ASSESSING PUBLIC OPINIONS OF AND INTEREST IN BIDIRECTIONAL EV CHARGING TECHNOLOGIES: A U.S. PERSPECTIVE

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Word Count: 6,102 words + 4 tables (250 words per table) = 7,102 words

ABSTRACT

An increasing number of battery-electric vehicles (BEVs) have bidirectional charging technology that provides motorists, homeowners, and power grid operators with new benefits. The study investigates the willingness of over 300 Americans to pay for added bidirectional charging features, namely, Vehicle-to-Load (V2L), Vehicle-to-Home (V2H), and Vehicle-to-Grid (V2G) technologies, along with their anticipated frequency of relying on these capabilities. The key summary statistics indicate that Americans are willing to pay (WTP) an average $280 and $776 for V2L and V2H, respectively. About 51.3% of people would let their power company discharge their vehicle via V2G during grid emergencies, if compensated and guaranteed a minimum battery level.

Estimated interval regression and ordered probit models explain how demographics, travel patterns, and attitudinal variables impact response variables including WTP for bidirectional charging features and expected reliance on technology. The statistically and practically significant relationships indicate that adults over 34 years of age have lower WTP values for V2L and V2H, and households with more vehicles are associated with higher expected use. The findings have implications for policymakers, manufacturers, and stakeholders involved in the BEV ecosystem, informing their decision-making processes related to the integration and commercialization of bidirectional charging technologies. These models may even help power grid planners understand who is likely to adopt technology that could be aggregated to shift BEV loads to help manage the grid in parallel and in island mode.

Keywords: *plug-in electric vehicles, bidirectional charging, ordered probit, interval regression, public opinion survey, willingness to pay*

INTRODUCTION

The rapid transition away from fossil fuels for electricity and transportation will help the world avoid climate change's most significant impacts (*1*). Electrified mobility may lead to significant load growth and can stress power grid infrastructure if left unaddressed (*2*, *3*). However, many power companies are designing new electricity rates and managed charging pilots (*4*–*6*) to incentivize drivers to shift charging to off-peak hours, which can lower grid operating costs, reduce the growth in net peak demand, and avoid the curtailment of variable renewables (*2*, *3*). In addition to managing electric vehicle (EV) charging's impact on the grid through unidirectional (V1G) smart charging tools, there is a growing interest of researchers and practitioners to develop bidirectional-capable vehicles and charging equipment that allows EVs' stored energy to serve external loads.

Bidirectional charging can serve many different use cases, and is most often mentioned in discussions of using battery-electric vehicles (BEVs) as grid resources through vehicle-to-grid (V2G)[1], primarily for peak shaving, renewable ramping support, and local distribution system supply balancing. BEVs may also discharge energy to buildings (V2B), to reduce electricity costs from peak power demand charges ($/MW) that industrial and commercial customers often pay, or to homes (V2H), usually for backup power during grid outages. Vehicle-to-load (V2L)[2] is the most basic version of bidirectional charging as it does not require a bidirectional charger, rather vehicles usually have standard AC power outlets or special DC-AC adapters that attach to the charging port. V2L can power computers, fridges, lighting, and construction tools.

A growing number of automakers, like Tesla, Volkswagen, and General Motors, are planning bidirectional charging capabilities, from V2L to V2G, and several charging equipment companies have announced bidirectional charging technology (e.g., Emporia's V2X, Wallbox's Quasar 2, and Nuvve), which through cyber-physical system management tools can automatically charge and discharge an EV's energy to lower electricity costs. At the same time, California's Senate Bill 233 proposes requiring model-year 2030 EVs sold in the state to be bidirectional capable (*7*), which may accelerate automaker plans to develop and refine bidirectional charging features. Since bidirectional charging technology is in its infancy, there is a need investigate consumer preference to better forecast the economic benefits of V2G.

Sovacool et al.'s systematic review of 197 peer-reviewed articles on V2G from 2015 to 2017 found that 2.1% of articles contained an analysis of consumer attitudes, like social acceptance of V2G technologies (*8*). Even then, early literature assumed BEV drivers would sign contracts with inflexible terms, like required plug-in time to get an annual incentive (*9*). Although consumer opinion surveys tell respondents they might sell electricity back to the grid with V2G, Parsons et al.'s discount rate for V2G was 41%, which the authors ascribe to either people's mistrust of power companies or a high uncertainty in future electricity savings with V2G (*9*). Thus, it may be beneficial to focus on consumer willingness to participate in V2G primarily for grid emergency

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[1] V2G and V2H-capable vehicles include the Nissan Leaf ZE1, Mitsubishi Outlander PHEV, while the Ford F-150 Lightning is V2H-capable with Ford's in-vehicle bidirectional charger and Ford-specific equipment (e.g., Ford Charge Station Pro and Ford Home Integration System). Some upcoming vehicles may have V2G and V2H technology but are not yet on the market (as of 06/28/2023).

[2] V2L-capable vehicles include the Ford F-150 Lightning, Hyundai IONIQ5, Kia EV6, BYD Atto 3, BYD Han EV, Genesis GV60, Rivian R1T/R1S, and MG ZS EV. Some upcoming vehicles may have V2L technology but are not yet on the market (as of 06/28/2023).

support and estimate the willingness to pay (WTP) for bidirectional features, such as V2L and V2H, as opposed to using bidirectional charging to generate additional revenue.

This study answers the question of whether consumers would let their local power companies discharge their EV's stored energy to help the power grid during critical times in the year. Further, there is no peer-review article, to the best of the author's knowledge, that estimates consumer's WTP for bidirectional charging features, like V2L and V2H, both of which are bidirectional features that benefit the consumer and not the power grid, per se.

This paper proceeds as follows. We summarize key literature on bidirectional charging in the next section, followed by sections that explain the survey design, present summary statistics, modeling specifications, results, and conclusions for policymakers, automakers, and power companies.

