AMERICANS' OPINIONS AND INTERESTS IN PLUG-IN ELECTRIC VEHICLE SMART CHARGING PROGRAMS

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ABSTRACT

Power companies are developing plug-in electric vehicle smart charging programs to shift charging to off-peak hours when demand is lower and to align charging with renewable energy. Anticipating public acceptance and attitudes toward smart charging programs can ensure a sustainable transportation-clean energy transition. An internet-based survey of more than 1,000 Americans ascertains opinions on supplier-managed charging (SMC) programs and the expected benefits of participating in a program. About a quarter of Americans say they would never accept SMC, but 8.8% would be willing to use an app or timer to stagger charging themselves. Up to 36.9% would cede some control to their supplier (17.6% at night only, 10.3% on grid-strained days only, and 8.9% every day to optimize the local grid). Multinomial logit models indicate that Americans with a household battery electric vehicle and wholesale-indexed energy rates are more willing to accept an SMC program. Tobit model results indicate the minimum required one-time and annual bill credits for participating in a future SMC program. These results can inform the communication and design of effective PEV charging programs to manage the new power demand by PEVs.

Keywords: *Plug-in Electric Vehicles, Smart Charging, Willingness to Pay, Charging behavior*

INTRODUCTION

The share of plug-in electric vehicles (PEVs), which include battery-electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), is rapidly increasing worldwide (*1*). Although PEVs offer a new revenue source for the power industry and lower carbon emissions from transportation, an increase in electricity may also create challenges in providing reliable electricity. Many power grids are increasing their share of variable renewable energy (VRE) and have either limited or aging transmission infrastructure not designed for a clean-energy transition (*2*, *3*). Fortunately, PEVs are considered flexible loads, meaning that their charging behavior can be influenced by infrastructure provisioning and price control, thereby affecting their impacts on power grid operations.

The location, supply, and type of charging infrastructure influence when and where drivers will charge their PEVs and their consequential impact on electricity demand (*4*). Building public and workplace charging stations can shift charging from nighttime to daytime, which may be advantageous in regions with an abundance of solar power. In 2021, utility-scale solar accounted for 17.1% of California's in-state generation (*5*), but due to spatio-temporal imbalances between supply and demand, the grid operator curtailed nearly 1.5 terawatt-hours (TWh) of solar power (or 5% of solar generation) (*6*). Aligning PEV charging demand with solar production can reduce PEV's charging emissions and curtailment due to overgeneration, especially in temperate months when electricity demand is relatively low (because of decreased heating and cooling demand). Flexible PEV charging demand can also address balancing issues in the net load curve—the total electricity demand curve minus VRE generation—which is the amount of demand that the grid operator must supply from dispatchable sources, like natural gas peaker power plants. Filling in valleys in the net load curve by shifting PEV charging decreases ramping requirements (up or down) and thus system costs (*4*, *7–9*). At the distribution system level, shifting charging to valleys in demand decreases the percentage of assets, such as transformers, that need to be augmented and delays when improvements are needed (*10*).

The introduction of time-varying electricity prices, like time-of-use (TOU) or wholesale-indexed rates, may also motivate PEV owners to avoid charging during peak hours because of higher electricity costs (*11*). Studies have found that most residential customers adapt to TOU rates by reducing electricity consumption during peak hours (*12*, *13*), depending on the ratio of peak price to off-peak price (*11*). TOU adoption rates of 20–40% can increase PEV hosting capacity by 20% (i.e., the number of PEVs that can charge on a distribution power network before impacts on voltage or power quality) (*10*).

The use of time-varying electricity prices is a form of passive smart charging since the owner responds to prices to alter charging behavior by either manually deciding when to plug or unplug the vehicle or using an app or timer to schedule charging (*7*, *14*). Advanced forms of smart charging can also include direct (or "active") control, where the local power supplier[1] alters charging behavior at smaller time steps to manage conditions in the distribution system. In this study, user-managed charging (UMC) refers to an app or timer program that shifts charging, controls charging speed, and/or staggers charging to avoid adding to the peak load or increasing emissions from electricity generation. Several smartphone apps are available to consumers to smart-charge their PEV (e.g., Optiwatt and FlexCharging). Supplier-managed charging (SMC) is when the charging schedule of the vehicle is coordinated and managed by the electricity supplier

[1] A power supplier is also known as a power company or electric utility.

(or contracted third-party aggregator) to meet the objectives of the supplier, so long as customer-defined constraints, such as departure times and battery levels, are met.

The benefits of smart charging depend on PEV drivers' responses to smart charging programs and their willingness to enroll in a program, be it UMC or SMC. Despite research on the financial and technical requirements of smart charging, only a few studies have directly investigated consumer opinions and willingness to participate in smart charging programs (*15*). To address this research gap in the literature, this study addresses the following research objectives:

1. Characterize opinions towards PEVs, smart charging, PEV-power grid integration, and preferences for smart charging (specifically within the United States context).
2. Quantify the minimum financial incentives for participating in a smart charging program managed by a power supplier (i.e., SMC).

PRIOR LITERATURE AND CONTRIBUTIONS

Recently, researchers have started surveying the public to understand their perceptions of PEV smart charging and their willingness to participate in current or future hypothetical programs, including how they might adjust their current or expected charging behaviors. The studies either employ charging interventions with semi-structured interviews and questionnaires or identify respondents' preferred smart charging programs through web-based surveys. Table 1 compares recent studies that surveyed the public about PEV smart charging[2].

