [112] provide detailed discussions on how electric vehicles (EVs) can help reduce peak demand while balancing the load on cables and transformers be used for minimizing the peak demand while sharing the load of cables and transformers.

3.6.6 Pricing Scheme for Demand Response

It's important to note that demand response doesn't take into account the timing of usage. Therefore, it's crucial to have a well-defined pricing scheme for demand response, as discussed in papers [81] - [86]. The authors of these papers have explored the feasibility of electric vehicle owners participating in demand response while ensuring they receive the necessary price for vehicle-to-grid (V2G) services.

3.6.7 Home Load Following and V2G

One research topic is the potential use of electric vehicles (EVs) as backup power sources. However, a key question is whether EVs can meet the energy demands of home appliances. Therefore, sources such as [89] to [90] have thoroughly discussed how EVs can indeed meet home energy demands and be effectively used as backup power during grid outages.

3.6.8 V2G and Carbon Emissions

Reducing carbon emissions is one of the main advantages of V2G technology, and there is a strong push for this goal. The amount of carbon emissions reduced depends on the type of electricity used to charge electric vehicles. All of these factors related to carbon emission reduction and electricity production are discussed in the sources cited as [91] - [94].

3.6.9 Field Tests for V2G

Even though V2G can be used for peak shaving and demand response, a field test must be conducted to apply V2G. Thus, the papers [17] and [95] discussed the factors that need to be considered for the field application of V2G.

3.6.10 Policies for buying EVs

It is also a fact that despite several advantages of EVs, people are still willing to buy ICEs. Thus, the papers [99], [104], [105] suggested some policies which can increase the willingness of consumers to buy EVs instead of ICEs.

3.6.11 Policies for V2G

[106], [107] discussed some policy regulations for the implementation of V2G while shaving the peak. The policy regulations will help the government regulate the prices of investments made by the EV owners or the distribution companies.

3.6.12 V2G Economics

The provision of Vehicle-to-Grid (V2G) is a significant investment for both electric vehicle (EV) owners and distribution companies. Therefore, the authors discussed in detail in [108] - [112] the hidden costs of microgrids, EV owners, charging infrastructure, and other factors that can greatly affect the economics of V2G

3.6.13 Technical Analysis of V2G

The papers [113] - [116] discuss the technical parameters involved in deploying V2G and consider the cost-benefit analysis for the feasibility of V2G, which can promote its positive uptake.

3.6.14 Real-World Implementation of V2G

There are several works have been done in peak shaving, demand response, field tests in the real world, and home load as discussed in 3.6.1 - 3.6.7, 3.6.9. Although the aforementioned works have made substantial contributions to the field, it is important to emphasize that they did not utilize real-world data or experiences in their experiments. It is challenging to determine the technical feasibility of bidirectional charging, including the speed and accuracy required for various power system applications, the methods used to control the power output of the EV, and the additional components required. The public does not widely adopt bidirectional charging due to its drawbacks. Motivated by the above works, Chapter 4 evaluates a two-way charger for home use concerning its response speed, output accuracy, and suitability for electrical systems, including demand response, frequency control, arbitration, and home load following. This chapter is a new attempt to distribute real data and field test results. Specifically, the charger was deployed in a real home

and tested with real home appliances, which results can inform future algorithms and practice programs related to two-way electric car research.

3.6.15 Mathematical Analysis for the Feasibility of V2G

Although the 3.6.10-3.6.11 have tremendously contributed to promoting V2G and EVs, there needs to be certain things that resist the uptake of V2H. For instance, there needs to be more mathematical analysis that encourage real-world implementation of V2H or V2G. While 3.6.8 have discussed in detail the factors of reduction in greenhouse gas emissions by V2G. However, policies that enable customers to purchase bidirectional EVs still need to be improved by promoting them to participate in V2G via giving some carbon incentive for reducing GHGs. Also, customers and manufacturers must know the advantages of bidirectional electric vehicles. Lastly, the bidirectional meters play a significant role in the setup. There are only a couple of bidirectional chargers available on the market. This clearly shows that there must be a proper policy for giving customers proper knowledge about the main actors of bidirectional charging setup. Chapter 5 provides a detailed mathematical analysis of the feasibility of V2G in Ontario, Canada, along with a survey of LDC websites in Ontario. It also outlines the necessary steps for successfully adopting V2G and reducing the urgency of carbon emissions.

3.6.16 Cost-Benefit Assessment of V2G in Demand Response

After the proper policy for bidirectional chargers and the real-world implementation of bidirectional chargers at home, the question arises whether it is economically viable to have a bidirectional charger and EV for all the stakeholders of the V2G. This feasibility study depends on several factors as discussed in 3.6.3, 3.6.5, 3.6.6, 3.6.12, 3.6.13. One of them is the application for which it will be demonstrated. Demand

response is considered in this study to observe this analysis. Although the above works have contributed to the state of the art, they do not consider the benefit-to-cost ratios (BCRs) for various stakeholders in a V2G program, such as LDCs, ratepayers, and EV owners. The cost-benefit analysis of V2G for all stakeholders is difficult since the power and energy capacity of an EV depends on its choice, making predictions unclear. V2G study is based on the EV and technological characteristics that enable bidirectional charging. Due to rising power consumption and electrification, LDCs may require significant infrastructure upgrades. System upgrades often involve replacing outdated infrastructure and updating novel devices. Chapter 6 of the thesis aims to reduce the cost of electricity grid upgrades by implementing a V2G program instead of building transmission, distribution, and transformation facilities. To evaluate a possible V2G program, it's important to create a cost-benefit evaluation model that considers all stakeholders' costs and benefits and the impact of changing inputs. This chapter presents a novel cost-benefit evaluation approach for V2G programs that offer demand response to LDCs. The approach was tested in Ontario and validated through case studies to ensure its efficacy.

Table 3.3: Comparison of the proposed work with prior studies in the literature

	CRITERIAS															
References	3.6.1	3.6.2	3.6.3	3.6.4	3.6.5	3.6.6	3.6.7	3.6.8	3.6.9	3.6.10	3.6.11	3.6.12	3.6.13	3.6.14	3.6.15	3.6.16
[61] - [75], [91]- [93] and [109]	✓															
[64] - [65], [91], [93] and [109]	✓	✓														
[66] - [67], [74] - [75], [83] - [88], [93] and [116]	✓	✓	✓													
[71], [72], [73], and [91]	✓			✓												
[61], [77] - [88], [108] and [112]					✓											
[81] - [86]					✓	✓										
[89] - [90]	✓						✓									
[91] - [94]								✓								
[17], [95]									✓							
[99], [104], [105]										✓						
[106], [107]	✓										✓					
[108] - [112]												✓				
[113] - [116]													✓			
Proposed work	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Chapter 4 - Field Testing of a Residential Bidirectional Charger - A Real World Demonstration

As mentioned in the section 3.6, there is a lack for real-world demonstration of V2G deployment. This chapter focuses on field testing for deploying RBC in a residential unit. The chapter is organized as follows: Section 4.1 provides the preliminary steps to install a bidirectional charger. Section 4.2 discusses the methodological framework for the applications of RBC. Additionally, section 4.3 explains the process for deploying RBCs in a residential unit, while section 4.4 mentions the experimental results. Finally, section 4.5 is dedicated to summarizing the chapter and outlining further improvements.

4.1 Preliminary Steps for the Deployment of RBC

Recalling that section 2.6 listed all the EV chargers that are available and support bidirectional charging. For real-world demonstration of V2G, Nissan Leaf is used which has ChaDeMo connector. Therefore, the chargers considered in this section has ChaDeMo protocol. This section discusses the interconnection process and timeline to perform a real-world residential bidirectional charging setup and summarize the lessons learned from this project. Initially, it was decided to do this

setup with three chargers in three homes, but due to some technical issues with two chargers, only one charger demonstration was successfully implemented. The chargers' vendors and make/model are not disclosed due to some agreements.

The technical specifications of the chargers are discussed in Table 4.4. But we get the results from charger #3.

Table 4.4: Bidirectional Charger Specification for Residential Pilot

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

The interconnection process and timeline for installing a bidirectional charger are shown in Figure 4.1. The steps in detail are discussed below:

Step 1: . Local utility checks network capacity constraints in anticipation of charger deployment #1 (6 kW).

Step 2: 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.

A 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

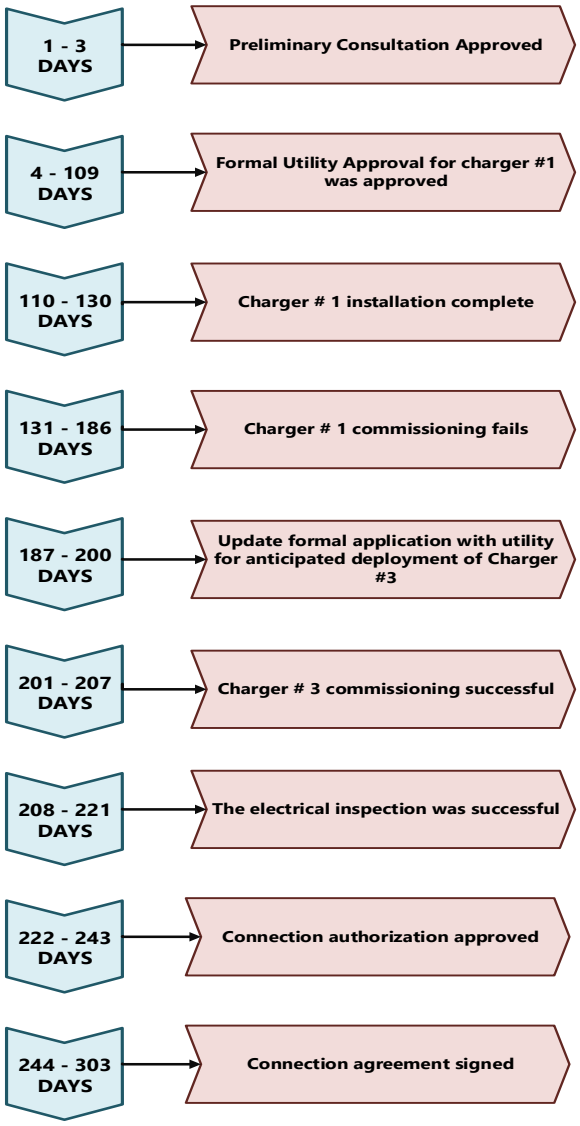


Figure 4.1: Flow Chart for Interconnection Process and timeline

monitor the net power consumption of the home and dispatch the charger to generate the requisite power in real-time.

Step 3: Charger #1 installation complete. Difficulties finding electrical con-

tractors willing to take on the project resulted in a 10-day delay. Eventually, a suitable contractor is found with knowledge of standard EV chargers and stationary battery storage systems.

Step 4: Charger #1 commissioning fails. The charger powers on but fails to communicate with the EV. Power transfer is not possible. Charger #2 exhibits similar behavior.

Step 5: Update formal application with utility for the anticipated deployment of Charger #3. Updates to the line diagram are made, and capacity constraints are rechecked due to the increased capacity of Charger #3.

Step 6: Charger #3 commissioning successful. The charger can communicate with the EV. The charger can charge/discharge the EV via mobile application and receive remote commands via Modbus protocol.

Step 7: Electrical inspection successful. The electrical authority was satisfied with the project intent and associated safety risks.

Step 8: Connection authorization approved. The utility approves connection authorization from the local safety authority—finalized connection agreement with the homeowner.

Step 9: Connection agreement signed. Project testing can begin.

4.2 Methodological Framework

This section explains in detail the components involved in RBC, the applications that can be utilized by deployment of RBCs, and the power transfer equations involved in it.

4.2.1 Components of RBC

The section 2.2.2 of Chapter 1.5 explains in detail about V2H and its schematic diagram shown in Fig. 2.3. Moreover, the bidirectional charging holds significant potential for assisting power system operators in improving power system operations. However, several performance characteristics need to be considered for it to be truly useful. Of particular importance are the response time and accuracy of the dispatch. Without loss of generality, response time can be generally characterized as follows:

$$\Delta T = T_{ST}(t) - T_{AC}(t) \tag{4.1}$$

where $\{T_{ST}, T_{AC}\}$ are the absolute times where a command was sent and achieved, respectively, in seconds. Response times for electric vehicles can be divided into three categories: start-up time, which is the duration needed for the EV to activate and be ready to deliver power; step response time, which is the duration needed for the EV to respond to setpoints in small steps; and ramping time, which is the EV response time across varying setpoints. An associated attribute for ramping time is the ramp rate.

$$RR = \frac{\Delta P}{\Delta T} \tag{4.2}$$

where ΔP is the change in the previous setpoint to the current setpoint, and is expressed in kW/s. On the other hand, EV setpoint accuracy can be formulated as

$$\epsilon_{SET} = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{P_{SET,i} - P_{EV,i}}{P_{SET,i}} \right| \times 100 \tag{4.3}$$

where P_{SET} is the power setpoint of the EV and P_{EV} is the actual, measured power of the EV after achieving steady-state [117]. With these known and formulated attributes, the following subsection will contextualize their importance for various power system applications.

4.2.2 Power System Applications of Residential Bidirectional Charging

4.2.2.1 Load Following With Zero Export

The load following with zero export test is a procedure in electrical engineering used to return power to the grid. During this process, we observe whether the generated power matches the electric power demand while maintaining grid stability. Here's how it works: a power generation system can adjust its output and respond to changes in electric load during load following [118]. The zero export test refers to a condition where the renewable energy system does not export any excess power back to the grid. This is important when grid regulations or agreements prohibit sending power back to the grid, or if the grid infrastructure cannot handle additional power flow during the export test [119]. The system operates in such a way that it adjusts its output to match the varying electric load in real-time, preventing any excess power from being exported back to the grid. Instead, any surplus power is stored in energy storage systems such as batteries for later use. This test ensures that the system can effectively integrate with the existing grid infrastructure while maintaining excellent stability and power quality, and helps assess the control algorithms and performance of the system under real-world conditions [120]. The dispatch setpoint of the EV, computed locally, can be formulated as [121]:

$$P_{SET}^{LF}(t) = P_{NET}(t-1) - P_{EV}(t-1) - \alpha \tag{4.4}$$

where t is a moment in time, P_{NET} is the net power of the home, and α represents a tolerance factor, in kW, used as an offset to ensure the EV does not backfeed the grid.

4.2.2.2 Energy Arbitrage

Arbitrage refers to buying and selling electricity in different markets, like purchasing electricity when the prices are low and selling it during peak hours. The concept behind this typically involves energy storage systems such as batteries [122]. Energy arbitrage also helps to balance supply and demand in the electricity market, reduces peak load on the grid, and contributes to overall more excellent stability. It also provides an opportunity for entities like utilities. Independent power producers and consumers optimize energy costs and potentially generate revenue by participating in energy markets [123]. An energy arbitrage test is performed in this experiment to observe that if we allow our EV to charge and discharge during the whole day according to the rates described by TOU Ontario, then how much will the EV potentially earn in one day? An EV performing arbitrage can be dispatched locally as follows:

$$P_{SET}^{ARB}(t) = \begin{cases} P_C, & \forall t \in \{t_F\} \;\&\; SOC(t) \leq SOC_{MAX} \\ P_D, & \forall t \in \{t_P\} \;\&\; SOC(t) > SOC_{MIN} \\ 0, & \text{Otherwise} \end{cases} \tag{4.5}$$

where $\{P_C, P_D\}$ are arbitrary charging/discharging values, respectively, $\{t_F, t_P\}$ are off peak and on peak periods of time, respectively, SOC is the current state of charge (SOC) of the EV, and $\{SOC_{MAX}, SOC_{MIN}\}$ are maximum and minimum

percentages for the SOC depending on EV owner preferences, respectively. Additionally, the earnings from the arbitrage are the cumulative periods of time where the EV is charging and discharging depending on the TOU period, formulated as:

$$\Theta = \sum_{k=1}^{N_P}\Big(\int_0^{D_P} P_{D,k}(t)\tau_P\, dt\Big) - \sum_{j=1}^{N_F}\Big(\int_0^{D_F} P_{C,j}(t)\tau_O\, dt\Big) \tag{4.6}$$

where Θ is the overall monetary earnings, $\{N_P,N_F\}$ is the number of peak and on-peak periods, respectively, $\{k,j\}$ are counters for the peak and off-peak periods, respectively, $\{\tau_P,\tau_O\}$ are the electricity tariffs for the peak and on-peak periods, respectively, and $\{D_P, D_F\}$ are the durations of peak discharging and off-peak discharging, respectively. It is worthwhile to note that emissions reductions can be calculated in a similar fashion to (4.6), except the tariffs can be replaced by the emission factor of the grid at that moment.

4.2.2.3 Demand Response

Demand response is frequently employed during energy shortages to relieve power system congestion. In household contexts, electric vehicles (EVs) can generate electricity to reduce demand on their houses or send any excess power to the power grid to assist in easing grid congestion. It is worth noting that demand response does not need a rapid response from the EV since acceptable timescales might range in the minutes scale [124].

4.2.2.4 Frequency Regulation

Power System Operators (PSOs) employ Frequency Regulation (FR) to balance power demand and supply while stabilizing system frequency. Primary frequency response entails fast correcting frequency variations in reaction to disruptions, such as losing a large load or generator. Using droop control and frequency/watt curves,

the Regulating Bid Coordinator (RBC) can supply suitable injection [125, 126]. Secondary frequency response recovers or maintains reserves by direct dispatch from the PSO for Automatic Generation Control (AGC) within 2-6 seconds [127]. Both situations necessitate correct and timely replies.

4.2.3 Power Transfer Equations

With modeling the qualities and power setpoints for each electric vehicle (EV) application, this part focuses on modeling the power transfer equations while considering various physical restrictions sometimes disregarded in literature. It is important to note that the EV's output power (P_{EV}) does not always match P_{SET}, especially when P_{SET} approaches the capacity of the RBC nameplate. This is owing to the loss of DC / AC conversion as well as limits regarding the maximum DC voltage of the EV battery (V_{EV}) and the maximum DC input current of the RBC (I_{DC}) [121,128]. The formula for modeling the RBC's maximal power transfer, P_{MAX}, is as follows:

$$P_{MAX} = \begin{cases} Max\big(I_{DC}V_{EV}\gamma, P_{CH}^{MAX}\big), & if \;\; I_{DC} > 0 \\ Min\big(-I_{DC}V_{EV}\gamma, P_{DCH}^{MAX}\big), & if \;\; I_{DC} < 0 \end{cases} \tag{4.7}$$

where P_{CH}^{MAX} and P_{DCH}^{MAX} are the maximum power capacity of the RBC on the nameplate in charge and discharge mode, respectively, and γ is the efficiency of the conversion process from DC to AC, expressed as a percentage. The power transfer of the EV affects its current energy level, which is modeled by:

$$E_{EV}(t) = E_{EV}(t-1) + P_{EV}(t)\gamma\Delta T \tag{4.8}$$

where E_{EV} is the energy of the EV in kWh. Using (4.8), the SOC of the EV can also be calculated:

$$SOC(t) = \frac{E_{EV}(t)}{E_{CAP}(t)} \times 100 \tag{4.9}$$

where E_{CAP} is current rated capacity, in kWh, of the EV.

4.3 Deployment of Residential Bidirectional Charger

In this experiment, a residential bidirectional charger is deployed in the home. The following processes and software were involved in its deployment.

4.3.1 Physical Interconnection with PSO Grid

The single-line diagram in Fig. 4.2 shows the physical interconnection and deployment of the bidirectional charger under test within a home in Ontario, Canada. The charger is rated for +/- 7.4 kW and is used with a 2019 Nissan Leaf SV with a 40-kWh battery capacity. To meet connection approval from the local PSO, a disconnect is deployed outside the home for the utility to turn off the charger during power outages. As seen in Fig. 4.2, a smart meter is deployed near the home's main electrical panel, which uses current transformers within the panel to take net power measurements of the entire house. Also seen in Fig. 4.2 is an external software-based controller developed to take real-time measurements from the smart meter and bidirectional charger while dispatching the charger with specific setpoints in kW units. It is worth noting that the charger is incapable of islanding during a power outage, so a transfer switch is not deployed within the home.

