Using Electric Vehicles for Grid Services: Capacity Available and Applications for Electric Utility Commercialization

by

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B.S., Mechanical Engineering
Loyola Marymount University, 2017

Submitted to the MIT Sloan School of Management and
Department of Mechanical Engineering
in partial fulfillment of the requirements for the degrees of

Master of Business Administration

and

Master of Science in Mechanical Engineering

in conjunction with the Leaders for Global Operations program

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 2022

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Abstract

As electric vehicle (EV) ownership increases, utilities face a high strain on electricity demand when vehicles charge at peak hours. EV grid services like managed charging (V1G) and bidirectional charging could enable electric vehicles' untapped energy storage capacity to improve grid resiliency. This thesis pertains to a detailed case study of EVs for grid services. Using Florida Power and Light residential charging data, the thesis lays out a method to estimate V1G and vehicle-to-grid (V2G) capacity and finds that EV grid services are most readily available in the early morning and evening. An aggregation algorithm designed for demand response is outlined to coordinate the discharge of vehicles during a dispatch event to meet an operator-defined target load reduction, and the resulting performance is highlighted. A V1G algorithm for residential chargers is proposed and highlighted as an opportunity to increase customer participation in offering their vehicle for grid services. A strategy is introduced to build off the concepts presented to create a simulation for utility planning for EV grid services. The thesis concludes with a road map of adoption for EV grid services and potential commercialization opportunities. Key risks and technical challenges are highlighted, and final recommendations for utilities are provided.

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Acknowledgments

This thesis was possible due to contributions from many individuals and organizations. I first want to thank my mother and father, Lorena and Gustavo Castillo, who are my inspiration in everything I do. Daniel Freund and Anuradha Annaswamy, my advisors, have been critical in shaping the direction of the thesis, and I appreciate the countless hours they dedicated to making this a success. Thank you to all those at NextEra, including Matt Valle, Jill Dvareckas, Carlos Hinojosa, Christina Zabala, Carlos Zada, and Ian Fiske, who graciously sponsored this project, and for their daily contributions to advancing this work. May this thesis highlight the importance of the work you all do and provide helpful knowledge that can accelerate the adoption of clean energy.

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Acronyms

DSM Demand Side Management. 21, 29

EV Electric Vehicle. 21

EVSE Electric Vehicles Supply Equipment. 27

FPL Florida Power and Light. 21

OCPP Open Charge Point Protocol. 36

OEM Automakers. 27

SOC State of Charge. 33

TLR Target Load Reduction. 50

V1G Managed Charging. 26, 61

V2G Vehicle-to-Grid. 21

V2H Vehicle-to-Home. 21

VPP Virtual Power Plant. 72

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Variables

Battery	Battery size of vehicle in kWh
c_i	Cost of discharging a vehicle, used in initial aggregation approach
d_i	Decision variable in initial approach aggregation algorithm that indicates the quantity of V2G used from a charger
E_a	Total energy available for discharge from a vehicle
E_f	Final energy stored in a vehicle battery at the end of a charging session
E_i	Initial energy stored in a vehicle battery at the start of a charging session
e_i	Number of discharge events a charger has participated in
e_{max}	Maximum number of discharge events a vehicle has participated in out a set of vehicles
$E_{potential}$	Total energy capacity of a vehicle battery minus the energy used in an charging session ($E_{total} - E_{session}$)
$E_{session}$	Energy consumed during a charging session
E_{total}	Total energy storage capacity of a vehicle battery at the start of a session (*Battery* * SOC_{max})
k	Cost of reducing charge to a vehicle, used in initial aggregation approach
m_i	Decision variable in initial approach aggregation algorithm that indicates the quantity of V1G used from a charger
P_a	Power available for dispatch, assumed to be 7.4 kW in this thesis
P_c	Power consumption during active charging session, assumed to be 7.4kW in this thesis
P_E	Power-energy; product of energy consumed and power consumed during an active charging session
P_{max}	Total day ahead peak power allowed by operator in a network of charging stations
P_{Total}	Total power consumption from EV charging by a network of chargers
P_{V1G}	Amount of power reduced to a charger using V1G
P_{V2G}	Amount of power discharged from a car using V2G
R	Power reduction from current charging level for a charger using in managed charging algorithm
SOC_f	Final state of charge during a charging session
SOC_i	Initial state of charge during a charging session
SOC_{max}	0.85, maximum assumed state of charge
SOC_{min}	0.15, minimum assumed state of charge
$T_{dispatch}$	Time in hours that a vehicle could be discharged at max power
$t_{interval}$	Time interval used between iterations of the aggregation algorithm
TLR	Target load reduction, operator defined power reduction to load on the grid
X_i	Binary decision variable in initial approach aggregation algorithm that indicates whether a charger participated in vehicle-to-grid during a dispatch event
Y_i	Binary decision variable in initial approach aggregation algorithm that indicates whether a charger participated in managed charging during a dispatch event

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Chapter 1

Introduction

As Electric Vehicle (EV) ownership increases, utilities face a high strain on electricity demand when vehicles charge at peak hours. Companies are investing in various solutions, including stationary battery storage to balance power demand; however, the high cost of batteries can make it challenging to deploy at scale. Bidirectional charging is a system that allows vehicles to charge a battery or discharge it back to another load. Applications of bidirectional charging include Vehicle-to-Home (V2H) and Vehicle-to-Grid (V2G). With many EVs coming to market, using vehicles for grid services, like bidirectional charging for V2H and V2G, could provide greater energy storage capacity than stationary batteries while being a lower-cost solution to improving grid resiliency.

NextEra Energy's regulated utility, Florida Power and Light (FPL) expects EV ownership to increase nearly ten times in Florida by 2030. If each vehicle could discharge 7.4 kW of power, the total power available by 2030 would be nearly 4 GW. To put this in perspective, this is greater than all of FPL's reserve installed power generation capacity[1] and total capacity from Demand Side Management (DSM) programs [24].

EV adoption by consumers is a huge financial opportunity for utilities and a tremendous operational challenge to meet the rapidly increasing demand for electricity

[1] Installed power generation capacity is defined as the difference between the total installed capacity minus the projected summer peak for each year as defined in FPL's 10-year site plan

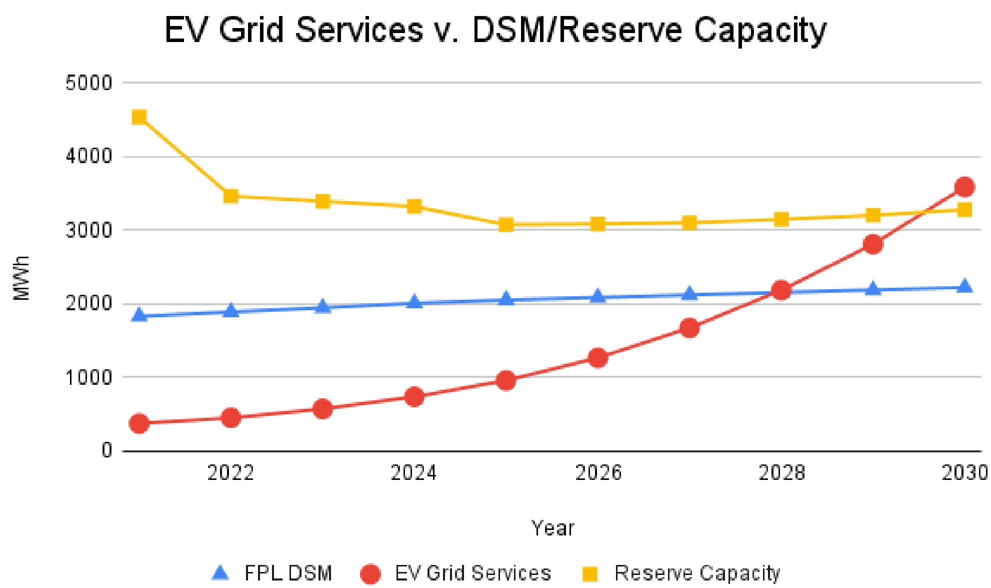

Figure 1-1: EVs' total estimated battery power generation potential will exceed all of FPL's DSM programs and installed reserve capacity in the next decade. Note: assumes all EVs are bidirectional capable

to charge vehicles. Utilities need to consider integrating EVs into their operations and using effective managed charging (V1G) and bidirectional charging programs to capture value from the EV transition and create a more resilient energy system. This thesis will overview EV charging and the state of bidirectional charging today. It will dive deeper into understanding when power is available through EVs by analyzing residential vehicle charger data. Technical strategies for aggregating EVs as a battery storage solution will be covered, and next steps will be proposed to propel bidirectional charging into a mature technology.

Chapter 2

Background

Understanding bidirectional charging requires some knowledge of EV charging. This thesis will focus on the charging protocols in the US. The different types of charging will be explained, including their applications for bidirectional charging. An overview of the bidirectional charging value chain will highlight stakeholders' needs and the importance of coordination to bring the technology to commercial maturity. Some terminology for electric utilities will be defined to provide a context for using bidirectional charging for grid services. The thesis will highlight why bidirectional charging programs should focus on the use of light-duty vehicles in a residential setting.

2.1 EV Charging

There are two types of vehicle chargers: AC and DC charging. In their simplest form an AC charger is an on/off switch that provides a power supply to the vehicle. In AC charging, EVs have an onboard charger that converts power from AC to DC. AC charging has two levels available, level 1, which is connected to a 110 V power supply (this is the typical wall plug), and level 2, which is connected to a 220 V power supply (this is the plug that most home dryers use in the US). The main benefit of the higher voltage is that level 2 chargers can charge vehicles much faster, delivering up to 20 kW of power compared to 2 kW for level 1 chargers [22]. Because of these quicker charging capabilities, many homes, public, and workplace chargers use level 2 chargers.

Both level 1 and 2 chargers use the J1772 charging protocol. The only OEM that uses a different protocol is Tesla which developed its proprietary plug for AC and DC charging.

DC chargers can deliver upwards of 350 kW of power to an EV . These chargers can drastically reduce vehicle charging times to 15 minutes [28] and are commonly found on interstates to allow vehicles to travel long distances. These chargers deliver DC power and use the inverter located in the charger assembly to bypass the onboard charger and directly connect to the vehicle's battery. There are two major plug types in the US, excluding Tesla: CCS1 and CHAdeMO. CHAdeMO was one of the earliest DC charging protocols primarily used on the Nissan Leaf. This charging protocol fully supports bidirectional charging [7] but was not widely adopted by other OEMs. In the US, most automakers have standardized around the CCS1 protocol. This protocol allows for up to 350 kW of power and shares a similar interface with the J1772 protocol giving it a packaging benefit for automakers (see figure 2-1). CCS1 is still developing capabilities for bidirectionality through the ISO 15118-20 protocol [23]. This protocol allows for communication between the EVSE and OEM. This thesis will not go in-depth about the status of this protocol, but it is important to note that bidirectionality for CCS1 is still in development.

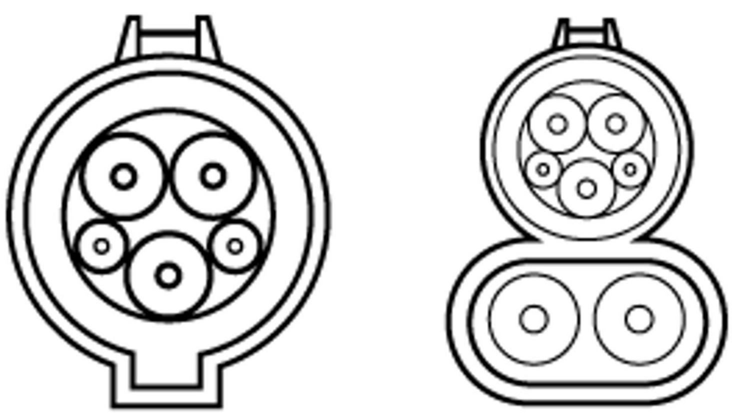

Figure 2-1: J1772 (left) and CCS1 (right) share some standard plug interfaces; CCS1 uses an additional two prongs

One of the significant differences between DC and AC charging is where the inverter is located. This point is essential in the bidirectional charging discussion for one primary reason: all components providing power to the grid must be UL certified. As part of UL certification, one requirement is that the component must be stationary. AC charging requires the use of an inverter onboard a vehicle and thus cannot currently be certified for bidirectional use [4]. In theory, AC charging can be used for bidirectional charging [5]; however, current safety standards do not allow it to be used in practice. The requirement for stationary components is practical for the grid's safe operation; however, advances in diagnostics for a vehicle's onboard inverter could ensure a high level of safety while allowing for the use of AC chargers for bidirectional use with the grid. This thesis will not focus on the use of AC charging for V2G. Still, it should be mentioned that a breakthrough in bidirectional charging with an AC charger could reduce the cost of installing a V2G system since level 2 AC chargers have a drastically lower cost than DC chargers. In hardware costs alone, AC chargers can be as low as a few hundred dollars, while DC chargers are thousands of dollars.

According to the Department of Energy, over 80% of EV charging occurs at home [19]. Nearly all residential chargers are AC chargers, but companies like DCbel [1] and WallBox are [2] developing DC chargers for residential use, finally enabling the use of residential bidirectional charging. This thesis will focus on applications of bidirectional charging for residential DC chargers with the CCS1 charging protocol.

	AC Charging		DC Charging	
	Level 1	Level 2	CCS1	CHAdeMO
Power Delivered	2 kW	20 kW	350 kW	50 kW
Plug Type	J1772	J1772	CCS1	CHAdeMO

Table 2.1: Overview of the major charging protocols in the United States

2.2 EV Grid Services

Unlike internal combustion vehicles, EVs have more applications beyond use for transportation. Their large battery is used to store electricity and the meager utilization rate [21] of light-duty cars make them fit for use with grid services. According to the US Department of Energy, grid services are activities grid operators perform to maintain system-wide balance and manage electricity transmission better. In the case of EVs, this paper considers two main types of services: Managed Charging (V1G) and bidirectional charging.

V1G is any service that limits power to an electric charger to balance electricity demand on the grid. These services can be as simple as implementing a time of use rate for electricity to encourage customers to charge off-peak hours. More advanced V1G can actively manage the load by turning off chargers entirely or limiting the maximum power output. As the number of EVs on the road increases, these systems will be crucial for grid operators to manage their electricity demand better.

Bidirectional charging is a system that allows the flow of electricity from the grid to charge a vehicle or from the car back to another load. This thesis will focus on the residential applications of bidirectional charging and will look at two specific applications: vehicle-to-home (V2H) and vehicle-to-grid (V2G). V2H is any use case where a car can be used to power a home. One of the first applications will be using V2H as home backup during a local power outage. This can help a customer run their home days at a time depending on the battery size and can be an effective tool for disaster relief. The more advanced version of V2H is for grid services. An operator could remotely control a vehicle to island the customers home from the grid in this application. Since the customer's electricity consumption would go off-grid, it would reduce electricity demand for an operator looking to shed load on the grid. V2G is the most advanced version of bidirectional charging that allows for the complete flexibility of sharing electricity stored in vehicles to any customer on the network.

2.3 Bidirectional Charging Value Chain

A complete bidirectional charging system requires the support of multiple stakeholders. Figure 2-2 highlights the five major segments of the value chain: OEM, EVSE, Aggregation Services, Electric Utility, and Customer.

Figure 2-2: There are many stakeholders involved in the bidirectional charging value chain; successful programs will require collaboration between all parties involved

Automakers (OEM) including traditional manufacturers and EV startups, are scaling the production of EVs. Many of these OEMs have voiced support for bidirectional charging, including Ford [15], Hyundai [25], and Nissan who has supported the feature since 2013 in the Nissan Leaf [29]. OEMs will be a critical part of the value chain since they will need to develop the hardware to allow vehicle batteries to charge and discharge, develop the software to communicate with all aspects of the value chain, and support bidirectional charging in their battery warranty. OEMs will be driven to adopt the technology if customers demand the feature. Positive feedback from Ford's V2H announcement may accelerate interest from customers and lead other OEMs to follow suit.