Consumer Surveys on Bidirectional Charging

As a relatively new technology, few studies have examined the public's willingness to accept and pay for bidirectional charging features; however, there are several papers that estimate the economic value of V2G (*10–12*). The value of V2G, although estimated to be $75/vehicle per season in California (*10*), is highly dependent on the services it provides the grid – electricity or ancillary services, the value to the market, and supply of other providers bidding into the market. Assuming the average new V2G-capable vehicle is scrapped at 17 years (after several owners, as is usual with most gas-powered vehicles) the EV could provide a net present value of about $3,380 (with a 5% discount rate).

Parsons et al. (*9*), Geske and Schumann (*13*), Lee et al. (*14*) conducted a web-based survey of Americans in 2009, Germans in 2013, and South Koreans in 2016 to understand people's sensitivity and willingness to accept V2G contract terms. Drivers heavily discount any potential V2G revenue because of the inconvenience of minimum plug-in time of their future EV and uncertainty with selling power back to the grid. Both studies suggest that power companies eliminate rigid contracts, provide cash payments up front for any V2G participation, and provide compensation to the EV owners as they discharge power to the grid. Motorists highly value flexibility and preserving the vehicle's purpose of mobility over V2G revenue.

Parsons et al. (*9*) estimated the cost of lowering the guaranteed minimum range after V2G from 175 miles to 75 miles was equivalent to increase an EV's purchase price by about $5,160 (in 2023 dollars) and increasing the contractual minimum plug-in time from 5 hours to 10 hours a day was about $1810. Lee et al. (*14*) estimated that 17.8% were not willing to accept V2G under any condition, mostly due to concerns over contract terms, but of those willing to accept V2G the minimum yearly compensation required was $133. Geske and Schumann (*13*) found that 57% are generally willing to participate in V2G (i.e., use this feature), but that does not mean they are entirely concerned about V2G. Almost 64% of respondents were concerned about battery life with more frequent battery cycling, 56% cannot plan out their trips well enough to reasonably use V2G, and 56% fear the battery would not be sufficiently charged at the start of each trip.

Kester et al. (*15*) studied perceptions of V2G through eight focus groups across five Nordic countries (sixty-one total participants) in 2016-2017. Responses indicated that drivers are not very familiar with this topic but would allow V2G if given sufficient compensation for battery degradation and information about when vehicles discharge to avoid disruptions to mobility. Participants in Iceland and Sweden suggested a guaranteed minimum battery level to ensure unplanned trips can be met. Other participants remarked that future EVs may be bidirectional capable so that power companies can use V2G to manage the grid (i.e., not a consumer technology choice, but an innate part of the EV ecosystem).

A bidirectional charging station company surveyed over 2,000 drivers in the United Kingdom in February 2023 and found that 49% were more likely to buy an EV if it was bidirectional capable to power one's home or the grid (*16*). If bidirectional features increase EV ownership, which itself helps decarbonize transportation and mitigate climate change's effects, then research is necessary to understand the WTP to add V2L and V2H features to the next EV purchase, especially if these technologies do not come standard. Since there is hardly any research on the WTP for bidirectional charging technology and its expected use, this research paper fills this this timely gap.

SURVEY DESIGN AND DATA PROCESSING

We conducted an internet-based survey, which ran from late November to early December 2022, in the United States. A randomized sample was collected by a survey distribution company, with the aim to be representative of the U.S. population at large in gender, age, educational attainment and region within the country[3]. Respondents had to be at least 18 years old and were invited to complete two survey sections—a survey on unidirectional smart charging (also called V1G) and bidirectional charging (most often abbreviated as V2G). The first section asked about respondent and household background, mobility patterns, importance of V1G benefits, interest in V1G programs, preferred charging style, opinions on the clean-energy transition, and minimum opt-out fees for a supplier-managed charging program. The results of the V1G section are covered in Dean and Kockelman (*17*).

The survey employed a screening question and two within-survey data quality checks nestled within multiple Likert-type questions, one in each section, to ensure reasonable responses. The sample included 1,395 complete responses; however, only n = 1,050 respondents answered the first half and 311 completely answered the optional 21-question V2G section, which is the focus of this study. When excluding respondents that selected "other: ________" and wrote-in a response equivalent to "unsure" the smallest sample size is n = 307.

Bidirectional Charging Concepts

Once a respondent opted into the optional V2G section the concept of bidirectional charging was described, as shown in Figure 1. This introductory text explains the difference between bidirectional charging features, namely V2L, V2H, and V2G. Additional text was provided to respondents in subsequent questions to avoid confusion between acronyms.

The bidirectional charging section was separated into the following key survey sections:

- Section A: Importance of bidirectional charging benefits to the respondent (5-point Likert-type scale: not at all important—extremely important), Prior knowledge of bidirectional charging (5-point Likert-type scale: no knowledge—extremely knowledgeable).
- Section B: Willingness to pay (WTP) to add V2L technology (right-censored interval data), Expected frequency of using V2L technology (6-point ordinal scale).

[3] The survey sample was population weighted/corrected using iterative post-stratification to match the marginal distributions of the sample to national level population margins (with gender levels (male, female, non-binary), age levels (18-24, 25-34, 35-44, 45-54, 55-64, 65+), highest education (high school, some college/associate's degree, bachelor's degree, master's/doctorate degree), and U.S. Census region (Northeast, Midwest, South, West)).

- Section C: Willingness to pay (WTP) to add V2H equipment (right-censored interval data), Expected frequency of using V2H equipment (6-point ordinal scale).
- Section D: Expected frequency of local power company using BEV's V2G technology (6-point ordinal scale), Expected participation in supplier-managed V2G.
- Section E: Expected participation in V2G under different conditions (5-point Likert-type scale: extremely unlikely—extremely likely).

Some new BEVs can both charge and discharge electricity (called bidirectional charging).

Some BEVs are designed to provide power through standard outlets (for worksite tools at construction sites, electric heaters or appliances at campsites, TVs, or sound equipment at tailgates/festivals), also called vehicle-to-load (V2L). Vehicles may even provide partial or full power for one's home if the home's circuit breaker is wired properly (vehicle-to-home, V2H). Power companies may even tap into BEV batteries to provide short-term power to the local power grid in emergencies or when electricity is in high demand (vehicle-to-grid, V2G).