4.3.2 Software Control of RBC

The control of bidirectional charging depends on the following criteria:

1. Modbus Protocol

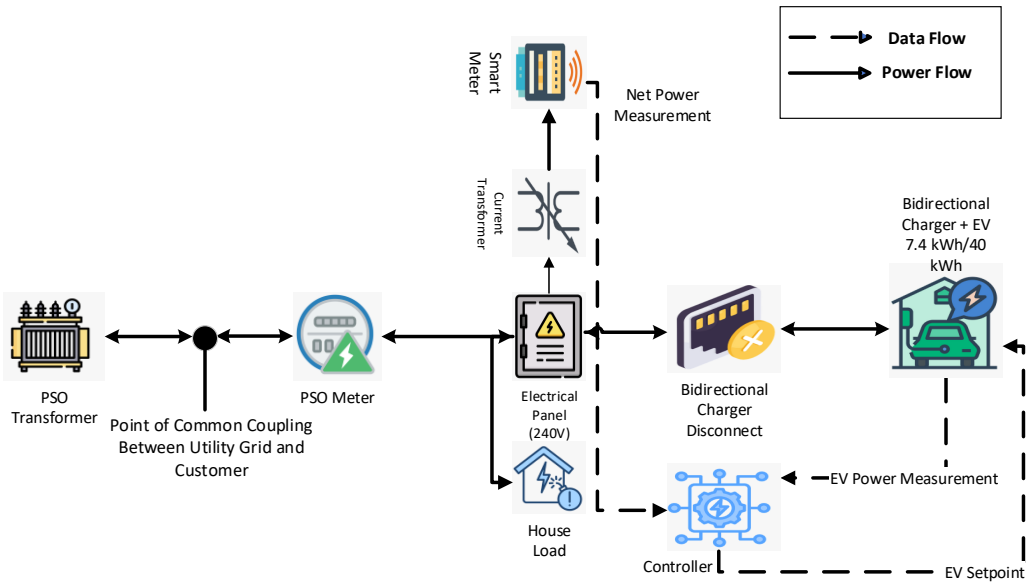


Figure 4.2: SLD of deployed charger within home

2. Distributed Energy Resource Management System (DERMS)

4.3.2.1 Modbus Protocol

The business "Modicon," a pioneer in the nascent programmable logic controller (PLC) field, invented Modbus in 1979. It was meant to serve as the internal point-to-point communication protocol between programming panels and Modicon PLCs used to program controllers [129]. The communication protocol used is Modbus TCP (Transmission Control Protocol), which works in the application layer of the TCP/IP model and adopts a master-slave communication mode. Communication can be done in one-to-one or many-to-many ways between the enslaver and the

enslaved person [130]. The smart meter, manufactured by Accuenergy (Acuvim-L series), and the charger allow external software to read/write values to these devices using the Modbus protocol.

Because of this, the charger and meter reveal specific registers that the external program may utilize to toggle different features. The active power measurement and the current going into and out of the house are the registers of interest for the smart meter. The capacity to remotely control the charger (through external software), to initiate and terminate charging or discharging, to set a kW setpoint, to read the power being supplied or received from the EV, and to determine the state of charge (SOC) of the EV battery are the registers of interest for the charger.

Charger status determines the state of the bidirectional charger, like whether the EV is charging, discharging, or in ready mode. It is observed during the experiment that when the EV is charging, the status is set to 1, while during discharging, the status is set to 11. The following description will explain how the charger status works in the state machine of the Modbus Protocol.

- 0: Ready
- 1: Charging
- 2: Connected: Waiting for car demand
- 3: Connected: Waiting for the following schedule
- 4: Connected: Paused by user
- 5: Connected: end of schedule
- 6: Disconnected locked
- 7: Error

- 8: Connected: In queue by power-sharing
- 9: Unconfigured Power
- 10: Connected: In queue by power boost
- 11: Discharging

4.3.2.2 Distributed Energy Resource Management System (DERMS)

A platform known as a distributed energy resources management system (DERMS) assists distribution system operators (DSO) in managing their distributed energy resource (DER)-based grids. Utilities and other energy companies use DERMS to aggregate a large energy load for participation in the demand response market [131]. The DERMS software used in this experiment to control the power flow of the EV, particularly concerning the loads of the home, was developed by Hero Energy and Engineering and is entitled Harmonize [132]. The DERMS coordinates the time of the measurements, enabling human and automatic EV management, reading pertinent measures from the charger and smart meter at a customizable sample rate, and recording the data to disc.

Fig, 4.3 displays a picture of the charger and electric vehicle (EV) combo, a Nissan LEAF 2019; Fig. 4.4 shows a screenshot of the DERMS software, which includes control panel features for the EV. To communicate the setpoint to the charger manually, the user can click the "Set Power (kW)" button and type a value in the "Setpoint (kW)" textbox. Conversely, the user can opt for automatic control by pressing the "Zero Export" button, allowing the EV to provide enough power to suit the household's needs. As seen in Fig. 4.4, the DERMS measures the home's net power from the smart meter and the EV power from the charger. Based on these measurements, the setpoint is determined and delivered to the charger.

Figure 4.3: Snapshot of EV and deployed bidirectional charger

4.4 Experimental Results

This section presents experimental results to evaluate the speed, accuracy, and responsiveness of the power transfer of the deployed residential bidirectional charger, enabling an evaluation of its applicability to the power system applications discussed in Section 4.2.

4.4.1 Start Test

In electrical engineering, the start test accepts a new device for testing. This test determines how long it will take for the equipment to receive the initial command

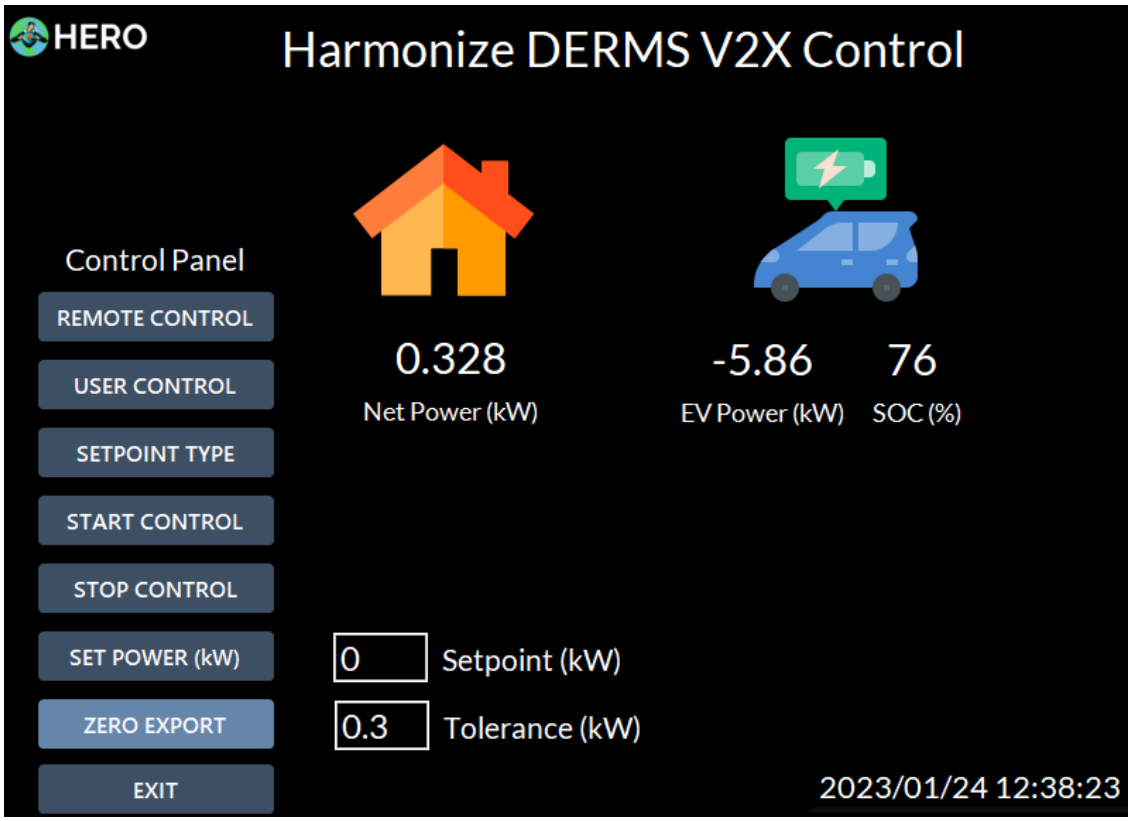


Figure 4.4: Software controller dispatches EV to meet house loads in real-time

[133]. Fig. 4.5 depicts the start test results, which chart the status of the RBC and its power output versus time, using time units of minutes, seconds, and milliseconds. The test begins with the EV plugged in, and the connection halted, as indicated by status 4 and a power transfer of 0 kW. At 22:44.44, a command is issued to start an EV session with a charging rate of 7 kW. The RBC's status immediately oscillates between 2 and 1, indicating the standard handshaking procedure as the RBC and EV start the connection, do safety checks, verify their capabilities, and negotiate the power level [134]. Indeed, at 24:11.32, there is a minor amount of power usage, consistent with EVs seeking and validating small amounts of power transfer before requesting the first setpoint. Thus, the start time may be determined when the

EV obtains status 1 and power consumption is detected, deducted by the time the command was delivered according to (4.1), resulting in 76.115 seconds. This delay is essential, and it emphasizes the need to carefully ensure that EVs are connected to the RBC and prepared to participate in a proper session before committing to a power system application or grid service. Interestingly, Fig. 4.5 also reveals that the RBC cannot produce the 7 kW setpoint because the measured EV value is 6.3 kW. This observation will be validated by more evidence in the step test.

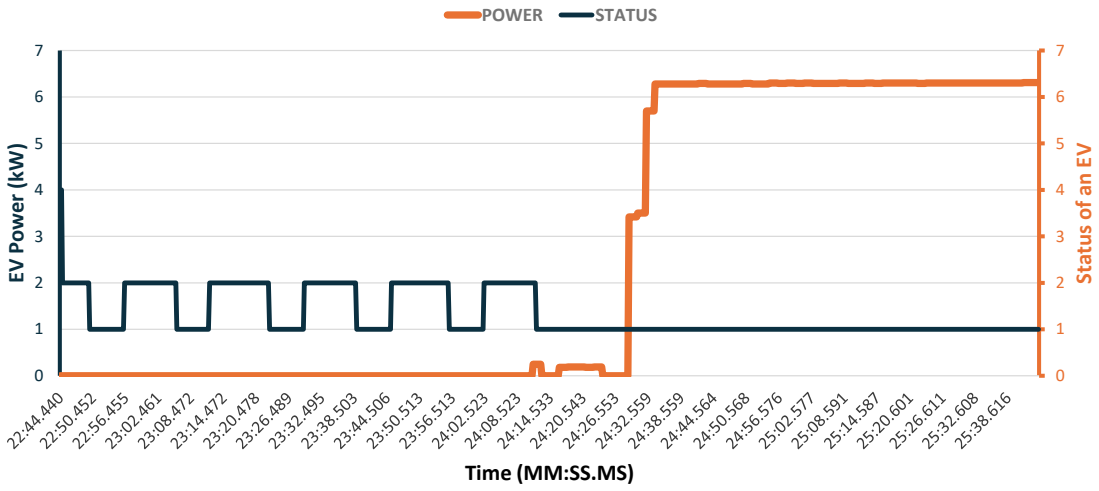


Figure 4.5: Power consumption and RBC status during start test.

4.4.2 Step Test

A step test in electrical engineering investigates how a system responds or behaves dynamically in the face of an abrupt change in input or operating conditions. This involves increasing the input signal and monitoring the system's reaction over time [135].

The step test is used in this experiment to monitor the charger's power, time, status, and state of charge (SOC) by altering power steps. Table 4.5 and Fig. 4.6

show the step test findings, with three key observations. The RBC has a nominal capacity of +/- 7.4 kW; however, the EV power provided at setpoints of +/- 7kW measures at 6.3 kW (as observed in the start test) and -6.05 kW as seen in Table 4.5. This is explained by (4.7), which limits the maximum power transfer from the RBC to the maximum DC input of the RBC and the maximum DC voltage of the EV's battery. In this example, the maximum DC input current of the RBC is 17 A, and the nominal DC voltage of the Nissan LEAF EV battery is 410 V; therefore, according to (4.7), the consequent power transfer of +/- 6.3 kW is feasible. Second, the RBC has a high level of accuracy and precision for each setpoint, except -7 kW, which is limited by the maximum power transmission. After deleting the -7 kW sample, the average inaccuracy is 0.15 percent, and the average precision is 0.005 kW. The step results show that the RBC may be suitable for power system applications with less stringent timing requirements, such as DR and arbitrage. Finally, the EV's SOC goes from 69% to 66%. Although all of the equipment was turned off during this experiment, and only setpoints were given to observe the EV's power, this SOC drop is observed due to the long duration of the test and power discharging.

4.4.3 Sweep Test

A sweep test is often a diagnostic process used to improve the performance and integrity of electrical systems or components under varying operating circumstances. This test is frequently used for preventative maintenance, quality control, and troubleshooting. This test ensures that the equipment satisfies performance specifications, regulatory requirements, and industry standards, improving dependability, safety, and lifespan [136]. This experiment includes a sweep test to evaluate how long the battery charger will take to move inside the authorized range for output

Table 4.5: Step Test Results

Setpoint (kW)	EV Power (kW)	Time (s)	Error (%)	Precis. (kW)
7 to 6	5.98	5.07	0.18	0.006
6 to 5	4.98	6.20	0.24	0.005
5 to 4	3.99	7.25	0.25	0.006
4 to 3	2.99	6.94	0.18	0.005
3 to 2	1.99	7.42	0.28	0.005
2 to 1	0.99	6.24	0.47	0.007
1 to 0	0.00	3.15	0	0
0 to -1	-0.99	6.78	0.11	0.005
-1 to -2	-2.00	6.75	0.04	0.005
-2 to -3	-3.00	7.10	0.00	0.004
-3 to -4	-3.99	7.13	0.04	0.004
-4 to -5	-4.99	6.55	0.04	0.007
-5 to -6	-5.99	6.49	0.07	0.1005
-6 to -7	-6.05	2.791	13.51	0.007

power. Monitoring the time and SOC values within this permitted range is also necessary.

Table 4.6 and Fig. 4.7 show the sweep test results, performed identically to the step test but with setpoints at +/- 6 kW. Table 4.6 and Fig. 4.7 indicate that the RBC provides exceptionally high setpoint accuracy with an average error of less than 0.1%. However, it takes an average of 8.74 s to shift from 6 kW to -6 kW and vice versa. Using (4.2), the RBC has an average ramp rate of 1.383 kW/s for charging and 1.385 kW/s for discharging. This shows that the output may lag behind the setpoint if the RBC is transmitted at short intervals of less than

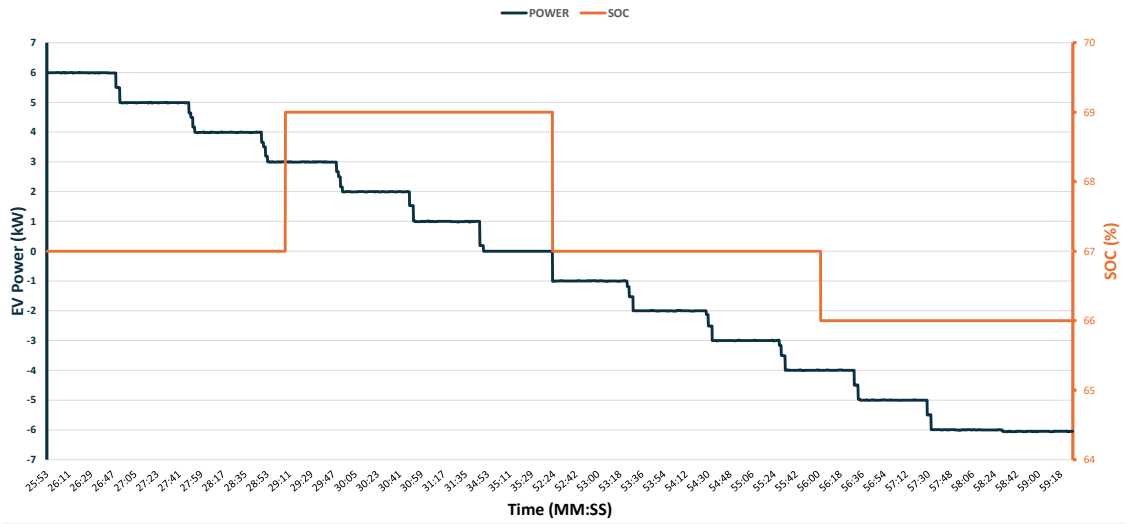


Figure 4.6: Step test for bidirectional charging.

7 seconds. The EV Power's SOC remains the same during this test because the power is frequently switched, and the test duration is short.

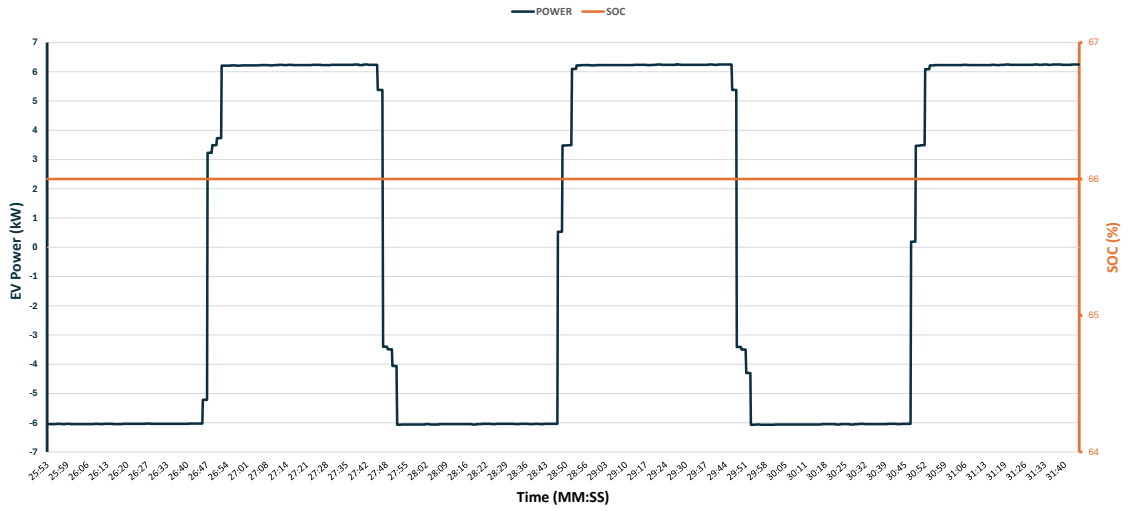


Figure 4.7: Sweep test for bidirectional charging.

Table 4.6: Sweep Test Results

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

4.4.4 Load Following

During this test, the EV is dispatched to monitor the loads at home. To achieve this goal, many popular domestic appliances, including the dishwasher, dryer, and washing machine, are turned on for around five hours to evaluate the EV and RBC's response to load following. To reduce back feeding to the grid, a tolerance of 0.1 kW is established while all other loads in the residences are switched off, leaving a base load of around 0.13 kW during the test. Figure 4.8 illustrates the energy usage of appliances and the energy supplied by the EV during the test. Fig. 4.9 depicts the plot of net house power, EV power, and house load. The net house power and EV powers are measured from the bidirectional meter deployed at the PCC between the house and the grid and the RBC, respectively, and the house load is the calculated difference between these two powers. The EV power is reversed to be positive better to demonstrate its power transfer about the home load. Fig. 4.10 illustrates the SOC of the EV during the test, which falls by 20%. The majority of the discharge occurs when the energy-demanding dryer is operating.

As illustrated in Fig. 4.9, the EV power mainly matches the house load, which

is predicted given that the EV is dispatched to offset the house load according to Eq. (4.4). To this purpose, the house's net load, which should be within the tolerance of 0.1 kW, remains close to this figure throughout the test. There are also instances where the net power of the residence surpasses 2 kW, which typically occurs when the dryer is turned on. The dryer's power usage fluctuates fast when it turns on and off its heating element, resulting in power variations ranging from 2 kW to 6 kW in 1-2 seconds. Recalling from the sweep test that the RBC's ramp rate is around 1.38 kW/s, the EV power lags behind the net house power for time intervals. As a result, the EV cannot constantly track the home's load, resulting in instances when net house demand exceeds the 0.1 kW tolerance. As indicated in Fig. 4.8, the EV can deliver 4.37 kWh of a total of 6.41 kWh of shiftable home load (68%). The findings of this test show that the EV's reaction time has to be improved before load following can be adopted, especially with the introduction of intermittent renewables linked to residential buildings.

4.4.5 Energy Arbitrage

The arbitrage simulation assumes that the EV charges at ultra-low overnight (ULO) rate in Ontario, which is \$0.028/kWh on weekdays between 11PM to 7AM, and discharges at the peak rate between 4PM to 9PM, which is \$0.286/kWh. Furthermore, the nameplate capacity of the EV is assumed to be 40 kWh, with the min and max SOC set at 30% and 100% respectively, and one complete cycle of charging/discharging is assumed to be completed every weekday (roughly 250 days of the calendar year). The SOC is calculated for each hour using Eq. 4.9. Battery electric vehicles play a significant role in reducing carbon emissions. Thus, carbon emissions are calculated during this experiment for the whole day. The emissions factors were taken from based on hourly data [137]. It is observed that using EVs

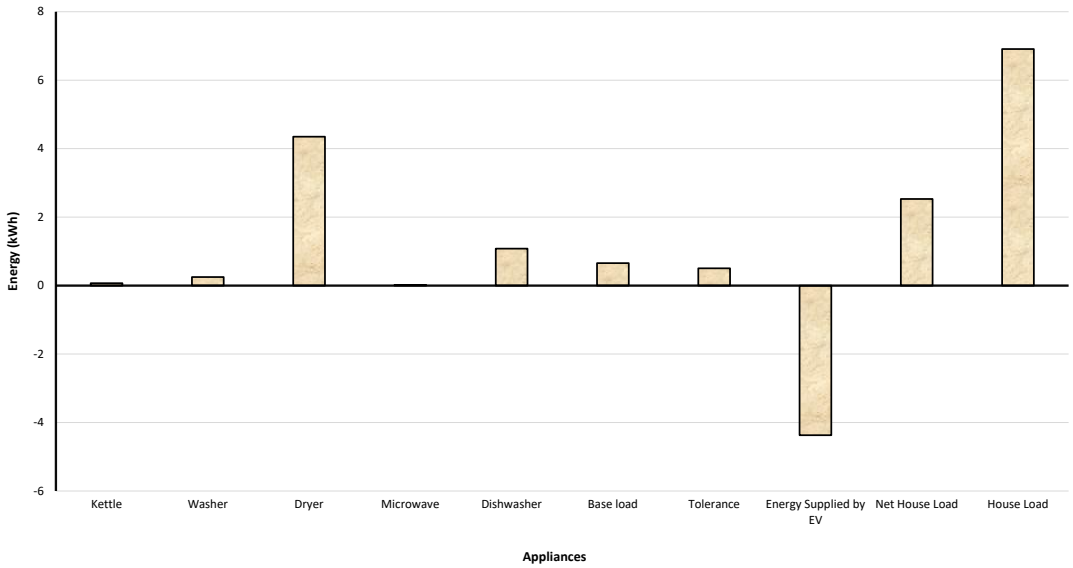


Figure 4.8: Energy consumption of appliances and energy supplied by EV.