Electric Vehicles Supply Equipment (EVSE) companies will also be critical in developing the hardware that enables vehicles to discharge to the grid. They will also be heavily involved in establishing communication protocols between the OEM and the utility. They will need to work closely with utilities to ensure their hardware meets power quality standards and complies with the correct safety protocols. EVSEs will be driven to develop this technology due to increased OEM interest in bidirectional charging. EVSEs run the risk of being pushed out of the market by OEMs, like Ford, that announced their vehicles would only support bidirectional charging using Ford's proprietary charger.

Aggregation Services are a developing area of the value chain. To better describe their function, it is helpful to think about bidirectional charging as a system. When considering just EVs and bidirectional chargers, the system is just a series of distributed cars that do not communicate with each other. Aggregation is the software layer that enables the communication and collaboration between vehicles and chargers to coordinate when vehicles charge and discharge across the utility's territory. Consider it the brain behind allowing the use of EVs for grid services. This will be a critical component in unlocking the use of EVs as a distributed energy source. Multiple companies, including Fermata, Nuvve, and Weavegrid, are working in this space, but there is still no dominant player. These companies will likely sell their services to utilities as an enterprise software solution. Their services will grow based on the utility's demand for V2G. Aggregation services run the risk of being pushed out of the market by EVSEs of utilities that decide to develop these capabilities in-house.

Electric Utilities (Utility) are the organizations that manage power distribution for the grid in a particular region. They stand to benefit from V2G by harnessing EVs as an additional energy storage solution. This can help increase grid reliability and potentially decrease operating costs. Higher reliability and lower prices will benefit their customers. Demand for V2G will be driven internally based on the need for grid resiliency as demand for electricity spikes from electric vehicle adoption. The most significant risk for utilities adopting bidirectional charging will be getting customers to offer their vehicles for grid services. Some form of compensation to the customer will be necessary to drive customer participation.

The customer is the most important part of the value chain. Ensuring that customers are willing to offer their vehicles for grid services will be critical to commercializing bidirectional charging. Customers in the V2G value chain are EV owners and have two crucial needs: they do not want to inconvenience their driving habits and be compensated for using their vehicle. It is still unclear who may own the customer relationship and the overall contracting procedure. In the value chain used in this thesis, the customer is listed next to the utility since, initially, it will depend on whether the customer's electric utility will offer a V2G program.

Understanding each value chain component will be essential to designing a successful bidirectional charging program because success with early programs requires thorough collaboration across all five stakeholders. Ensuring each stakeholder's needs and thinking through different monetization strategies will be critical to a program's success. Since utilities such as Florida Power and Light (FPL) stand to benefit from bidirectional charging, they will likely be leaders in driving initiatives. They will need to consider two primary needs:

1. OEMs have voiced concerns with covering bidirectional use of batteries under warranty due to increased battery degradation

2. Customers cite inconvenience to their driving habits from participation in bidirectional charging

To ensure these needs are met, initial programs should be designed to be rare use cases to ensure limited battery cycling and inconvenience. This thesis will build out the proposed bidirectional charging program based on the critical need for rare initial use cases.

2.4 Demand Side Management

Utilities use a variety of Demand Side Management (DSM) programs to improve grid resilience. DSM programs can fall into two categories: efficiency upgrades and demand response. Efficiency upgrades can include investing in newer appliances like air conditioning in customer homes through incentives. These types of investments help reduce the overall electricity load. Demand response is the active management of electricity load on the grid. These programs imply that a utility can directly control specific loads to shut them off for brief periods while total energy demand is high. This serves as a last-minute resort before an operator resorts to dropping power at individual feeders to avoid destabilizing the grid. The benefit to a customer for participating in these programs is that they get some monthly incentive on their bill depending on the number of appliances signed up for a demand response program (see Table 2.2).

Demand Response is essential in the bidirectional charging discussion since these events are rare. They provide a framework for future V2G programs since they require customers to volunteer for potential reductions in their electrical service for monetary

Appliance	Applicability	Monthly Bill Credit
Central Electric Air Conditioner	April – October	$6.00
Central Electric Heater	November – March	$2.75
Conventional Electric Water Heater	Year-Round	$1.50
Swimming Pool Pump	Year-Round	$1.50

Table 2.2: Monthly incentives given to Florida Power and Light customers for participating in demand response programs

benefits. When thinking about early applications of using electric vehicles for grid services, it is essential to think of it through the lens of demand response.

2.5 Electricity Transmission and Distribution

To understand when a demand response event may occur, it is essential to know how power transmission and distribution work at a high level (see Figure 2-3). The following overview is based on Florida Power and Light's distribution system and uses company terminology to define the components of the system.

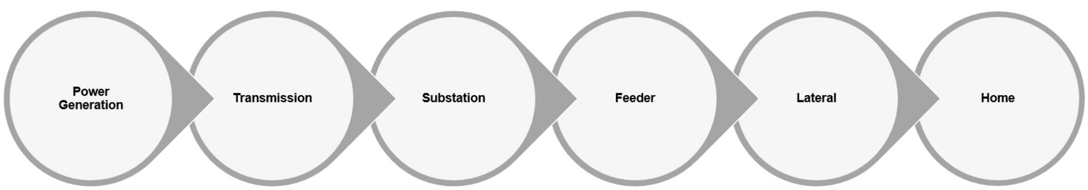

Figure 2-3: High-level overview of subsystems in the electrical grid

In a distribution grid, the bottleneck can be one of two areas. In extreme scenarios, power consumption can be so high that power generation could be a bottleneck. In other scenarios, even with ample generation, if demand under a specific substation becomes so high, there is a risk that the operator could overload the substation. There could be a power shortage because no more power can be added to the system. An operator could then rely on a demand response system to reduce load below a specific substation or, in more extreme cases, could resort to dropping entire feeders altogether. With bidirectional charging and other EV grid services, an operator could have an additional degree of freedom where they could now add power directly to the lateral before resorting to more extreme load reductions.

2.6 V2G with School Buses v. Light Duty Vehicles

Most V2G Pilots in the US have focused on school buses rather than light-duty vehicles [9]. This strategy is reasonable for early applications since school buses operate on set schedules allowing for a more predictable use case. School buses also have larger battery packs than light-duty vehicles, allowing more energy storage per installation. Since school buses park in large outdoor areas, there is more space to install a bidirectional charger with higher power output. Predictable schedules, higher energy storage, and higher power output make school buses the perfect first choice for V2G pilots. Despite being great candidates, V2G with school buses provides a relatively small impact on grid operations due to relatively low volumes. For example, the Florida School District, in their 2019-2020 Transportation Profile, reported 17,896 school buses [13]. The Federal Highway Administration reported 7,736,727 registered light-duty vehicles in Florida in 2020 [27]. Past school bus V2G pilots have used 60 kW chargers [9], meaning if all school buses in Florida were electrified and V2G enabled, there would be a total of 1.1 GW of dispatchable power. This number is not insignificant, but for context, FPL projects a total installed power generation capacity of 34.1 GW by 2030. V2G from school buses would represent a 3% increase in power generation. By comparison, if only 10% of all vehicles were electrified, a scenario FPL projects could happen by 2030, adding 5.7 GW of power and a 17% increase in power generation.

When talking about V2G, light-duty vehicles are the "holy grail." There has been less progress on V2G pilots with light-duty vehicles in the United States; however, given the enormous potential to unlock significant capacity for the grid, utilities need to make a concerted effort to make advances toward using electric vehicles for grid services. Since most light-duty vehicles charge at home, V2G programs will need to focus on V2G in a residential setting.

	School Buses	Light-Duty Vehicles
Number of Vehicles	17,896	7,736,727
Power Generation/Vehicle	60 kW	7.4 kW
Assumed EV Market Penetration	100%	10%
Available Energy	1,074 MW	5,725 MW

Table 2.3: Comparison of V2G power capacity available from school buses and light-duty vehicles. Even if all school buses were electrified by 2030, they would provide a fraction of the power than 10% of electrified light-duty vehicles

Chapter 3

Estimated Power Capacity for Electric Vehicle Grid Services

There is little data and research to show EVs' available power and energy storage capacity for grid services. This thesis used residential charging data from Florida Power and Light's residential charging program to estimate the capacity. It lays out the concept of vehicle states and the methodology used to arrive at the results. Early data suggests most power is available in the early morning, making it a potential resource for a winter storm scenario.

3.1 Vehicle States

When using EVs for grid services, it is essential to know two critical pieces of information: whether the vehicle is connected, and the State of Charge (SOC). Vehicle connected is represented as a binary number, where 0 denotes that the car is not connected, and 1 is that it is connected. Vehicle connected informs the operator which cars are available for grid services. SOC shows how much energy is stored in the battery as a percentage. SOC is critical in prioritizing which vehicles to discharge. For example, if a utility had the option to discharge a car at 85% SOC or one at 30%, it would be better to discharge the one with a higher SOC since that vehicle owner would still be left with ample energy to drive their car. A vehicle at 30% SOC may be unusable to the owner from how little energy would be left after the discharge event. This thesis considers 15% $SOC_{\min}$ and 85% $SOC_{\max}$. This thesis does not use the complete 0% to 100% range since many vehicle owners do not fully discharge their batteries. Many vehicles also allow the owner to reduce the full charge capacity to conserve total battery life.

Connected vehicles have two potential levers the operator can use for grid services: V1G and V2G. Imagine a connected vehicle charging at 7.4 kW. If the utility wanted to reduce the amount of power the total grid was consuming, they could use V1G to minimize the charge going to the vehicle or turn it off from charging altogether. This would reduce the load to the grid by up to 7.4 kW. If there was an additional need to reduce grid load, the exact vehicle could be used with V2G to discharge 7.4 kW. The potential for discharge could be greater than 7.4 kW depending on the car's charger, but this study will assume 7.4 kW for charging and discharging. With this in mind, each vehicle has the potential of up to 14.8 kW of power for grid services (see Figure 3-1).

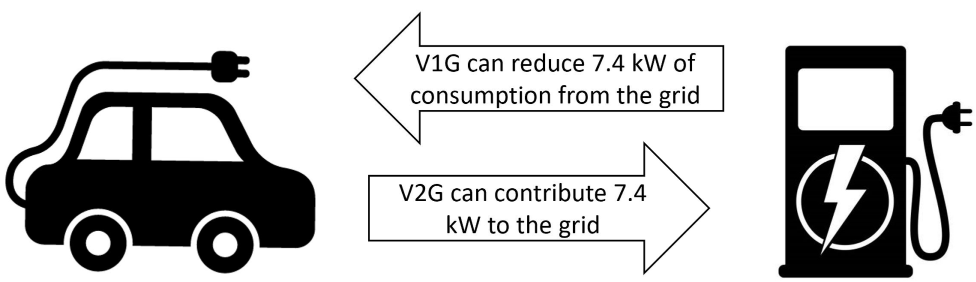

Figure 3-1: The diagram shows the two potential EV grid services considered in the capacity analysis: V1G to reduce power consumption and V2G to add additional power back to the grid for a total of 14.8 kW potential per vehicle

There are some cases where a car will not have 14.8 kW to serve the grid. One example is if the vehicle is finished charging, the operator cannot use V1G to reduce the total power load. A separate example is if the vehicle is charging below a specific SOC, the operator may not want to discharge the car to avoid inconveniencing the customer with too low a SOC. In this case, a vehicle may be available for V1G but not V2G. A final possibility is when the car is disconnected from the charger; then, the vehicle is not available for V1G nor V2G. The vehicle's different "states" can influence the amount of power available for grid services. This study uses four states to determine what grid services a car can offer.

State 0: vehicle disconnected or below 15% SOC. In this case, the car is not available for V1G nor V2G. SOC below 15% is included in this state even though the vehicle is connected to allow the battery to charge back to a bare minimum SOC. Keeping a car at low SOC contributes to severe battery degradation [17]. Customers in this situation would be allowed to charge their vehicle without hindrance back to the bare minimum.

State 1: vehicle connected and below 50% SOC. Consumer's number one concern with buying EVs is short driving range [10]. Allowing their utility to use their cars to discharge could further exacerbate these concerns. To encourage consumers to participate in bidirectional programs, defining a threshold below which a vehicle cannot be discharged will be essential. This study will use 50% as the threshold; however, future bidirectional charging programs may consider making this a sliding scale with varying compensation levels for the customer based on their willingness to offer a larger share of their battery for grid services. Vehicles in state 1 will be available for V1G but not V2G.

State 2: vehicle connected, greater than 50% SOC, and charging. This vehicle state provides the most flexibility since it is available for V1G and V2G. The customer will never have their battery depleted below a 50% threshold, and the utility gets the total 14.8 kW of usable power. This thesis weighs all state 2 vehicles equally regardless of SOC. For example, a car with 55% SOC is weighed equally to a vehicle with 80% SOC. This was done for simplicity, but further studies should continue exploring strategies to prioritize the use of vehicles within state 2.

State 3: vehicle connected and finished charging. Since the car does not require additional power, this state is available for V2G but not V1G. This is the preferred state to start with when it comes to discharging vehicles since it has the highest SOC.

	State 0	State 1	State 2	State 3
Description	Vehicle disconnected or below 15% SOC	Vehicle connected; below 50% SOC	Vehicle connected; greater than 50% SOC and still charging	Vehicle connected and finished charging
SOC	-	< 50%	50% ≤ SOC < 85%	85% (or user defined max SOC)
V1G	X	✓	✓	X
V2G	X	X	✓	✓

Table 3.1: Summary of all four vehicle states. A thorough understanding of vehicle states will be critical since it forms the basis for finding the capacity available of V2G and also for developing aggregation algorithms

3.2 Theory

FPL has a residential charging pilot with 48 chargers connected to an Open Charge Point Protocol (OCPP) server. OCPP is a communications protocol that enables an EV charging station operator to connect their devices to the internet and collect data. Using OCPP, FPL collects data from their chargers and stores it on their server as two separate databases: Residential Charging Sessions (Session Data) and Residential Charging Meter Data (Meter Data).

Whenever a vehicle is first connected to a station, the station pings the server to initiate a new charging session. Session Data records all individual sessions as a single line in the database. This includes information like energy consumed, start/end time, session ID, station ID, etc. Table 3.2 highlights the data used for this thesis. An example of Session Data can be found in Table A.1 in the Appendix.

station_id	session_id	energy (kWh)	start_time	end_time

Table 3.2: Data in residential charging sessions database used to estimate capacity

To get a more detailed look at what happened during each session, the charging station also reports more frequent data every 15 minutes while a vehicle is connected. This constant data stream is collected and stored in the Residential Charging Meter Database. Meter Data includes the timestamp, transaction_pk (called session_id in

Session Data), kW reading (called value in Meter Data), etc. Table 3.3 highlights the data used for this thesis. An example of Meter Data can be found in Table A.2 in the Appendix.

transaction_pk (session_id)	value_timestamp	value (kW)	charge_box_id (station_id)

Table 3.3: Data in Residential Charging Meter database used to estimate capacity

One of the initial challenges in working with OCPP data is ensuring all EVSE companies report data in a standard format. Although OCPP defines how to report data, there could be discrepancies in how often the data is transmitted, what units a company might use, and how much data is sent. FPL piloted several EVSE suppliers, and extensive work was done so that all chargers reported in a standard format. With the data streaming correctly, two main issues needed to be resolved prior to finding capacity available:

1. OCPP only collects data from a charging station while a vehicle is charging. This data needs to be converted to a format that includes all times of day and includes blank data for the times when no car was connected.

2. All the chargers in the residential charging program are AC chargers that use the J1772 protocol. J1772 has a hardware limitation that does not allow it to read SOC. An algorithm needs to be developed to estimate the SOC

The solution used in this thesis for both issues is highlighted in the methodology. After accounting for these two issues, the goal is to report data in the format shown in Table 3.4. This new database is called the capacity database.