The Ford F-150 Lightning, shown below powering worksite tools, demonstrates V2L technology. There are at least 7 vehicles (Nissan Leaf ZE1, Mitsubishi Outlander plug-in, Ford F-150 Lightning, Hyundai Ioniq 5, Kia EV6, BYD Atto 3, MG ZS EV 2022) with some form of bidirectional charging capabilities, each with different battery sizes, plug connection types, and maximum power draw.

Figure Source: Hampel (*18*)

Figure 1 Survey's introductory text on bidirectional charging

Data Set Statistics

Our survey was online, anonymous, and designed to be representative of U.S. national-level demographic attributes. The respondents that voluntarily completed the 21 bidirectional charging questions after completing the first section, which is covered in Dean and Kockelman (*17*), may be more interested in this research topic than other respondents, but are otherwise similar to the pool in the larger data set (+/- a few percentage points). Table 2 summarizes key characteristics of Dean and Kockelman's (*17*) data set, this study's data set, and comparable U.S.-level data, some of which are used as covariates in models. Although the sample is nearly representative of the general population across key variables, the paper results are population-weighted.

The average American is willing to spend $280 and $776 for V2L technology and V2H home energy system equipment on their next BEV purchase[4]. In contrast, 58.4% are not WTP more than $250 to add V2L technology, 32.5% are not willing to spend any money at all to add it, and 35.6% would not pay extra for V2H equipment. As expected, the average WTP increases with the size of the bidirectional charging feature, although there is less appetite for V2H. Assuming the average cost experienced by a residential customer during a single one-hour summer afternoon outage is $5 (in 2023 dollars), there is an equivalent expectation that the average American expects at least 155 hours of power outage over the equipment's lifetime[5] (*19*).

If Americans had a BEV with V2L technology or V2H equipment, around 21.3% and 14.3% expect to use V2L and V2H as often as once a month, respectively. On the other hand, a larger share of people (33.1% and 37.5%) does not expect to use V2L and V2H at all, respectively. If people with V2G-capable BEVs had the option to opt into a power company program to slightly discharge power back to the grid during emergencies (with appropriate compensation for reduced range and guaranteed minimum range) only 12.7% would definitely participate but a larger share (41.1%) would probably participate.

One question told respondents to assume they primarily drove a BEV and allowed their power company to do V1G smart charging (i.e., interrupt or stagger charging) and slightly discharge energy during power emergencies for a quarterly reward on top of compensation for reduced range per event. The measured outcome was the expected frequency that their power company would slightly discharge their BEV's battery to support the electrical grid. The ordinal responses ranged from never, once a year, once a quarter, at least once a month, at least once a week, and more than once a week. The largest group (40.8%) said they do not expect their local power company would access their BEV's battery, perhaps because they live in regions of the country with historically reliable electricity or because of a lack of innovation or will on the part of their utility to tap this resource. About a quarter of people (25.4%) expect their utility to use V2G once a year, while 21.1% expect V2G use at least once every three months.

Figure 2 shows the likelihood that a person would allow their local power company to discharge their future BEV, at most twice a year with advanced warning by method of your choice (e.g., app notification, text message, email, or phone call) with the option to opt-out if the timing is inconvenient. This supplier-managed V2G scheme would likely be used only during critical peak hours in the year when power grids are operating with reserve generators and have deployed other emergency response measures, like demand response. Most people are likely to participate in supplier-managed V2G (68.8%) when compensated for the unlikely event of battery loss; however, power companies may find it difficult in measuring and verifying event-specific battery loss. If

[4] Respondents were asked to select their WTP for V2L and V2H using an ordinal response scale. V2L responses ranged from $0, <$250, $250–$500, $500–$750, $750–$1,000, $1,000–$1,250, >$1,250 and V2H responses ranged from $0, <$1,000, $1,000–$2,000, $2,000–$3,000, $3,000–$4,000, $4,000–$5,000, >$5,000. The population-weighted summary statistics used the weighted linear predictors of WTP.

[5] Short-duration outages have a lower economic impact than hours-long outages (i.e., no spoiled food, limited interruption to work, or human health impacts due to cold/heat). Although Lawton et al.'s short-term cost was adjusted to 2023 dollars, the share of people that telework from home has increased and would likely increase the average cost. The average U.S. household faces nearly two hours of power outages during the year, excluding major events (5.8 hours otherwise). People residing in areas of the country with total power outages lasting longer than the average residential customer may have selected a higher WTP for V2H equipment; however, this study did not ask respondents to provide us with their annual total power outage (in hours) or their utility to map respondents with national electricity reliability data.

battery warranties covered battery loss from discharging, then another majority of people (54.5%) would likely provide V2G grid resources upon request. If warranties do not cover V2G battery loss, a similar share of people would likely participate if only 5% of the battery was drained (provided the battery level does not drop below 75%). Power companies must act judiciously when discharging BEVs during grid emergencies, as shown with the 50% battery level guarantee. More people would likely not participate (46.0%) since their mobility needs (planned or unplanned) take priority. Although the last scenario in Figure 2 is unlikely, it shows the need for addressing battery loss when designing a supplier-managed V2G program, else 63.7% of people would not take part.