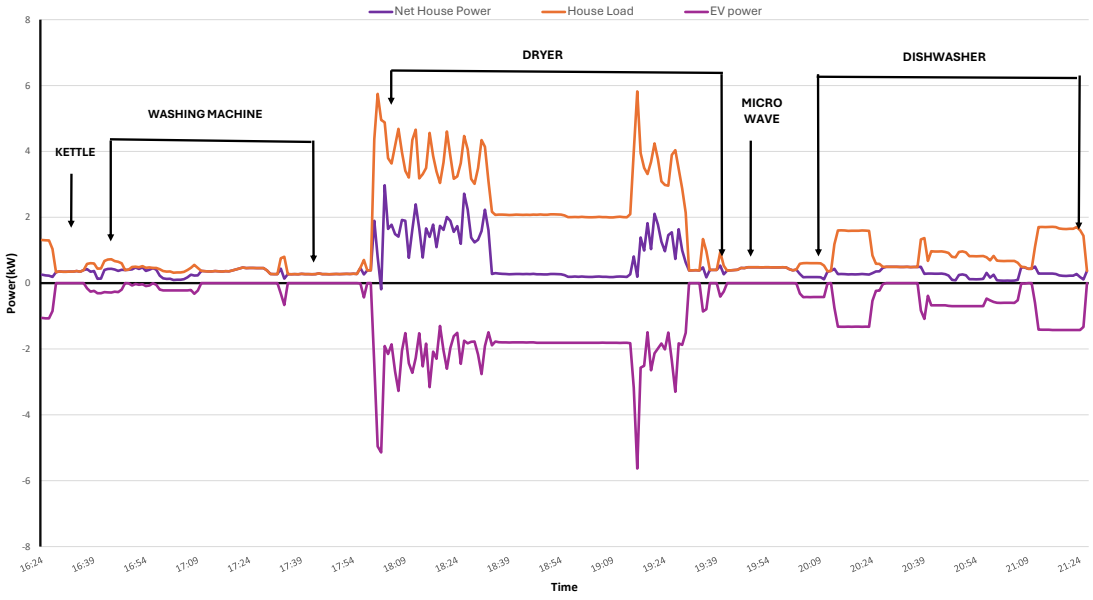


Figure 4.9: Power transfer during load following test.

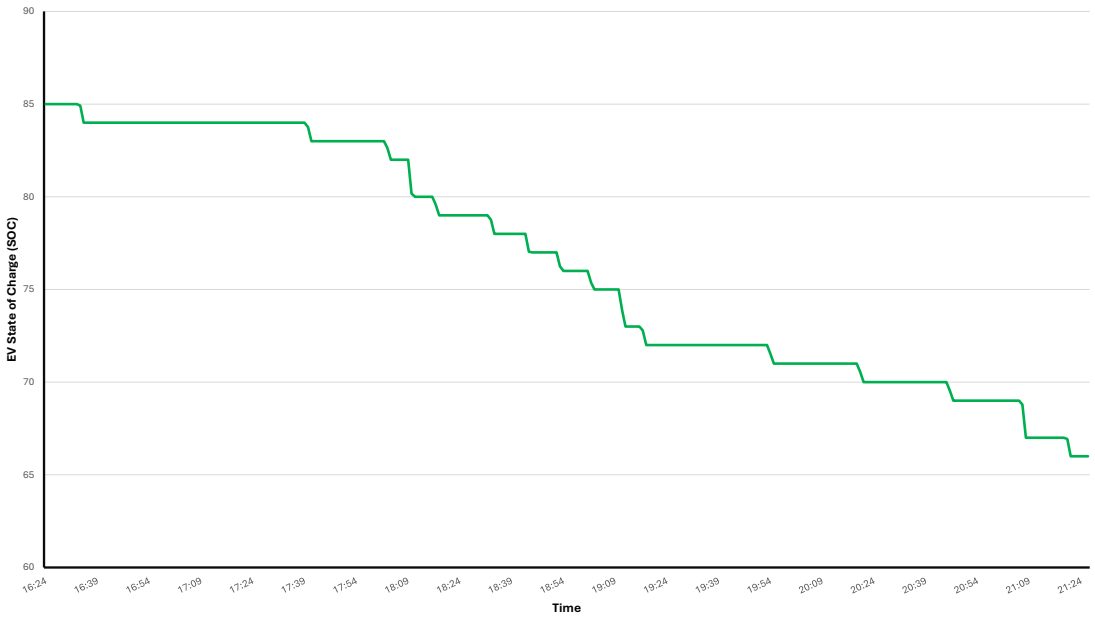


Figure 4.10: SOC of the EV during the load following test.

for bidirectional charging purposes will positively reduce carbon emissions.

The emission from the gasoline passenger vehicle on average is 12.6 kgCO2eq [138], while Fig. 4.11 shows the steady charging and discharging of the EV during the off-peak and ULO hours, respectively, and also creating a net negative emissions reduction. Table 4.7 shows the emission reduction on an hourly basis for the 24-hour period of time. It is also observed that at the start of the day, the SOC of the EV is 18, and it remains approximately the same after the whole cycle of charging and discharging.

4.4.6 Long Range Test

In electrical engineering, a long-range test typically refers to a series of tests or analyses conducted to evaluate the performance, reliability, and functionality of electrical systems, components, or devices over an extended period or under specific

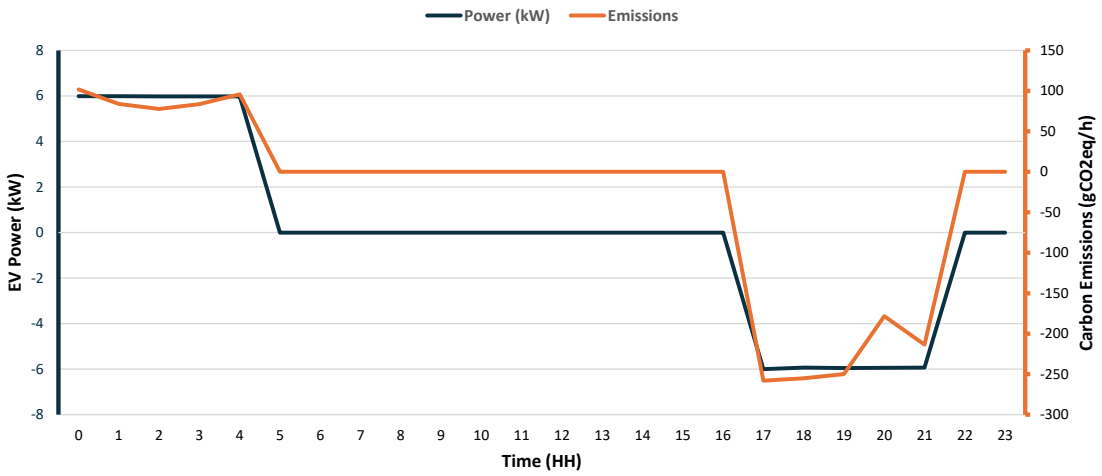


Figure 4.11: 24-hour snapshot of EV arbitraging for cost and emissions reduction.

conditions [139]. There are various examples of extended-range tests, but here, a pilot test is conducted for bidirectional charging products. So here we are validating the performance of the charger and its reliability and suitability. How long will it take for the charger to discharge to its nominal or minimal value, and how long will it take to return to 100%?

A long-range test is performed to observe how long it will take for an EV to go from one cycle of discharging to charging. This test predicts the durability of this bidirectional charging for an extended period. Fig. 4.12 shows the SOC values for the one complete cycle of charging and discharging of an EV. It is observed that when the SOC value reaches below 10, it disconnects from the charger and stops giving any output power during the discharge process. Although, it was expected that it would provide power to -6 kW while discharging. Moreover, the time it takes to go from one power to another is the same compared to previous tests.

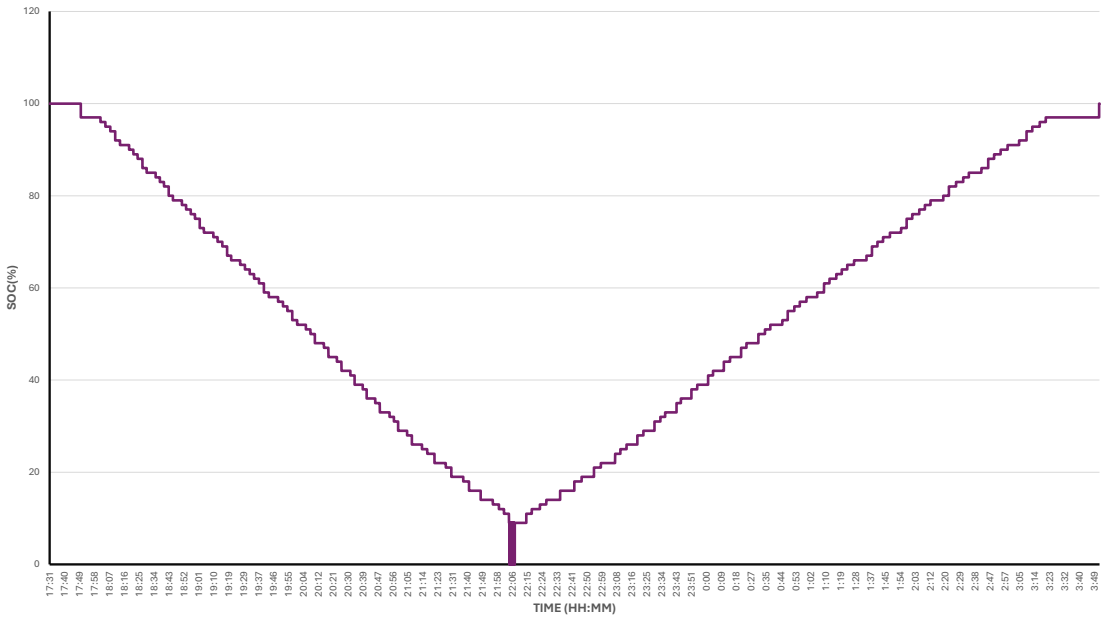


Figure 4.12: Charging and Discharging of an EV for the whole cycle of SOC

4.5 Summary

This chapter presents the real-world demonstration of the bidirectional EV charging installed in a residential unit in Ontario. DERMS software has added the ability to monitor and manage an EV in real time in reaction to household loads. It is observed that the smart RBC was able to follow the commands during the step and sweep test, but it takes some time to start, as shown in the start test, which is the communication between the EV and the charger. Moreover, EV could follow the load demand but showed some abruption, precisely when the dryer was on. This is a significant observation as it highlights the challenges in bidirectional EV charging when dealing with dynamic household loads. The dryer, being dynamic, required a rapid response, which the selected system was not capable of providing. EV owners can also earn incentives from the government by participating in peak shaving or demand response. It has also been observed that V2G can reduce greenhouse gas

emissions. But when it comes to other power system applications like frequency regulation, which requires fast response, the particular setup needs to be more capable of it. Table 4.8 shows the list of power system applications that the selected EV and charger can perform. As the setup has no rapid response, it cannot perform in frequency regulations and contingency support applications. In conclusion, the field testing results have provided invaluable insights that can shape future algorithms, policies, and programs related to bidirectional EV research. The potential of testing new generation RBCs with multiple EVs and testing for round-trip efficiencies at different power setpoints and at different ranges of SOC is promising. However, it's crucial to note that the participant could not give feedback energy to the grid, highlighting the need for a bidirectional policy in Ontario, Canada. The urgency and importance of this policy need further validation through additional analysis, which will be discussed in the next chapter.

Table 4.7: Emission factor calculation during V2H

Time	**EF**	**Power (kW)**	**SOC (%)**	**Emissions (kgCO2eq)**
0	17	5.99	18	101.83
1	14	5.99	32.975	83.86
2	13	5.98	47.95	77.74
3	14	5.98	62.9	83.72
4	16	5.98	77.85	95.68
5	19	0	92.8	0
6	23	0	92.8	0
7	26	0	92.8	0
8	28	0	92.8	0
9	31	0	92.8	0
10	34	0	92.8	0
11	36	0	92.8	0
12	38	0	92.8	0
13	39	0	92.8	0
14	41	0	92.8	0
15	42	0	92.8	0
16	43	0	92.8	0
17	43	-6	92.8	-258
18	43	-5.93	77.8	-254.99
19	42	-5.95	62.975	-249.9
20	30	-5.94	48.1	-178.2
21	36	-5.93	33.25	-213.48
22	30	0	18.425	0
23	23	0	18.425	0
SUM			72	**-711.74**

Table 4.8: Power system applications and the capability of the related setup.

Applications	**Capability**
Arbitrage	✓
Firm Capacity	✓
Primary Frequency Regulation	×
Secondary Frequency Regulation	×
Contingency Spinning	×
Replacement/Supplemental	✓
Ramping/Load Following	✓
Transmission and Distribution and Deferral	×
Black-Start	✓

Chapter 5 - Open Challenges and Recommendations for Economic Feasibility of V2G

The literature survey 3.6 shows a need of mathematical analysis for feasibility of bidirectional charging systems, specifically in Ontario. The previous chapter represented a real-world demonstration of residential bidirectional charging systems. However, based on one experiment, the need for a policy cannot be justified. A proper mathematical analysis is necessary to prove the urgent need for the policy in Ontario.

Therefore, this chapter describes a proper methodological framework that can validate the urgency of the policy in section 5.1 while section 5.2 mentioned all the assumptions that have been considered in this analysis. Section 5.3 gives the result of the mathematical analysis, challenges an EV owner might face in installing bidirectional meters and recommendations to mitigate these barriers. Last but not least, section 5.4 gives the conclusion.

5.1 Methodological Framework

The framework of this chapter is shown in Fig. 5.13.

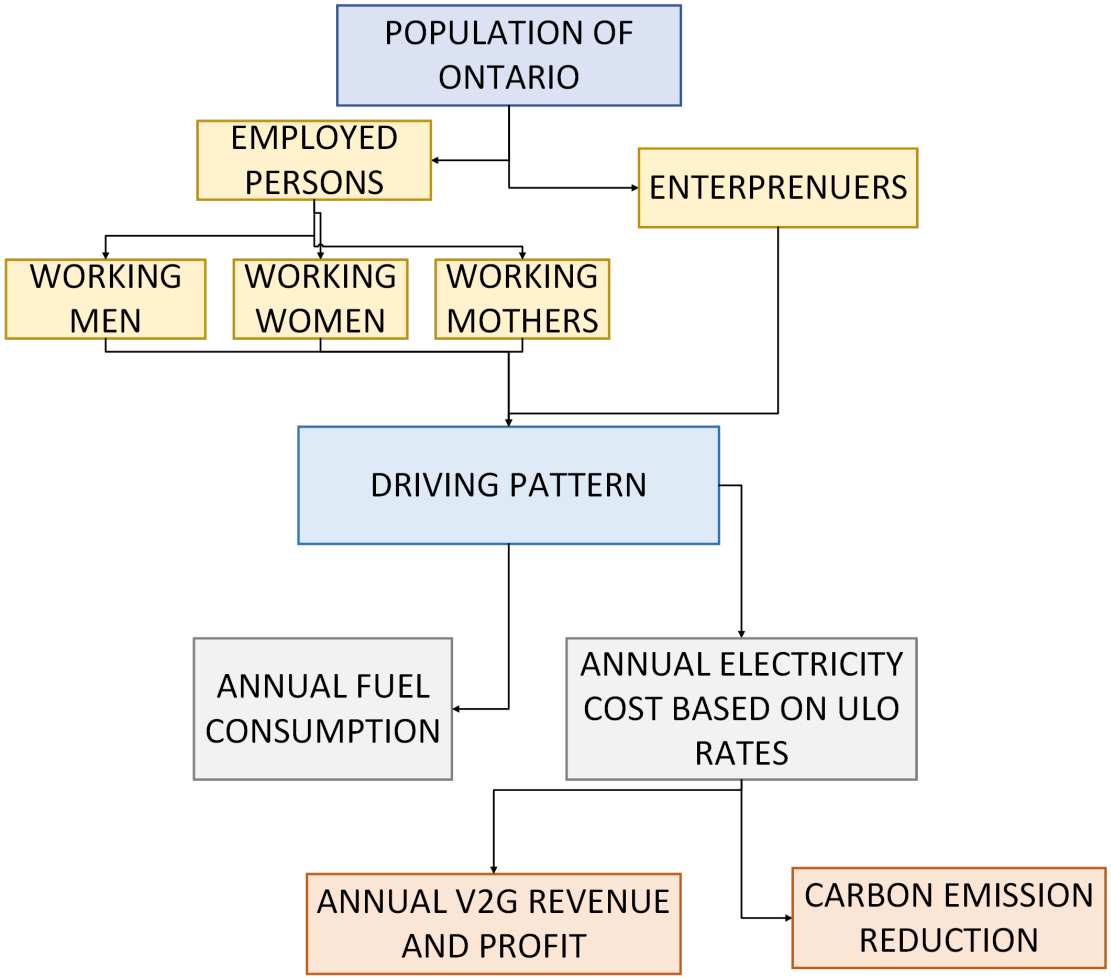


Figure 5.13: Methodological framework for open challenges and recommendations for Economic Feasibility of V2G

5.1.1 Mathematical Analysis

A thorough mathematical analysis has been performed to underscore the importance of establishing the feasibility of bidirectional charging infrastructure in Ontario. This analysis encompasses the following steps:

5.1.1.1 Distance Travelled

For the participation of EV owners in V2G, their availability at the right time and place plays a significant role [140]. Therefore, a typical driving schedule is considered in this analysis for employed persons in Ontario aged between 25-64 years. The following equation can calculate the total driving distance for a person:

$$TD = DT/day \times N \tag{5.1}$$

where, DT is the total distance travelled in km. N is the number of days in which the vehicle is travelled on this particular distance.

5.1.1.2 Annual Fuel Consumption

Based on the driving distance, annual fuel consumption varies depending on the vehicle and its efficiency. Therefore, the annual fuel consumption and gas cost can be calculated as follows:

$$AFC = TD \times FE \tag{5.2}$$

where, AFC is the annual fuel consumption in liters. FE is the fuel efficiency in L/km.

$$AGC = RG \times AFC \tag{5.3}$$

where, AGC is the annual fuel consumption in $ and RG is the average cost of unleaded regular gasoline in Ontario.

5.1.1.3 Annual Electricity Cost

To analyze the feasibility of V2G among the residents of a region. It is important to compare the consumption of gasoline by the electricity cost to charge an EV. However, the charging time depends upon the depletion of the battery over a certain period of time. Thus, the time required to charge an EV can be calculated as follows:

$$H_C = \frac{BC_D}{P_{Ch}} \tag{5.4}$$

where, H_C is the time required to charge an EV in hours. BC_D is the battery capacity that is used in the whole day and P_{Ch} is the maximum charger output. The annual cost to charge an EV depends upon the hours the EV requires charging, the number of days, and, typically, the rate at which the EV will be charging. ULO rates are considered in this analysis when charging an EV. As mentioned in the previous chapter, Ontario has introduced ULO Rates for EV owners to provide low-price electricity, specifically at night. These rates are the same in summer and winter [48]. The ULO rates are 0.028$/kWh between 11 P.M. to 7 A.M. throughout the year, including weekends and holidays. Thus, the Annual cost of charging an EV can be calculated as follows:

$$AC(\$) = N \times H_C \times P_{Ch} \times ULO \tag{5.5}$$

where, AC is the annual cost in $. N is the number of days, H_C is the number of hours for which the EV will be charged, and ULO is the Ultra Low Overnight rates for charging an EV in $/kWh [48].

5.1.1.4 Annual Revenue Cost of V2G

The financial assessment of V2G revenue cost depends upon various factors, depending on the usage and availability of every person. Thus, for the base year 2024, a generalized calculation for V2G on an annual basis can be done as follows:

$$AVR = BC_y \times ON \times N_c \tag{5.6}$$

where, AVR is the annual V2G Revenue Cost in \$, BC_y is the battery capacity in that particular year, N_c is the number of cycles of charging and discharging, and ON is the ULO On-Peak Rate.

For the ten-year analysis, the hours of charging or discharging will be difficult to estimate. Therefore, it is assumed that the EV will start participating in V2G with 70% of the battery capacity and reserve the remaining 30% for driving. The battery degradation for the capacity of the EV battery over time, which can be represented as [141]:

$$E_{CAP}(t) = E^*_{CAP} - \sum_{y=1}^{LF}(\phi * \psi + \mu) \tag{5.7}$$

where E_{CAP} is the current capacity of the EV battery in kWh, E^*_{CAP} is the nominal capacity, y is a counter for years, LF is the lifetime of the EV battery in years, ϕ is the number of charge/discharge cycles, ψ is a cycle-wise degradation factor, and μ is an annual calendar year degradation factor. As such, as E_{CAP} continues to degrade over time, the maximum power transfer will also degrade.