3.3 Methodology

When analyzing residential charging data to estimate the capacity available, the user must specify the start and end dates that the algorithm should consider. These dates

Columns	Description
id	Unique station identifier for charging equipment
date	MM/DD/YYYY
time	Time on a 24-hour scale
day	Day of the week as a string
battery_ size	Size of battery in kWh
vehicle_connected	Binary where 0 is disconnected, and 1 is connected
power_consumed	Power consumed to charge the vehicle in kW
soc	State of charge represented as a decimal (0.0-1.0)
power_available	If the vehicle is above 50% state of charge, this value is set to 7.4 kW
energy_available	soc * battery_size (in kWh)
dispatch_time	energy_available / power_available (gives time in hours)

Table 3.4: The final format for data used to calculate capacity available has each of the following columns. A brief description of each column is provided

filter the Session Data and Meter Data to leave sessions and meter data between the period in question. The time values for both databases are rounded to the closest 15-minute intervals. For any session data that may have started before the period in question, the session's start time is set as 00:00 of the start date. For session data that ended after the period in question, the session's end time is set as 23:45 of the end date.

Once both data sets are filtered and adjusted to the correct time interval, the user should identify all the unique charger IDs. For each charger in the list of unique charger IDs, a data frame is created using Python Pandas, where each row is a 15-minute time interval from 00:00 on the first date and ending on 23:45 of the last day in question. The Session Data is filtered to find the unique charger values in the analysis period.

Since FPL's Residential Charging program outlines that only one car can charge at a specific charger, each charger is assumed to be connected to only one vehicle. We can then use the charging session data to estimate the size of the car's battery. The minimum battery size for vehicles in the thesis was assumed to be 50 kWh, a conservative estimate given EV battery capacity can reach up to 200 kWh [8]. Using the unique list of charger IDs, the user filtered the Session Data to all the sessions for that particular charger. The maximum energy used to charge the car is found from the filtered sessions. If the max energy is less than 50 kWh, then the vehicle's battery size is assumed to be 50 kWh. If the estimated battery size is greater than 50 kWh, then the battery size for that car is set to the calculated value rounded up to the nearest integer. Image 3-2 shows how the process for estimated battery size works. Table 3.5 shows the data populated in the dataframe up to now.

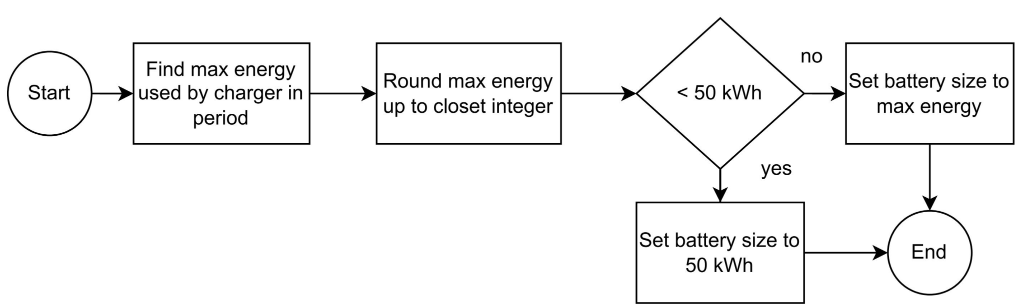

Figure 3-2: Process flow diagram for estimating battery size

id	date	time	day	Battery_size (kWh)
0001	10/01/2021	00:00	Friday	50
0001	10/01/2021	00:15	Friday	50
0001	10/01/2021	00:30	Friday	50
0001	10/01/2021	00:45	Friday	50
0001	10/01/2021	01:00	Friday	50
0001	10/01/2021	01:15	Friday	50

Table 3.5: After filtering data out of the period in the analysis and the battery size is estimated, the capacity database resembles this table

Using the session_id in the Session Data, the algorithm filtered Meter Data by transaction_pk (Meter Data used a different name to refer to session_id). The start and end times were read from the filtered Meter Data to set vehicle_connected to 1 for all the times during the session.

Estimating SOC depends on whether the vehicle finished charging during the session. If the meter value dropped to zero kW before the session ended, the car stopped charging while connected, and the final SOC, SOC_{f}, equals SOC_{max}. The last non-zero kW reading during the charging session is where the car achieved SOC_{max}. The algorithm then backtracked to find the SOC at the start of the session, SOC_{i}.

$$E_i = (SOC_{max} * Battery) - E_{session} \tag{3.1}$$

$$SOC_i = E_i / Battery \tag{3.2}$$

$$SOC_f = SOC_{max} \tag{3.3}$$

If the meter reading did not fall back to 0, the vehicle did not finish charging. The algorithm would estimate SOC_{i} and SOC_{f} as follows:

$$E_{total} = Battery * SOC_{max} \tag{3.4}$$

$$E_{potential} = E_{total} - E_{session} \tag{3.5}$$

$$E_i = E_{potential}/2 \tag{3.6}$$

$$SOC_i = E_i/Battery \tag{3.7}$$

$$SOC_f = (E_i + E_{session})/Battery \tag{3.8}$$

To find the SOC values between SOC_{i} and SOC_{f}, a *linspace* function was used. For a charging session that finished charging, the length of the *linspace* array was equal to the number of 15-minute intervals between the start of the session and the time when the vehicle finished charging. For a charging session that did not finish charging, the *linspace* array was equal to the number of 15-minute intervals between the start and end of the session. The *linspace* array was added to the SOC column of the Capacity Database. All the timestamps where the vehicle was charging were set to 7.4 kW. The results after this step resemble the form of Table 3.6.

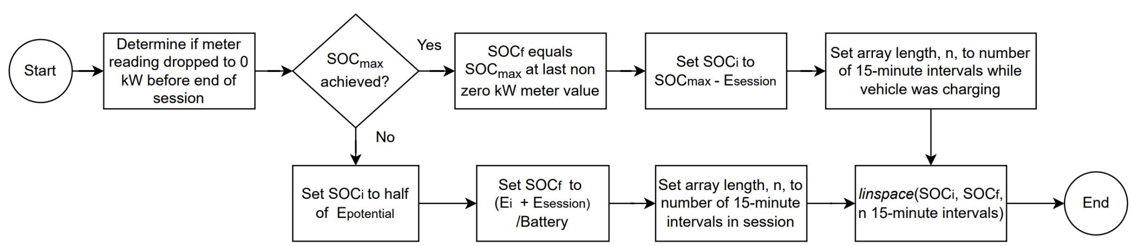

Figure 3-3: Process flow diagram for estimating SOC during a charging session

The algorithm must find the remaining values: power_available, energy_available, and dispatch_time. Power_available, P_{a}, was the measure used to say whether a vehicle could discharge. This value was set to 7.4 kW if the car was connected and SOC was greater than 0.5. If P_{a} was greater than 0, energy_available, E_{a} and

id	date	time	day	battery_size	vehicle_ connected	power_ consumed (kW)	soc
0001	10/01/2021	00:00	Friday	50	1	7.4	0.79
0001	10/01/2021	00:15	Friday	50	1	7.4	0.81
0001	10/01/2021	00:30	Friday	50	1	7.4	0.83
0001	10/01/2021	00:45	Friday	50	1	7.4	0.85
0001	10/01/2021	01:00	Friday	50	1	0	0.85
0001	10/01/2021	01:15	Friday	50	1	0	0.85

Table 3.6: After iterating through all the charging sessions, the dataframe will have the following information populated

dispatch_time in hours, T_{dispatch}, were calculated as follows:

$$E_a = Battery * (SOC - 0.5) \tag{3.9}$$

$$T_{dispatch} = (E_a / P_a) \tag{3.10}$$

id	date	time	day	batt _size	vehicle_ conn	power_ cons	soc	power_ available (kW)	energy_ available (kWh)	dispatch _time (hours)
1	10/01/21	00:00	Fri	50	1	7.4	0.79	7.4	39.5	5.4
1	10/01/21	00:15	Fri	50	1	7.4	0.81	7.4	40.5	5.5
1	10/01/21	00:30	Fri	50	1	7.4	0.83	7.4	41.5	5.6
1	10/01/21	00:45	Fri	50	1	7.4	0.85	7.4	42.5	5.7
1	10/01/21	01:00	Fri	50	1	0	0.85	7.4	42.5	5.7
1	10/01/21	01:15	Fri	50	1	0	0.85	7.4	42.5	5.7

Table 3.7: Final format for Capacity Data

Table A.3 and Table A.4 in the Appendix show a post-analysis charging session where the vehicle finished charging and did not finish charging, respectively. Once each charging session was analyzed, all separate dataframes were combined into one database. This final data set was used to analyze the capacity available.

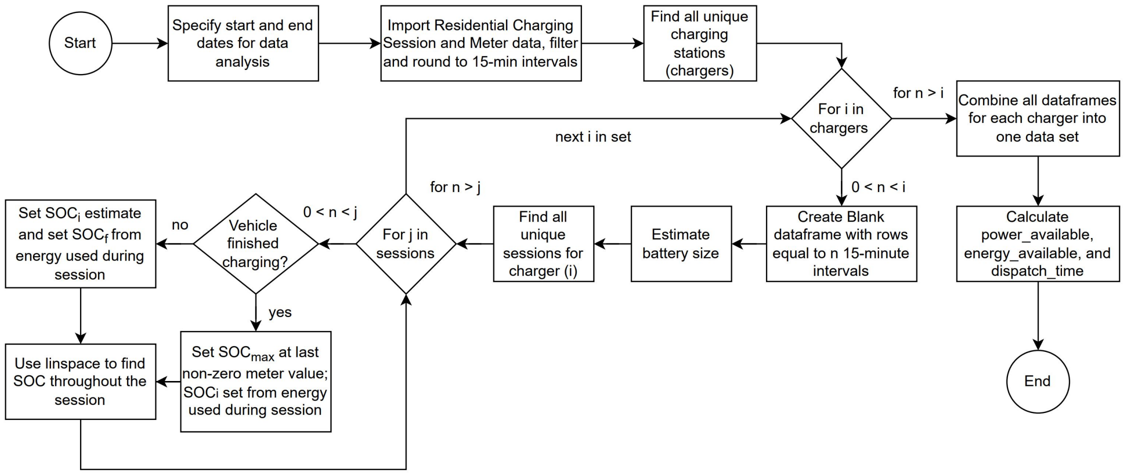

Figure 3-4: Process flow diagram for estimating capacity available of EV grid services

3.4 Data Analysis

Once charging session data was formatted to include all time periods and to estimate SOC, the thesis focused on finding two critical pieces of information:

1. Average power_available, power_consumed, and energy_available across all chargers for each 15-minute interval throughout the day, for each day of the week

2. Distribution for power_available, power_consumed, and energy_available across all chargers for each hour of the day

To find the first piece of information, the data was grouped by id, day, and time. This grouping was used to calculate average power_available, energy_available, and power_consumed. Three separate tables were made for each day of the week where the columns were each 15-minute interval, and the rows were each id (charger id). The values in the table were the respective averages for that day of the week, at that particular time, for the unique charger. Table 3.8 shows this intermediate step.

ID	00:00	00:15	00:30	…	23:15	23:30	23:45
1	3.4	3.4	3.4	…	0	0	0
2	4.2	4.2	4.2	…	5.1	5.1	5.1
3	2.8	2.8	2.8	…	6.3	6.3	6.3

Table 3.8: Three tables were created for each day of the week where average_power_available, average_power_consumed, and average_energy_available were listed. The table below shows a sample of the average_power_available for Monday

To find the overall system average by day, the sum of each column shown in Table 3.8 for average_power_ available, average_power_consumed, and average_energy_available was calculated and populated in a table where columns were 15-minute time intervals, and the rows were the day of the week. This final table is displayed in Table 3.9.

Day	00:00	00:15	00:30	…	23:15	23:30	23:45
Monday	16.3	17.8	16.3	…	19.2	19.2	19.2
Tuesday	19.2	19.2	19.2	…	16.3	16.3	17.8
Wednesday	17.8	17.8	17.8	…	8.9	8.9	10.4
Thursday	10.4	10.4	10.4	…	16.3	17.8	17.8
Friday	17.8	17.8	17.8	…	5.9	5.9	5.9
Saturday	5.9	5.9	7.4	…	7.4	7.4	7.4
Sunday	8.89	10.4	10.4	…	20.7	20.7	20.7
Average	13.7	14.2	14.2	…	13.5	13.7	14.2

Table 3.9: The table shows a sample of the average_power_available

To find the distribution for power_available, power_consumed, and energy_available, the data was grouped by date and time. The grouping was used to calculate the sum of power_available, power_consumed, and energy_available. Three separate tables were created to display the values for each. Each column was used to create a histogram showing the distribution of values over the period in question.

Date	00:00	1:00	2:00	…	21:00	22:00	23:00
11/1/21	0	0	0	…	0	0	0
11/2/21	7.4	7.4	14.8	…	7.4	7.4	7.4
…	…	…	…	…	…	…	…
11/14/21	14.8	14.8	14.8		0	0	0
11/15/21	14.8	14.8	14.8	…	14.8	22.2	22.2

Table 3.10: The table shows a sample of the power_available by date

3.5 Results

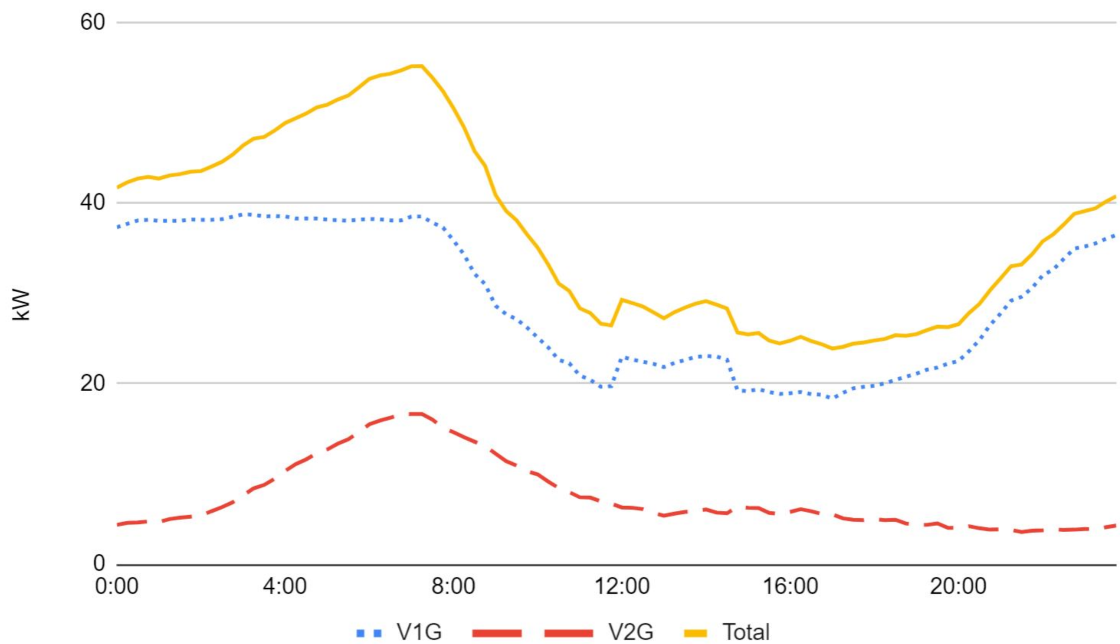

Figure 3-5: Average capacity available for 27 chargers from 10/01/2021 - 04/14/2022. The plot shows the overall average of power_available and power_consumed. EV grid services are most readily available in the early morning and evening, with some power available throughout the day.

There are two key takeaways from the analysis:

1. Capacity available from EV grid services is most readily available during the early morning and evening

   This learning makes conceptual sense since most EV owners charge their car overnight to have a full charge by the following day. In the late evening, we also see that power_available starts to rise again as more vehicles connect again. Figure A-1 in the Appendix shows a breakdown of capacity by day of week.