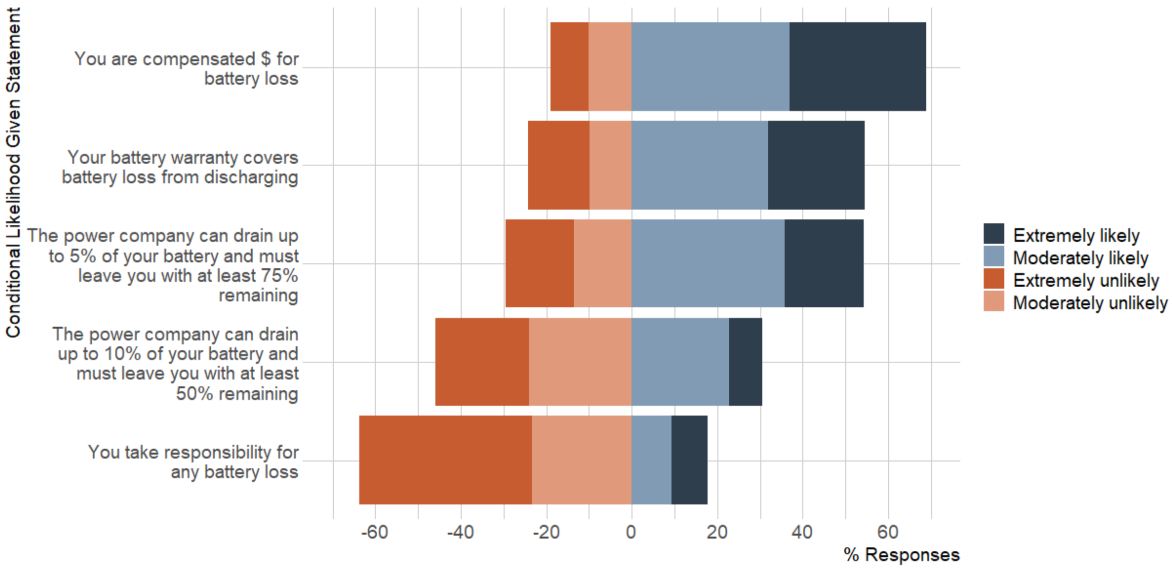

Figure 2 Likelihood to let power company discharge BEV given a condition (neither likely/unlikely responses not shown)

TABLE 1 Characteristics of Respondents Compared to U.S.-level Data

Explanatory Variables	**Original n = 1,050**	**Current n = 311**	**US Population**	**Source**
Gender (of person filling out the survey)				
Male	46.8%	46.3%	49.5%	ACS 2021 (1-Year)
Female	52.4%	53.4%	50.5%	
Non-binary/other	0.9%	0.3%	NA	
Age (of person filling out the survey)				
18–24 years of age	16.0%	17.7%	17.1%	ACS 2021 (1-Year)
25–34	21.9%	22.2%	22.9%	
35–44	17.2%	17.4%	16.9%	
45–54	16.8%	19.3%	15.8%	
55–64	17.3%	14.5%	16.5%	
65+	10.7%	9.0%	10.8%	
Highest level of education completed (of person filling out the survey)				ACS 2021 (1-Year)
High school or less	36.9%	35.3%	38.1%	
Some college/Associate degree	31.0%	33.4%	29.5%	

Bachelor's degree	20.5%	19.9%	20.3%	
Master's degree or higher	11.7%	10.3%	12.2%	
Race (of person filling out the survey)				
White	75.6%	78.5%	61.2%	
Black	12.1%	11.6%	12.1%	
Asian	7.1%	4.8%	5.8%	ACS 2021 (1-Year)
American Indian	1.3%	1.6%	1.0%	
Mixed	2.3%	2.6%	12.6%	
Other/not disclosed	1.5%	0.9%	7.2%	
Census Region				
Northeast U.S.	20.0%	21.9%	17.2%	
Midwest	20.6%	16.7%	20.7%	ACS 2021 (1-Year)
West	17.8%	18.3%	23.7%	
South	41.6%	43.1%	38.3%	
Household Income, pre-tax				
Less than $30,000	21.0%	19.6%	21.2%	
Between $30,000 and 49,999	18.5%	20.3%	15.3%	
Between $50,000 and 74,999	21.0%	22.8%	16.8%	ACS 2021 (1-Year)
Between $75,000 and 99,999	12.4%	11.6%	12.8%	
Between $100,000 and $149,999	13.1%	12.6%	16.3%	
$150,000 and up	11.1%	11.0%	17.7%	
Prefer not to answer	2.9%	2.3%	NA	
Household Vehicles				
0 vehicles	6.9%	7.4%	8.9%	
1	40.2%	32.8%	33.5%	2017 NHTS
2	34.4%	37.6%	33.1%	
3+	18.3%	22.2%	24.4%	
Residence Type				
Detached House	65.9%	63.7%	63.6%	
Attached House (e.g., townhouse, duplex)	5.2%	5.1%	6.3%	2021 AHS
Apartment	22.4%	21.5%	24.7%	
Mobile Home	4.8%	5.5%	5.2%	
Other	2.7%	1.9%	0.05%	
Household Size				
1 household members	19.0%	18.6%	28.3%	
2	33.1%	32.8%	34.2%	2020 Census
3	20.4%	19.3%	15.4%	
4+	27.4%	29.3%	22.2%	
Household Technology Present				
Smart thermostat	22.4%	22.5%	18.3%	Walton (*20*)
Solar power	5.6%	5.1%	3.8%	2021 AHS

Notes: ACS = American Community Survey, NA = not available, NHTS = U.S. National Household Travel Survey. The American Housing Survey (AHS) excludes group quarters (e.g., nursing homes, dormitories, military housing).

MODEL SPECIFICATION

A causal model was developed to understand the multivariate correlation between explanatory variables and response variables including WTP for bidirectional charging technology and expected reliance or use of this technology.

An interval regression (IR) model estimated the WTP to add bidirectional charging technology. Respondents were asked to choose the respective WTP interval (e.g., another \$500 to \$750 to add V2L technology), with values scaled based on cost estimates from the author's correspondence with BEV technology experts. WTP intervals included \$0 as a base choice and an option for "\$1,250 or more" and "\$5,000 or more" in the questions about WTP to add V2L technology and V2H equipment, respectively. Thus, the response variable is right-censored interval data. IR is formulated as:

$$y_j = \beta' x_j + \varepsilon_i, \quad (1)$$

where the subscript j denotes one observation from the set of all observations ($j \in C$). IR reflects all boundaries as known values (i.e., $y_j \in [y_{lj}, y_{uj}]$, where y_{lj} is the lower bound and y_{uj} is the upper bound). The covariates vector for each respondent is x_j; β represents a vector of to-be-estimated regression coefficients; and ε_i is the error term that is normally distributed with a mean zero and standard deviation σ.