[2] This study focuses on smart charging that controls power flow to the vehicle (also called V1G) and ignores studies on bidirectional charging (also called V2G). Readers interested in a thorough review of study methodologies and results are referred to (*7*).

1 **TABLE 1 Synthesis of Studies Surveying the Public About PEV Smart Charging**

Reference	Research Method	Sample Size	Research Questions	Main Findings
Bailey & Axsen (*16*)	WB-survey, LCCM	1470 new LDV buyers interested in PEVs [Canada]	- What are consumer attitudes toward SMC, including perceptions of VRE, charging inconvenience, and privacy?	- UMC support among 50% to 67% of respondents interested in purchasing a PEV. - Concerns over privacy & loss of control with UMC. - LCCM (4 segments) vary in UMC acceptance, value of renewables, power bill savings, & charging inconvenience. - Cost-minimizing UMC program garnered 63% to 78% enrollment vs. 49% to 59% with a renewable-priority UMC. - Avg. WTP 59 CAD/year for +10 km in GMC in night-only UMC (base of 84 km).
Schmalfuß et al. (*17*)	Interview, Survey, SMC pilot	10 BEVs [Germany]	- What are consumer perceptions of SMC benefits, costs, and ease within daily routine? - Do users trust SMC?	- 7/10 participants felt the perceived benefits of SMC balanced with costs of participation. - Frequency of charging increased with SMC and trust in SMC had no statistically significant change with the pilot.
Bauman et al. (*18*)	Interview, SMC pilot	30 PEVs [Canada]	- Would participants enroll in SMC if the algorithm did not consider battery levels? - What compensation would lead to participation in SMC?	- 72% of participants would not have enrolled in SMC if the supplier curtailed charging without considering battery levels. - Over half of participants would accept SMC for less than $10/month (and over 2/3 would accept for less than $15/month).
Will & Schuller (*19*)	SEM	237 EV enthusiasts (41% PEV owners) [Germany]	- How do users perceive SC interventions in their charging behavior & what are the main factors driving the acceptance of SC programs?	- Awareness of grid operational benefits & VRE integration were important factors, while financial compensation was not significant (for early PEV adopters). - SC was associated with uncertainty & anxiety. Capacity to relinquish control depended on working patterns, financial resources, & charging access.
Delmonte et al. (*20*)	Semi-structured interviews	60 current PEV owners & PEAs [United Kingdom]	- What are PEV users' charging behaviors? - How do PEV users respond to UMC and SMC concepts? - What specific aspects of UMC and SMC are appealing to PEV users & off-putting to PEV users?	- SC engagement is conditional on lowering charging costs. - 2/3 prefer UMC due to personal control, while 1/3 prefer SMC because of societal benefits. - Cons of SMC are the loss of freedom and choice ("big brother") & detractors don't trust their power company.

			- How do responses differ between BEV & PHEV users?	- UMC with TOU rates is easier to grasp but more difficult to use – driver must time the EV & plug-in before off-peak – while SMC is more difficult to grasp but easy to use.
Kubli (*21*)	WB-survey, LCCM	202 PEV drivers & PEAs [Switzerland]	- Which consumer segments are crucial to consider when designing SC solutions? - What compensation should operators offer to incentivize PEV drivers to adopt SC?	- LCCM (3 segments) identify 53.2% are driven by charging costs & are likely earliest adopters. - Incentives to switch from home to work/public charging cost more than avg. charging session. - WTP for faster charging (4 hr faster) at home under SMC mode is 2.62 CHF.
Libertson (*22*)	WB-survey, semi-structured interview	1483 respondents, 27 interviews with PEV drivers [Sweden]	- What are PEV drivers' flexibility in delayed charging?	- About half of drivers were upset & frustrated that PEVs were not fully charged with SMC. PHEV drivers saw a delay in charging as increasing gas costs. BEV drivers spent more time finding other public chargers. - Custom SMC features can instill a sense of co-control & trust in charging.
Wong et al. (*23*)	WB-survey	784 residents in states with ZEV mandates or high BEV adoption [33 U.S. states + DC]	- What are the charging patterns of PEV drivers now? - How can incentives influence SC among PEV drivers, potential adopters, & ICEV drivers?	- A combination of free charging equipment, GMC, & financial incentives increases acceptance in SC. - Nearly a quarter (23%) of PEV owners & 13% of ICEV drivers would participate in SC without any incentive.
Lavieri & Martins de Oliveira (*24*)	WB-survey	1,000 drivers [Australia]	- What are general charging preferences & attitudes (if PEV, then what are your usual charging behaviors)? - What is the preferred charging option (unmanaged, UMC, SMC) and data collection (yes/no)?	- 51% of BEV drivers & 59% of PHEV drivers often or always charge to minimize downtime or maximize convenience, vs. 21% of ICEV drivers (they prefer min. charging costs). - 66% of PEV drivers feel comfortable ceding control vs. 32% of the public.