2. There may be capacity available at all hours of the day

   The data suggests most EVs connect in the afternoon and disconnect in the morning; however, the data also shows there are EVs that charge throughout the day. As the amount of EVs in the analysis grows, there should always be some level of capacity available. Figure A-2 and Figure A-3 highlights the distribution of power_consumed and power_available at each our of the day.

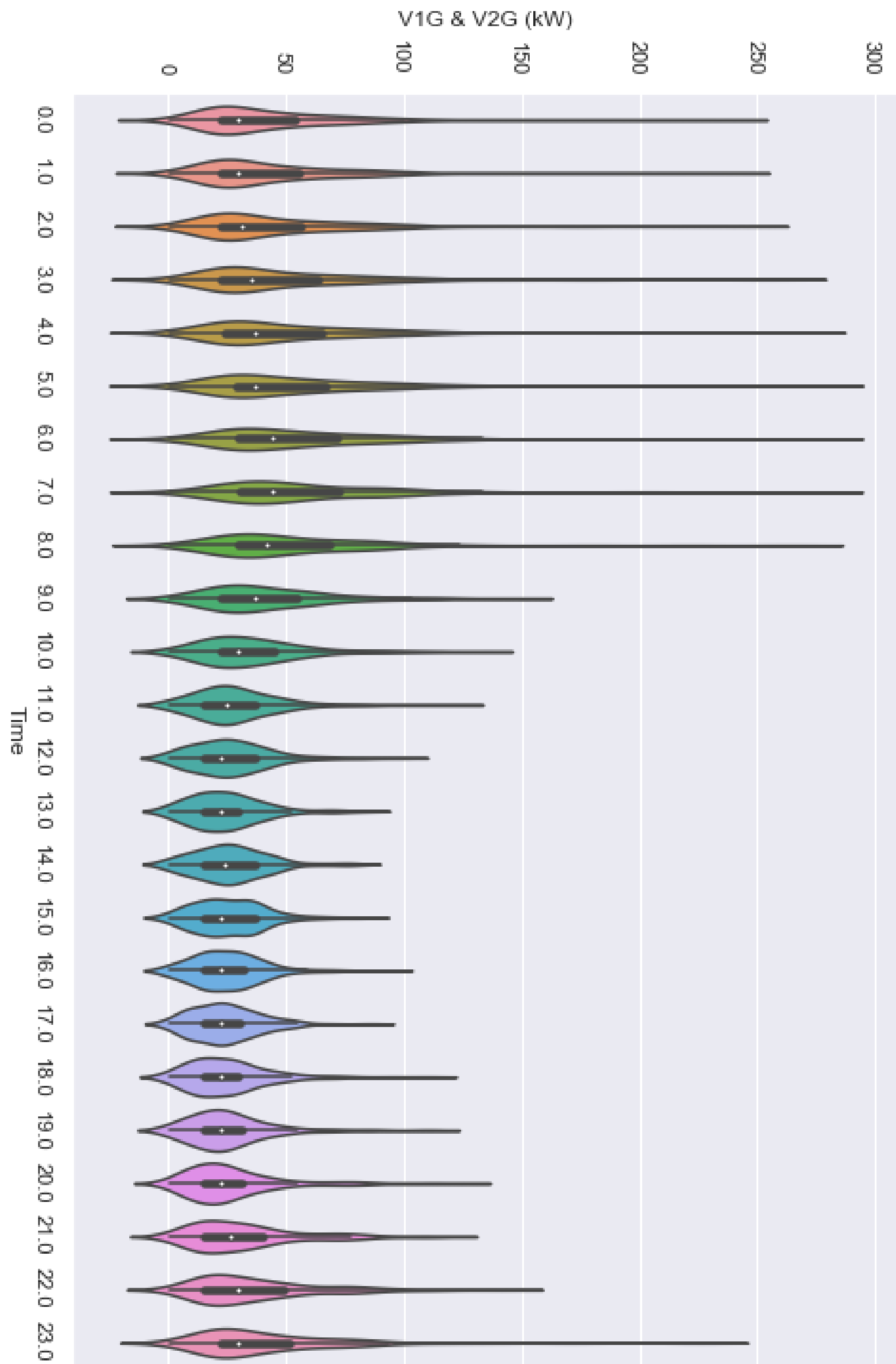

Figure 3-6: Violin plot for total V1G and V2G capacity by the hour

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Chapter 4

Demand Response Aggregation Algorithm

The capacity available analysis shows promise in using electric vehicles for grid services. In demand response programs, customers have shown willingness to give up some control of their electricity use for a financial benefit. Early bidirectional charging programs should emulate demand response programs to increase customer participation. Using EVs for demand response could be a lever the operator may use before relying on demand response with home appliances. In FPL territory, one of the main drivers of electricity use is air conditioning. During a demand response event, a customer may lose power to their AC, causing great inconvenience to their home, particularly if the demand response event occurs during a summer day. In the proposed solution of using EVs for demand response, a customer may lose some charge to their vehicle (Figure 4-1 shows how this system would operate). If done strategically, the customer may not notice any effect. For example, if a customer is charging their vehicle for 12 hours and the car stops charging for 2 hours in that time frame, they may never know their utility turned off their charger. Going a step further, if that same customer had their battery discharged partially during those 12 hours, they might still have enough time to charge their battery before using their car. In either case, the customer had zero impact on their driving behavior.

The remaining challenge to making this system operate is deciding which vehicles

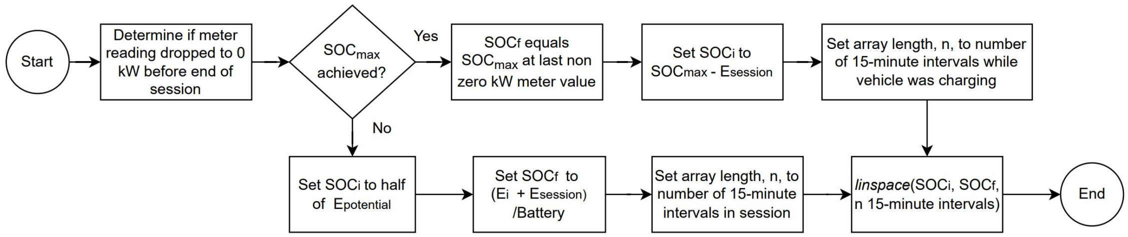

Figure 4-1: Process flow diagram for how an operator would engage a demand response using EVs for grid services event. This system would be manually started and ended by the operator

need to participate in meeting the Target Load Reduction (TLR). This step of the process flow diagram is called V2G Aggregation. This thesis assumes the operator has two levers they can use: V1G and V2G. This section develops three characteristics that the aggregation algorithm must satisfy to minimize customer inconvenience.

1. V1G is preferable to V2G

   If the operator could meet the TLR through V1G, in most cases, it is preferred since there would be minimal degradation to the vehicle from a reduction in charge. If V1G is not enough to meet the TLR, then the system should also consider using V2G.

2. Maintain overall SOC as high as possible

   If the aggregation algorithm needed to choose between discharging two vehicles at different SOC, it would be best to select the one with the higher state of charge first. Overall, each customer can have the highest possible SOC. In a more complex case, suppose one vehicle is in state 1 (battery below 50% SOC) and can use V1G, and another car is in state 3 (connected and not charging) and can use V2G. With only constraint one in mind, the system would select V1G with the car in state 1. This decision would keep the vehicle in state 1 at a low SOC while preserving one that is fully charged. In this case, it would be better to discharge the fully charged car first. It is preferred to make the decision that leads to higher SOC overall.

3. It is preferable to choose vehicles that have participated in fewer demand response events

   The number of times the customer has participated in demand response events must be considered. Suppose the algorithm needs to choose between two vehicles with equal SOC. Vehicle one has participated in two discharge events, while vehicle 1 has participated in zero. It would be best to choose vehicle 2 since it would minimize the inconvenience to the customer over time.

Keeping these points in mind, an order of priority can be laid out when selecting which vehicles should participate in a demand response event. This algorithm is summarized in Figure 4-2.

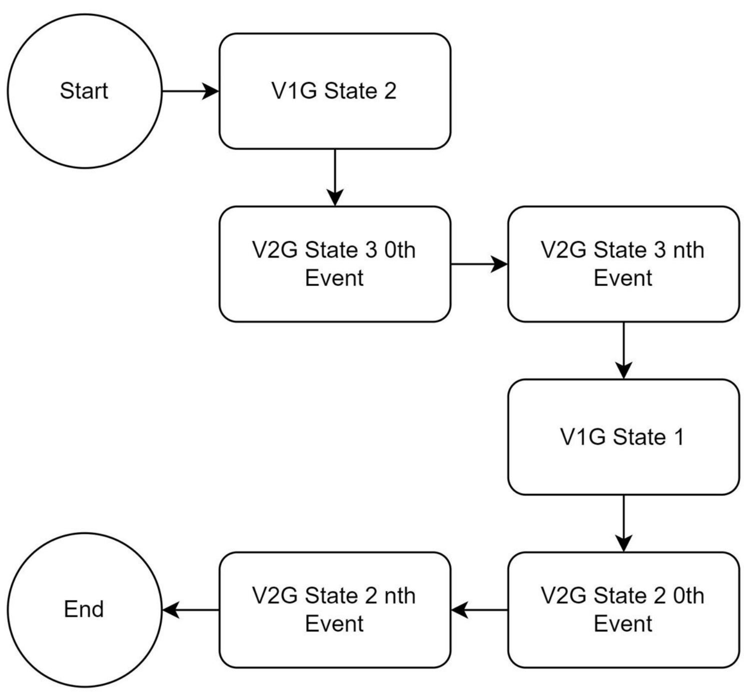

Figure 4-2: The flow diagram shows the order of prioritization when using EVs for demand response

4.1 Initial Approach and Results

The first iteration of the proposed aggregation algorithm used linear optimization. The goal was to select vehicles during a dispatch event according to the order defined in Figure 4-2. Each car was assigned a cost according to its state, where cars earlier in the priority list were given a lower cost. The algorithm's objective function was to seek the lowest cost solution with each vehicle cost defined.

Each vehicle had up to two potential grid services it could offer: V1G or V2G. Cars with V2G had two decision variables, X_i, a binary variable where 1 indicated the vehicle had been selected for discharge, and d_i, a continuous variable between 0 and 1 that showed how much of the total power to discharge. Cars with V1G had two decision variables, Y_i, a binary variable where 1 indicated the vehicle had been selected for managed charging, and m_i, a continuous variable between 0 and 1 that demonstrated how to reduce the vehicle charge. Table 4.1 shows the decision variables by vehicle state.

State	1: Connected ≤50% SOC	2: Connected, ≥50% SOC & Charging	3: Connected & Not Charging
Decision Variables	$Y_{1i} \in \{0,1\}$ $0 \leq m_{1i} \leq 1$	$X_{2i} \in \{0,1\}$ $Y_{2i} \in \{0,1\}$ $0 \leq d_{2i} \leq 1$ $0 \leq m_{2i} \leq 1$	$X_{3i} \in \{0,1\}$ $0 \leq d_{3i} \leq 1$

Table 4.1: Summary of decision variables used for the linear optimization formulation

Since X_i and Y_i serve as a decision variable indicating whether the charger was used, and d_i and m_i denote the quantity of power needed from that resource, a constraint was defined to only allow d_i and m_i to be non-zero if X_i and Y_i are also non-zero.

$$m_i \leq Y_i \tag{4.1}$$

$$d_i \leq X_i \tag{4.2}$$

State 2 vehicles can offer both V1G and V2G, so two additional constraints must be added to ensure that V1G is used entirely before V2G is used.

$$X_i \leq Y_i \tag{4.3}$$

$$X_i \leq m_i \tag{4.4}$$

The final constraint for the formulation needs to incorporate the Target Load Reduction (TLR). In simple terms, the amount of power added from V2G must be greater than TLR minus the amount of power reduced from the use of V1G. P_c is the power consumption of the charger, and P_a is the power available for dispatch.

$$\sum_{i=1}^{n} P_{A2i} * d_{2i} + \sum_{i=1}^{n} P_{A3i} * d_{3i} \geq TLR - \sum_{i=1}^{n} P_{C1i} * m_{1i} - \sum_{i=1}^{n} P_{C2i} * m_{2i} \tag{4.5}$$

Power added from V2G comes from two sources: vehicles in state 1 and 3. Power reduced from V1G comes from two sources: vehicles in state 1 and 2.

State	1: Connected ≤50% SOC	2: Connected, ≥50% SOC & Charging	3: Connected & Not Charging
Constraints	$m_{1i} \leq Y_{1i}$	$X_{2i} \leq Y_{2i}$ $d_{2i} \leq X_{2i}$ $m_{2i} \leq Y_{2i}$ $X_{2i} \leq m_{2i}$	$d_{3i} \leq X_{3i}$
	$\sum_{i=1}^{n} P_{A2i} * d_{2i} + \sum_{i=1}^{n} P_{A3i} * d_{3i} \geq TLR - \sum_{i=1}^{n} P_{C1i} * m_{1i} - \sum_{i=1}^{n} P_{C2i} * m_{2i}$		

Table 4.2: Summary of constraints used for the linear optimization formulation

The objective function of the algorithm is to minimize cost according to the priority defined in Figure 4-2 where the lowest cost selection would be earlier in the hierarchy. Costs for V1G are represented as, k, while V2G costs are represented as, c_i. Vehicles that can offer V2G also need to account for the number of events, e_i, they have participated in historically. In practice, e_i can be designed to reset to zero at a set period defined by the program. This thesis recommends a yearly period. Each charger cost is assigned as follows where e_max is the most events any one charger has participated in:

$$k_2 = 1 \tag{4.6}$$

$$c_3 = 2 * (e_i + 1) \tag{4.7}$$

$$k_1 = c_3 * (e_{max} + 1) + 1 \tag{4.8}$$

$$c_2 = k_1 + e_i + 1 \tag{4.9}$$

Rather than giving predetermined values, this framework allows the cost to change as the number of events increases over time. The objective is to minimize the sum of all costs of using state 1 V1G, state 2 V1G, state 2 V2G, and state 3 V2G.

$$min \sum_{i=1}^{n} k_1 * Y_{1i} + \sum_{i=1}^{n} k_2 * Y_{2i} + \sum_{i=1}^{n} c_{2i} * X_{2i} + \sum_{i=1}^{n} c_{3i} * X_{3i} \tag{4.10}$$

The summary of the formulation can be found in Table 4.3. Figure 4-3 shows the compute time to solve for n = 10 - 1,000,000.