5.1.1.5 Carbon Emission Reduction

The calculation of carbon emission reduction depends upon the emission factors, which vary hourly and annually [137].

(a) Hourly Analysis: In this analysis, the hourly driving pattern is considered, therefore emission reductions will be the product of power during that hour and emission factor as shown by the equation below:

$$ER_h = P \times EF_h \tag{5.8}$$

where ER_h is the hourly emission reduction in gCO_2eq, EF_h is the hourly emission factor, and P is the EV power in kW. The value of P will be positive when the EV is charging and negative when discharging.

(b) Annual Analysis: The financial assessment is also done for a period of ten years. For that, the annual emission factor is considered, and it is multiplied by the battery capacity of the EV in that particular year.

$$ER_a = BC_y \times EF_a \tag{5.9}$$

where ER_a is the annual emission reduction in gCO_2eq, and EF_a is the annual emission factor

5.1.2 Survey of LDCs Websites

Ontario is Canada's most populated region, and 60 LDCs serve different areas of it. A survey is conducted for all LDC websites regarding the information they have for installing a bidirectional charging system at a residential unit.

5.2 Assumption for Analysis

The assumptions made referring to the section 5.1 are mentioned below:

5.2.1 Driving Pattern

The Ontario has a population of 14.03 million [142]. To analyze the feasibility of V2G among Ontario residents, the driving patterns of the employed residents aged between 25 and 64 years. Although the driving pattern is unpredictable and varies every second. Therefore, a typical driving pattern is considered in this analysis

based on the commuting duration mentioned in the statistics Canada [143]. The employment rate in Ontario is 64.9%. Among these people, the full-time working men and women are 4,179,100 and 3,765,300, respectively [144]. Working women can be mothers, too. According to the statistics of Ontario, 91% of mothers decided to return to their jobs after 2021, and they found to be 125,351. The women who are mothers are considered separately in this analysis because their vehicle usage is high due to the daily pick-ups and drop-offs for kids. The business owners are also considered in this analysis; they were found to be 448,007. The numbers in this analysis are variable, but the recent data is taken based on the Canadian census of February 2024 [145].

The complete daily driving pattern for working men, women, mothers, and entrepreneurs can be found in the section A.1. In this analysis, working men are considered as X, working women as Y2, while working mothers as Y1, and businessmen as Z. Based on the assumptions, the total driving distance traveled by the considered subjects is shown in Fig. 5.14.

The distances mentioned here are based on the average driving distances for people in Ontario across all categories [143]. It has been observed that working men and women typically commute around 90 km per day, while working mothers cover a distance of 190 km. On the other hand, businessmen usually travel around 180 km. The common time for all three cases to start work is between 7 A.M. and 8 A.M., as indicated by Statistics Canada's data showing the peak commuting times [146]. However, this schedule may not apply to the entire population. It's important to note that not all employed individuals use personal vehicles, although the majority opt for cars, trucks, or vans over other modes of transportation [143]. As such, the analysis takes into account the number of passenger vehicles. In 2023, 90% of Ontario residents preferred gasoline engines, resulting in 542,372 new

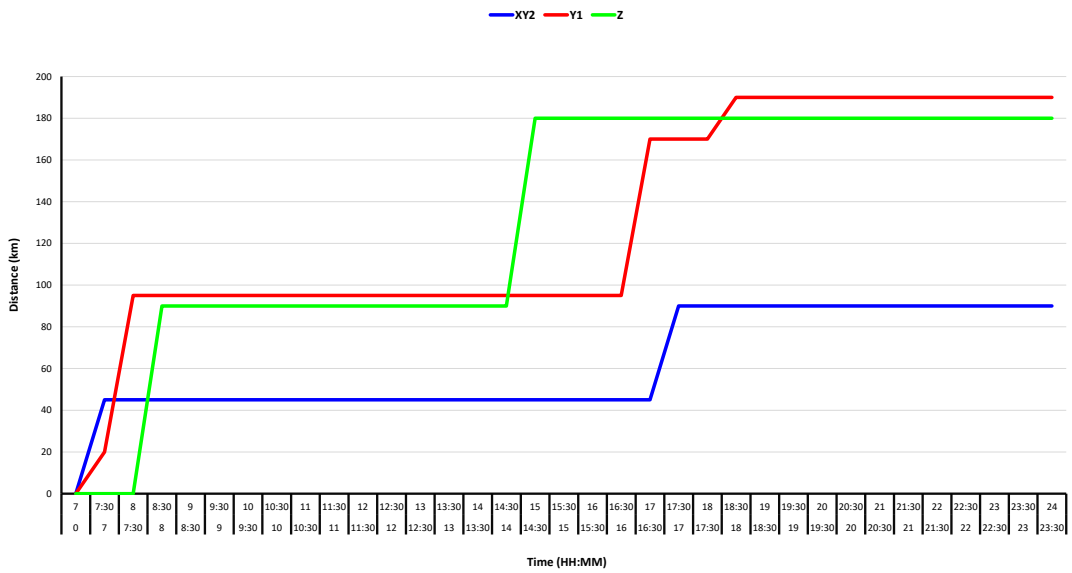


Figure 5.14: Total Driving distance by the considered subjects in km

gasoline vehicles purchased [147].

5.2.2 Choice of vehicles

The choice of a vehicle is crucial and depends on several factors, including efficiency, price, comfort, size, budget, performance, and safety. It is worth noting that gasoline engines have a higher market share in Ontario, around 94.2%. Therefore, the most common vehicle considered in this analysis is the 2023 Toyota Corolla SV, priced at $31,150, with a fuel economy of 0.069L/km. This vehicle is considered to use regular fuel and is the most practical and economical. However, the calculations based on these vehicles will be the minimum amount of fuel, and the price will be higher for the gasoline engines, which take premium fuel.

To evaluate the feasibility of Vehicle-to-Grid (V2G), an in-depth examination was conducted. The same driving patterns and passenger capacity will be factored

in when using an electric vehicle (EV). While various EVs are available in the market, only a few support bidirectional charging. Gasoline engines are deemed the most practical and economical, but different criteria were considered for EVs. The new EVs in the market are more cost-effective in terms of pricing and charging capabilities. For this analysis, the 2024 Kia EV 9 was chosen based on these criteria:

- Supports bidirectional charging
- Economical
- High electric range
- Efficient

Kia EV 9 2024 has a retail price of around $60,000 with an electric range of 370 km. It has a battery capacity of 99.8 kWh with an energy consumption of 0.259 kWh/km and requires 7 hours to charge entirely to the onboard charger of 10.9 kW. Very few chargers support bidirectional charging in the market, and their price estimation varies from the onboard charger power. Therefore, based on its charger rating, the Wallbox Quasar2 is considered in this analysis, whose price will be $10,000 considering $1,000/kW.

In order to charge an electric vehicle (EV) at home, it's important to consider the household's electricity usage. The charging system must not overload the home's electrical system, which is limited by the capacity of the cables and transformer from the LDC, with a maximum energy consumption of 10 kW. The charger chosen here has a maximum power rating of 7.7 kW. In Fig. 5.15, you can see the typical electricity demand of a household without an EV, with a maximum consumption of 3 kW. There's a threshold of 2.32 kW, and it's recommended not to charge the EV during peak times. Fig. 5.15 shows that the peak time during summer is between

10 A.M. and 8 P.M. while in winter, between 4 P.M. and 9 P.M. However, this will not be an issue between 11 P.M. and 7 A.M. when the subjects considered in this analysis will be at home based on the driving schedule.

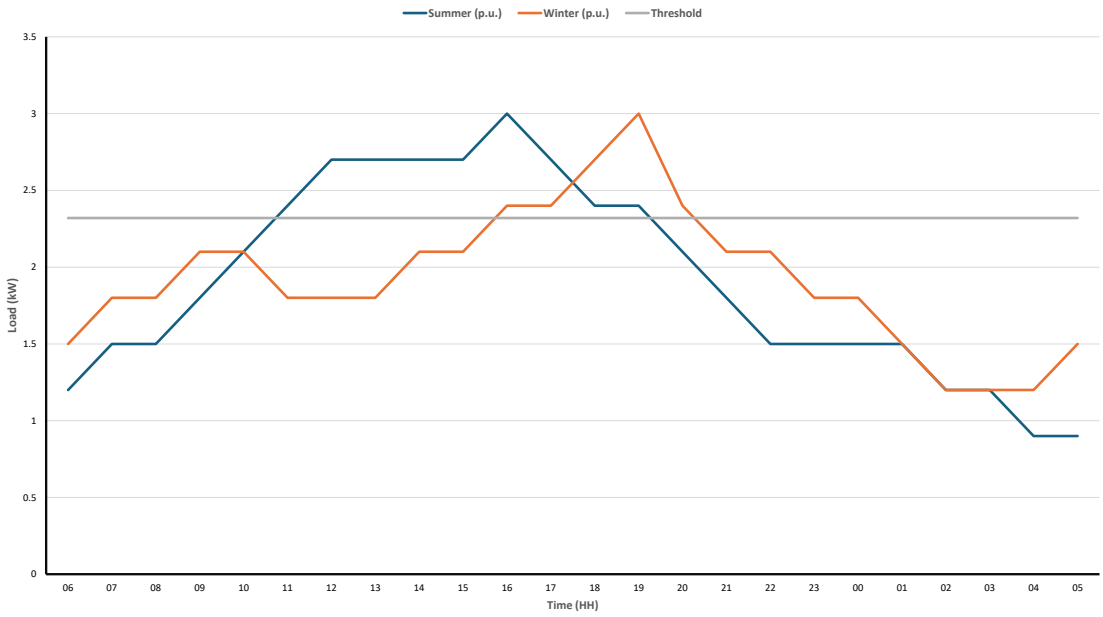


Figure 5.15: Demand Profile of a Residential Unit without an EV

5.2.3 Assumptions for Bi-directional charging analysis

To estimate the financial analysis of bi-directional charging, some assumptions have been changed as mentioned below:

- Subjects X and Y2 have the same routine and can participate in V2G from 6 P.M. to 9 P.M. during weekdays.
- Subject Y1 will be doing the hybrid job and stays at home on Monday, Wednesday, and Friday. Participation in V2G is from 6:30 P.M. to 9 P.M. on Tuesdays and Thursdays while 4 P.M. to 9 P.M. on other weekdays.

- Subject Z are entrepreneurs, and according to the considered schedule, they will be at home by 4 P.M. and can participate in V2G for 5 hours during weekdays.

5.3 Results

The results based on the mathematical analysis and assumptions made in the section 5.2 will be discussed in this section.

5.3.1 Annual Fuel and Electricity Cost

Table 5.9: Annual Consumption of Fuel and Electricity for Gasoline Vehicles and EVs

Subjects	TD (km)	AFC (L)	AGC ($)	AC ($)	H_C
X and Y2	22500	1552.5	2530.58	181.636	3h 4min
Y1	47500	3277.5	5342.33	370.258	6h 9min
Z	45000	3105	5061.15	349.3	6h 5min

The table 5.9 shows the annual cost of fuel and electricity for driving at the same pattern, which is considered for subjects X and Y2, Y1 and Z. By considering the economic vehicle with regular gas consumption and the average driving distance traveled by X, Y2, Y1, and Z in the whole year. It is found that an employed person has to pay on average $4311.35 just on fuel for travel. Recalling that, TD is the driving distance in km, AFC is the annual Fuel Consumption in liters, AGC is the annual gas cost in $, AC is the yearly cost to charge an EV is $ while H_C is the time required to charge an EV. It is observed that the battery usage for X and Y2 is 26%, and they might not need to charge an EV every day if they do not wish to participate in V2G. While for Y1 and Z, the battery usage is 53% and

50%, respectively. Thus, they have to charge their EVs every day. Furthermore, the annual fuel consumption is 13.93, 14.43, and 14.49 times more than the price of charging an EV for X and Y2, Y1, and Z, respectively. The X and Y2 can save around $2348.94, Y1 can save $4972.07, while Z can save $4711.85 annually.

5.3.2 Financial Analysis of Bi-directional Charging

Recalling that due to the 10 kW limit, the EV can only be charged between 11 P.M. and 7 A.M., which is enough for charging. While the ULO peak hours are between 4 P.M. and 9 P.M. with charges of 0.286$/kWh throughout the year. To get the maximum revenue, it is essential to discharge EV for 5 hours during weekdays. The Wallbox Quasar 2 has bidirectional charging capabilities, but an additional $6,000 is considered for the labor cost from a certified electrician and net-metering system [40]. Based on these, the total cost of V2G provision for bidirectional purposes will be $16,000.

5.3.2.1 Base year 2024

The annual V2G revenue can be calculated based on Eq. 5.6 and the profit will be the difference of Eqs. 5.6 and 5.5 as shown in Table 5.10.

Table 5.10: Annual V2G Revenue and Profit

Subjects	AVR ($)	AVP ($)
X and Y2	2283.424	2101.788
Y1	2854.28	2484.022
Z	5708.56	5359.26

It is shown in Table 5.10 that subject Z participates in V2G every day and

can make a profit of approximately $5,000 in one year. At the same time, the other subjects make a profit between $2,000 and $2,500 each year. The profit is high because of the ULO rates, which give EV owners an edge for charging at a meager rate while discharging at a higher rate. Moreover, the EV considered in this analysis has a high battery capacity, allowing the EV owners to participate in V2G even after driving more than 150 km daily.

Based on the schedule considered for V2G and the emission factors on an hourly basis from The Atmospheric Fund [137]. The emission factors daily from the subjects considered are shown in Table5.11.

Table 5.11: Carbon Emission Reduction in gCO_2eq from the considered subjects daily

Reduction From X and Y2	-387.08
Reduction From Y1 during office days	-235.73
Reduction From Z during office days	-882.90
Reduction From Y1 and Z during work from home days	-931.7

It's important to note that gasoline engines make up a higher percentage of passenger vehicles. If these vehicles travel the assumed distance daily, the average carbon dioxide (CO_2) emissions per day is -609.35g. It's important to consider that 1 liter of gasoline emits 630 g of carbon [148]. The gasoline engine considered here is Toyota Corolla 2023 SV for all the subjects, based on the distance travelled by each subject and the number of gasoline engines available in Ontario at the moments. The annual CO_2 emissions amount to 3,615,126,330 g, recalling that the number of gasoline engines are 542,372. This is a matter of urgency, especially given the increasing global warming in Ontario. As a result, a ten-year analysis has been conducted to assess the feasibility of V2G.

Table 5.12: Population of the considered subjects for the next ten years

SUBJECTS	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
X	4021757	4074040	4127002	4180653	4235002	4290057	4345828	4402323	4459553	4517528
Y1	120631	122199	123788	125397	127027	128679	130352	132046	133763	135502
Y2	3502905	3548443	3594573	3641302	3688639	3736591	3785167	3834374	3884221	3934716
Z	431140	436744	442422	448174	454000	459902	465880	471937	478072	484287

5.3.2.2 2025-2034

A ten-year analysis assessed the profit potential for electric vehicle (EV) owners through vehicle-to-grid (V2G) technology. The analysis is conducted based on the profit the EV owners will earn in ten years, the increment in the reduction of GHGs with the increase in population for the whole region, and how much EV owners will be able to provide power to the distribution system with an increase in power demands.

1. Profit earned by EV owners: According to Fig. 5.16, subject Z has the potential to earn a profit of around $4,000 per year. Meanwhile, participants X and Y2 can collectively make a total profit of $2,000 per year, and participant Y1 is eligible for incentives worth approximately $1,500 per year. While these profits just include the incentive earned by the government for participating in V2G based on ULO rates. The carbon emission reduction from each considered subject based on the Eq. 5.9 is calculated and found out that each subject can reduce carbon emission by 8,000 g of CO_2 annually.

2. Carbon Emission Reductions by each subject: With each passing year the population of Ontario will increase by average of 1.3% [149]. Based on that the population for the considered subjects for the next ten years is shown in Table 5.12.

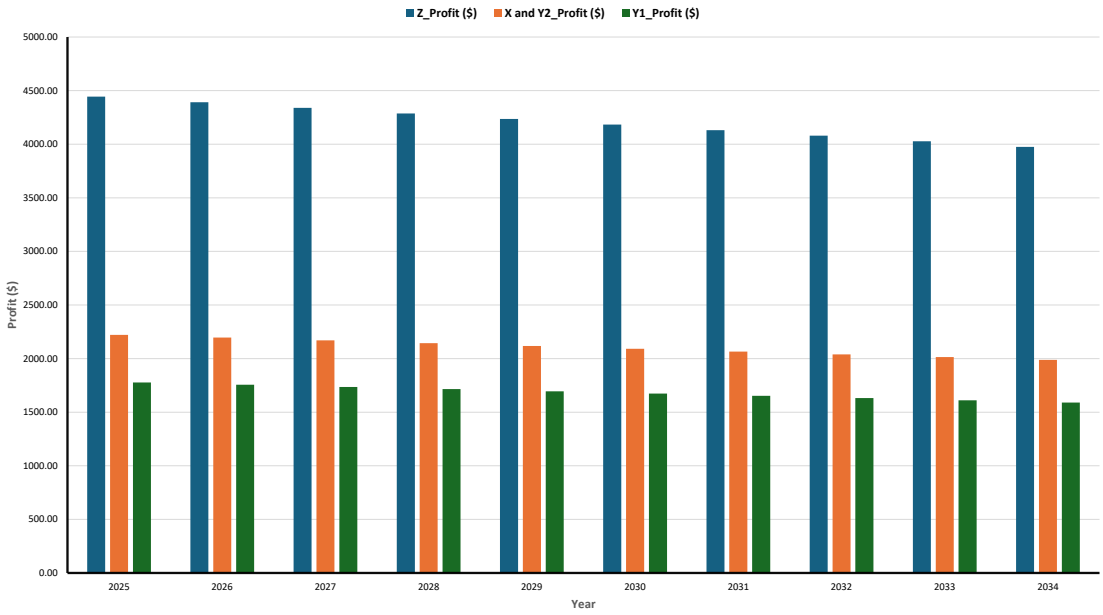


Figure 5.16: Profit of each subject over the period of ten years

Each subject will reduce an average of 0.008 tonnes of CO_2 emissions annually, a tangible and significant reduction. Based on this value, collectively, the emission reduction by each subject is shown in Fig. 5.17. The GHG emissions were reduced collectively by subjects Z, X, Y1, and Y2 with an average of 3658, 34123, 1024, and 29721 tonnes of CO_2 emissions, respectively. This specific reduction in CO2 emissions is a clear sign of our progress and success in combating global warming.

It's important to note that EV owners who opt to participate in V2G have the potential to increase their profits and can expect to begin making a profit. Even after ten years, the cost of battery replacement can be offset by the profit earned during this period. Therefore, V2G appears to be economically viable in this analysis, especially if EV owners choose to participate in V2G on a daily basis.

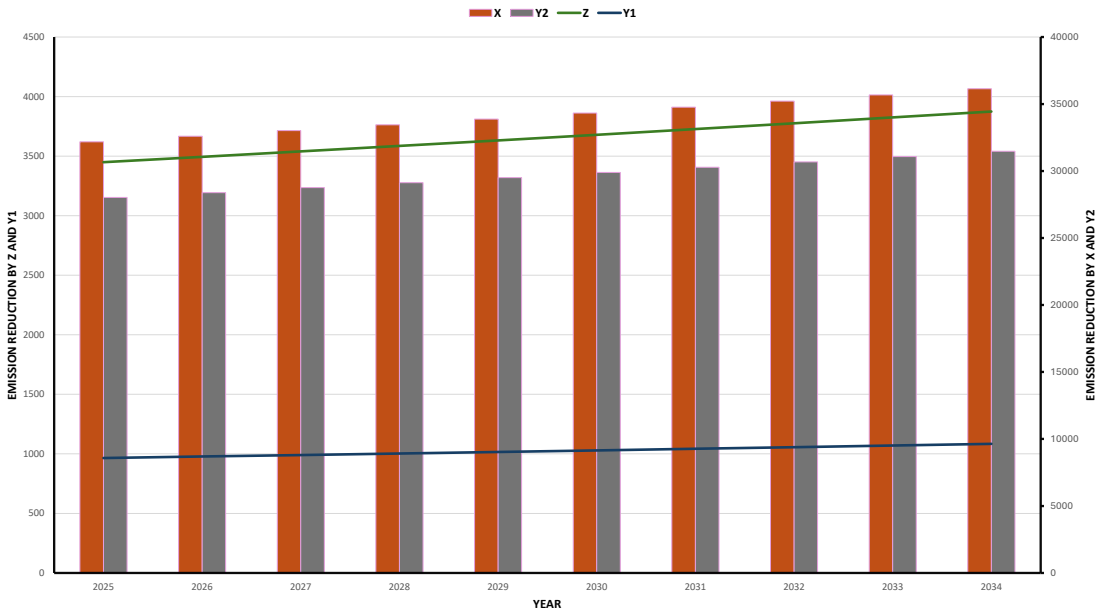


Figure 5.17: Emission reductions by all considered subjects for the period of ten years

5.3.3 Challenges

The survey is conducted for all 60 LDCs websites in Ontario serving a population of 14.3 million [150] calculated on April 1, 2023. The population each LDC serves is shown in A.1. The information gathered by all these LDCs for installing a bidirectional charging setup for V2H were non-uniform. Fig. 5.18 will show the information collected by all these LDCs websites, while Table 5.13 will represent the symbolic representation of the issues.