Abbreviations: CAD = Canadian dollar, CHF = Swiss franc, EV = electric vehicle, GMC = guaranteed minimum charge, ICEV = internal combustion engine vehicle, LCCM = latent class choice model, LDV = light-duty vehicle, PEAs = potential early adopters, PEV = plug-in electric vehicle, SC = smart charging, SEM = Structural equation modeling, SMC = supplier-managed charging, TOU = time-of-use electricity prices, UMC = user-managed charging, VRE = variable renewable energy, WB-survey = web-based survey, WTP = willingness to pay, ZEV = zero-emission vehicle.

Smart Charging Intervention Studies

Early interventions asked a small group of PEV owners (30 or fewer people) to test a smart charging system at home to understand both technical feasibility and participant experience and to develop recommendations for future pilot programs (*17*, *18*). The majority of participants felt that SMC's benefits balanced out with its costs (*17*) thanks to user-defined constraints, such as minimum battery levels that must be guaranteed at departure time and readily available data on their vehicle's battery levels on a smartphone app. Participants in the study by Bauman et al. (*18*) were able to view charging sessions on a web portal and pre-set departure times and automatic opt-outs from charging curtailment based on the vehicle's battery level. A survey of participants after the intervention found that 72% would participate in future SMC programs if the supplier considered user-defined constraints, like the vehicle's current battery level (*18*).

SMC interventions were also tested outside of the home at two public parking garage charging stations in Malmö (*22*). Drivers charging their PEVs in the first garage were told about the intervention, while drivers charging their vehicles in the second garage were only notified after the study was completed. About half of the PEV drivers across garages were upset that their vehicles were not fully charged upon their return to their vehicles. PHEV drivers felt this increased gas cost because SMC did not fully charge their batteries in time for departure, while BEV drivers had to spend additional time finding alternative public chargers. A subsequent web-based survey of Stockholm area residents with a PEV found that 40% would accept SMC, regardless of how long charging was interrupted or controlled, mostly due to perceived environmental benefits (39%), and grid stability (38%). Still, if public charging stations adopted SMC, people would compensate by installing home charging equipment, buying PHEVs over short-range BEVs, or buying long-range BEVs instead of short-range BEVs. In other words, one's comfort level and trust in an SMC system may be a function of one's financial resources.

Participation Incentives In Smart Charging Programs

Other researchers have surveyed current and potential adopters of PEVs to understand consumer attitudes toward smart charging programs and identify important attributes among respondents. Research across different countries has consistently identified higher support for UMC than SMC because of concerns about loss of control, privacy, anxiety, and a lack of trust in their power supplier (*16*, *19*, *20*, *24*). Recent work has found that acceptance of SMC may now exceed that of UMC, depending on PEV ownership and when people are likely to adopt a PEV. Over half of current surveyed Australian BEV drivers (59.6%) would prefer SMC to UMC, compared with less than a third (30.2%) of potential early PEV adopters (i.e., those who intend to buy a PEV in less than a year) and 23.6% of the general driving population (i.e., those who do not intend to buy a PEV in less than a year) (*24*). Early studies may not have observed this heterogeneity in survey responses due to relatively small numbers of EVs at the time of survey dissemination and participant samples that were identified as entirely potential early PEV adopters[3] (*16*) or recruited from PEV associations and newsletters (*19*).

Several studies have investigated the factors that increase participation, including financial incentives. Delmonte et al. (*20*) found respondents' engagement with smart charging was conditional on reducing charging costs. Kubli (*21*) identified segments in their participant pool using a latent class choice model and found the majority of individuals (53%) placed an emphasis

[3] Bailey and Axsen (*16*) identified these drivers through a design space exercise, where the participants designed a PEV with a purchase price that was only relatively higher than ICEVs.

on reducing charging costs over other charging attributes and would more likely alter their stated charging behaviors if given a time-varying electricity rate. Wong et al. (*23*) found a 2% to 3.5% increase in an SMC program per $50 increase in credit, with an overall participation ceiling of 87% for current PEV drivers and 79% for potential early adopters of PEVs. Bauman et al. (*18*) found that half of the participants in their 2015 SMC pilot would enroll in a similar program for a monthly credit of $10 (CAD), and over 67% would participate if receiving $15 or less per month. However, early PEV adopters may be more motivated to reduce costs than current PEV owners, who reportedly prioritize convenience and fast charging (*24*). While compensation may help in attracting PEV drivers to enroll in and stay with a smart charging program, power suppliers can provide drivers with charging information and user-centric controls to reduce anxiety relating to ceding control to a third party.

Lavieri and de Oliveria (*24*) evaluated the likelihood of participants accepting SMC if an override feature were available in a smartphone app. Acceptance of SMC increased from 35% to 56% among current ICEV drivers. Up to 24% of PEV owners would accept no compensation if given information on past and current vehicle charging patterns through a web portal (*18*). Similarly, Wong et al. (*23*) found that 26% of PEV owners and 13% of ICEV drivers would participate in an SMC program (for load reduction purposes) without a financial incentive. Providing a guaranteed minimum charge by departure time increased the probability of the general population participating in an SMC program by 14.5 percentage points. Kubli (*21*) found that nearly 28% of respondents preferred SMC to unmanaged or a form of guaranteed charge to reduce PEV charging peaks and align with solar power, so long as suppliers did not substantially increase charging duration. Power suppliers may be able to call on at least 25% of PEVs to provide grid support at no additional cost, with more drivers willing to support the grid if suppliers account for individual PEV battery levels and charging delays.