State	1: Connected ≤50% SOC	2: Connected, ≥50% SOC & Charging	3: Connected & Not Charging
Decision Variables	$Y_{1i} \in \{0,1\}$ $0 \leq m_{1i} \leq 1$	$X_{2i} \in \{0,1\}$ $Y_{2i} \in \{0,1\}$ $0 \leq d_{2i} \leq 1$ $0 \leq m_{2i} \leq 1$	$X_{3i} \in \{0,1\}$ $0 \leq d_{3i} \leq 1$
Constraints	$m_{1i} \leq Y_{1i}$	$X_{2i} \leq Y_{2i}$ $d_{2i} \leq X_{2i}$ $m_{2i} \leq Y_{2i}$ $X_{2i} \leq m_{2i}$	$d_{3i} \leq X_{3i}$
	$\sum_{i=1}^{n} P_{A2i} * d_{2i} + \sum_{i=1}^{n} P_{A3i} * d_{3i} \geq TLR - \sum_{i=1}^{n} P_{C1i} * m_{1i} - \sum_{i=1}^{n} P_{C2i} * m_{2i}$		
Objective	$min \sum_{i=1}^{n} k_1 * Y_{1i} + \sum_{i=1}^{n} k_2 * Y_{2i} + \sum_{i=1}^{n} c_{2i} * X_{2i} + \sum_{i=1}^{n} c_{3i} * X_{3i}$		

Table 4.3: Summary of the formulation for the aggregation algorithm using linear optimization

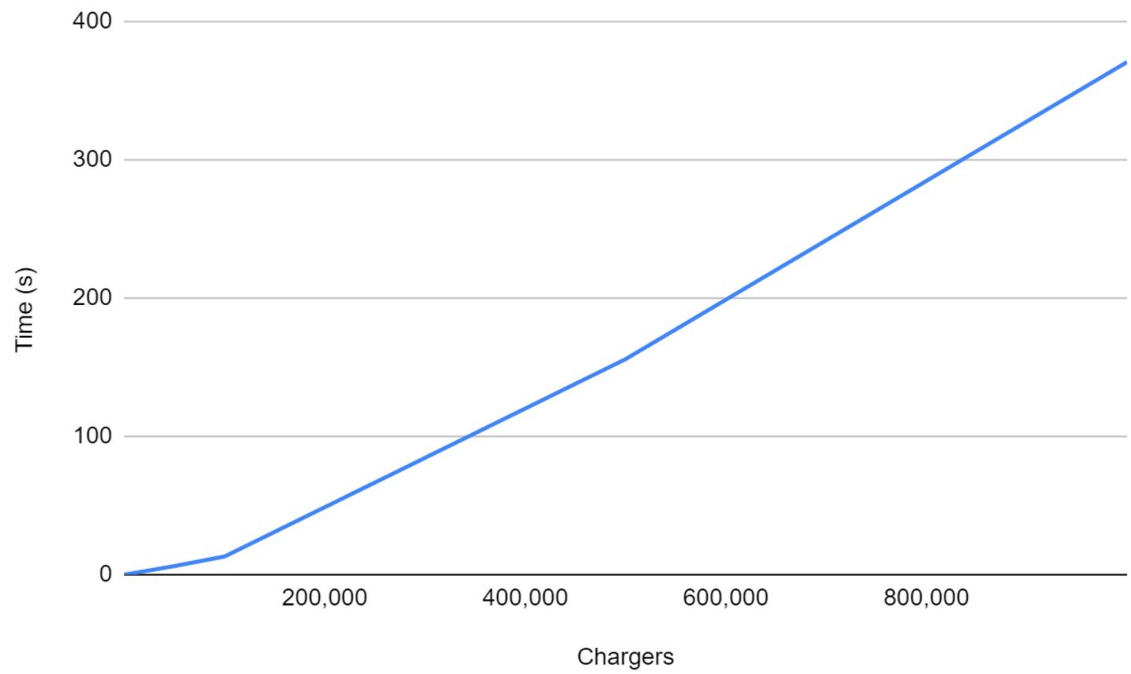

Figure 4-3: The plot shows the time it takes in seconds for the algorithm to compute a solution using the GLOP solver in Google OR tools

4.2 Simplified Approach and Results

Using linear optimization for aggregation is time-intensive, which prompts the need for a faster solution. Since the aggregation algorithm needs to follow the order of priority defined in Figure 4-2, an operator would know that the program should first utilize an entire resource before moving on to the next bucket. It is possible to design an algorithm that analyzes charger data by vehicle state to determine if the TLR can be met with the sum of the total power available in a particular vehicle state. If the power can be met, it can split the load across all the chargers in that set. If it cannot meet the TLR, it can activate all available V1G or V2G and move on to the next bucket. This algorithm would follow this logic through each vehicle state until the TLR had been met. One additional heuristic the algorithm should solve is to test whether there is a feasible solution at the start of a demand response event. With the charger data as input, the algorithm adds the total V1G and V2G capacity to see if it can meet the TLR. Suppose the TLR is greater than all EV capacity. In that case, the charger activates all V1G and V2G to return the remaining power deficit, encouraging operators to utilize other DSM programs to curtail electricity demand further.

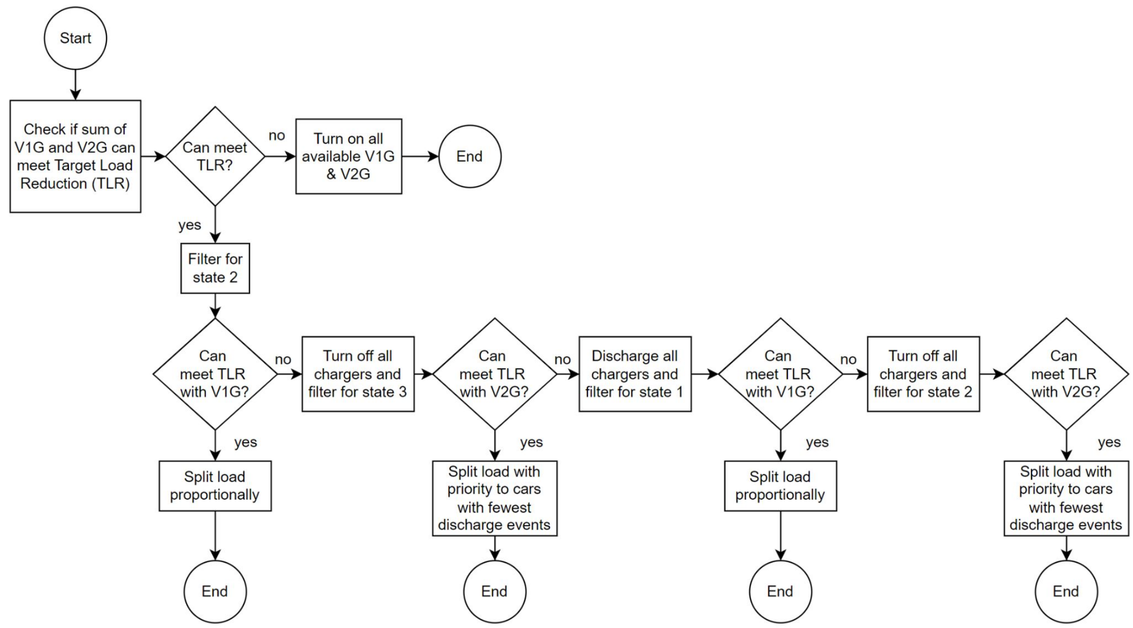

Figure 4-4: The simplified approach followed this process flow and would filter the input by vehicle state to solve where to dispatch power from

The new simplified process takes a fraction of the time to compute a solution using the same computer. With 1,000,000 chargers in the dataset, the new method took around 10% of the time to find a solution compared to 1,000,000 chargers in a linear optimization program.

4.3 Next Steps

The proposed algorithm provides a framework for bidirectional charging programs for utilities. Future studies should continue developing the framework to include three additional considerations:

1. Vehicle location and electrical grid losses

   In a demand response event, an operator would resort to EV grid services if a substation was at risk of being overloaded. In this case, only EVs

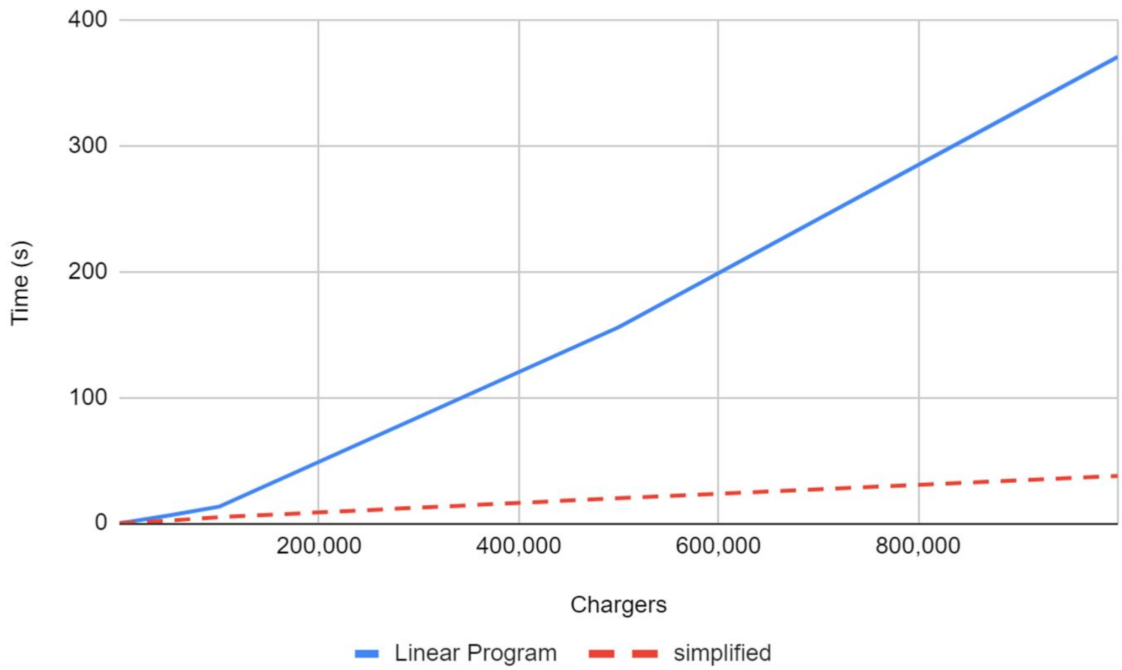

Figure 4-5: The plot shows the time it takes in seconds for the simplified approach to compute a solution

connected to that substation would need to be considered. The proposed algorithm could be solved at each substation to account for this physical constraint. Another essential consideration would be understanding which feeder under a substation is experiencing high electricity demand. EVs connected to that feeder should be prioritized to meet demand since there would be fewer transmission losses during a dispatch event. In a separate case, suppose a feeder is experiencing high demand, but most EVs are connected to a different feeder. In this case, the cars would need to discharge in unison to increase the voltage on the feeder enough to backflow to a separate feeder. As V2G develops, consideration of the physical layer will become a critical part of a successful solution.

2. Vehicle disconnecting during a dispatch event

During a demand response event, some vehicles will disconnect from the charger. This can be problematic if many cars are disconnecting at once.

For example, if a demand response event occurred in the morning when many drivers were projected to leave for work, the total capacity would drastically decrease. There could be three possible solutions to address this risk: keeping a priority list of vehicles to dispatch as others disconnect, considering the likelihood of a car remaining connected, or requiring customers to stay connected during a dispatch event. Keeping a list of priority should be included in any V2G program. Some vehicles disconnecting is expected, and effective programs should be designed to account for this behavior. This list should be updated as the dispatch event continues. A more advanced solution to account for vehicles disconnecting is understanding each vehicle's charging patterns. With known charging behavior, it is possible to compute a solution that prioritizes choosing cars that are likely to stay connected until the next interval. A final potential solution requires customers to stay connected during the dispatch event. This could be very effective since it eliminates the risk of a vehicle disconnecting, at the risk of providing a worse customer experience. Utilities could consider giving varying levels of customer compensation based on whether a customer is willing to ensure their car stays connected.

3. Further prioritization within each vehicle state

   The proposed algorithm weighs all vehicles within the same vehicle state equally. This would mean two cars in state 2 would be used equally even though one may be at 0.57 SOC while the other is at 0.8 SOC. Further prioritization is encouraged but will need to balance the tradeoff of longer computation times. Successful prioritization could reduce customer inconvenience and improve the overall experience.

There are remaining technical challenges to implementing a successful bidirectional charging program; however, the most significant challenge is ensuring customer participation. Utilities need to think of strategies to educate customers. Some utilities are launching managed charging programs to curtail electricity demand. These programs are effective in developing the technical capabilities required for demand response using EVs. Still, more importantly, they are avenues to help customers get accustomed to their utility having partial control over their vehicles. For this reason, utilities need to prioritize managed charging programs as a method of customer education.

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Chapter 5

Managed Charging Algorithm

Managed Charging (V1G) is an approach where power used to charge electric vehicles is partially or fully limited to reduce total grid power consumption. Current industry solutions use machine learning to understand a vehicle's charging behavior and design charging profiles that minimize total power consumption by having a slower charge over an extended period [14]. For example, a vehicle connected for 12 hours without V1G may use the charger's max power output to charge over 4 hours fully. This would mean a high spike in power followed by no power consumption for 8 hours. An alternative charging profile could lower the power output to charge the car over the entire 12 hour period. In both cases, the vehicle receives the same amount of charge. However, the slow control over a more extended period puts less strain on the grid. Utilities, like FPL, have sought to manage vehicle charging load during peak hours by incentivizing a customer to charge off-peak with lower rates [12]. What often happens with this incentive structure is once peak hours end, EVs come online and cause another peak in electricity demand [16]. A more effective strategy for V1G should balance total EV charging demand in aggregate.

A managed charging program should allow customers flexibility when they charge. The system should only limit charging when the total charging demand across the grid exceeds a certain amount. This amount could be set in day-ahead planning, and an algorithm could limit charging use whenever the total demand exceeds the limit. For example, if there are ten cars connected and the charging limit is set to 50 kW total, the vehicles would be allowed to charge at any time. If the system limit were never reached, there would be no effect on any cars charging. If the system reached 60 kW, each vehicle could limit its charging use by 17% to stay below the system peak. This would mean charging at 6.1 kW instead of 7.4 kW, an indistinguishable amount to the customer for an individual car.

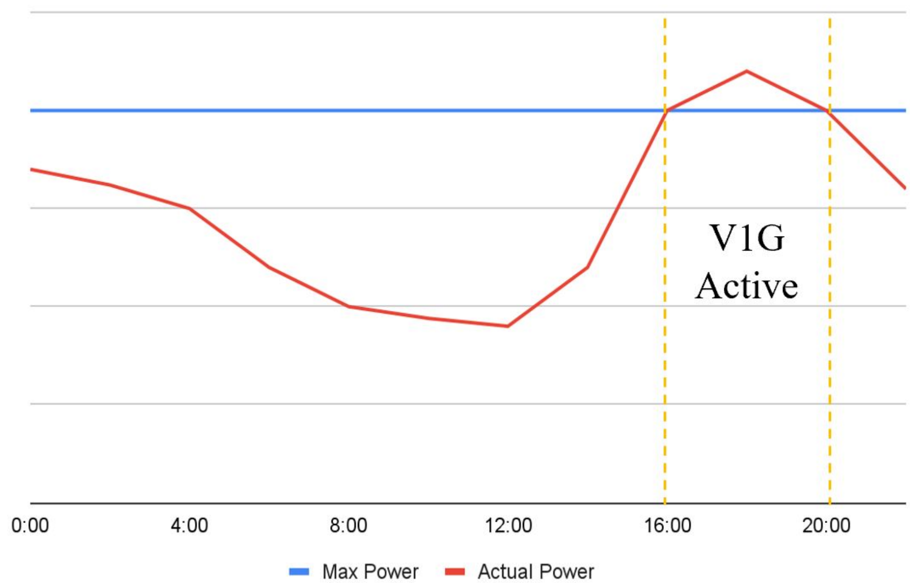

Figure 5-1: Proposed managed charging algorithm would seek to minimize inconvenience to the customer by allowing charging at all-day hours and only minimizing power to the system whenever it exceeds the preset max capacity. The V1G algorithm would activate once the Actual Power exceeds the Max Power in this example

A more informed approach could prioritize limiting the charge to cars at a lower SOC rather than reducing power evenly across all vehicles. This is not possible with current level 2 chargers since J1772 cannot read SOC from a car. For connected level 2 chargers, a utility could use the total energy used during a charging session as a proxy for SOC. A vehicle that has consumed 30 kWh during a charging session is more likely to be at a higher SOC than a vehicle that's used 5 kWh during a charging session. The following section highlights an algorithm to prioritize limiting charge to a system of cars by total session energy used.

5.1 Methodology

The proposed V1G algorithm would run continuously throughout the day and monitor the total system demand, P_{Total}. If the system exceeds its maximum power, $P_{\max}$, the Target Load Reduction (TLR) is the amount of power above the maximum limit (P_{Total} – $P_{\max}$). Suppose we have a grid with four vehicles connected. $P_{\max}$ is set at 15 kW, and P_{Total} for the four cars reaches 35 kW, meaning TLR is 20 kWh. Table 5.1 shows the four vehicles the system and their current kWh and kW used during the session.