An ordered probit (OP) model estimated the respondent's expected frequency of relying on V2L and V2H and their expectations of how frequently their local power company would access their BEV to support the electrical grid (i.e., slightly discharge using V2G). OP is formulated as:

$$y_j^* = \beta' x_j + \varepsilon_j \quad (2)$$

where y_j^* is respondent *j's* latent tendency to rely on V2L/V2H or expect their local power company to use V2G, x_j is a vector of explanatory variables for respondent j, β is a vector of regression coefficients, and ε_j is a normally-distributed error term. The number of thresholds is one less than the binned categories (μ_1 to μ_5). The probabilities for the expected use of V2L are as follows:

$$\Pr(\text{do not expect to rely on V2L}) = \Pr(y_j^* \leq \mu_1) \quad (2)$$

$$\Pr(\text{expect to rely on V2L around 1-2 times a year}) = \Pr(\mu_1 \leq y_j^* \leq \mu_2) \quad (3)$$

$$\Pr(\text{expect to rely on V2L around 3-4 times a year}) = \Pr(\mu_2 \leq y_j^* \leq \mu_3) \quad (4)$$

$$\Pr(\text{expect to rely on V2L at least once a month}) = \Pr(\mu_3 \leq y_j^* \leq \mu_4) \quad (5)$$

$$\Pr(\text{expect to rely on V2L around once a week}) = \Pr(\mu_4 \leq y_j^* \leq \mu_5) \quad (6)$$

$$\Pr(\text{expect to rely on V2L more than once a week}) = \Pr(y_j^* \geq \mu_5) \quad (7)$$

A subset of explanatory variables was first included when estimating the models. In subsequent steps, the covariates with the lowest statistical significance were removed using likelihood ratio tests, except for some variables like gender and race, as such covariates may offer statistical significance in future studies. In addition to statistical significance, practical significance values are shown to reflect the importance of covariates on the dependent variable.

MODEL RESULTS

Willingness to Pay for Bidirectional Features

Table 2 summarizes the IR model estimates of Americans' WTP for adding V2L technology and V2H equipment to their next BEV purchase, respectively. The final model includes household-level information (household income, photovoltaic (PV), household size, number of vehicles) and respondent-level characteristics (race, age, residence location), driving patterns, knowledge and attitudes on V1G and V2G capabilities. Gender was initially included in these models and was found not statistically significant at the 20% level and was removed. Different age and household income groups were tested, with the reference level set to ages 18 to 24 and household pre-tax incomes of $30,000 or less, respectively. To account for differences in preferences towards V2G capabilities of individuals who were already knowledgeable about this concept and those who not, an indicator variable accounting for prior knowledge of bidirectional charging (including V2L, V2H, and V2G) was added. The indicator variable was statistically significant for both WTP models, indicating a $134 and $337 (V2L and V2H, respectively) difference between individuals with knowledge on V2G before the survey and those who were not.

Two-person households that own PV, make at least a combined pre-tax income of $30,000, have more household vehicles, and where the respondent drives between 10,000 and 20,000 miles a year[6] (all other predictors constant), are estimated to have higher WTP for adding V2L technology. White, Non-Hispanic adults 25 years or older and would buy a BEV with a range of 50-150 miles if making a BEV purchase are estimated to place a lower value on adding V2L technology to a future BEV purchase. Those unwilling to buy long-range BEVs, perhaps due to budget constraints or daily mobility needs, expect that V2L should be a low-cost add-on to new BEVs.

The cost of buying and installing V2H systems depends on the type of home charging equipment, the amperage of the home's electrical panel, construction costs (i.e., trenching or adjustment to existing utility connections), and the cost of an additional home energy system. In this study, we asked respondents to state their WTP for the additional home energy system equipment and to exclude any electrical upgrade costs[7].

Young adults (age 18–34) having higher perceived importance of smart charging's contribution to global climate goals and bidirectional charging's potential to provide emergency power to their home, and have a household pre-tax income of at least $100,000 and own PV have a higher estimated WTP for V2H equipment. Apparently, these people would pay no more than $1,682, which is less than half (43.2%) of the price of Ford's F-150 Lightning V2H system. California residents 35 years or older are estimated to place a lower value on adding a V2H system to their next BEV purchase. Perhaps California's incentives[8] for energy storage systems are influencing their WTP for an additional upfront cost when buying a BEV.

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[6] According to FHWA, the average miles driven per year by Americans is 14,263 miles, which varies vastly by location (density and fuel costs), gender, employment status, and other key demographic characteristics (*21*).

[7] Respondents were told the cost to upgrade a home's electrical system may be $1,000 to $3,000. If households already have the electrical system required for V2H or are able to upgrade to a better panel at a lower cost the estimated WTP for V2H may be biased low. The cost of Ford F-150 Lightning's home energy management system sold through their partner, Sunrun, costs $3,895 pre-tax.