Research Gaps

Despite the potential opportunities for EV smart charging to increase power grid reliability, reduce charging emissions, and defer investments in storage and dispatchable generators, little work has investigated the motivations for drivers to participate in a smart charging program, regardless of EV ownership or intent to buy a PEV in the future. Researchers have focused on current PEV owners or those intending to purchase a PEV in the near future in their sample (*16*, *19–21*). Thus, these studies ignore the preferences and motivations of the anticipated late PEV adopters, who represent the majority of car buyers and drivers (*24*). Early BEV models had substantially smaller ranges, which might explain why Bailey and Axsen (*16*) found the largest group of their participants (33%) valued increases in guaranteed range when participating in an SMC program, compared to cost-motivated (27%) and renewable-focused users (19%). Later work has identified that while charging convenience and guaranteed range are important, financial incentives may motivate more people to adopt SMC, particularly those likely to adopt PEVs in the short term. It is imperative to also survey individuals who may not buy a PEV in the next few years since many auto companies will stop manufacturing ICEVs between 2030 and 2040, and governments around the world are proposing or implementing ICEV purchase bans (*1*).

Studies that survey or interview PEV owners and potential adopters are few and concentrated in Western European countries, as shown in Table 1. The public's trust in science and technology, especially that promoted by the government, like PEVs (*25*), and trust in institutions and companies, like one's power supplier or power grid operator, is regionally dependent. Thus, a stronger understanding of charging preferences and financial incentives could guide the design of

smart charging programs and increase buy-in among current and future PEV drivers. Despite some behavioral work on PEV smart charging, only one study has investigated attitudes and preferences in the United States (*23*). Consequently, it is important to understand how Americans[4] perceive smart charging programs since their acceptance and willingness to alter PEV charging behavior will influence the transition to a transportation-clean energy system. In contrast to prior work, this study 1) presents respondents with seven PEV charging alternatives (instead of dichotomous choices, like UMC versus SMC) and 2) segments results on the respondent's financial incentives for participation in SMC by preferred charging alternative.

SURVEY DESIGN AND DATA PROCESSING

The data were collected via Qualtrics, a web-based survey tool, from late November to early December 2022 across the United States. Respondents were recruited from Dynata's panel of American respondents, ages 18 and older, ensuring no duplicate responses. The survey asked respondents about their perceptions of EVs, smart charging benefits, SMC and UMC, and the power grid. Respondents listed their knowledge of SMC, their preferred PEV charging style, expected compensation with SMC, WTP to leave an automatically-enrolled PEV charging program, current travel patterns, and demographics.

The survey employed one screening question and one within-survey data quality check to minimize straight-lining in a section with multiple Likert scale questions. A total of 1,394 complete responses were collected. After removing respondents that failed the data quality check (i.e., "please select slightly important") and did not meet other sanity checks, 1,050 responses remained eligible for further analysis. Dynata recruited respondents to obtain a nearly representative sample of the United States population according to specific demographic classes in the 2021 1-year American Community Survey estimate (*26*). The unlinked classes used were gender, age, ethnicity, educational attainment, and the four U.S. Census Bureau regions. Although additional variables like household residence structure type and vehicle-miles driven were not included in quotas, the clean survey was representative of the population.

To account for built environment impacts on vehicle purchasing decisions and perceptions of EV smart charging benefits, the respondents' zip codes were mapped to census block groups (CBG). Built environment attributes available at the CBG level were obtained from the Smart Location Database (SLD), available from the U.S. EPA (*27*).

Smart Charging Concepts

In addition to the screening question, which briefly introduced the topic of smart charging, respondents were shown Figure 1's information before answering any questions on charging preferences.

[4] People in the United States of America (USA) refer to themselves as Americans, which is not to be confused with the people of the Americas (the region).

> Electric power companies can use prices to incentivize EV owners to charge their vehicles during low-cost hours to reduce the impacts of many EVs on the power grid. The power company can use time-of-use prices or pass down the real costs of producing electricity to the EV owner. Some EV owners use apps or timers to only charge during off-peak (or low-cost) periods. Instead of using prices to shift EV charging, power companies can directly control EV charging. Called supplier-managed charging, the goal is to reduce charging costs for the EV owner, use more renewable energy, and improve power grid reliability.

Figure 1 Survey's introductory text on smart charging programs

The introductory text provided (1) a rationale behind smart charging programs (i.e., reduce the impacts of many EVs on the power grid) and (2) explained two approaches that power suppliers are taking (e.g., passive smart charging through prices, adopted by users through apps/timers (UMC), and active smart charging through SMC). The survey instrument had the following key sections on smart charging:

- Section A: Importance of smart charging benefits to the respondent (5-point Likert-type scale: not at all important—extremely important), Prior knowledge of SMC (5-point Likert-type scale: no knowledge—extremely knowledgeable), and Interest in a smart charging program for current/future PEV (5-point Likert-type scale[5]: not at all interested—extremely interested).
- Section B: Preferred charging style (with nominal choices), Minimum one-time financial incentive to accept SMC (truncated slider), and Minimum annual financial incentive to continue participation in SMC (truncated slider).
- Section C: Opinion on different topics related to PEVs, clean-energy transition, and values (5-point Likert scale: strongly agree—strongly disagree).
- Section D: Minimum monthly fee to leave an SMC program (truncated slider).