Chargers	**kWh**	**kW**
1	46.97	9
2	23.46	10
3	1.44	10
4	33.2	6
	P_{Total}	**35**

Table 5.1: Four vehicles have varying levels of power and energy consumed during a charging session. P_{Total} is 35 kW, and $P_{\max}$ is 15 kW meaning the system must reduce power by 20 kW

When reducing the amount of power to a charger, each charger's reduction (R) should be proportional to the amount of energy and power the vehicle has consumed during an active session. The total power and energy will be referred to as power-energy (PE), the product of kWh multiplied by kW. In the example in Table 5.1, charger 1 has used the most energy. Using energy as a proxy for SOC means the operator would expect the vehicle to have the highest SOC and thus have the largest R. PE gives a weighted value that can be used to limit the charge to each vehicle based on the total share of PE to the sum of PE for n chargers. The total R to a car can be calculated as follows:

$$R_i = \frac{PE_i}{\sum_{i=1}^{n} PE_i} * TLR \tag{5.1}$$

Table 5.2 shows the results for reduction to each charger. This approach meets the TLR while considering how much strain each vehicle adds to the system. This first iteration highlights the issue that the charging profile could sometimes be set to a negative value. This is fine if the operator is also using V2G, but in a V1G application, it is impossible to have a negative charging profile.

Target Load Reduction		**20 kW**			
Chargers	**kWh**	**kW**	**P_E**	**R**	**Charging Profile**
1	46.97	9	422.73	9.71	-0.71
2	23.46	10	234.6	5.39	4.61
3	1.44	10	14.4	0.33	9.67
4	33.2	6	199.2	4.57	1.43
		Total	**870.93**		

Table 5.2: After one iteration of the algorithm, the charge profiles are set, but charger 1 is set to a negative profile which cannot be true for V1G

To address the issue of negative values, the system must check if any charging profiles are set below zero after each iteration. When it identifies a charger with a negative value, it should set the reduction equal to the current power output, which for charger 1 would be 9 kW. This would mean the charging profile would equal zero. The system should then reduce the TLR by the total reduction from negative value chargers (9 kW in the example above) and recalculate R with the remaining chargers. Table 5.3 shows the results from the second iteration, where the total TLR is met without setting chargers to a negative value.

This approach to V1G allows for great flexibility in charging for all customers without limiting what times a customer can charge. Most vehicles in the example are still allowed to charge and, in some cases, like with vehicle 3, the reduction to their charging profile is changed by less than 4%.

Target Load Reduction	**11 kW**

Chargers	kWh	kW	P_E	R	Charging Profile
1	46.97	0	0	0.00	0.00
2	23.46	10	234.6	5.76	4.24
3	1.44	10	14.4	0.35	9.65
4	33.2	6	199.2	4.89	1.11
		Total	**448.2**		

Table 5.3: By iterating through the table until no negative values are present, the algorithm can find a feasible solution

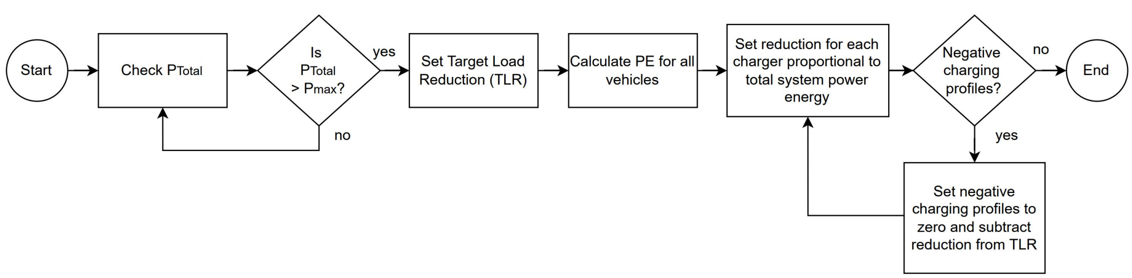

Figure 5-2: Cost comparing three battery storage solutions. Bidirectional charging has the lowest cost because it does not require the utility to buy the battery

5.2 Next Steps

V1G is an essential step toward bidirectional charging adoption. It gives utilities the technical capabilities needed to utilize EVs for grid services and makes customers more comfortable giving their electric utility some control over their EV. A well-designed V1G program should cause minimal to no inconvenience to a customer's driving needs. The algorithm proposed shows how the system can operate with a fixed system peak throughout the day. Future iterations should consider using a variable system peak where a lower peak is set during peak hours, and a higher peak is set at all other times of the day. Utilities with an existing charging network connected to OCPP 1.6 can use charging profile commands defined in the OCPP protocol to execute the program described above.

Chapter 6

Next Steps and Recommendations

This thesis discovered that most capacity for EV grid services is available in the morning. It also proposed two aggregation strategies to deploy bidirectional charging in practice and a V1G algorithm. Although these pieces are essential in enabling EVs for grid services, many challenges to enabling commercialization remain. This section will highlight additional work ahead and critical risks that must be addressed.

6.1 Application - Winter Storm

Regions with warm weather like Florida and Texas generally rely on electric heating [6]. When there are extreme cold weather events, this leads to significantly higher electricity demand. A recent example of a winter storm occurred in Texas in 2021 during the Texas freeze. This event was caused by both extremely low temperatures and one of the longest periods of temperatures remaining below freezing in parts of Texas on record. The result of this winter storm was an overloaded grid and widespread power outages [18].

The 2021 Texas Freeze was a shock that highlighted the fragility of the US energy grid and the need to invest in resilience to cold weather electricity demand. FPL has studied the risks of a winter storm in Florida. A spike in electricity demand in the early morning combined with low solar load could pose a risk for grid operations. This thesis found that capacity from EV services is most readily available in the late evening and early morning, the times when solar capacity is low. FPL and other utilities should explore the use of EV grid services as a winter storm mitigant.

6.2 Simulation for Planning

The following section lays out a method to combine the results from the capacity available analysis and aggregation algorithms to create a tool for simulation and planning for EV grid services.

Before running a simulation, the user needs to find the historical probability for a charger to be connected for each day of the week at each time of the day in 15-minute intervals. Using the output from the capacity available algorithm, the data should be grouped by date and time. The grouping is used to calculate the sum of vehicles connected for each date and time. These values are listed in the table where the columns were each 15-minute intervals, and the rows were the dates. Table 6.1 shows this intermediate step.

Date	Day	00:00	00:15	00:30	…	23:15	23:30	23:45
10/1/21	Fri	3	4	4	…	9	10	13
10/2/21	Sat	7	4	4	…	8	9	9
10/3/21	Sun	2	2	2	…	6	6	6

Table 6.1: After grouping the capacity available data, the sum of chargers connected for each date and 15-minute interval in the analysis was populated in a table with this format. Note: Values in the table are not reflective of real data

To find the probability for each day and 15-minute interval, a new dataframe was created where the columns were each 15-minute interval and the rows were days of the week. For each day of the week and 15-minute interval, the mean number of chargers connected was found and divided by the total number of chargers in the dataset to find a historical probability of chargers connected. Table 6.2 shows the format of the dataset.

To test a scenario, the user will need to input the following:

Date	00:00	00:15	00:30	…	23:15	23:30	23:45
Monday	0.15	0.16	0.16	…	0.2	0.2	0.2
Tuesday	0.2	0.2	0.2	…	0.16	0.16	0.16
Wednesday	0.16	0.16	0.16	…	0.1	0.1	0.1
Thursday	0.1	0.1	0.1	…	0.16	0.16	0.16
Friday	0.16	0.16	0.17	…	0.5	0.5	0.5
Saturday	0.06	0.6	0.6	…	0.9	0.9	0.9
Sunday	0.09	0.9	0.9	…	0.21	0.2	0.2

Table 6.2: The historical probability is listed in a table. Note: Values in the table are not reflective of real data

1. Target Load Reduction (in kW): operator-define power requested from the system
2. Dispatch Time (in minutes): how long the system should run ford to meet the power deficit
3. Number of chargers: how many chargers will be modeled in the simulation
4. Time Interval (in minutes): time in between each iteration of the aggregation algorithm; this thesis used 15-minute intervals
5. Day of the Week: a string specifying the day of the week
6. Time of day: hours in military time and minutes in 15-minute intervals

A data set will need to be created to run a simulation that resembles a database of all the chargers in the system and their properties. After initiating the simulation, the algorithm will generate a dataset that includes the information listed in Table 6.3.

An example of this data is shown in Table A.5. Once the first data set is created, the simulation will filter out vehicles in state 0. The remaining chargers will be fed as an input to the algorithm outlined in this thesis, where the TLR is met, and the solution is used for the defined time interval. After the first interval, the simulation will update the values in the dataset. Cars that were not used will update their SOC to reflect a higher SOC from charging. Cars selected for the dispatch event would

Columns	Descriptions	How Value is Assigned
ID	Alphanumeric string assigned to each charger	Random alphanumeric string (this thesis used a length of 8 characters)
Rated charge (kW)	Manufacturer specified power rating	Thesis used 7.4 kW for all chargers
rated discharge (kW)	Manufacturer specified discharge rating	Thesis used 7.4 kW for all chargers
day	Day of week specified by user	Specified by user input
time	Time in military time and 15-minute intervals	Specified by user input
SOC	Vehicle battery state of charge	Randomly assigned value between 0 and 1, can also be determined from sampling real charging sessions
battery size	OEM listed battery size; assumes charger can read this information	Randomly assigned value between 50 and 100
vehicle connected	Binary indicating whether the vehicle is connected (1) or disconnected (0)	Assigned based on the historical probability of a vehicle being connected to a charger
vehicle charging	Binary indicating whether the vehicle is charging (1) or not (0)	If vehicle connected = 1 and SOC < 0.85 then the vehicle is set to 1
power consumption (in kW)	Power output used to charge the vehicle	If vehicle charging set to 1, then set to rated charge
power available (in kW)	Power available for dispatch to the grid	If vehicle has a SOC greater than 50%, then value set to rated discharge
dispatch events	Number of dispatch events charger has participated in	Random number between 0 and 5
state	Vehicle state assigned depending on vehicle SOC and charging status (0,1,2,3)	State is assigned as follows: • **State 0**: vehicle is disconnected or < 0.15 SOC • **State 1**: vehicle is connected and < 0.5 SOC • **State 2**: vehicle connected, vehicle charging, and > 0.5 SOC • **State 3**: vehicle connected, vehicle not charging

Table 6.3: A charger database for V2G would need to include the following information to run

have to update the SOC to reflect a lower SOC. Sample calculations are shown below for a car that was connected and continued charging during the first iteration:

$$E_i = SOC_i * Battery \tag{6.1}$$

$$E_f = E_i + (P_{consumption} * t_{interval}/60) \tag{6.2}$$

$$SOC_f = E_f/Battery \tag{6.3}$$

For a vehicle that was selected for V2G, the SOC was calculated as follows:

$$E_i = SOC_i * Battery \tag{6.4}$$

$$E_f = E_i - (P_{V2G} * t_{interval}/60) \tag{6.5}$$

$$SOC_f = E_f/Battery \tag{6.6}$$

For a vehicle that was selected for V1G and thus reduced the charging rate, the SOC was calculated as follows:

$$E_i = SOC_i * Battery \tag{6.7}$$

$$E_f = E_i + (P_{consumption} - P_{V1G}) * t_{interval}/60) \tag{6.8}$$

$$SOC_f = E_f/Battery \tag{6.9}$$

The second iteration of the simulation has an added layer of complexity: determining whether vehicles that were connected remain connected and those that were not connected become connected. To address this challenge the simulation should randomly sample real charging sessions from past sessions and assign them to vehicles in the simulation. The session selected should have been active during the day of week and time of day for which the simulation is being modeled. Overlaying this information would give simulated charging sessions a preset SOC at the start of the session and would assign it a time to disconnect or connect for vehicles whose session had not started. This additional step was not implemented as part of this thesis, instead relying solely on the probability of a vehicle to remain connected between time periods and the probability for it to connect in the next time interval.

With this simulation tool, planners can run scenarios at different days of the week and time of day to see if the system can meet a TLR. The planners could use this system to determine how many chargers are needed to meet certain power levels and get a realistic idea whether using EVs for grid services can be used to meet load deficits in their forecasts.

6.3 Cost of Bidirectional Charging

Bidirectional charging is an alternative to utility-scale battery storage or Virtual Power Plant (VPP). VPP in this study refers to programs where batteries like the Tesla Powerwall are installed in customer homes to use as distributed storage. The most expensive component in battery storage is the battery cells; however, with bidirectional charging, the cost of batteries is free to the utility since the customer owns the battery. In theory, this should mean bidirectional charging will be the lowest cost battery storage solution.

Bidirectional charging costs were calculated using the values in Table 6.4. The VW ID.4 and Ford F-150 Lighting were used to reflect varying battery sizes on the market. Figure 6-1 compares bidirectional charging with VPP and utility-scale battery storage. Since the utility does not need to buy the battery, bidirectional charging already has the lowest cost per kWh than other forms of battery storage.

6.4 Challenges to Adoption

Despite the benefits of bidirectional charging, the technology and ecosystem are still in their infancy. This section will cover four key challenges that need to be addressed before wide-scale adoption: customer willingness to participate, availability of bidirectional chargers, lack of regulatory framework, and no standard communication protocols.

	VW ID.4	Ford F-150 Lightning
Battery Size[1]	40 kWh	75 kWh
Charging Hardware[2]	$5,000	$5,000
Installation[3]	$2,500	$2,500
Total Cost	$7,500	$7,500
Cost/kWh	$188	$100
Uptime[4]	50%	50%
Adjusted Cost/kWh	$376	$200

1. Assuming only 50% of the battery is used, assumed vehicle battery is paid for by the customer
2. Assuming Dcbel r8 used ($2,500), Lumin Smart Panel ($2,000), and $500 for other miscellaneous hardware
3. Installation costs from FPL virtual power plant pilot
4. Since bidirectional charging would not always be available compared to utility-owned battery storage, the cost is adjusted with the assumption the vehicle is only connected 50% of the time

Table 6.4: Bidirectional charging costs range from $200-$376 per installed kWh. The cost depends on the size of the vehicle battery.

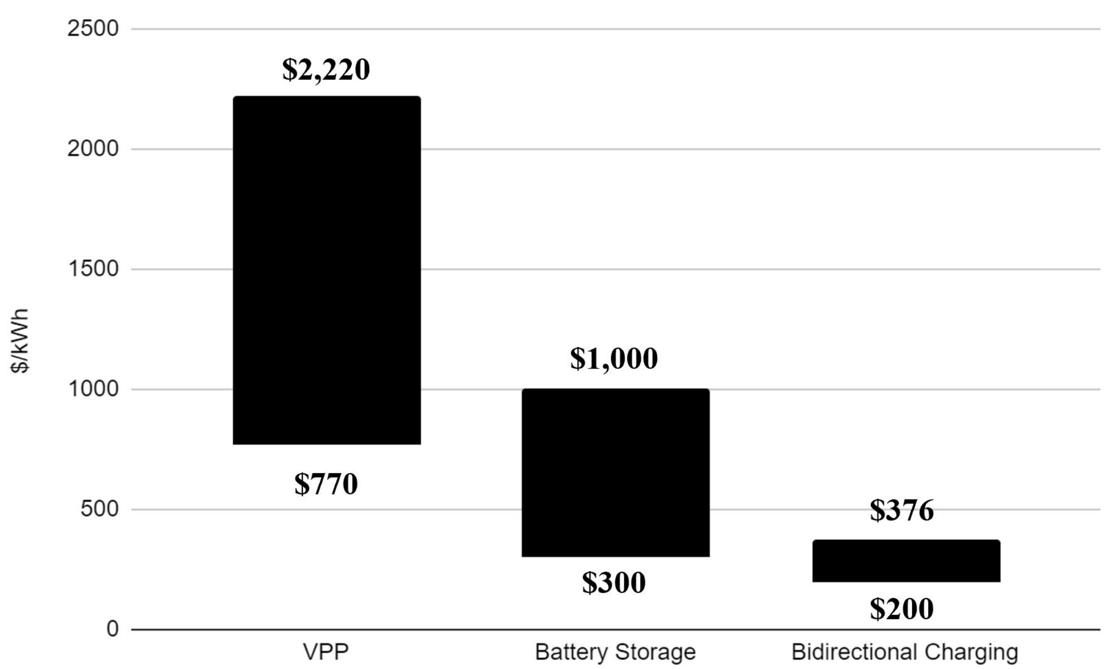

Figure 6-1: Cost comparing three battery storage solutions. Bidirectional charging has the lowest cost because it does not require the utility to buy the battery

Customer participation is by far the most significant challenge. Concerns about battery degradation and its impact on their driving habits make it difficult for many to consider buying an EV. These concerns get further exacerbated when layering on the idea of the electric utility having some control of the customer's driving range. Despite the considerable feat of overcoming this challenge, a failure to get customers to buy in will result in a failed bidirectional charging program.