5.3.3.1 Uncertain and Potentially Expensive Upfront Costs for Installation

- Various bidirectional chargers are available in the market. Every charger comes with its features. Uncertainty about the different components and ex-

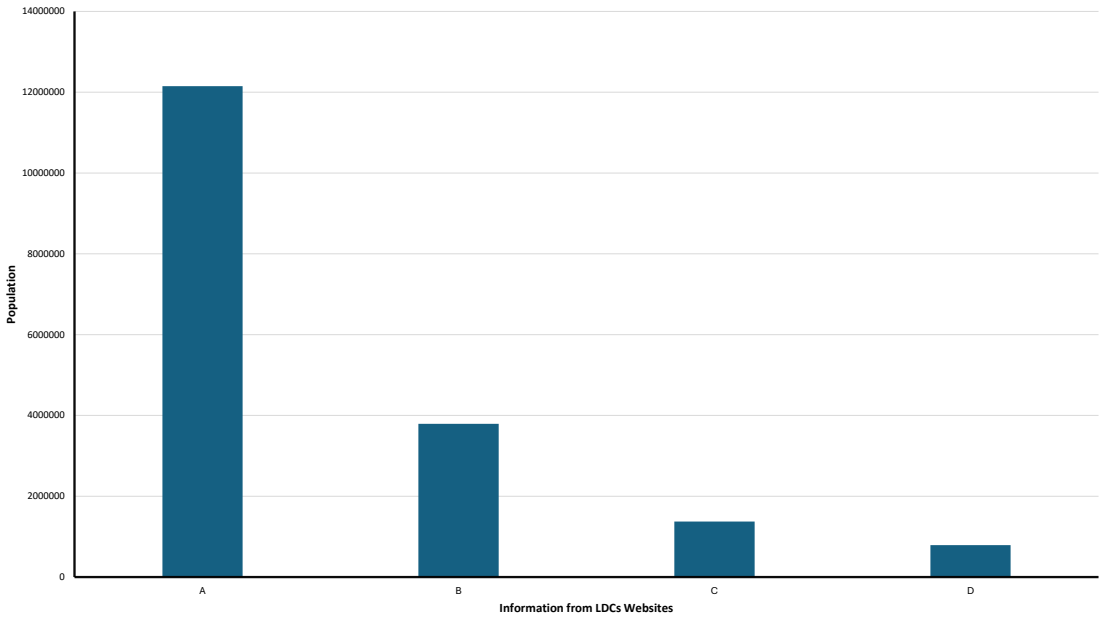


Figure 5.18: Information collected from LDCs websites

penses of bidirectional charging leaves customers unsure about the technology.

- Customers might need to upgrade their electrical panels to install a bidirectional charging setup. Most residential areas in Ontario have an electrical panel of 100A; while providing bidirectional power flow, more power will be required, and we can't exceed 125% of the capacity according to Canadian Electrical Code 64-112 (4) for homes. The upgrade of an electrical panel in Ontario is around $1,400 to $5,125 depending upon the customer's needs and condition, such as cabling, location, etc. [151]. The LDCs serving a population of around 1.2 million in Ontario have the proper step-by-step instructions available on the website. These instructions emphasize the importance of upgrading the electrical panel, if needed, under the supervision of a certified electrical contractor. This professional ensures that the upgrade is done safely and according to code. Once these things are done, the EV owner can

Table 5.13: Symbolic Representation of the information from LDC websites

SYMBOL FOR INFORMATION	INFORMATION
A	Proper step by step information for installing charger
B	No information, just PCIR Form
C	Nothing
D	They are referring to the OEB website and look for the safety authority first, then upgrade.

contact LDCs to install a bidirectional charging setup.

5.3.3.2 Fragmentation

The information collected from Local Distribution Companies (LDCs) needs to be more cohesive. LDCs that serve approximately 67% of Ontario's population provide step-by-step guidance for installing bidirectional chargers. In contrast, those serving about 21% of the population offer information on installing renewable energy resources but must cover independent energy sources. Additionally, LDCs serving only 8% of the population need more information about these resources. Finally, LDCs catering to a mere 4% of the population refer users to Ontario Energy Board (OEB) websites for safety guidelines. This latter group primarily consists of rural areas where the building code differs from the new standards differs from the new standards.

5.3.3.3 Lack of Education and Awareness

Bidirectional Charging will create significant differences in the future of power generation and in reducing Greenhouse gas emissions [49]. All LDCs must follow uniform criteria. Every LDC is going in their direction. Even if some do not provide a bidirectional power supply, if any customer wants that facility in their region, it will be a problem for them. This will create more confusion for the customers. All LDCs should contact EVs' original equipment manufacturers (OEMs) and the government to develop a regulated policy. The policy must be well thought out and coordinated with all the Ontario energy guidelines. The next concern is who will supervise this responsibility of education, like the OEMs, utilities, or regulators. The price of education is also a big factor that aggravates this issue. It must be well thought out and coordinated with the primary aspects of a bidirectional charging system.

5.3.3.4 Net Metering

As discussed above, some utilities do not allow customers to be involved in bidirectional charging as an EV is an independent energy source, not renewable. Moreover, in Ontario, a customer with only an EV bidirectional power supply might move towards the tiered rate, which depends on usage, not the time [40]. For example, if a customer is using their EV for V2H purposes, then they can run all of their essential appliances during peak hours while using the energy stored by the EV which will be shown in section 4.4. They can also take advantage of the ULO rates. But if they move towards tiered rates, then the whole purpose and the investment they made will vanish. It means that an EV owner cannot take advantage of the lower rates and hence cannot contribute to improving the emission factors of the

grid [49].

5.3.4 Recommendations to Mitigate Barriers

To overcome these challenges, the authors have the following recommendations, aided by feedback from stakeholders in the electricity sector.

5.3.4.1 Policy for Standalone Unit

The Ontario government has to take steps by introducing a policy other than net metering [40] for standalone units. This policy must consider the fact that the charging and discharging of EVs vary from one person to another, and there is also a factor of battery degradation involved in it [43]. Suppose the customers providing bidirectional power move towards tiered rates, and none of the customers will invest in setting up a bidirectional charging setup. In that case, the people of Ontario will be left behind in producing clean electricity.

5.3.4.2 Workshops for LDCs

All of the LDCs in Ontario are suggested to arrange workshops related to the real-world deployment of V2H for the staff working in the maintenance and engineering department specifically. These workshops will give them sufficient knowledge about the importance of its technical, environmental, and economic aspects.

5.3.4.3 Uniformity

There must be a uniform policy for installing the bidirectional setup as we have for renewable energy resources. As discussed in the previous section, every LDC has its way of installing it, and the structure for bidirectional chargers is fragmented.

5.3.4.4 Provide Education to the Customers

It is essential to provide education to the customers, specifically to those who are buying Electric Vehicles (EVs), on how they can take part in reducing GHG [49], produce backup power and reduce their bill by taking incentives from the government.

5.3.4.5 Carbon Incentives to Reduce GHGs

As shown in the section 5.3, the participation of EV owners in V2G can lead to a substantial reduction in GHGs. However, the government has not yet introduced a carbon incentive program. By implementing a program where EV owners earn carbon points based on their reduction can empower them to take a more active role in reducing GHGs and make them feel more responsible for the environment.

5.3.4.6 Supervision of the Workshop

The workshops that needed to be arranged to provide sufficient knowledge of a bidirectional charging setup must be supervised by highly professional and technical persons who can design these workshops so efficiently that they will be understandable by people of all hierarchies.

5.4 Summary

In this chapter, a mathematical analysis was conducted to emphasize the importance of implementing Vehicle-to-Grid (V2G) technology in the Ontario region. It was noted that there is a need to reduce the number of gasoline engines by increasing awareness among residents and encouraging the adoption of V2X technology.

To achieve this, the government has taken steps such as offering rebates for purchasing electric vehicles (EVs) and introduction of ULO ratses. With Ontario's growing population and increasing number of passenger vehicles, CO_2 emissions are also on the rise. As a result, this chapter provides recommendations supported by mathematical results to demonstrate the necessity of transitioning to V2G technology. There is still some work needs to be done for its improvement and security as the privacy of the EV owners will be compromised by considering their driving distance, their location, vehicles' information will be available publicly which is a high risk for their security.

However, this chapter does a general analysis. Other factors are also involved in V2G. Most importantly, the cost-benefit analysis for all the stakeholders involved in V2G is considered. The detailed economic analysis will be discussed in the next chapter.

Chapter 6 - Cost Benefit Assessment of V2G in Demand Response

The previous chapter was related to the feasibility of V2G in Ontario. It is also discussed in Section 3.6 that there is a lack of cost-benefit analysis for the V2G program considering all the stakeholders involved. Therefore, this chapter is dedicated to the techno-economic analysis of the feasibility of V2G for twenty years. Section 6.1 gives the methodological framework for the study, while section 6.2 lists all the assumptions and the results obtained from the adopted method. Lastly, section 6.3 gives the conclusion and the future recommendation

6.1 Methodological Framework

For LDCs, cost reductions can be achieved by flattening the demand curve by reducing the size of daily peaks. This would be accomplished by cutting consumer rates and the cost of energy and infrastructure upgrades. The techniques used to evaluate the cost-effectiveness of using V2G for peak shaving for LDCs in Ontario are covered in this section. Fig. 6.1 illustrates the analysis of V2G service programs where owners of EVs in residential areas, hereafter referred to as battery EVs (BEVs), are contacted directly by LDCs and given incentives. It is worth noting that the results of this study are highly input- and assumption-dependent and, thus, are not intended to be definitive judgments on the programs addressed. For

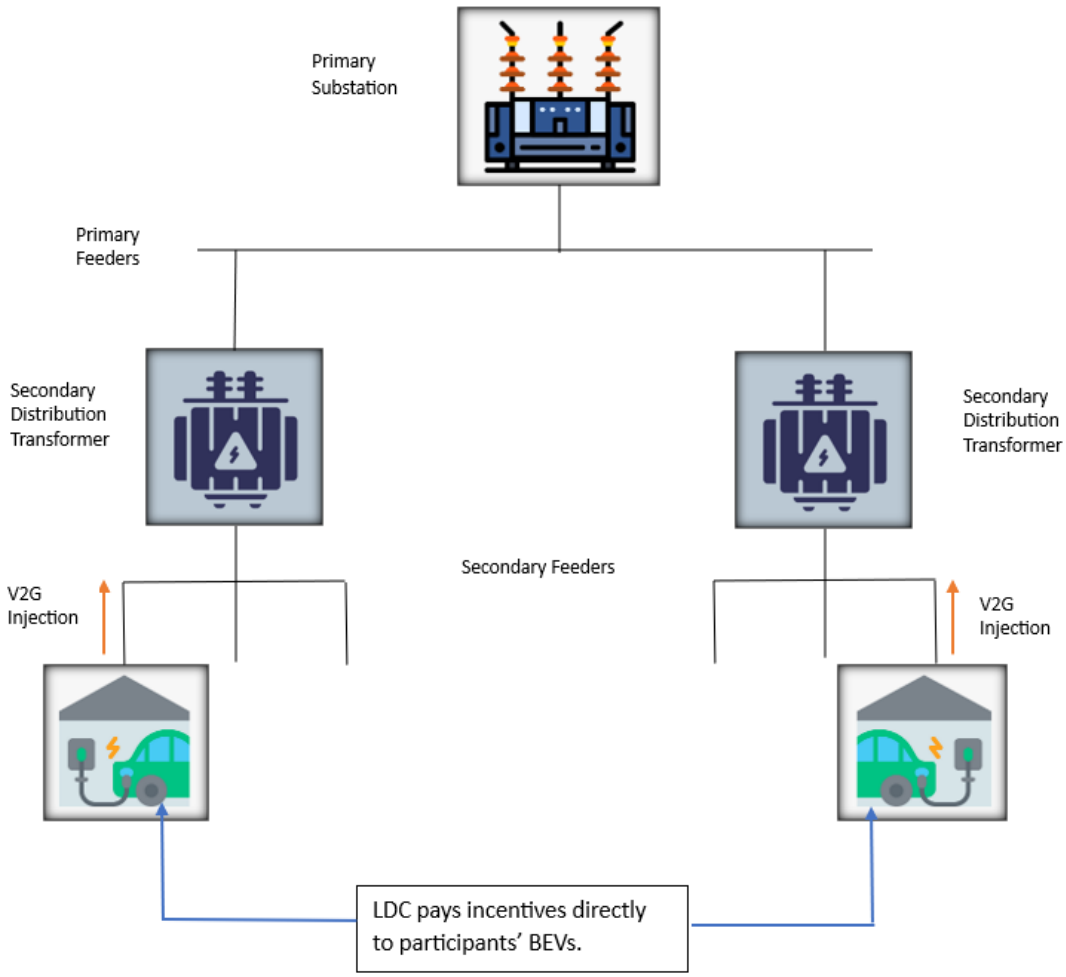


Figure 6.1: V2G Service Program for Residential BEVs

this reason, we also provide the model we used to generate these results so that the Working Group may adjust the inputs as members see fit. Additionally, members of the Working Group may use the model to tailor various costs and benefits of their programs as per their expected inputs.

Fig. 6.2 provides the key parameters for the input and output of the V2G benefit and cost analysis implemented in this study.

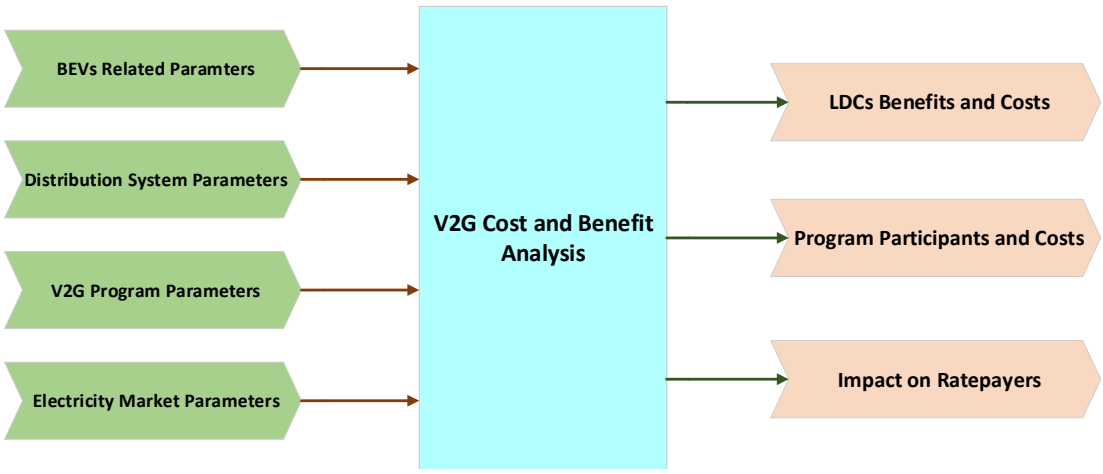


Figure 6.2: Key Parameters for V2G Benefit and Cost Analysis Calculations

The key benefits and costs in this study are as follows:

1. LDC Costs:

a. Administrative costs of the program.

b. Incentive costs paid to participants.

c. Equipment used for the program, such as communication devices.

d. Bill reduction due to the program.

2. LDC Benefits:

a. Avoided Transmission and Distribution System Capacity Costs.

b. Avoided Peak Energy Costs.

3. Participants Costs:

a. Cost of Bidirectional Charger.

b. Battery Degradation Costs for BEVs.

c. Energy Cost (e.g., Charging of EVs during off-peak hours).

4. Participation Benefits:

a. Incentive Costs paid by the utility.

b. Capacity Payments paid by the utility.

c. Bill Reductions by providing V2G services.

The ratepayer's costs will be the same as administrative costs, including the revenue reductions. However, its benefits remain the same as those of the administration. A detailed framework of these specific parameters is shown in Fig. 6.3.

6.1.1 V2G Capacity Estimation

Estimating the actual useable capacity that BEVs can provide the LDC for peak shaving is the first step in assessing the costs and advantages of the proposed V2G schemes. The estimation's mathematical formulation is provided below.

6.1.1.1 Capacity Estimation from the Residential V2G Program

The number of participants in a residential V2G program in the year y for the proposed residential V2G program is calculated as follows:

$$N_y^{V2G} = N_y^{BEV} R_y^{V2G} \tag{6.1}$$

where: N_y^{BEV} is the number of BEVs in Ontario in the year y. R_y^{V2G} is the expected participation rate in the V2G program in year y.

The total capacity of deliverable V2G power at peak times by BEVs in Ontario for the year y in MW is calculated as follows:

$$P_y^{V2G} = \eta N_y^{V2G} P_y^{BC} A_y^{V2G} \tag{6.2}$$

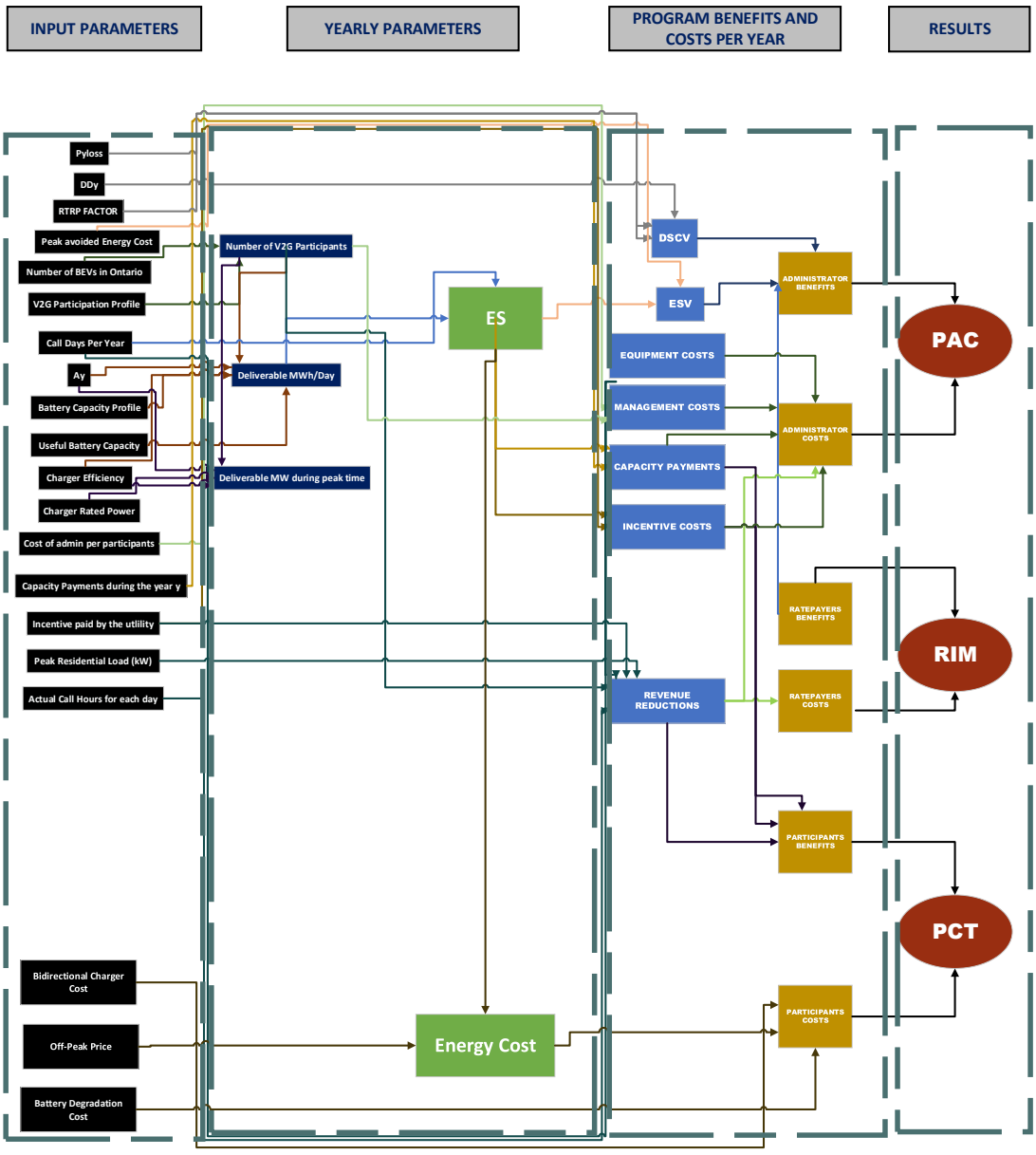


Figure 6.3: Framework for Parameters of V2G Cost Benefit Analysis

where A_y^{V2G} is the availability factor for the year y in %. P_y^{BC} is the average rated power for bi-directional chargers in Ontario for the year y in kW. η is the

average efficiency of BEV chargers in %.

The total deliverable V2G energy during a day by BEVs in Ontario for the year y in MWh is calculated as follows:

$$E_y^{V2G} = \eta N_y^{V2G} A_y^{V2G} B^{V2G} B_y^{BEV} \tag{6.3}$$

where B^{V2G} is the useful battery capacity percentage in %. B_y^{BEV} is the average battery capacity of BEVs in Ontario for the year y in kWh.

The element of availability is the value of A_y^{V2G}, which is the fraction of capacity that the V2G program may obtain, given the quantity and duration of requests (calls) permitted. . For instance, BEVs will be accessible for half of the period when they are called upon if $A_y^{V2G} = 60\%$.