Sections B and D in the survey required additional text, like easy-to-understand program constraints, to elicit reasonable responses from participants. Those prompts are provided in subsequent sections of this paper. The survey separated questions soliciting opinions and beliefs into Sections A and C to provide cognitive relief and distinguish between Section B and Section D (opt-in to SMC versus opt-out of SMC).

DATA SET STATISTICS

Table 2 summarizes the respondent's demographic, household composition, residence, and vehicle variables from the complete data set. A comparison is given to U.S. census data and other appropriate data sources. The study uses some of these variables as covariates in models. The paper results are population-weighted using Table 2's sources to ensure its findings are representative of Americans' preferences and values around the transportation-clean energy transition.

TABLE 2 Summary Statistics of Sample and Comparison to Nationally Representative Data Sources

[5] Respondents with a PEV were asked about their interest in a program for their current PEV(s), while those without a PEV were asked about a future PEV. Thus, there was an additional option for those with a current PEV to capture those who already participate in a smart charging program. All results from this question grouped those already participating in programs with individuals that were "extremely interested" in participating in a smart charging program.

Explanatory Variables	**Sample**	**Population**	**Source**
Gender (of person filling out the survey)			
Male	46.8%	49.5%	ACS 2021 (1-Year)
Female	52.4%	50.5%	
Non-binary/other	0.9%	NA	
Age (of person filling out the survey)			
18–24 years of age	16.0%	17.1%	ACS 2021 (1-Year)
25–34	21.9%	22.9%	
35–44	17.2%	16.9%	
45–54	16.8%	15.8%	
55–64	17.3%	16.5%	
65+	10.7%	10.8%	
Highest level of education completed (of person filling out the survey)			ACS 2021 (1-Year)
High school or less	36.9%	38.1%	
Some college/Associate degree	31.0%	29.5%	
Bachelor's degree	20.5%	20.3%	
Master's degree or higher	11.7%	12.2%	
Race (of person filling out the survey)			ACS 2021 (1-Year)
White	75.6%	61.2%	
Black	12.1%	12.1%	
Asian	7.1%	5.8%	
American Indian	1.3%	1.0%	
Mixed	2.3%	12.6%	
Other/not disclosed	1.5%	7.2%	
Census Location			ACS 2021 (1-Year)
Northeast U.S.	20.0%	17.2%	
Midwest	20.6%	20.7%	
West	17.8%	23.7%	
South	41.6%	38.3%	
Household Income, pre-tax			ACS 2021 (1-Year)
Less than $30,000	21.0%	21.2%	
Between $30,000 and 49,999	18.5%	15.3%	
Between $50,000 and 74,999	21.0%	16.8%	
Between $75,000 and 99,999	12.4%	12.8%	
Between $100,000 and $149,999	13.1%	16.3%	
$150,000 and up	11.1%	17.7%	
Prefer not to answer	2.9%	NA	

Household Vehicles			
0 vehicles	6.9%	8.9%	2017 NHTS
1	40.2%	33.5%	
2	34.4%	33.1%	
3+	18.3%	24.4%	
Residence Type			2021 AHS
Detached House	65.9%	63.6%	
Attached House (e.g., townhouse, duplex)	5.2%	6.3%	
Apartment	22.4%	24.7%	
Mobile Home	4.8%	5.2%	
Other	2.7%	0.05%	
Household Size			2020 Census
1 household members	19.0%	28.3%	
2	33.1%	34.2%	
3	20.4%	15.4%	
4+	27.4%	22.2%	
Household Technology Present			
Smart thermostat	22.4%	18.3%	Walton (*28*)
Solar power	5.6%	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). The respondents self-selecting non-binary/other gender were grouped with females into a non-male category in regression models.

SUMMARY OF RESULTS

The survey asked respondents many questions related to their household structure type, their vehicle use, where their primary vehicle (if any) is parked at home, future car buying decisions, and barriers to buying or leasing a PEV and charging one at home. Respondents also answered attitudinal questions about charging PEVs, from their participation in smart charging to how the power grid might support a high number of PEVs, and how important expected PEV smart charging benefits are to them. To focus on the novelty of the current paper—Americans' preferences and financial incentives needed to adopt smart charging programs—the summary statistics of these variables are omitted.

Preferences for PEV Smart Charging

Respondents, regardless of whether they currently owned a PEV or were a zero-vehicle household, were asked about their preferred PEV smart charging type. They were told to assume they drive a BEV with a range of 250 miles and can charge at home at a speed providing up to 20 miles of recouped range for every hour of charging (i.e., 12.5 hours from 0-100%). Respondents were provided with the following text and choice options (Figure 2):

> Given your weekly driving and (expected) charging habits, *would you allow your local power company to directly control charging*? The power company would use this power to mostly stagger charging schedules to avoid peaks in energy demand from BEVs.