Utilities can introduce customers to using their vehicles for grid services through a V1G program. To paint a better picture of how this could be done in practice, FPL is launching a residential charging program where they offer an EV charger in a customer's home at a monthly subscription fee. This charger is connected to a centralized OCPP 1.6 server. The server can be used to set charging profiles, limiting the maximum power output of a charger. OCPP 1.6 already supports charging profiles for use in a managed charging program. By leveraging their current residential charging program to launch a V1G program, customers can get accustomed to giving up some control of their vehicle. This will be a crucial first step, but utilities will need to ensure the limits in charging have minimal impact on the customer's driving habits.

OEMs, like Ford, have made headlines for their announcement that the F-150 Lighting will support V2H [15]. Customers, especially many in Texas who experienced power outages from their homes in the 2020 freeze, see V2H as a way to increase their energy independence. The popularity of this announcement indicates that customers are willing to use their vehicles to power their own homes to hedge against grid outages, but this does not suggest that customers may be willing to take the next step of using V2G also to allow their neighbors to benefit from their vehicle's battery. Ford's announcement nonetheless does expose customers to the idea that EVs can be used for applications outside point-to-point transportation. Many more OEMs may likely follow suit and offer bidirectional capabilities in their vehicles, given the positive reception from Ford's announcement. This industry shift will significantly help with customer education, but more work must be done for customers to take the next step of offering their vehicles for grid services. This work will largely fall on electric utilities since they stand to benefit from more excellent operational reliability. Partnering with

OEMs to introduce V2H programs in their service territory will significantly increase customer trust and willingness to participate.

The availability of bidirectional chargers is still limited. EVSE companies are developing bidirectional chargers; however, they are hesitant to make the requisite investments without widespread OEM adoption. Two companies have announced products for the US market: DCbel and WallBox. DCbel announced the r16, a bidirectional charger and solar inverter that could be used for V2H and V2G in 2020 [11]. This product is still low volume, and most units are for testing purposes. It is also worth mentioning that the r16 only supports bidirectional use using the CHAdeMO protocol. The primary vehicle that uses this protocol in the US market is the Nissan Leaf. Nissan as a whole is moving away from the CHAdeMO protocol with their new EV, the Nissan Ariya [20]. DCbel also announced a lower-cost product, the r8, released in late 2022. Wallbox unveiled Quasar, a bidirectional charger for European markets, at the Consumer Electronics Show (CES) in 2020. This was the first product of its kind but was still a low-volume product. At CES in 2022, WallBox unveiled Quasar 2, a bidirectional charger for the US market that will support CCS1. It is also worth mentioning that Ford will be selling a bidirectional charger in partnership with SunRun. This charger will be required if a customer wants to use the V2H feature on the Ford F-150 lighting. This charger will not be sold to non-Ford customers initially.

Although more products have been released and tested, there is still no widely available product. It may take a few years before significant numbers of bidirectional chargers are deployed for utilities to integrate EVs for grid services in their operations. Partnering with OEMs and EVSE companies will be one way utilities can expedite this process. Commitments from utilities to purchase large quantities of bidirectional chargers will also push the market to make the requisite investments to scale bidirectional charger development and production.

A limited regulatory framework exists in the US that would allow a utility to launch a wide-scale bidirectional charging program. To address this challenge, utilities will need to conduct small feasibility studies. Initially, these may be pilots that include less than five homes to understand the challenges to installation, back feeding to the grid, and understanding the correct customer incentives. These feasibility studies should leverage the net metering [3] and small generator interconnection agreements [26] framework initially since they offer some precedence to the bidirectional flow of power from a customer's home back to the grid (as is the case with rooftop solar). These small-scale bidirectional charging feasibility studies will provide a low capital investment opportunity with results that can be shared with the regulator. Success in these feasibility studies may allow regulators to approve more extensive programs in the hundreds to thousands of homes to understand better how the system will operate at scale.

<u>There are no standard protocols</u> for communication between EVs and EVSE companies using the CCS1 protocol. This is one of the reasons CCS1 does not yet fully support bidirectionality. CharIN, the organization that coordinates work for CCS1, is developing ISO 15118 as a standard protocol for vehicle-to-charger communication; however, this standard will require broad industry support. Beyond communication between the vehicle and the charger, there are still no standard interfaces between the charger and the utility. Significant work is being done towards developing the IEEE 2030.5 protocol to manage distributed generation resources. The two protocols mentioned above are potential solutions to this issue but require general industry coordination to settle on a standard protocol.

6.5 Commercialization Opportunities Across the Value Chain

Many unknowns exist in the bidirectional charging future, including how each portion of the value chain can monetize its offering. This section considers each stakeholder and discusses potential opportunities and risks.

<u>OEMs</u> benefit from offering a bidirectional feature like V2H in their products by attracting customers who want to become independent of their electric utility. By providing their bidirectional charger, they can increase their sales in their aftermarket

Challenge	Description
Customer willingness to offer their vehicle for grid services	Bidirectional charging is not a widely known technology among consumers, and there is still sparse data indicating whether customers would be willing to offer their vehicles
Availability of bidirectional chargers	Bidirectional charging programs will require a DC charger in customer homes. Companies are working on these products, but they are not widely available for sale, and it will take time to deploy large quantities in customers' homes.
Limited regulatory framework for V2G programs in the US	V2G programs will be subject to regulatory approval; little precedence
No standard V2G communication protocols	The CCS1 charging protocol has no standard communication protocol to enable communication between EV and EVSE. Stakeholders must collaborate to reach a consensus.

Table 6.5: Summary of the highlighted challenges in enabling wide-scale bidirectional charging

components. Some OEMs may also consider offering V2H as a service, charging customers a monthly subscription fee for enabling their vehicle to have bidirectional capability. OEMs that explore V2G for grid services could even unlock new revenue-generating opportunities by charging a subscription fee to utilities that want to use their customers' vehicles. This fee could include an API that allows communication with their cars.

EVSE companies benefit from V2G by offering a new charging technology. Level 2 chargers are highly commoditized (even Amazon offers one through Amazon Basics). The introduction of bidirectional chargers could give a technical advantage to EVSEs first to market. EVSEs investing in bidirectional chargers should target utilities as customers. Utilities can offer the security of large orders, and ultimately, wide adoption of bidirectional chargers will require their buy-in. Like OEMs, EVSE companies could also find additional revenue opportunities by charging utilities a subscription fee for using their chargers or API as part of a V2G program. One of the most significant risks to EVSE companies is if OEMs decide to follow Ford's lead and only offer bidirectionality with their proprietary chargers. This would, in large part, cut EVSE companies out of the bidirectional charging value chain. EVSE companies can hedge this risk by licensing bidirectional chargers to OEMs looking to offer a V2H/V2G feature in their vehicles.

Aggregation services will likely be offered as an enterprise software solution to utilities. This could probably be a lucrative sector that can expand to provide additional services to integrate distributed resources into grid operations. One of the most significant risks this sector has is if many utilities decide to develop aggregation service capabilities in-house. Aggregators can hedge this risk by partnering early with utilities and leveraging their first-mover advantage to stay ahead. Since this sector consists of start-ups, Aggregators can lean into their nimble organizational structures to stay ahead.

Electric Utilities can benefit from V2G by having a lower-cost solution for battery storage and a method to increase grid reliability. Utilities have two effective strategies they can take: offering a subscription service for the bidirectional charger or including the capital investment of bidirectional chargers in their rate base. FPL offers a subscription service for residential chargers where the company pays for equipment and installation costs up-front. In return, the customer pays a monthly fee that amortizes the cost of the charger over its life plus some return on equity (ROE) for the utility. This could be an effective strategy for bidirectional chargers; however, the higher cost of bidirectional systems may result in a monthly fee higher than the customer is willing to pay. More work needs to be done to determine customer willingness to pay for an at-home charger, plus home backup using their EV. The other model a utility can consider is including the capital investment of installing chargers in their rate base. This could be a substantial new investment opportunity for energy companies.

The suggested approach is a blend of both strategies. Utilities should determine the willingness to pay for customers in their territory to have a residential charger, plus home backup. Once the utility determines what that monthly fee could be, they can rate base the remaining amount. For example, if a charger could be installed for $10,000 and be amortized over five years, the customer would pay $167 each month for the equipment[1]. If the utility determines the customer is willing to pay $100 each

[1] Assuming zero operating cost and return on equity

month for the installed system, they should rate base $4,000 and only charge the customer $6,000 over the life of the subscription, meaning the customer would pay $100 per month. In the likely event OEMs require customers to use their proprietary bidirectional charger, the utility should partner with OEMs to purchase the equipment for the customer and offer a subscription for the product to the customer. If the future bidirectional charging ecosystem allows for a universal charger sold by the EVSE, the utility should purchase directly from them and offer installation in their territory.

Customers willing to participate in bidirectional charging programs can unlock a revenue opportunity for their vehicle while it is idle. If a program is designed with the appropriate incentives, customers should see a lower cost of vehicle ownership. Customer incentives could include reducing their electricity bill for being enrolled or repurchasing electricity above the retail electricity price. Additional work still needs to be done to determine what incentive structure benefits customers to participate while keeping bidirectional charging costs competitive with other utility battery storage alternatives.

OEM	Additional sales on vehicles and the potential to unlock recurring revenues from customers or utilities by offering bidirectional charging as a subscription
EVSE	Additional charger sales and the potential to unlock recurring revenues from customers or utilities by offering bidirectional charging as a subscription
Aggregation Services	Enterprise software solution for utilities
Utility	Recurring revenues by offering subscription service to customers for a bidirectional charger, or capital investment opportunities to include in their rate base
Customer	Unlock revenue opportunities for their electric vehicle, which in turn will reduce their cost of vehicle ownership

Table 6.6: Summary of commercialization opportunities in the bidirectional charging value chain

The successful launch of a bidirectional charging industry will require significant coordination among the stakeholders in the value chain. The exact value chain is still unknown; influential players in the space should make strategic partnerships to ensure they can shape the future of the industry. Interested parties should also remember that the most important stakeholder is the customer. All bidirectional charging programs must be designed to make customer participation compelling.

6.6 Proposed Strategy for Bidirectional Charging Deployment

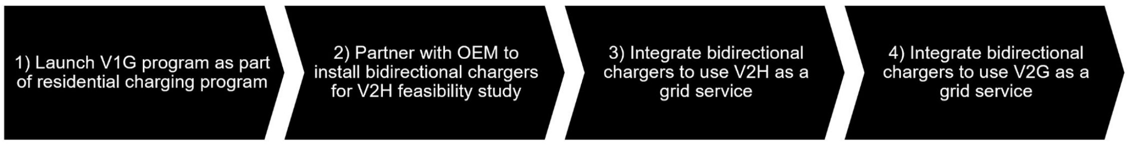

Figure 6-2: Utilities looking to launch a successful bidirectional charging program should follow this strategy; it sets clear milestones that progressively work towards a full-scale V2G program

Bidirectional charging will require a long-term plan as the technology and infrastructure develops. The thesis proposes following a four-part strategy to provide the incremental steps needed to launch a full-scale program.

Launching a V1G program will establish the technical foundation needed for large-scale programs. Utilities like FPL with an existing residential charging network can use charging profiles defined in OCPP 1.6 to manage load across their network actively. The algorithms necessary to control load will provide a framework that can later be expanded to incorporate more complex commands, including V2H and V2G. Utilities with an OCPP server and a developed residential charging network can deploy managed charging in a short time frame. The main benefit of this phase will be getting customers accustomed to relinquishing partial control of their vehicle to their utility. V1G programs should be designed to collect customer feedback frequently so that managed charging provides minimal inconvenience to the customer. The OCPP server will also collect data that will inform the available capacity for V2G.

Partnering with an OEM to install bidirectional chargers can be started concurrently to phase 1. It will be critical to have an OEM to work with so that there are established communication channels to share technical information and incorporate feedback from customers. This phase should initially install a few chargers. The volume must be low in areas without an existing tariff to avoid legal backlash from the public service commission. To limit the technical scope and ensure safe operation, the initial build should use the bidirectional chargers for V2H enabled only during power outages. The hardware required for V2H and V2G is similar; however, V2G may require updates to the electric distribution system. Keeping this phase solely focused on V2H will provide lessons in the installation and operation of the system. With the bidirectional chargers installed, the parties involved will collect accurate data about the available capacity since the DC chargers would also read SOC directly from the vehicle.

Integrating bidirectional chargers to use V2H for grid services will build upon the V2H system built-in phase 2 that operates during power outages. V2H for grid services would allow the operator to control when V2H is engaged remotely. This would require remote control of the automatic transfer switch (ATS) to island the house from the grid and power the home with the vehicle's battery. Suppose the utility needs to shed load in a demand response event. The operator can reduce the amount of power a home consumes by disconnecting the house from the grid when the vehicle is connected and having the vehicle power the home for a set period. The customer would have little to no interruption to their electricity use during this event. This phase will require a secure connection to control the ATS and an aggregation algorithm to determine which homes to island. This system provides a tremendous technical milestone to develop the systems needed for a full-fledged V2G system without making updates to the grid.

Integrating bidirectional chargers to use V2G for grid services is the last part of the feasibility study. The system would enable vehicles to have the complete flexibility to serve as a V1G, V2H, and V2G service. This will require the utility to test back feeding to the grid and make the necessary investments to ensure the electrical distribution system can support it. The utility will need fully developed aggregation algorithms and secure communication channels. The data and results provided from this last phase will help shape the framework to create a new regulatory tariff and inform the incentives to offer customers.

After completing all four phases, the OEM and utility should use the learnings to inform how to scale V2G across the territory.

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Chapter 7

Conclusion

As electric vehicles become more prevalent in the US, utilities will need to consider strategies to integrate them into their operations. There are still several challenges to overcome, the largest of which will be incentivizing customers to participate in bidirectional charging programs. This thesis covered various aspects of using electric vehicles for grid services, estimating capacity, aggregation algorithms, and managed charging. These tools will be essential in establishing a framework for electric utilities to use EVs as a distributed energy source to improve grid resiliency. There are three key takeaways from this thesis:

1. Most bidirectional charging capacity is available in the morning.

   Early data in this thesis shows that EVs can most readily be used for grid services in the morning. As utilities think of incorporating bidirectional charging in their operations, they should find applications at these times. One particular use case for EV grid services is a winter storm mitigant

2. Utilities should first focus on V1G to increase customer willingness to participate in bidirectional charging programs

   Addressing customer willingness to offer their vehicle for grid services needs to be a priority for all utilities considering launching a bidirectional charging program. V1G is a strategy that gets customers accustomed to offering partial control of their EV to their utility. The technology is well developed and can be implemented using existing communication protocols like OCPP 1.6. V1G can already offer benefits toward grid resiliency and reduces the risk of increased power demand as EV adoption proliferates.