6.1.2 Avoided Distribution System Capacity Cost

The "avoided cost"—that is, the cost that utility consumers would not experience if the T&D upgrade is not made—is the essence of the T&D deferral benefit. The income requirement is equal to the saved cost. An upgrade deferral option is frequently available for a year or several years. In those circumstances, the annual averted cost (the annual revenue requirement) for the year or year the upgrade is postponed represents the deferral benefit [152].

An LDC determines annual investment in its distribution network through its capital budgeting procedure. Distribution networks are built to handle expected peak loads. The budget for the next five years can be predicted (for example, by transmission estimates), but investments for the upcoming year are far more crucial, and lead times are less critical. Investments in systems typically relieve limitations and address dependability issues, meeting projected needs for several years. Distribution planners evaluate the overall performance of the LDC system to create

a capital budget, but they also suggest targeted expenditures in feeders, substations, and other distribution system hardware. Several criteria are considered when assessing whether specific improvements are needed, including historical outages, predicted load growth, substation, feeder line load estimates, and investments that may have been rescheduled from the previous year. For alternatives requiring more in-depth examination, distribution planners will employ complex power flow models to evaluate a network's resilience across various potential scenarios. During capital budgeting, prospective investments are ranked according to a predetermined set of standards [153].

V2G services can help postpone distribution system expenditures so that their potential capacity contribution is represented in the prioritizing calculation. Concerning Fig. 6.1, capacity can be limited at a substation location even when the feeders behind that substation have sufficient capacity. This restriction is lessened by any V2G injection located behind the substation. In other situations, a substation may be able to meet demand, but a particular feeder may be constrained and need modernization. Only V2G injections in a specific feeder will provide capacity deferral value.

Upgrading a distribution system depends on how much it will cost to buy and install the equipment needed when the projected load exceeds the installed equipment capacity. Reactive power and harmonic currents are not considered when analyzing the distribution system deferral advantage of BEVs. This study disregards the monetary value of equipment removed to create a place for new distribution system equipment, even though some may be used again. Given that the installed equipment currently has a P_c capacity, should the anticipated load exceed P_c, an upgrade factor of 25% to 50% [154] must be applied to the equipment. This upgrade factor is described as follows:

$$\beta = \frac{P_n - P_c}{P_c} \tag{6.4}$$

where: P_n is the capacity of the upgraded equipment. Based on the anticipated load in that year and the capacity of the currently installed equipment, the minimum necessary V2G capacity P_y^R in the year y is determined as follows:

$$P_y^R = P_y^m - P_c \tag{6.5}$$

where: P_y^m peak forecasted load during the year y. The distribution system deferral for the year y (DD_y) in ($/kW-yr) with respect to the V2G capacity is calculated as follows:

$$DD_y = \frac{FCR \times C_n}{P_y^R} \tag{6.6}$$

where: C_n is the cost of purchase and installation of upgrade equipment with a capacity of P_n. FCR is fixed charge rate (FCR) %. The annual cost to cover the capital investment is covered by the FCR, including insurance, taxes, interest, depreciation, and any operating and maintenance costs that are not based on the number of kilowatt-hours sold by the system [152]. Lastly, the following formula is used to determine the distribution system capacity value (DSCV):

$$DSCV = \frac{DD_y}{(1 - P_y^{loss}) \times RTRP} \tag{6.7}$$

where: DD_y is distribution system deferral in Ontario for the year y in($/kW-yr). RTRP is the distribution system's right time and right place (RTRP) adjustment factor in % [155]. P_y^{loss} are distribution system on-peak losses in %.

The RTRP factor adjusts the distribution system deferral benefits from the V2G program according to whether it will directly affect the regions that require an upgrade. This implies that a V2G injection is not program-beneficial if it occurs

when no capacity improvement is necessary or when the equipment is not under stress.

6.1.3 Avoided Peak Energy Costs

Peak-time V2G discharge reduces energy loss, which may be measured as follows:

$$ES = E_y^{V2G} \times CD_y \tag{6.8}$$

where: ES is the energy that is saved during peak hours. CD_y is the number of days the V2G program is expected to be called upon during the year y. ES must be less than or equal to E_y^{V2G} for a single day. The avoided energy value is calculated as:

$$ESV = Cost_{PAE}ES \tag{6.9}$$

where: $Cost_{PAE}$ is the Peak Avoided Energy Cost calculated using the 2020 deferral information worksheet, 2021 global adjustment Estimates, and Actual Recovery rates [156].

6.1.4 Program Costs and Benefits

6.1.4.1 Administrator (LDC)

The program's equipment requirements, participant incentives, and project management expenses are all included in the V2G project's administrative costs. Here's how these expenses are computed:

$$\begin{aligned}\text{Program Administrator Cost (PAC)} = \text{Management Costs} + \text{Incentive Costs} + \\ \text{Capacity Payment} + \text{Equipment Costs}\end{aligned} \tag{6.10}$$

The management costs are:

$$\text{Management Costs} = N_y^{V2G} C_y^{Admin} \tag{6.11}$$

where: C_y^{Admin} is the administration cost per participant for the V2G program during year y.

The incentive costs are:

$$\text{Incentive Costs} = ESC_y^{Incentive} \tag{6.12}$$

where: $C_y^{Incentive}$ is the incentive paid during the year y for each kWh injected into the grid.

The capacity payment is provided to participants based on the V2G capacity they provide to the grid.

$$\text{Capacity Payment} = P_y^{V2G} C_y^{CP} \tag{6.13}$$

where: C_y^{CP} is the capacity payment during the year y for each kW availability.

The equipment costs are the software required to control all participants' bidirectional charging setup from the LDCs' perspective.

The total benefits to the LDC include the summation of DSCV and the avoided peak energy value:

$$\text{Adminstrator Benefits} = \text{DSCV} + \text{ESV} \tag{6.14}$$

For all tests, an index of benefit/cost ratio is defined as the total benefits divided by the total expenses. The program benefits the tested person when an index is more than one. In contrast, an index of less than one indicates that the program is detrimental to the individual overall. The program administrator costs index is defined as follows considering this discussion:

$$\text{PAC Index} = \frac{\text{Administrator Benefits}}{\text{PAC Costs}} \tag{6.15}$$

6.1.4.2 Ratepayers

The ratepayers are those customers who don't have EVs. They might be affected by increasing the electricity rate and costs of other things. That's why their index is also calculated in this model. The Rate Impact Measurement (RIM) cost includes the effects of the V2G program on the energy bills paid by LDC ratepayers in the area served by a program. In addition to the administration costs, RIM includes the revenue lost due to the program.

$$\text{RIM Costs} = \text{PAC} + \text{Revenue Reductions} \tag{6.16}$$

The revenue reductions are calculated based on the revenue lost due to reduced energy consumption (net metering) via participation in the V2G program:

$$\text{Revenue Reductions} = \text{Peak Residential Load} \times CH_D \times \text{Bill Savings Rate (\$/kWh)} \times CD_y \times N_y^{V2G} \tag{6.17}$$

where: Peak Residential Load is the peak load in kW that EV will provide. CH_D is the average actual call hours for each call hour per day. Bill Savings Rate is the peak rate.

The benefits of RIM will be the same as administrator benefits. Based on the discussed equations, the RIM index is defined as:

$$\text{RIM Index} = \frac{\text{Administrator Benefits}}{\text{RIM Costs}} \tag{6.18}$$

6.1.5 Participant BEVs Costs and Benefits

BEVs are expected to purchase their bi-directional charger and pay for maintenance and energy to power the LDC. Additionally, owners must bear the expense of

battery degradation as EV batteries deteriorate. Benefits include bill savings from V2G injections, lowering their net usage, and incentives from LDCs. Capacity fees for being available at the anticipated call time are another advantage.

$$\text{BEVs Particpants Cost} = \text{Cost of Bidirectional Charger} + \text{Energy Costs} + C_D \tag{6.19}$$

where: Cost of a Bidirectional Charger is the cost of buying a new bidirectional charger or upgrading the unidirectional charger to a bidirectional charger. Energy Costs=ES x Off Peak Price x 1000 C_D is the battery degradation cost in ($/kWh), which is discussed below: The battery degradation calculation is critical, varying from one person's usage to another. The EV owner's residential area is vital in the calendar aging process. Here, we are considering Ontario's cost-benefit analysis. Therefore, the following degradation cost ($/kWh) is adopted [113].

$$C_D = \frac{C_B + (W \times t)}{L_c B^{V2G} DoD} \tag{6.20}$$

where: C_D is the degradation cost in ($/kWh). C_B is the capital cost of the battery. W is the hourly wage of an electrician. t is the installation time of the battery in hours, which is considered here 8. L_c is the number of cycles of EVs. DoD is the depth of discharge of EVs. On the other hand, BEV participant's Benefit can be calculated as follows:

$$\text{BEVs Participants Benefit} = \text{Incentives+Revenue Reductions+Capacity Payments} \tag{6.21}$$

The PCT Index can be calculated as follows:

$$\text{PCT Index} = \frac{\text{Participants Benefits}}{\text{PCT Costs}} \tag{6.22}$$

6.2 Results and Analysis

The impact of V2G in Ontario is investigated using the technique outlined in Section 6.1. The findings of this study should be interpreted as something other than definitive assessments of the programs under discussion because they heavily rely on input and assumptions.

6.2.1 Input Data and Assumptions

6.2.1.1 Choice of Electric Vehicles

Only a few EVs that support bidirectional charging are available [157]. But Tesla and Nissan are the most selling EVs in Canada [158]. However, only two EVs support V2G: the Nissan Leaf SV and the Ford F-150 Lightning of 2024 [157]. Recalling that all of Tesla's EVs will become bidirectional in 2025 [159]. Also, the Tesla Model Y was the best-selling EV in 2023 [160]. That's why three EVs are considered: Nissan Leaf SV, Tesla Model Y, and Ford F-150 Lightning. The market share of selected EVs is assumed to be 35%, 45%, and 20%, respectively. The analysis is done for ten years. There is a high probability that more EVs will come into the market and that the study will change. The choice of car is crucial and depends on every person's preference. Some sensitivity analyses are also performed on the critical parameters of this model.

The V2G program is assumed to start in 2024 and run for ten years (2024-2033). The number of passenger light-duty BEVs in Ontario for Q2 of 2023 is 98419 based on the data registered on the Ontario website [161]. The annual growth rate of BEVs in Ontario is projected based on the forecasted annual BEV sales from a study conducted in the Peel region [162]. Most chargers are 90% efficient, so this value is assumed. The charger-rated output power in kW of Nissan, Tesla, and Ford

Table 6.14: Forecasted number of BEVs and their specifications with forecast V2G power output and energy input

	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Number of BEVs in Ontario	154.9 K	227.6 K	328.7 K	495.8 K	744.8 K	1054.2 K	1431.8 K	1871.9 K	2373.8 K	2926.5 K
Number of V2G Participants	7.7 K	22.8 K	49.3 K	99.2 K	186.2 K	316.3 K	501.1 K	748.7 K	1068.2 K	1463.3 K
Total Battery Capacity Profile	207.3	213.519	219.925	226.522	233.318	240.318	247.527	254.953	262.601	270.479
Total Forecast Deliverable MWh	41.35	121.51	263.18	529.28	993.95	1688.12	2674.91	3996.72	5701.92	7810.75
Total Forecast Deliverable MWh/Day	162.61	492.16	1097.93	2274.3	4399.11	7695.51	12559.75	19329.18	28403.24	40075.28
Forecast Call Days per Year	110	110	110	110	110	110	110	110	110	110

is 7, 11.5, and 11.3, respectively. The ULO rates recently introduced by Ontario are considered in this model [48]. The hourly wage of an electrician is $40 in Ontario. Other data are assumed to be as follows:

- We have assumed the number of calls to be 110 in one year. It means that all the EVs will be charging/ discharging 110 times in a year. The participants will certainly be using their EVs for other purposes, too. It's a high probability that the battery will need to be replaced after five years, and it will reach its maximum number of charging/ discharging cycles. The number of

processes assumed in this model is 1500 after five years.

- The cost of upgrading the CHAdeMO charger is $6185.55. In contrast, the price of a Tesla charger is assumed to be $10,000 as there are no Tesla chargers available in the market that supports bidirectional charging. On the other hand, the Ford Charging Station Pro costs $12,878 [163].

- The V2G program participation is assumed to be 5% at the program's start and is increasing by 5% yearly.

- The useful battery capacity percentage is 60% of the total capacity to reduce battery degradation.

- It is assumed that BEVs will be available every other day, setting the availability factor at 60%.

The battery capital costs of Nissan Leaf, Tesla, and Ford are $ 6,500, $ 7,500, and $ 8,500, respectively, in 2029. The depth of discharge for Nissan, Tesla, and Ford is 60%, 100%, and 80%, respectively. The degradation cost for all EVs in $/kWh is mentioned in the table below. It is worth noticing that although Nissan's battery capacity is low compared to the other EVs, the degradation cost is higher than the others. The primary reason for this is the depth of discharge provided by Nissan, the charger's output power.

Table 6.15: Degradation Cost in $/kWh for all EV batteries.

	2029	2030	2031	2032	2033
Degradation Cost in ($/kWh) for Nissan	$0.19	$0.20	$0.21	$0.22	$0.23
Degradation Cost in ($/kWh) for Tesla	$0.08	$0.08	$0.08	$0.09	$0.09
Degradation Cost in ($/kWh) for Ford	$0.08	$0.08	$0.08	$0.09	$0.09

Table 6.16 lists the annual input data for the V2G program in Ontario in terms of distribution system deferral, on-peak market prices, and average capacity payments.

Table 6.16: Forecasted Distribution Inputs for the V2G program in Ontario

	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Distrubtion System Deferral $/kW-yr	78	81	84	86	90	93	96	99	103	106
Average Capacity Payment ($/MW-Day)	162	165	169	172	175	179	182	186	190	194
On-Peak Market Price ($/MWh)	165	170	175	180	185	191	197	203	209	215

The following assumptions have been made to get the above results:

- The distribution system deferral values are chosen from the typical distribution system deferral values range from 50 to 250 USD [152]. An increase rate of 3.5% is applied for the consequent years.
- The capacity payments 2023 are based on the average of the IESO capacity auction clearing prices for the summer and winter of 2022 [164]. An inflation rate of 2% is applied for the consequent years.
- The on-peak market prices are based on the wholesale market of Ontario plus the global adjustment costs.
- The distribution system right time right place (RTRP) adjustment is set at 100% [165], while the distribution system on-peak losses is assumed to be 4.2%.
- The administration costs per participant are assumed to be $38.2275.

6.2.1.2 Input Data and Assumptions for 2035-2044

It should be noted that there will be 100% BEV sales by 2035. The federal government is working to phase out all gas-powered light-duty vehicles, and all new

BEVs will be sold in Canada. That is why some assumptions were made for the next twenty years [166]. The type of EV is not considered in this analysis because, by that time, all the manufacturers will be producing only ZEVs [167]. Based on the current trend of light-duty passenger vehicles, the number of BEVs is assumed to be 4,682,439 for 2035. All other parameters remain the same, except the BEV annual growth profile, which was taken based on the current statistics of Ontario for light-duty passenger vehicles—the forecast call days per year increased to 200, keeping in mind that there will be more demand for electricity by 2035 and the cost of bidirectional charger is assumed to be $10,000. It might be a possibility that the cost of chargers came down, but the inflation is also increasing. That's why the price of chargers is assumed to be the same as the current new bi-directional chargers. Moreover, the CHAdeMO charger will be discontinued in 2024 [168]. All the costs are considered the same in this analysis, considering that when there are more manufacturers in the market, the price of equipment required for V2G will decrease or remain the same.

6.2.2 Results and Sensitivity Analysis

6.2.2.1 Residential V2G Program

Benefits and costs with critical indices for the residential V2G program are listed in Table 6.17

The table 6.17 shows the BCR index of the administrator, ratepayer, and participant as 1.28, 1.03, and 0.75, respectively. The participants and ratepayers profit from this analysis, but participants cannot normalize the investment cost in ten years. The primary reason behind this is the cost of bidirectional chargers. Some sensitivity analysis is also performed, considering that some values were assumed

Table 6.17: Key Benefits to Cost Ratios for Residential V2G Program

	Benefits	Costs	Net Benefits	Net $/kW-Yr.	Ratio
PAC	$2,300,108,635.91	$1,799,939,171.64	$500,169,464.26	$37.5	1.28
RIM	$2,300,108,635.91	$2,233,891,716.06	$66,216,919.85	$5.0	1.03
PCT	$2,155,654,177.86	$2,871,784,898.09	$(716,130,720.23)	$(53.6)	0.75

and can be changed in ten years.

A sensitivity analysis has been carried out to show the impact on the indices by changing the critical input parameters on the residential V2G program BCR, and the results are shown in Figs. 6.4 to 6.16.

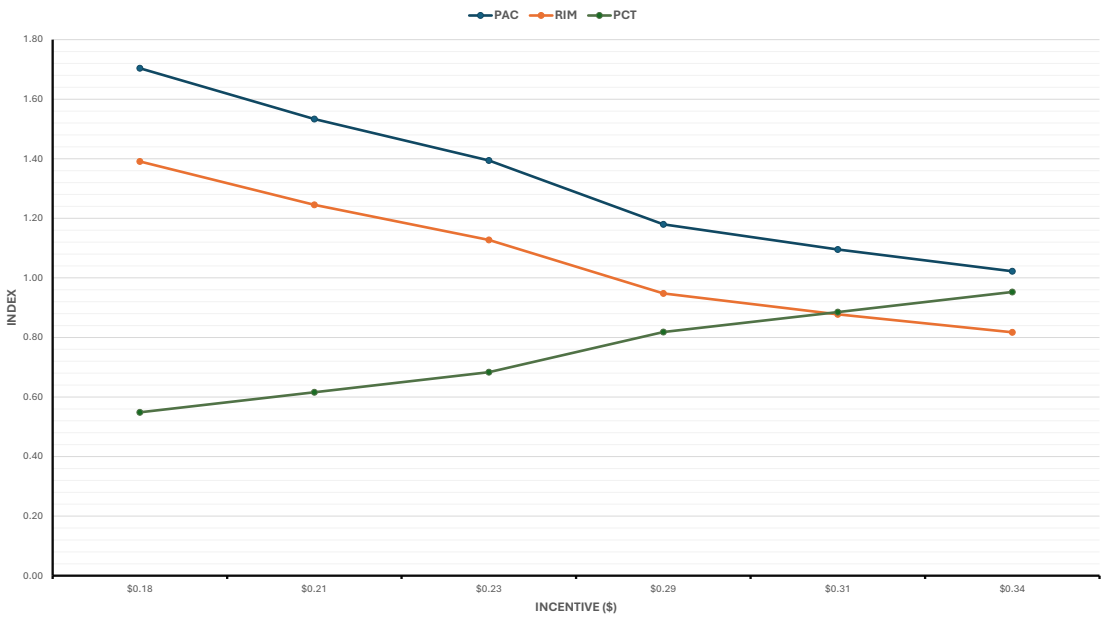


Figure 6.4: Impact on Residential V2G by Changing Incentive

The critical points of the results in Fig. 6.4 to Fig. 6.16 are as follows:

- Figure 6.4 shows that the PCT started normalizing when the incentive reached

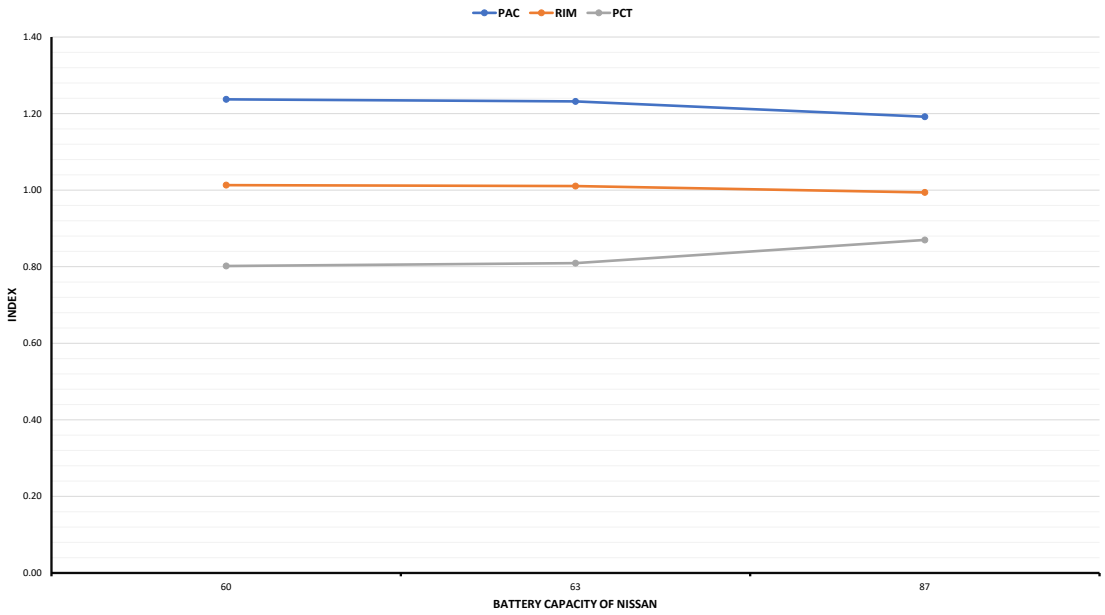


Figure 6.5: Impact on Residential V2G by Changing Battery Capacity of Nissan

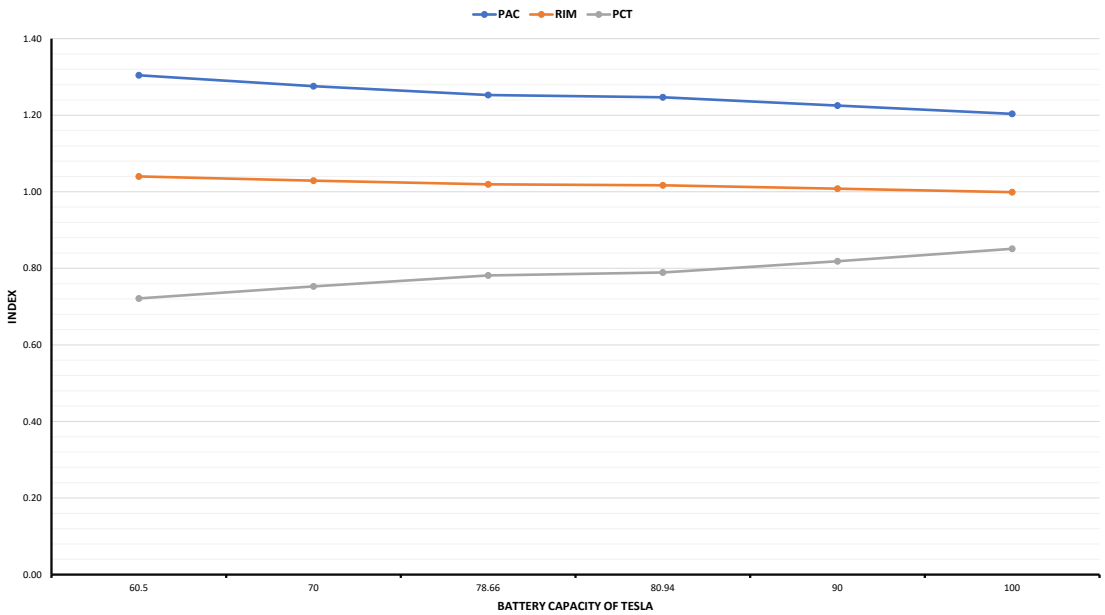


Figure 6.6: Impact on Residential V2G by Changing Battery Capacity of Tesla

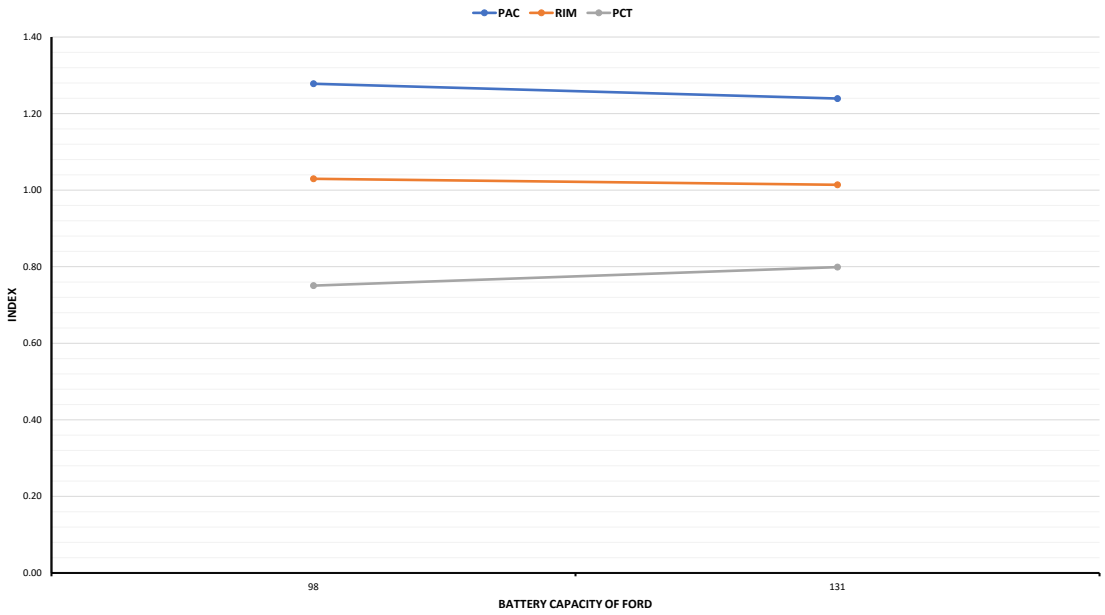


Figure 6.7: Impact on Residential V2G by Changing Battery Capacity of Ford

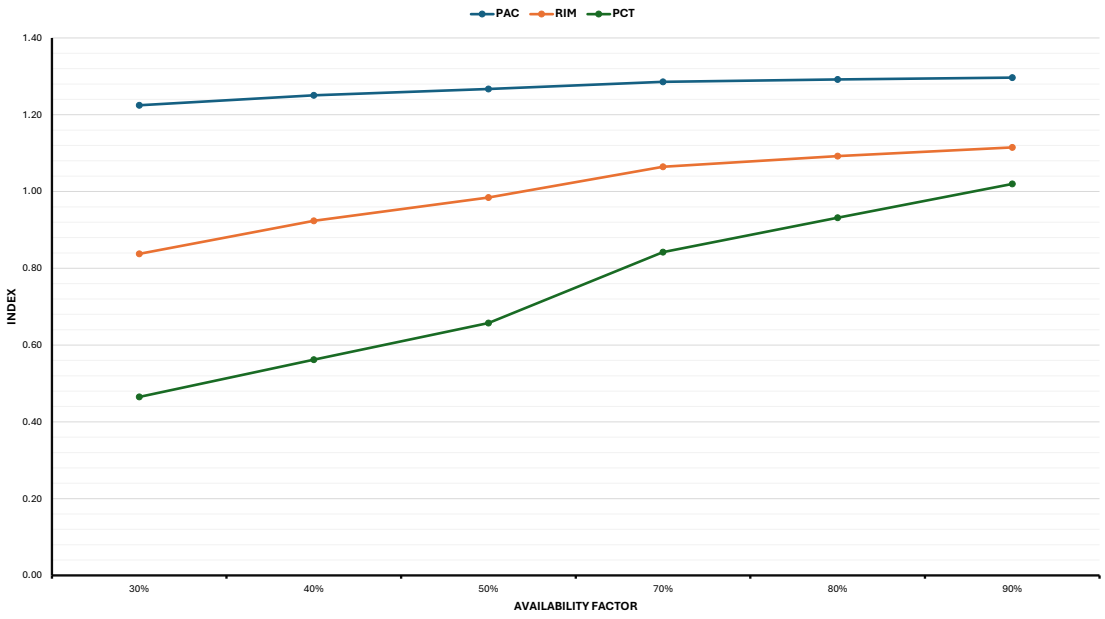


Figure 6.8: Impact on Residential V2G by Changing Availability Factor

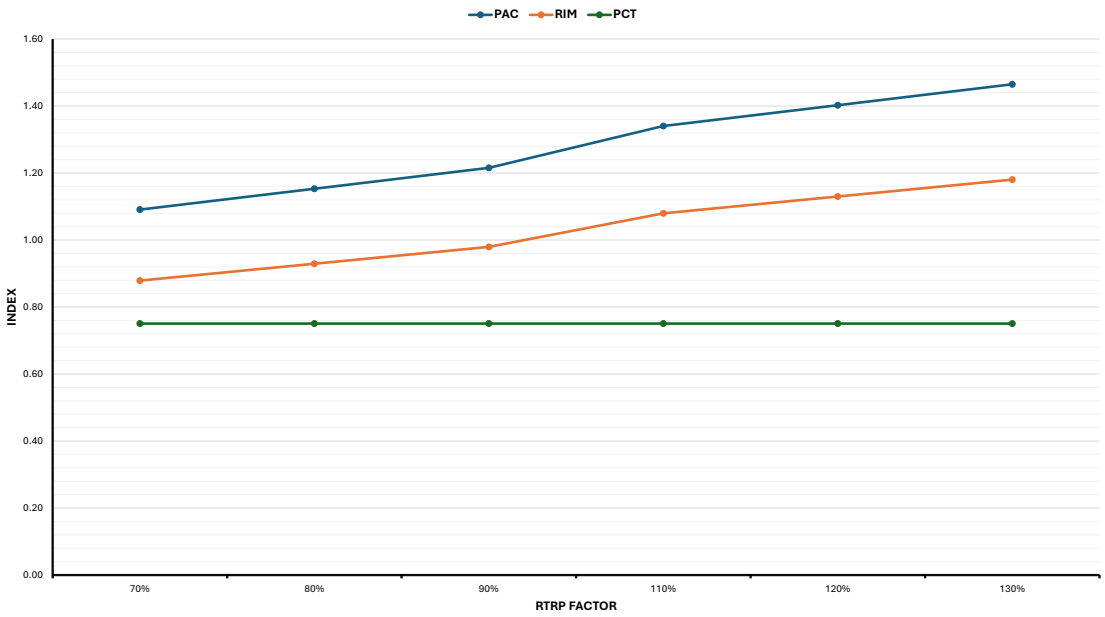


Figure 6.9: Impact on Residential V2G by Changing RTRP Factor

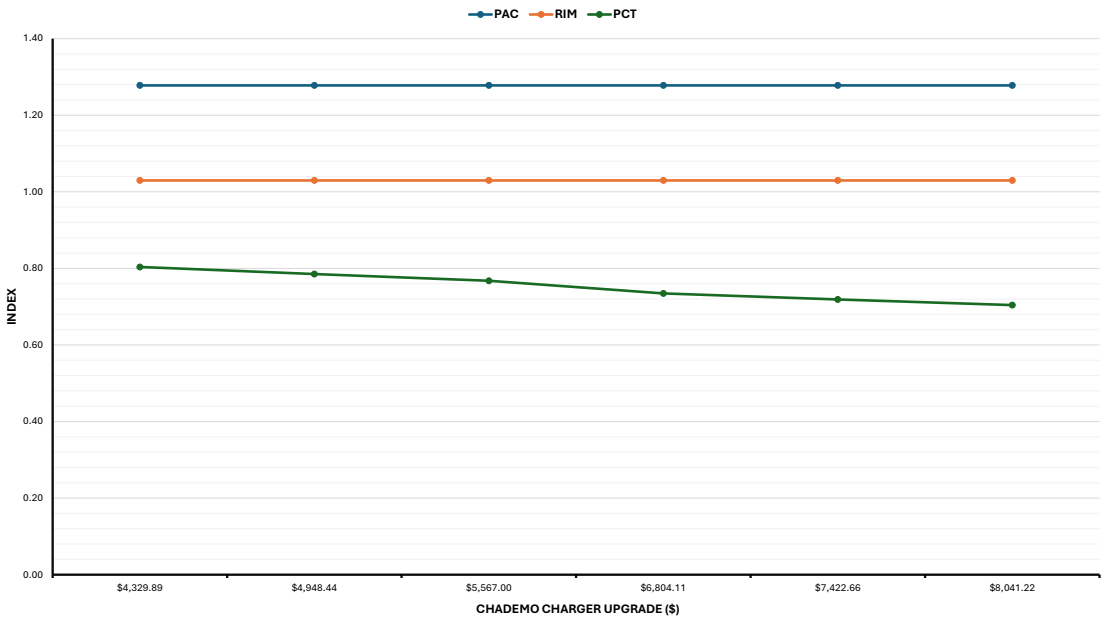


Figure 6.10: Impact on Residential V2G by Changing Cost of CHADEMO Charger

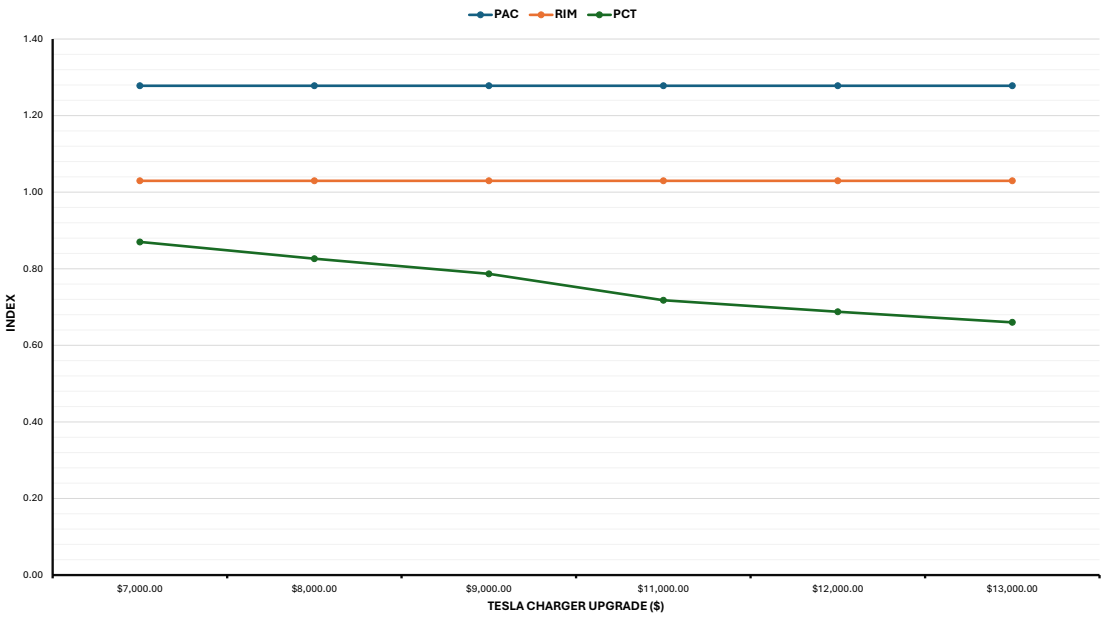


Figure 6.11: Impact on Residential V2G by Changing Cost of Tesla Charger

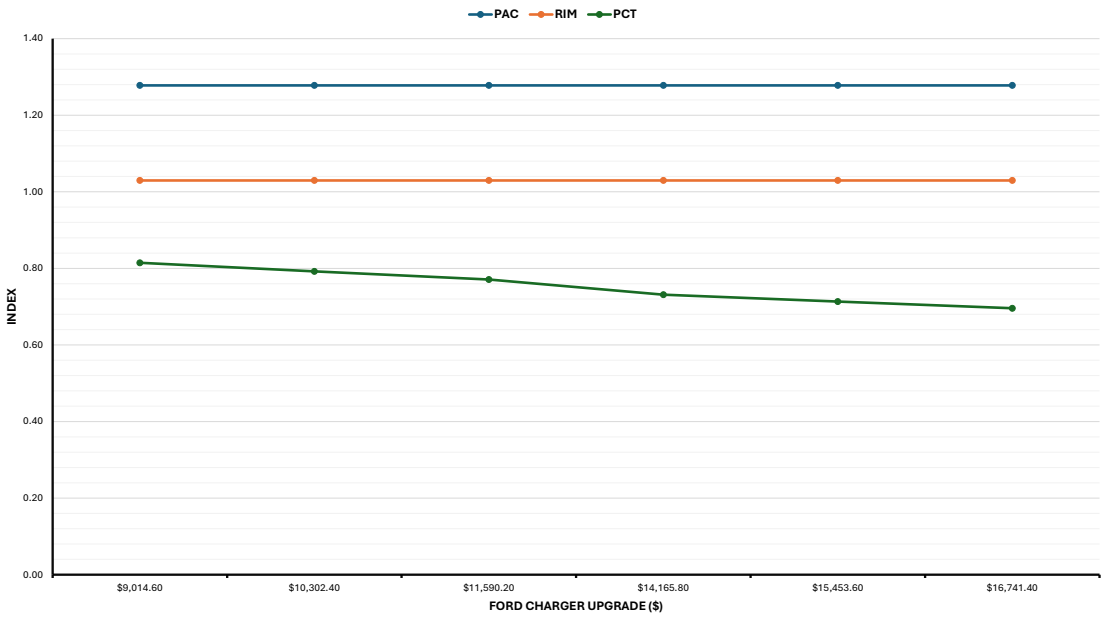


Figure 6.12: Impact on Residential V2G by Changing Cost of Ford Charger

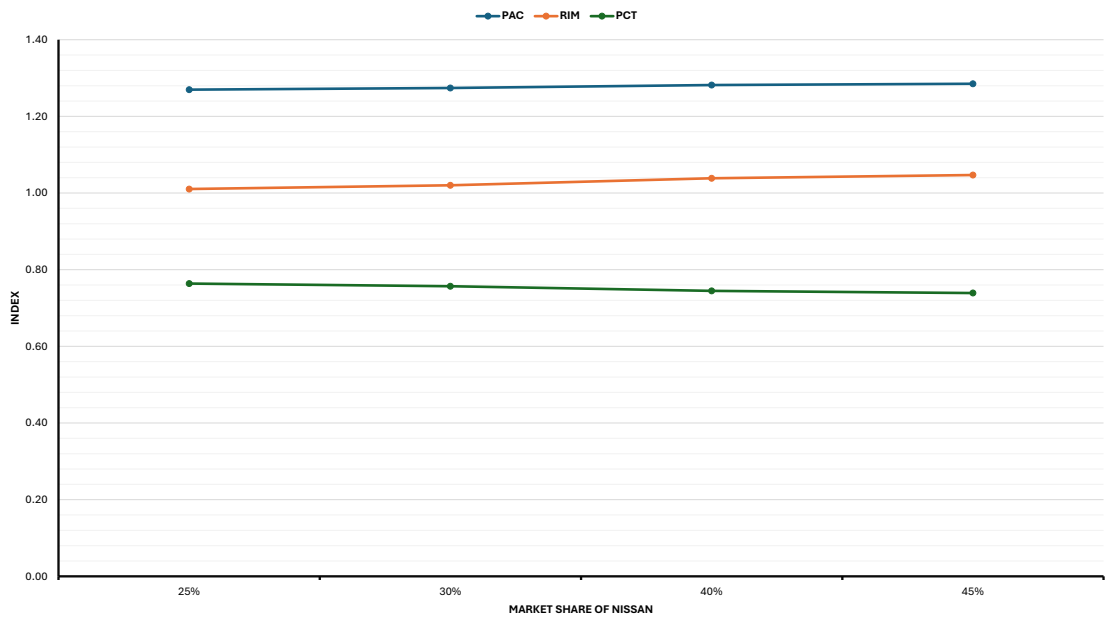


Figure 6.13: Impact on Residential V2G by Changing Market Share of Nissan

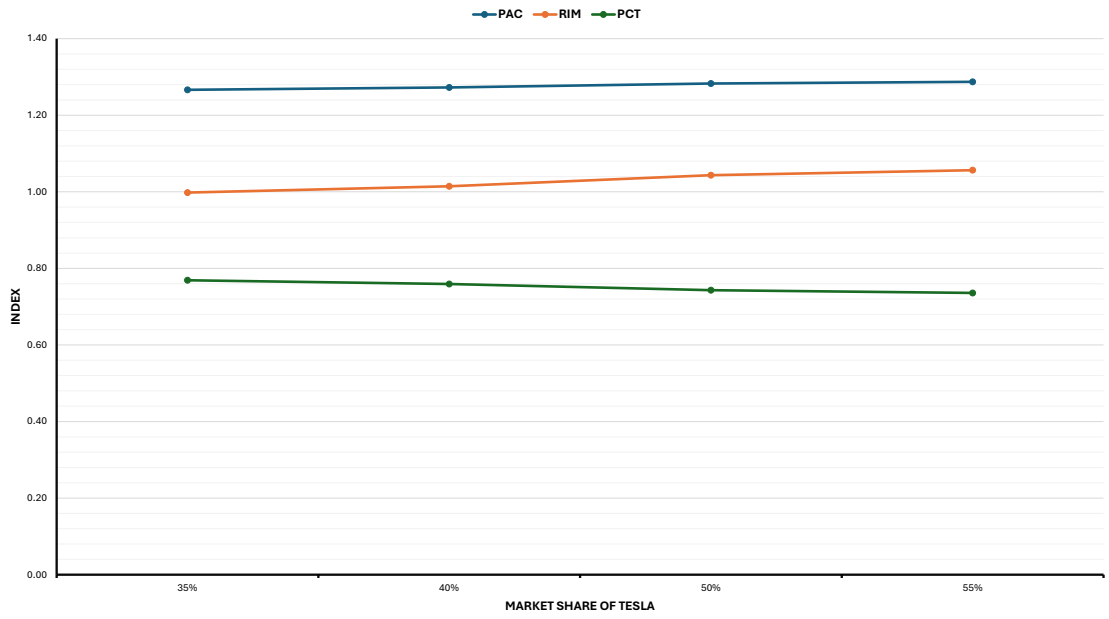


Figure 6.14: Impact on Residential V2G by Changing Market Share of Tesla

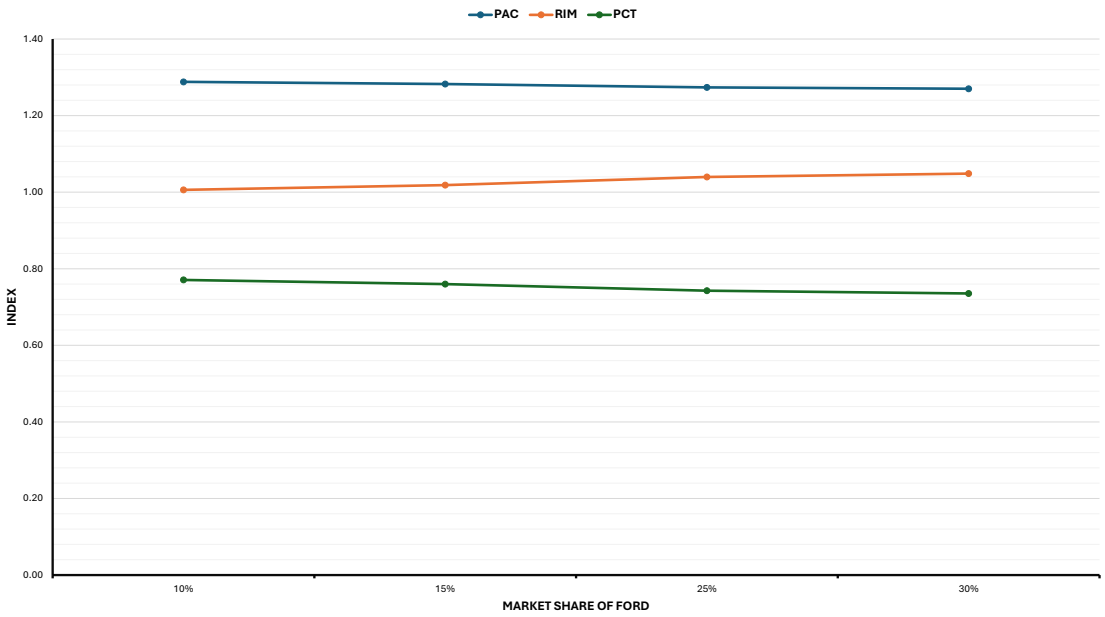


Figure 6.15: Impact on Residential V2G by Changing Market Share of Ford

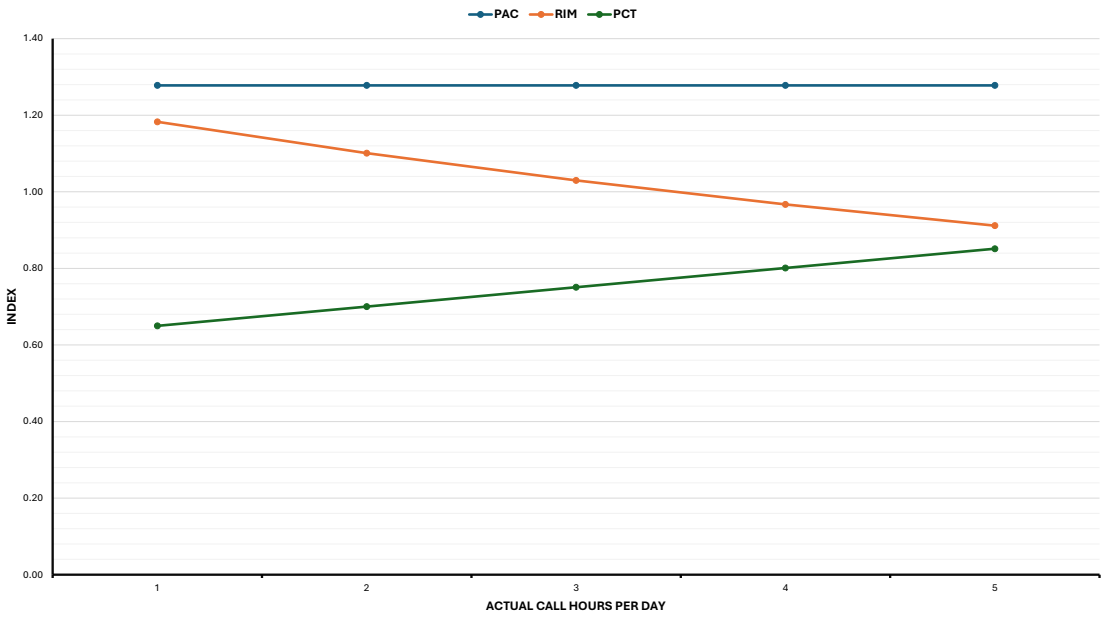


Figure 6.16: Impact on Residential V2G by Changing Call Hours per Day

the value of $0.34/kWh. It means that participants can't make a profit without increasing the rate of other customers.

- Figs. 6.5 to 6.7 show the impact on residential V2G by considering the battery capacities of Nissan, Tesla, and Ford passenger EVs in the market. It is observed that by increasing the battery capacity of EVs, the PCT ratio rises, and PAC and RIM decrease, but their value is not negatively affected.

- Figs 6.8 and 6.9 show the impact of availability and RTRP Factor, respectively. It is demonstrated that PAC, RIM, and PCT were raised to a particular factor by increasing the availability factor. However, there is a significant impact on the value of PCT when the factor increases to 90%, which will be the ideal scenario for EVs and is quietly not possible. However, PCT is not affected by RTRP, but PAC and RIM were increased.

- Figs 6.10 to 6.12 show the impact of changing the cost of the bidirectional charger. PAC and RIM are unaffected by their variation, which comes at participants' expense. Thus, the cost of the charger is inversely proportional to the PCT index.

- The effect on PAC, RIM, and PCT by changing the market share of each EV is shown in Figs. 6.13 to 6.15. By increasing their share, PCT value decreases because other EVs of the same brand available in the market can provide that demand response. There is also a probability of bidding to supply a demand response. However, PAC and RIM values have increased by 1% or 2%.

- Finally, the number of call hours each day is shown in Figure 6.16. If there are more call hours each day, participants' benefits will increase, but RIM will be negatively affected. The ratepayers will be the ones paying this cost to the participants. While the administrator ratio remains the same.

This analysis assumed the EVs and their critical parameters, except for battery capacity and charger output power. That's why, for EVs, some sensitivity analyses can be done by changing each parameter of the EV and observing how it will affect our results. The results are listed in the table below:

The parameters whose values are changed are highlighted in all the tables.

The observations by changing the value of these parameters are mentioned below:

- It is observed that changing Nissan and Ford's charger-rated power has no significant impact on the results. The reason behind this is Nissan's low DoD value and Ford's low market share, which is assumed to be expected in this analysis. However, by increasing Tesla's rated power, the PAC, RIM, and PCT values increased by 1% as Tesla offers 100% DoD and a high market share in this analysis.

- After analyzing all the parameters individually, the effect is now observed by creating some scenarios for the EVs considered in this analysis. The first condition is in favor of the participants. As they were not able to cope with their investment after ten years. Second, in favor of ratepayers and admins. It is observed that even after altering all the parameters in favor of the participants. Still, they were not able to normalize their costs. The primary reason, again, is the high cost of the bidirectional chargers.

6.2.2.2 Residential V2G Program for 2035-2044

Based on the assumptions for the next twenty years. The results are shown in the table below:

The PAC, RIM, and PCT ratios for the next twenty years are shown in the

Table 6.18: Impact on key indices on Residential V2G key changing key parameters of Nissan LEAF.

	Current Values:	By increasing charger-rated power, battery capacity, DoD, and market share but decreasing the cost of charger upgrade	By decreasing charger-rated power, market share, and cost of charger upgrade
Changing Cells :			
Charger Rated Power	7	7.4	6.6
Battery Capacity	40	60	40
DoD	60%	80%	60%
Market Share	35%	45%	25%
Cost of Charger Upgrade	6185.55	5000	5000
Results:			
PAC	1.28	1.24	1.26
RIM	1.03	1.03	1.01
PCT	0.75	0.84	0.79

table. It is observed that after twenty years, when there will be more demand for V2G and the number of EVs will increase, participants will be able to come up with a 1.6% profit. Although, the ratepayer's ratio will be negatively affected. Remember that this analysis assumed costs as in the previous one. The ratepayers

Table 6.19: Impact on key indices on Residential V2G key changing key parameters of Tesla.

	Current Values:	By increasing charger-rated power, battery capacity, DoD, and market share but decreasing the cost of charger upgrade	By decreasing charger-rated power, market share, and cost of charger upgrade
Changing Cells :			
Charger Rated Power	11.5	13	10
Battery Capacity	69.3	78.66	60
Market Share	45%	55%	35%
Cost of Charger Upgrade	10000	7000	7000
Results:			
PAC	1.28	1.29	1.26
RIM	1.03	1.07	0.98
PCT	0.81	0.91	0.84

were affected because ULO rates are considered for them. This issue can be solved with a separate policy for bidirectional charging setup.

Some sensitivity analysis was also performed to look after this period of twenty years. The results are shown in the table below.

The observations from the Table 6.22 are as follows:

Table 6.20: Impact on key indices on Residential V2G key changing key parameters of Ford.

	Current Values:	By increasing charger-rated power, battery capacity, DoD, and market share but decreasing the cost of charger upgrade	By decreasing charger-rated power, market share, and cost of charger upgrade
Changing Cells :			
Charger Rated Power	11.5	13	10
Battery Capacity	69.3	131	90
Market Share	45%	30%	10%
Cost of Charger Upgrade	10000	8000	8000
DoD	80%	100%	60%
Results:			
PAC	1.28	1.24	1.29
RIM	1.03	1.04	1.00
PCT	0.75	0.92	0.81

- By increasing the value of the incentive and decreasing the cost of the bidirectional charger, PCT will be doubled, which means that participants will be able to get 200% profit by participating in residential V2G. It means that if the cost of the charger is reduced, it will undoubtedly benefit participants.

Table 6.21: Impact on key indices on Residential V2G for twenty years.

	Benefits	Costs	Net Benefits	Net $/kW-Yr.	Ratio
PAC	$355,388,105,771.75	$317,172,976,873.71	$38,215,128,898.04	$33.90	1.12
RIM	$355,388,105,771.75	$412,580,312,079.20	$(57,192,206,307.45)	$(50.74)	0.86
PCT	$407,294,744,128.99	$243,926,253,992.82	$163,368,490,136.16	$144.93	1.67

Table 6.22: Sensitivity Analysis for twenty year

		PAC	RIM	PCT
Incentives	$0.18	1.12	0.86	1.67
	$0.34	1.52	1.18	1.21
RTRP Factor	70%	0.99	0.76	1.67
	130%	1.25	0.96	1.67
Availability Factor	42%	1.11	0.78	1.34
	78%	1.12	0.91	1.98
Average Charger Power	8.05	1.03	0.78	1.63
	14.95	1.21	0.94	1.71
Admin Cost Adjustment	25.20	1.13	0.86	1.67
	46.81	1.11	0.86	1.67
Average Call Hours/Day	3.00	1.12	0.95	1.51
	7.00	1.12	0.79	1.83
Cost of Charger Upgrade	5000	1.12	0.86	2.95
	7000	1.12	0.86	2.26
	9000	1.12	0.86	1.83

Remember that the cost of chargers will not affect the administrators and ratepayers. But by increasing the incentive, their profit will decrease.

- It is also worth noticing that by increasing the RTRP Factor, the ratio for

PAC and RIM increased linearly. But with the increment in admin cost, its adjustment PAC value will decrease. PCT is unaffected by the RTRP Factor and Admin cost adjustment, while RIM is unaffected only by cost adjustment.

- On the other hand, the availability factor is significant to all program stakeholders since all program indices are affected by the change of this factor. In this regard, increased BEV availability increased the V2G program power and energy impact, which helps the program administrator and participants gain more value from their investments.

- Lastly, the number of call hours is inversely proportional to RIM while directly related to PCT.

6.3 Summary

This chapter introduces a regional-based cost-benefit assessment model for residential V2G providing demand response. The model incorporates three stakeholders in the V2G program: LDCs (program administrator), ratepayers, and EV owners. Using the proposed model, case studies have been conducted to assess the economic viability of V2G programs participating in demand response in Ontario. Further, a sensitivity analysis is performed to determine the effect of input parameters on the benefit-to-cost ratios. The results show that for residential V2G, the program benefits the administrator and will not affect the Ontario province's ratepayers. However, the costs incurred by program participants are higher than the benefits obtained. This is mainly due to the high cost of bi-directional chargers, making it difficult for program participants to recover their capital investment unless incentives increase. Moreover, it is concluded from the results that program participants cannot gain profit without raising rates for other customers (ratepayers). It is

also observed that the EV specifications play a significant role in deploying a V2G program.

For the twenty year analysis, it is observed that the participants will be able to make a profit as the number of EVs have increased to 100% approximately. But the ratepayers are negatively effected, this is just because the ULO rates are considered for the calculation of their BCRs. This will not be the scenario, if their is a proper policy in place for standalone unit.