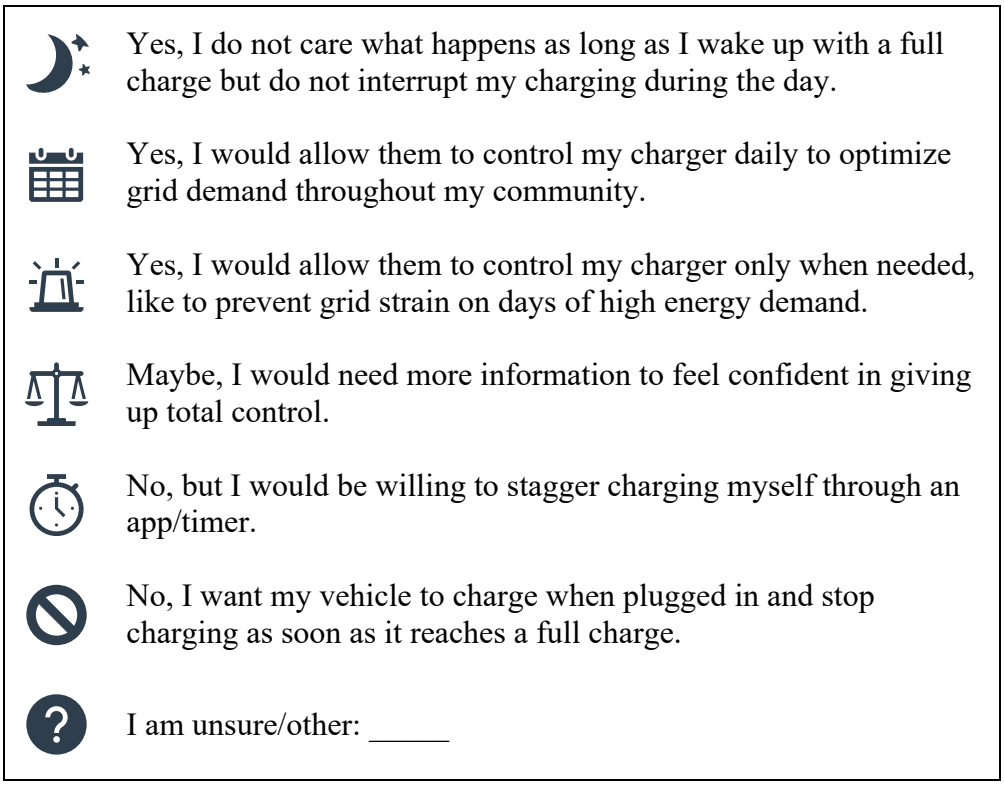

Figure 2 Preferred PEV smart charging option

A quarter of people (25.6%) say they would never allow their local power supplier to interfere in charging their PEVs, but 8.8% would be willing to use an app or timer to stagger charging. Another quarter (25.3%) may cede control but need more information to feel confident in giving up total control. Up to 36.9% would accept SMC, but under different conditions. Most prohibit SMC during the day but give up control at night, so long as the vehicle is fully charged by the morning (17.6%). The next highest group would allow SMC only when needed, like during high grid strain days (10.3%). And a smaller share (8.9%) would permit their power company to help optimize the local grid daily.

Current EV owners that indicated some interest in a managed charging program (n = 124) were more likely to accept an SMC program or UMC program with an app or timer than reject managed charging outright (Figure 3). As non-EV owners obtain PEVs and gain firsthand charging experience, they may cede some control to their local power company. About two-thirds of zero-vehicle households (65.1%) stated they are likely to obtain a vehicle for the respondent's primary use in the future, and these respondents are more unsure about accepting any charging program. Designing smart charging programs that respect low trust levels may be useful in shifting unmanaged and unsure respondents to UMC.

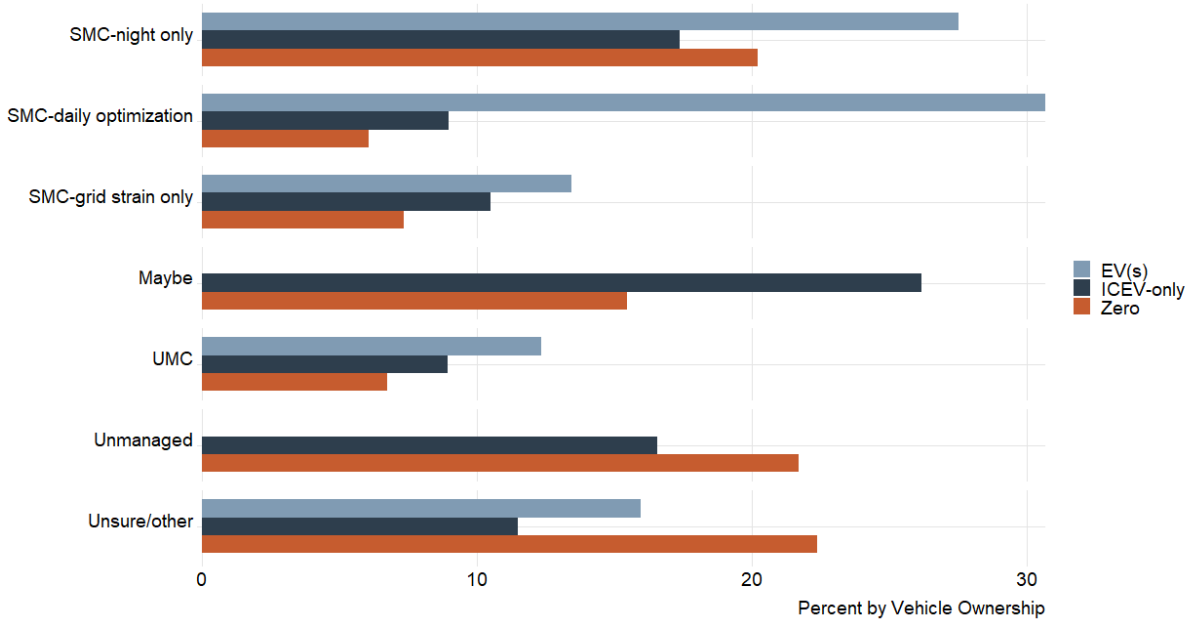

Figure 3 Preferred PEV smart charging option by household vehicle status

Note: Results are population-weighted. UMC = User-managed charging. SMC = Supplier-managed charging.