[8] California's primary storage incentive, Self-Generation Incentive Program (SGIP), provides residential and non-residential entities a rebate for installing an energy system. The upfront incentive depends on the number of existing, qualified installations (i.e., a tiered-block program), the size of the battery, and whether the recipient qualifies for the California Equity Resilience incentive. The latter program includes "low-income households, customers living in

TABLE 2 WTP to Add V2L Technology and V2H Equipment (using Interval Regression)

Model 1: V2L Technology WTP Covariates	**Coef.**	**Std Coef.**	**Z-stat**
Intercept	254.35	--	2.87
Household Income ($30k to $50k)?	152.17	**0.412**	2.80
Household Income ($50k to $100k)?	103.36	0.329	2.40
Household Income ($100k and up)?	129.75	0.368	2.37
White Non-Hispanic/Latino?	-75.10	-0.215	-1.73
Ideal BEV Range Under 150 miles?	-110.53	-0.149	-1.90
Two-person Household?	95.50	0.301	2.47
PV owner?	179.86	0.268	1.90
Age 25 to 34?	-142.14	-0.396	-2.46
Age 35 to 54?	-165.24	**-0.535**	-2.74
Age 55 to 64?	-212.31	**-0.498**	-3.09
Age 65 and Older?	-323.24	**-0.613**	-5.03
Annual VMD by Respondent is 10k to 20k miles?	104.72	0.319	2.50
Number of Household Vehicles	35.05	0.250	2.27
Importance of Smart Charging Contributing to Global Climate Goals (1-5 Likert Scale)	37.07	0.330	2.71
No Prior Knowledge on Bidirectional Charging?	-133.79	**-0.413**	-3.38
sigma (σ)	282.02	--	--
N = 307 Americans LL (final) = -1072.52 McFadden's R-Square = 0.043			

Model 2: V2H Equipment WTP Covariates	**Coef.**	**Std Coef.**	**Z-stat**
Intercept	377.69	--	1.92
Household Income ($30k to $50k)?	246.03	0.261	1.50
Household Income ($50k to $100k)?	131.11	0.164	0.93
Household Income ($100k and up)?	441.78	**0.493**	2.46
PV Owner?	605.03	0.354	1.84
California Resident?	-360.59	-0.234	-1.90
Age 35 to 54?	-358.48	**-0.456**	-2.58
Age 55 to 64?	-480.86	**-0.443**	-3.21
Age 65 and Older?	-589.62	**-0.439**	-4.66
Importance of Smart Charging Contributing to Global Climate Goals (1-5 Likert Scale)	102.46	0.358	2.70
Importance of Bidirectional Charging Providing Emergency Power to My Home (1-5 Likert Scale)	155.00	**0.500**	3.48
No Prior Knowledge on Bidirectional Charging?	-336.71	**-0.408**	-2.65
sigma (σ)	905.22	--	--
N = 308 Americans LL (final) = -1179.55 McFadden's R-Square = 0.029			

Note: All Std. Coef., which are greater than 0.40, are in bold, and indicate practically significant predictors[9]. Results are population weighted/sample corrected. VMD = Vehicle-miles driven.

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high-risk fire areas, customers who experienced Public Safety Power Shutoffs (PSPS) events on two or more distinct occasions, and critical facilities that provide services to the affected areas" (*22*).

[9] Standardized coefficients were estimated by multiplying the unstandardized coefficient by the ratio of the standard deviations of the independent variable and estimated dependent variable.

Expected Frequency of Using V2L and V2H

Table 3 summarizes the OP model estimates of Americans' expected frequency of relying on V2L technology and V2H equipment, respectively. Older, well-educated adults (age 55 and up with at least a master's degree) with no prior knowledge of bidirectional charging before this survey tend to expect to use V2L less often, assuming they primarily drove a V2L-capable BEV. African American adults having higher perceived importance of smart charging's ability to reduce power plant air pollution and access to more household vehicles (all else constant) are estimated to expect to rely on V2L more frequently. Perhaps using V2L may reduce emissions exposure from portable diesel generators and provide more opportunities for social gatherings in areas without electricity access.

White Hispanic adults having higher perceived importance of bidirectional charging's potential to provide emergency power to their home, have access to more household vehicles, and whose household pre-tax income is between $100,000 and $150,000 are more likely to rely on V2H to manage their home's power demands, including lowering their charging bill[10]. Perhaps those expecting to use their V2H system more regularly will have the means to "buy" flexibility through additional household vehicles for unplanned trips. Older adults (age 65 and up) who do not pay wholesale-indexed residential electricity prices and would prefer a long-range BEV if faced with a BEV purchase decision are less likely to rely on V2H, assuming they primarily drove a BEV and had V2H equipment. Although long-range BEVs could provide more hours of backup power, perhaps those wanting BEVs with more range expect to drive their vehicle more often or have range anxiety, both of which may not overlap with the expectation of using a BEV for emergency home power.

Expected Frequency of Power Company Using V2G

Table 4 reports the OP model for a research question on using a BEV to support the power grid. Although V2G could be used to buy energy at low prices and sell stored energy back to the grid at high prices (i.e., energy arbitrage) or to offer ancillary services, like grid frequency support, it is expected that personal BEVs might only discharge power back to the grid during grid emergencies, at least in the foreseeable future. The regularity at which local power companies call on personal BEVs to provide power depends on a number of factors, including short-term and long-term grid resource adequacy, extreme weather, planned and unplanned power grid outages (of generators and transmission lines), and the ability for a local power company to manage a BEV V2G program, with or without the help of a third-party grid aggregator. In this study, we told respondents the following information in Figure 3 before asking them if they would participate in supplier-managed (or utility-controlled) bidirectional charging during grid emergencies.

[10] PV ownership was initially included in the model but was removed due to a lack of statistical significance (*t*-stat of 0.63). In the future, the transition from net metering to net billing solar policies may create conditions where price signals incentivize V2H systems with a behind-the-meter battery storage system (BSS) to make charging more affordable at off-peak prices and incentivize discharging the BSS during the net peak. Although not presented in this study, the ability for V2H to operate in parallel with the power grid to reduce high differentials in power prices and even to allow for V2G under a net billing system is an interesting research question.

Power companies could use smart charging to interrupt charging when demand for electricity is at or near capacity (to avoid grid blackouts). They could also use bidirectional charging to send power back into the grid (with vehicle-to-grid, V2G) during emergencies.

Assume you primarily drive a battery-electric vehicle (BEV) and have V2G charging capabilities at home. Assume that bidirectional charging degrades your vehicle's battery 1% faster over the lifespan of the vehicle.

Note: You are compensated $0.70 per mile of range reduced and the power company ("utility") cannot reduce your range more than 50 miles per emergency.

Would you allow your power company to discharge power from your battery during grid emergencies?