Chapter 7 - Conclusion and Future Work

7.1 Conclusion

As the world grapples with escalating greenhouse gas emissions, the imperative to transition to Electric Vehicles (EVs) becomes increasingly clear. This thesis is dedicated to amplifying the adoption of Vehicle-to-Grid (V2G) technology in the power grid. It's crucial to acknowledge that while there are factors impeding the widespread acceptance of V2G, more real-world demonstrations are needed. Hence, Chapter 4 delves into the real-world demonstration for deploying V2G in a residential unit. The study reveals that the selected charger and the EV can actively engage in V2G, with the charger and controller responding in seconds with an accuracy rate of approximately 99%. Meanwhile, it takes some time to start the process, which is the communication between the EV and the charger, and it takes about 109 seconds to reach the desired setpoint. It is also observed that the installed setup can follow the load demand of the home, except for the appliances that have abrupt changes, like a dryer. The load following test showed us that this setup cannot be used for dynamic loads and frequency regulations, which require swift response in milliseconds. The response time for this setup is seconds. Moreover, the EV owner is at home during this experiment. In the load following test; around 20% of SOC of the EV and the charger have been utilized. This usage of SOC raises the concern of battery degradation and inclined attention toward battery replacement

if EVs are used daily for V2G. It is also worth noticing that the EV owners can gain incentives from the government while participating in V2G. However, in this experiment, the EV owner was not allowed to feedback energy to the grid. But, a simulation has been done based on the ULO rates, and it is observed that the EV owner can earn $6.99 and emission reduction of 10.4 kgCO_2eq daily. In this experiment, an extended range test was performed to observe the time the EV takes to complete one cycle of charging and discharging, as well as when it stops providing power. It was noted that the response time remained the same as in the previous test. But, when the power reaches 10, it disconnects from the charger and starts preserving the battery to maintain its state of health. It is also worth noting that, without loss of generality, this experiment was done at a residential unit regardless of the home load. Thus, similar experiments can be done at other units. The difference between these experiments will be in the installation pricing and timelines for the specifications and infrastructure of the other unit. Moreover, this experiment was done in an urban area. However, limitations might further increase for the suburban or rural areas.

Based on the real-world demonstration, the mathematical analysis is conducted for the population of Ontario, which will consider the driving patterns for the employed persons of the region, and based on that; a financial analysis has been done, which can identify the feasibility of V2G among the residents of Ontario. Moreover, a survey was conducted of the LDC websites in Ontario to gather information about the procedure for setting up the bidirectional charging setup in a residential unit. Thus, Chapter 5 concludes that the number of vehicles in Ontario is increasing and significantly impacting greenhouse gas emissions, as 96% of vehicle usage is based on the ICEs. If EVS replaces these ICEs, it can significantly reduce GHGs and also beneficial for EV owners as they will pay less for electricity as compare to fuel for

gasoline engines. It has also been observed that new EVs are coming to the market with bidirectional capability specifically, V2G has higher battery capacity, allowing EV owners to participate in V2G on the same day without charging even after driving 180 km daily. This has created an immense impact on the uptake of V2G. However, the availability and testing of bidirectional chargers are still unavailable, and all these analyses are based on assumptions. It is also worth noticing that the information collected from LDC websites are dispersed, and no proper policy is in place specifically for standalone units. Therefore, some recommendations have been suggested in the chapter for the proper policy implications, which can significantly impact the positive uptake of V2G and create technical and environmental benefits for LDCs and EV owners.

While Chapter 6 focuses on the techno-economic analysis of V2G and considers the benefit-to-cost ratios of all the stakeholders involved in the participation of V2G, a general model is adopted for this analysis and based on some assumptions of the case study is done for the region of Ontario for twenty years. Some sensitivity analyses were also performed while the choice of vehicles and their specifications highly impact the BCRs. It is observed that due to the unavailability and high cost of bidirectional chargers, the EV owners will not be able to normalize the cost for ten years unless their availability increases to 90%, which is quite impossible, or the incentive increases to \$0.34/kWh. However, it is also observed in the following ten-year analysis that if the number of EVs keeps increasing with the assumed factor, then the EV owners will be able to make a profit. But, it will negatively impact the ratepayers who decide not to participate in V2G. While, the administrators (LDCs) will be able to profit for whole twenty years even after investing a million dollars in the software control setup for bidirectional charging.

7.2 Future Work

The work in this thesis is based on the residential unit. But similar work can also be extended at the industrial level, which requires more complex parameters. At the commercial level, the EV owner gets profit from the EV parking lot owner, so the EV owner receives gets divided into the EVPL owner and the EV who decided to charge their EV in that parking lot. Moreover, the real-world demonstration is based on the Nissan Leaf SV, whose battery capacity is 40 kWh. However, the same experiment needs to be validated by other EVs coming into the market with a higher battery capacity, considering that more bidirectional chargers can respond faster with better software programs for the experiment's control. They can validate the fast response and participate in frequency regulation or spinning reserve applications, which cannot be done with the setup observed in this thesis. This research has significant potential for real-world applications, particularly in regions where Internal Combustion Engines are playing a significant role in the increasing Greenhouse Gas Emissions and do not have proper policies in place for it.

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Appendices

A.1 Appendix 1

Table A.23: Typical driving pattern for working men and women

Time	Distance (km)	Total distance travelled (km)	Notes
00:00 - 07:00	0	0	Vehicle is charging
07:01 - 08:00	45	45	From home to office
08:01-17:00	0	45	Working
17:01-18:00	45	90	From Work to home
18:01-23:00	0	90	Vehicle is in idle state
23:01-23:59	0	90	Vehicle is charging

Table A.24: Typical driving pattern for working mothers

Time	Distance (km)	Total distance travelled (km)	Notes
00:00 - 07:00	0	0	Vehicle is charging
07:00 - 07:30	20	20	From home to daycare/school
07:30 - 08:55	75	95	From daycare/school to work
08:56 - 16:30	0	95	Working
16:31 - 18:00	75	170	From work to daycare/school
18:01 - 18:30	20	190	From daycare/school to home
18:31 - 23:00	0	190	Vehicle is in idle state
23:01-23:59	0	190	Vehicle is charging

Table A.23, A.24, and A.25 show the driving pattern of the busiest days of the week for the subjects considered in this analysis. The distance can vary from one person to another.

Table A.25: Typical driving pattern for businessmen

Time	Distance (km)	Total distance travelled (km)	Notes
00:00 - 07:00	0	0	Vehicle is charging
07:01 - 08:00	0	0	Vehicle is in idle state
08:01 - 09:30	90	90	Travel because of some business
09:31 - 14:30	0	90	Working
14:31 - 16:00	90	180	Travel from work to home
16:01 - 23:00	0	180	Vehicle is in idle state
23:01-23:59	0	180	Vehicle is charging

Table A.26: Population served by each LDC in ontario

COMPANIES	POPULATION
Toronto Hydro-Electric System Limited	6372000
Alectra Utilities Corporation	3894491
Enova Power Corp.	1141803
Kingston Hydro Corporation	597124
Elexicon Energy Inc.(formerly Veridian and Whitby Hydro)	587724
London Hydro Inc.	519000
Niagara Peninsula Energy Inc.	450925
En Win Utilities Ltd.	342000
Grand Bridge Energy (formerly Brantford Power and Energy+)	287490
Oakville Hydro Electricity Distribution Inc.	234149
Burlington Hydro Inc.	198557
Oshawa PUC Networks Inc.	185611
Entegrus Power lines Inc.	160054
Milton Hydro Distribution Inc.	151751
Synergy North Corporation (formerly Kenora Hydro and ThunderBay Hydro)	128274
Inn Power Corporation	120378
Newmarket-Tay Power Distribution Ltd.	118922
Algoma Power Inc.	113777
Hydro One Networks Inc./Cat Lake Power Community	113054
Essex Power lines Corporation	104158
Westario Power Inc.	84530
Bluewater Power Distribution Corporation	82551
North Bay Hydro Distribution Limited	71736
PUC Distribution Inc.	70956
ERTH Power Corporation (formerly Erie Thames Power and West Coast Huron)	65295
Halton Hills Hydro Inc.	64300
E.L.K. Energy Inc.	57173
Well and Hydro-Electric System Corp	54712
Canadian Niagara Power Inc.	49934
Festival Hydro Inc.	46443
Northern Ontario Wires Inc.	46234
Lakeland Power Distribution Ltd.	41370
Orangeville Hydro Limited	37679
EPCOR Electricity Distribution Ontario Inc. (formerly Collus Power Stream)	35930
Niagara-on-the-Lake Hydro Inc.	34323
Rideau St.Lawrence Distribution Inc.	34087
Grimsby Power Inc.	30364
Centre Wellington Hydro Ltd.	27005
Ottawa River Power Corporation	22824
Lakefront Utilities Inc.	20807
Hydro 2000 Inc.	20589
Tillson burg Hydro Inc.	16707
GreateR Sudbury Hydro Inc.	14670
Hydro Hawkesbury Inc./Hawkesbury Hydro Inc.	9873
Cooperative Hydro Embrun Inc.	8680
Renfrew Hydro Inc.	8018
Wellington North Power Inc.	7703
Fort Frances Power Corporation	7159
Sioux Lookout Hydro Inc.	6105
Guelph Hydro	5488
Hearst Power Distribution Company Limited	4794
Hydro Ottawa Limited	3563
Hydro One Networks Inc./Chapleau Public Utilities Corporation	2091
Atikokan Hydro Inc.	1929
Attawapiskat Power Corporation	1586
Fort Albany Power Corporation	1404