Educational attainment can explain one's resistance to smart charging. Those preferring unmanaged charging (i.e., PEV charges as soon as it is plugged in and stops charging once it is full) have not earned higher education degrees. Almost a third (32.3%) of those with some grade/high school education prefer unmanaged charging, versus 10.2% with a doctoral degree, 13.4% with a master's degree, and 12.9% with a bachelor's degree.

Households with a smart thermostat may also participate in a load reduction program (i.e., demand response) with their local power supplier, which raises the indoor temperature during the highest demand peaks of the year to reduce total electricity demand from cooling. SMC programs may also be designed to include a load reduction component during days of the year with the highest demand for electricity. Households with a smart thermostat may be more willing than other households to accept SMC on grid strain days. This study finds that a higher share of people would allow SMC of their future PEV when needed, like on days with high energy demand (14.4% to the average 9.1%). Regions with smart thermostat load reduction programs may see higher participation rates in a PEV smart charging program because households can understand the impact of demand response on cooling and compare it to their PEV[6].

Many people (37.3%) were unable to recall how they pay for electricity consumption out of a list of common options (e.g., fixed/flat, tiered, TOU, and wholesale-index prices). Of those that were knowledgeable about their power bill, respondents with a wholesale-index power bill were more likely to accept SMC for grid strain days and every day to optimize the local power grid's conditions.

[6] Behavioral research is needed to understand whether the sequential ordering of demand response programs impacts the acceptance of PEV smart charging programs with a demand response component.

MODEL ESTIMATION

A causal model was developed to assess the factors influencing the choice to participate in a managed charging program. Households with a PEV in some areas of the world can choose two or more charging styles (unmanaged charging, UMC with an app/timer, or SMC)[7]. Further, the choices have no natural order that is uniform across individuals. Consistent with theory of consumer behavior, the charging preference problem may be posed as an individual maximizing its utility function. The multinomial logit (MNL) model can deal with multiple, unordered choices, even with the restrictive independence of irrelevant alternatives (IIA) assumption. Even with this assumption, MNL models are employed in PEV choice problems, such as where individuals charge their PEV (*30*). The multinomial logit (MNL) model specification was preferred to nested logit models via log-likelihood ratio testing and is shown in Table 3. Covariates were chosen based on a combination of statistical significance and behavioral importance (and results in a less precise model, which is fine). The survey question on charging preference included a choice for "unsure" and "other" to avoid a potential bias in results by those who are truly unsure or apathetic to the listed alternatives. As a result, those respondents are not included in the n=922 sample.

The model included demographic variables like gender, age, educational attainment, and employment status. The negative alternative specific constants (ASCs) imply a preference for unmanaged charging (all else constant), with UMC more negatively perceived with respect to unmanaged charging than the SMC and "maybe [SMC]" alternatives. Households with a BEV overcome the negative constants for SMC-night only and SMC-daily optimization when they also pay wholesale energy prices. A full-time male worker who is not middle-aged and has at least two household vehicles can overcome the negative ASC for SMC-night only. If one ignores the attitudinal variables, a part-time worker that pays TOU energy prices and has at least four household vehicles, one of which is a BEV, can overcome the negative ASC for UMC.

Gender is not particularly significant in characterizing the preferred PEV charging method relative to unmanaged charging. However, males are more willing to accept an SMC program to optimize local grid conditions and night-only intervention (all else being constant). Individuals ages 35 to 54 who are also unemployed (all else constant) are more willing to accept SMC-daily optimization and less resistant to SMC-night-only programs relative to other choices. Individuals ages 55 to 64 are less willing to accept SMC-night-only programs. Perhaps these non-working adults anticipate needing their PEV for nighttime travel and do not want to have their supplier interfere with charging. The coefficients for other choices and age groups relative to the base of 18–34 years old and unmanaged PEV charging were statistically insignificant. Individuals that completed a degree higher than a GED were more willing to accept SMC-daily optimization; however, education does not reduce the need for more information to make an informed decision about an SMC program. Full-time and part-time workers are willing to choose UMC, but full-time workers are also willing to accept SMC-night only and SMC-grid strain only. Working more hours may reduce vehicle use relative to individuals working fewer hours each week and increase the opportunity for SMC, particularly if the driver works from home or spends more rest time at home.

[7] Please see Wong et al. (*23*) for a list of smart charging pilots and programs in North America; Smart Electric Power Alliance (*14*) for a review of 51 utilities with managed charging programs; and Hildermeier et al. (*29*) for a review of TOU rates and supplier-managed charging programs in Europe.