Figure 3 Survey's explanatory text on expected frequency of V2G-necessitating events

The results indicate that male adults having a higher perceived importance of bidirectional charging's ability to provide emergency power to their home and the grid and pay wholesale-indexed residential electricity are more likely to participate in a supplier-managed V2G program during grid emergencies, provided that the power company compensates them $0.70/mile[11] of reduced range and guarantees a minimum range of 50 miles remaining. Older adults (age 55–64) who pay time-of-use (TOU) residential electricity prices (all else constant) are less likely to participate in a supplier-managed V2G program during grid emergencies.

TABLE 3 Parameter Estimates for OP Model of Expected Reliance on V2L Technology and V2H Equipment

Model 1: V2L Technology Expected Reliance Covariates	**Coef.**	**t-value**	**ΔPr$_1$**	**ΔPr$_2$**	**ΔPr$_3$**	**ΔPr$_4$**	**ΔPr$_5$**	**ΔPr$_6$**
Black/African American?	0.493	2.51	**-15.3%**	-4.2%	4.3%	6.3%	5.9%	3.0%
No Prior Knowledge on Bidirectional Charging?	-0.369	-2.69	12.3%	2.1%	-4.1%	-4.7%	-3.9%	-1.7%
Importance of Smart Charging Reducing Power Plant Air Pollution (1-5 Likert Scale)	0.146	2.61	14.2%	-0.1%	-5.4%	-4.5%	-3.1%	-1.1%
Number of Household Vehicles	0.179	2.84	**18.3%**	-0.4%	-7.0%	-5.7%	-3.9%	-1.4%
Master's degree (or higher) holder	-0.383	-1.87	**39.1%**	-6.8%	-14.8%	-9.7%	-5.9%	-1.9%
Age 55 to 64?	-0.490	-2.67	-5.1%	-0.6%	1.8%	1.8%	1.4%	0.6%
Age 65 and Older?	-1.028	-4.01	-6.3%	-0.7%	2.2%	2.3%	1.8%	0.7%
Thresholds (I expect to rely on V2L…)	**Coef.**	**t-value**						
never **vs.** 1-2x/year	-0.193	-0.79	--	--	--	--	--	--
1-2x/year **vs.** 3-4x/year	0.553	2.21	--	--	--	--	--	--
3-4x/year **vs.** 1x/month	1.230	4.83	--	--	--	--	--	--
1x/month **vs.** 1x/week	1.781	6.78	--	--	--	--	--	--
1x/week **vs.** more than 1x/week	2.469	8.41	--	--	--	--	--	--
N=307 LL (final) = -454.45 McFadden's R-Square = 0.107 AIC = 932.909								
Model 2: V2H Equipment WTP Covariates	**Coef.**	**t-value**	**ΔPr$_1$**	**ΔPr$_2$**	**ΔPr$_3$**	**ΔPr$_4$**	**ΔPr$_5$**	**ΔPr$_6$**
White Hispanic/Latino?	0.442	1.18	-14.8%	-1.9%	6.2%	5.5%	3.3%	1.7%

[11] The financial incentive of $0.70/mile is based on California's compensation rate of $2/kWh of avoided electricity consumption during an emergency load reduction program (ELRP) event and an average BEV's driving efficiency of 2.9 mi/kWh.

Ideal BEV Range (25-mile steps)	-0.034	-2.21	**25.7%**	-6.5%	-10.4%	-5.5%	-2.4%	-0.9%
Importance of Bidirectional Charging Providing Emergency Power to My Home (1-5 Likert Scale)	0.303	4.91	-12.5%	-0.7%	5.3%	4.3%	2.4%	1.2%
Number of Household Vehicles	0.133	2.15	**-20.7%**	-4.7%	8.1%	8.5%	5.5%	3.3%
Age 65 and older?	-0.658	-2.54	1.3%	-0.1%	-0.5%	-0.4%	-0.2%	-0.1%
Household Income ($100k to $150k)?	0.358	1.89	-11.3%	0.7%	4.9%	3.3%	1.7%	0.7%
Wholesale Power Prices Paid at Home?	0.661	1.94	-4.9%	0.3%	2.1%	1.5%	0.7%	0.3%
Thresholds (I expect to rely on V2H…)	**Coef.**	**t-value**						
never **vs.** 1-2x/year	0.384	1.46	--	--	--	--	--	--
1-2x/year **vs.** 3-4x/year	1.268	4.65	--	--	--	--	--	--
3-4x/year **vs.** 1x/month	1.981	7.04	--	--	--	--	--	--
1x/month **vs.** 1x/week	2.561	8.76	--	--	--	--	--	--
1x/week **vs.** more than 1x/week	3.137	9.54	--	--	--	--	--	--
N=307 LL (final) = -412.28 McFadden's R-Square = 0.172 AIC = 848.56								

Note: All ΔPr's greater than 15% are bolded, and indicate practically significant predictors (i.e., how one unit change in a covariate changes the probability of each choice outcome, in percentage points, while holding all other covariates at their mean. Binary variables are not as if continuous to calculate the marginal effects). Results are population weighted/sample corrected (for age, region, gender, and education – see footnote 3).