3. Collaboration will be the key to ensuring success for bidirectional charging programs until the industry reaches maturity

   Bidirectional charging can positively impact the grid by increasing resiliency and offering a lower-cost battery storage solution. The bidirectional charging value chain involves numerous stakeholders with competing interests. Success in this space will require collaboration between these parties. Regulated utilities are accustomed to operating as monopolies and seldom have they needed to form partnerships with other companies. This will require a cultural shift and a change in business practices as utilities will need to partner with OEMs to bring this technology to market. Collaboration between these companies will be necessary to develop standard communication protocols and provide a better customer experience. Inability to collaborate will likely lead to delays in deploying this technology or failure to commercialize. As the technology matures and standardizes, collaboration between stakeholders will become less critical.

Electric vehicles will help reduce carbon emissions from transportation in the US. With broader adoption and effective bidirectional charging programs offered to customers by electric utilities, EVs may also improve grid resiliency and provide the battery storage needed for a cleaner grid.

Appendix A

Appendix

station_id	session_id	energy (kWh)	start_time	end_time
11	1698hc	28.967	9/23/21 22:16	9/24/21 11:57
15	1841hc	24.398	9/28/21 21:28	9/29/21 13:45
17	1882hc	27.84	9/30/21 21:56	10/1/21 16:40
19	1916hc	26.377	10/3/21 0:29	10/3/21 11:21
23	1995hc	26.474	10/7/21 21:49	10/8/21 12:01
25	2034hc	27.821	10/9/21 21:36	10/12/21 17:48
33	2229hc	35.067	10/17/21 1:12	10/17/21 11:02
36	2379hc	24.566	10/20/21 20:26	10/21/21 8:16
38	2394hc	24.868	10/21/21 22:11	10/22/21 16:38
39	2426hc	35.246	10/23/21 18:51	10/24/21 16:42
42	2486hc	28.758	10/26/21 22:25	10/27/21 13:58
43	2510hc	23.105	10/27/21 22:23	10/28/21 9:49
48	2614hc	31.437	10/30/21 19:20	10/31/21 11:23
50	2645hc	33.02	11/1/21 21:48	11/2/21 10:36
51	2669hc	32.492	11/2/21 22:02	11/3/21 14:00
53	2691hc	27.995	11/4/21 10:14	11/4/21 14:25
60	2900hc	25.31	11/11/21 22:11	11/12/21 11:07
63	2954hc	24.752	11/13/21 22:39	11/14/21 9:22
65	2984hc	24.964	11/14/21 22:20	11/15/21 11:28

Table A.1: Residential Charging Session data example data. Each data entry is a unique charging session. Note: station$_i dvalues anonymized$

transaction_pk	value_timestamp	value	unit
73	2021-07-14 22:15:00+00:00	0.2	kW
73	2021-07-14 22:30:00+00:00	9.4	kW
73	2021-07-14 22:45:00+00:00	9.4	kW
73	2021-07-14 23:00:00+00:00	9.4	kW
73	2021-07-14 23:15:00+00:00	9.4	kW
73	2021-07-14 23:30:00+00:00	9.5	kW
73	2021-07-14 23:45:00+00:00	9.5	kW
73	2021-07-15 00:00:00+00:00	9.7	kW
73	2021-07-15 00:15:00+00:00	9.4	kW
73	2021-07-15 00:30:00+00:00	9.4	kW
73	2021-07-15 00:45:00+00:00	9.5	kW
73	2021-07-15 01:00:00+00:00	9.5	kW
73	2021-07-15 01:15:00+00:00	9.5	kW
73	2021-07-15 01:30:00+00:00	9.5	kW
73	2021-07-15 01:45:00+00:00	9.8	kW
73	2021-07-15 02:00:00+00:00	9.7	kW
73	2021-07-15 02:15:00+00:00	9.4	kW
73	2021-07-15 02:30:00+00:00	9.4	kW
73	2021-07-15 02:45:00+00:00	0	kW
73	2021-07-15 03:00:00+00:00	0	kW
73	2021-07-15 03:15:00+00:00	0	kW
73	2021-07-15 03:30:00+00:00	0	kW
73	2021-07-15 03:45:00+00:00	0	kW
73	2021-07-15 04:00:00+00:00	0	kW

Table A.2: Residential Charging Meter data example. The table shows an example of one charging session and all the respective meter data for the session. In this example, the vehicle finished charging since the power output fell back to 0 kW before the end of the session

ID	Date	Time	Day	Battery_ Size	Vehicle_ Connected	Power_ Consumption	SOC	Power_ Available	Energy_ Available	Dispatch_ Time
1	11/5/2021	16:15	Fri	50	1	7.4	0.51	7.4	0.68	0.09
1	11/5/2021	16:30	Fri	50	1	7.4	0.56	7.4	3.08	0.42
1	11/5/2021	16:45	Fri	50	1	7.4	0.61	7.4	5.49	0.74
1	11/5/2021	17:00	Fri	50	1	7.4	0.66	7.4	7.89	1.07
1	11/5/2021	17:15	Fri	50	1	7.4	0.71	7.4	10.29	1.39
1	11/5/2021	17:30	Fri	50	1	7.4	0.75	7.4	12.69	1.72
1	11/5/2021	17:45	Fri	50	1	7.4	0.80	7.4	15.10	2.04
1	11/5/2021	18:00	Fri	50	1	7.4	0.85	7.4	17.50	2.36
1	11/5/2021	18:15	Fri	50	1	7.4	0.85	7.4	17.50	2.36
1	11/5/2021	18:30	Fri	50	1	7.4	0.85	7.4	17.50	2.36
1	11/5/2021	18:45	Fri	50	1	7.4	0.85	7.4	17.50	2.36
1	11/5/2021	19:00	Fri	50	1	7.4	0.85	7.4	17.50	2.36
1	11/5/2021	19:15	Fri	50	1	7.4	0.85	7.4	17.50	2.36
1	11/5/2021	19:30	Fri	50	1	7.4	0.85	7.4	17.50	2.36

Table A.3: Capacity Data example; charging session after estimating SOC where vehicle finished charging

ID	Date	Time	Day	Battery_ Size	Vehicle_ Connected	Power_ Consumption	SOC	Power_ Available	Energy_ Available	Dispatch_ Time
2	11/10/2021	14:15	Wed	50	1	7.4	0.28	0	0.00	0.00
2	11/10/2021	14:30	Wed	50	1	7.4	0.32	0	0.00	0.00
2	11/10/2021	14:45	Wed	50	1	7.4	0.35	0	0.00	0.00
2	11/10/2021	15:00	Wed	50	1	7.4	0.39	0	0.00	0.00
2	11/10/2021	15:15	Wed	50	1	7.4	0.43	0	0.00	0.00
2	11/10/2021	15:30	Wed	50	1	7.4	0.46	0	0.00	0.00
2	11/10/2021	15:45	Wed	50	1	7.4	0.50	0	0.00	0.00
2	11/10/2021	16:00	Wed	50	1	7.4	0.53	7.4	1.61	0.22
2	11/10/2021	16:15	Wed	50	1	7.4	0.57	7.4	3.40	0.46

Table A.4: Capacity Data example; charging session after estimating SOC where vehicle did not finish charging

Figure A-1: Average power available, power consumed, and dispatch time for each day of the week

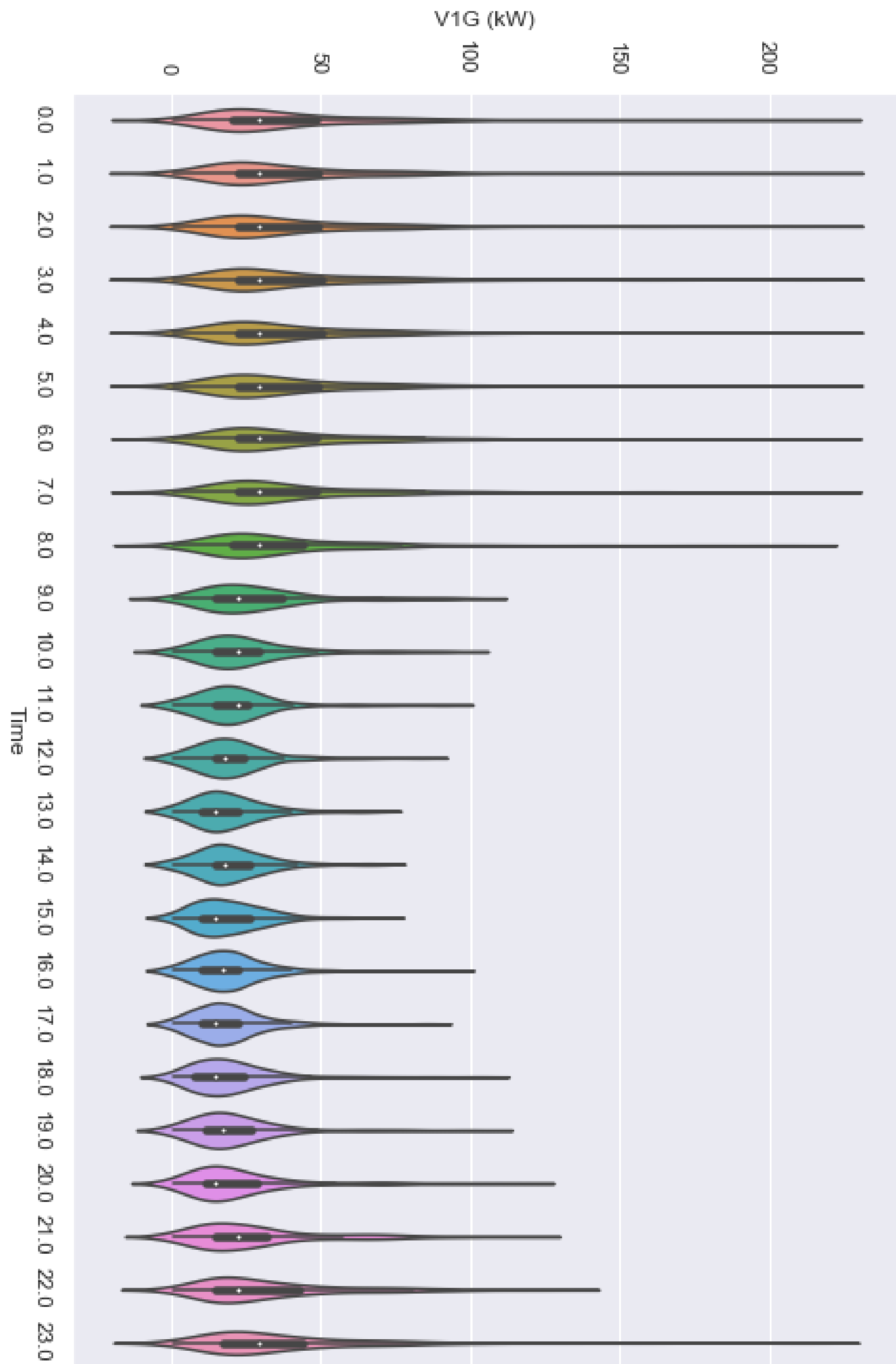

Figure A-2: Violin plot of V1G capacity available at every hour of the day

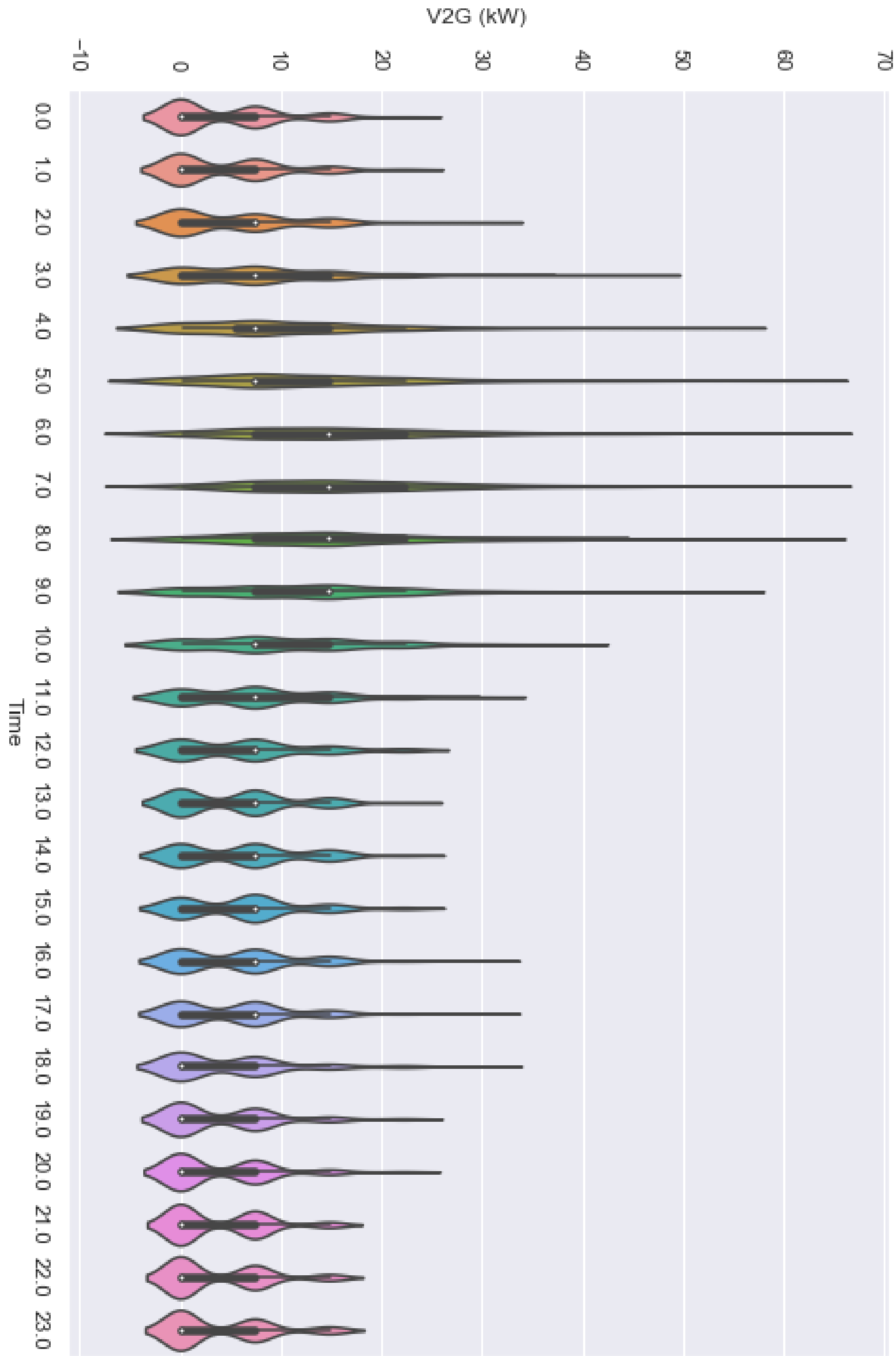

Figure A-3: Violin plot of V2G capacity available at every hour of the day

id	rated_ charge	rated_ discharge	day	time	soc	Battery (kwh)	vehicle_ connected	vehicle_ charging	power_ consumption	power_ available	dispatch _events	state
1	7.4	7.4	Sat	1:00	0.47	52	1	1	7.4	0	4	1
2	7.4	7.4	Sat	1:00	0.99	85	0	0	0	0	0	0
3	7.4	7.4	Sat	1:00	0.97	56	1	0	0	7.4	4	3
4	7.4	7.4	Sat	1:00	0.59	94	0	0	0	0	0	0
5	7.4	7.4	Sat	1:00	0.06	82	0	0	0	0	0	0
6	7.4	7.4	Sat	1:00	0.18	64	0	0	0	0	0	0
7	7.4	7.4	Sat	1:00	0.67	79	0	0	0	0	0	0
8	7.4	7.4	Sat	1:00	0.79	90	1	1	7.4	7.4	3	2
9	7.4	7.4	Sat	1:00	0.74	68	0	0	0	0	0	0

Table A.5: Sample data used in planning simulation

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