TABLE 4 Parameter Estimates for OP Model of Expected Participation in SMC-V2G During Power Grid Emergencies

SMC-V2G Participation Covariates	**Coef.**	**t-value**	**ΔPr_1**	**ΔPr_2**	**ΔPr_3**	**ΔPr_4**	**ΔPr_5**
Female?	-0.470	-3.86	9.80%	6.70%	2.00%	-9.60%	-8.80%
Age 55 to 64?	-0.442	-2.46	11.00%	5.60%	0.90%	-10.80%	-6.60%
Wholesale Power Prices Paid at Home?	0.748	2.04	-10.30%	-10.70%	-5.40%	6.50%	**19.90%**
Time-of-Use (TOU) Power Prices Paid at Home?	-0.352	-2.00	8.40%	4.70%	0.90%	-8.40%	-5.60%
Importance of Bidirectional Charging Providing Emergency Support to the Power Grid (1-5 Likert Scale)	0.189	3.07	-4.00%	-2.70%	-0.80%	4.00%	3.50%
Importance of Bidirectional Charging Providing Emergency Power to My Home (1-5 Likert Scale)	0.136	1.87	-2.90%	-2.00%	-0.60%	2.90%	2.50%
Thresholds	**Coef.**	**t-value**					
Definitely would NOT participate **vs.** probably would NOT participate	-0.667	-3.17	--	--	--	--	--
Probably would NOT participate **vs.** unsure	-0.021	-0.10	--	--	--	--	--
Unsure **vs.** probably would participate	0.348	1.65	--	--	--	--	--
Probably would participate **vs.** definitely would participate	1.706	7.44	--	--	--	--	--

N=308
LL (final) = -428.98   McFadden's R-Square = 0.065   AIC = 877.95

Note: All ΔPr's greater than 15% are bolded, and indicate practically significant predictors (i.e., how one unit change in a covariate changes the probability of each choice outcome, in percentage points, while holding all other covariates at their mean. Binary variables are treated as if continuous to calculate the marginal effects). Results are population weighted/sample corrected (for age, region, gender, and education – see footnote 3).

Future Work and Limitations

This paper estimates WTP and expected use of an emerging technology on a population that is still learning about EVs. Although stated preference experimental results may not hold up over time, they are valuable in informing policy and technology development. Furthermore, the estimates found in this study are context-dependent, to late 2022 and a United States randomized respondent pool which voluntary elected to complete a 21-question follow-up survey on bidirectional charging. Future work may consider surveying Americans, or people in other countries, across time and without a potential interest bias to see if patterns differ.

Our survey presented V2G only through the lens of serving as grid resources in emergencies and would be controlled by the local power company. Although each was presented as a pay-as-you-supply V2G compensation scheme, some regions may allow third-party companies pool BEV resources to coordinate V2G and participate in the wholesale power market (i.e., discharge electricity when prices spike to make money). Additional work is necessary to understand opinions and acceptance of flexible V2G schemes to make money and understanding trust and perceptions of third-party companies versus traditional power companies.

CONCLUSIONS

This study estimated interval regression (IR) and ordered probit (OP) models to understand the impacts of demographics, travel characteristics and preferences, and attitudes on bidirectional charging benefits on Americans' WTP and expected use of bidirectional charging technologies and equipment.

Population-weighted summary statistics suggest that roughly a third of Americans do not yet see a value in adding V2L technology to a future BEV purchase and would not buy additional V2H equipment to provide emergency power to one's home during grid outages. If V2L technology was a feature on all BEVs and Americans primarily drove a BEV, as few as 21% expect to rely on this feature to charge auxiliary loads at recreational, work, and home locations. The average WTP for V2L technology and V2H home energy systems (not including any electrical panel upgrades) is estimated to be \$286 and \$793, respectively. Likely because power outages in the U.S. mainland are infrequent and short in nature, on average, only 14.3% of Americans expect to rely on V2H as often as once a month. Locational variables, like a utility's resilience to climate change, vegetation clearing practices, and challenging terrain do play a factor in power outages and are likely hidden factors that influenced the respondent's expected use of a future V2H system. As expected, if people had a BEV and allowed their local power company to slightly discharge power back to the grid during emergencies (assuming compensation for reduced range and minimum range requirements) a corresponding 12.7% expect their BEV's battery would be accessed as often as once a month. Not everyone would participate in a program with their local power company to provide emergency V2G power from personal BEVs, but over half (53.8%) of Americans stated they would definitely or probably opt into a program.

Older adults (age 35 and up) and those who had no knowledge of bidirectional charging prior to this survey expressed lower WTP for V2L and V2H, whereas households making at least $30,000 in pre-tax income, with PV at their home, and who believe smart charging (V1G)'s benefit of contributing to global climate goals is of high importance to themselves are WTP more to add these technologies to their future BEV purchase. If people had BEVs with these technologies the households with more vehicles are estimated to use these features more frequently, while adults over the age of 64 appear to be less frequent users of this technology. Finally, if people had V2G-capable BEVs and a V2H system and currently paid wholesale-indexed residential electricity prices they are likely to be more frequent users of V2H and would be willing to participate in a utility-controlled V2G program to slightly discharge stored energy from personal BEVs to the grid during emergencies.

This study provides a timely analysis of Americans' perceptions on bidirectional charging features through WTP and use measurements. The knowledge of which covariates have statistical and practical significance shed light on who might be early adopters of this technology—which are of interest to automakers, policymakers, and local power companies. The relatively low WTP values indicate a need to lower the costs of V2L and V2H equipment or awareness campaigns on the part of automakers to show the value of these technologies. This study found that 37.5% of Americans would not expect to use a V2H system, assuming they had one, which can be helpful in setting the tone for the long-term adoption of a V2H technology, and certainly the advertised vision of a BEV powering a home through a short-term power outage. As the policy landscape changes with PV net metering and the costs of BEV and battery storage systems decline, future work may revisit these questions to understand whether Americans have shifted their views on a vehicle-home integrated system. Lastly, this study indicates that if compensated at $0.70/mile of reduced range with a guaranteed minimum range of 50 miles that over half of Americans would opt into a utility-controlled V2G plan to provide emergency grid support to prevent major grid outages that arise due to electricity demand exceeding generation's supply.

ACKNOWLEDGEMENTS

This material is based on work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE-1610403. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. This research is also funded by the 2022-2023 Energy Seed Grant Program from the Energy Institute at The University of Texas at Austin. The authors acknowledge Balasubramanian Sambasivam, Saagar Pateder, and Cameron Freberg for their helpful comments and insights on the survey design.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: Dean, M.D. and Kockelman, K.M.; data collection: Dean, M.D.; analysis and interpretation of results: Dean, M.D.; draft manuscript preparation: Dean, M.D. All authors reviewed and edited the results and approved the final version of the manuscript.

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