TABLE 3 Preferred Smart Charging Program (Using MNL and Population Weights)

Covariates	Coefficient	t-stat	p-value
Constants (unmanaged PEV charging as base)			
SMC-night only	-0.986	-1.58	0.114
SMC-daily optimization	-2.456	-2.58	0.010
SMC-grid strain only	-1.103	-1.62	0.105
UMC	-4.915	-4.79	0.000
Maybe	-1.258	-1.59	0.112
Gender (non-male as base)			
Male (SMC-night only)	0.290	1.64	0.101
Male (SMC-daily optimization)	0.554	2.30	0.021
Age (18 to 34 years old as base)			
Age 35-54 (SMC-night only)	-0.416	-2.06	0.040
Age 35-54 (SMC-daily optimization)	0.413	1.76	0.079
Age 55-64 (SMC-night only)	-0.726	-2.77	0.006
Education Attainment (HS or less as base)			
Associate degree (SMC-daily optimization)	0.736	2.27	0.023
Associate Degree (Maybe)	0.191	1.00	0.319
Bachelor's Degree (SMC-daily optimization)	1.003	2.91	0.004
Bachelor's Degree (Maybe)	0.664	3.19	0.001
Master's and up (SMC-daily optimization)	1.085	2.89	0.004
Master's and up (Maybe)	0.259	0.99	0.324
Employment (Non-employed as base)			
Full-time (SMC-night only)	0.375	2.00	0.045
Full-time (SMC-grid strain only)	0.397	1.72	0.085
Full-time (UMC)	0.485	1.71	0.088
Part-time (UMC)	0.677	2.08	0.037
# of Household Vehicles			
SMC-night only	0.182	1.57	0.117
SMC-daily optimization	0.219	1.50	0.133
SMC-grid strain only	0.293	2.11	0.035
UMC	0.435	3.17	0.002
Maybe	0.291	2.71	0.007
BEV Owner?			
Yes (SMC-night only)	0.784	1.25	0.209
Yes (SMC-daily optimization)	1.335	2.14	0.032
Yes (UMC)	1.937	3.41	0.001
Smart Thermostat?			
Yes (SMC-grid strain only)	0.399	1.63	0.102
Time-of-Use Prices for Power Bill?			
Yes (UMC)	0.783	2.97	0.003
Wholesale Prices for Power Bill?			
Yes (SMC-daily optimization)	1.849	3.12	0.002
Yes (SMC-grid strain only)	1.475	2.59	0.010
Household Income x Importance of Smart Charging in Reducing my Power Bill			
$50,000 - $74,999 x Importance of Smart Charging in Reducing my Power Bill (SMC-night only)	-0.156	-2.06	0.040
$50,000 - $74,999 x Importance of Smart Charging in Reducing my Power Bill (SMC-daily optimization)	-0.172	-1.54	0.123
Prefer not to think about how my EV charges, once my EV is plugged in (disagree-agree)			
SMC-night only	0.221	2.88	0.004

Supplier-managed charging has more risks than benefits for my lifestyle (disagree-agree)			
SMC-night only	-0.458	-4.17	0.000
SMC-daily optimization	-0.655	-4.78	0.000
SMC-grid strain only	-0.721	-5.48	0.000
UMC	-0.143	-1.07	0.285
Maybe	-0.387	-3.80	0.000
Smart charging can maximize zero-carbon renewables (importance)			
SMC-night only	0.244	2.41	0.016
SMC-daily optimization	0.480	3.56	0.000
SMC-grid strain only	0.548	4.24	0.000
UMC	0.191	1.56	0.118
Maybe	0.255	2.72	0.007
Smart charging can make the grid more reliable (importance)			
SMC-night only	0.352	3.03	0.002
SMC-daily optimization	0.099	0.66	0.511
SMC-grid strain only	0.298	2.00	0.045
UMC	0.561	3.71	0.000
Maybe	0.223	2.14	0.032
PM2.5 Annual Average (μg/m^3)			
SMC-daily optimization	0.154	2.17	0.030
UMC	0.184	2.39	0.017
Gini Index			
Maybe	2.996	2.21	0.027
Traffic Proximity and Volume			
SMC-grid strain only	1.14E-04	2.36	0.018
Extremely inconvenient to install a home charger?			
SMC-night only	-0.006	-0.02	0.984
SMC-daily optimization	-1.254	-2.61	0.009
SMC-grid strain only	-0.748	-1.88	0.060
UMC	-0.442	-1.15	0.251
Maybe	-0.856	-3.11	0.002

N = 922
LL (all constants [AC]) = -1649.33, LL (final) = -1430.39
ρ^2 (AC) = 0.1327, Adj. ρ^2 (AC) = 0.0970
AIC = 2978.78, BIC = 3263.55

Households with more vehicles tend to prefer UMC, SMC-grid strain only, and "maybe" SMC relative to unmanaged charging, while SMC-night only and SMC-daily optimization are not statistically significant at the 10% level. Having more household vehicles can provide travel security if the respondent's primary vehicle is not fully charged because of a managed charging program. Of the household vehicle variables that were statistically significant at a 95% confidence interval, all are minimally invasive choices. Individuals with a household BEV are more likely to accept UMC and SMC-daily optimization, although there is less certainty that they will accept SMC-night only.

Households with a smart thermostat may accept SMC-grid strain over other choices since many power suppliers use smart thermostats for peak load reduction a few days a year. In the future, this variable might be statistically significant at a higher confidence level, especially if the variable is more specific (i.e., the household participates in a load reduction or demand response program). If the individual's power bill uses time-of-use prices, they are more willing to accept UMC with an

app or timer. Once the driver sets up their charging schedule with UMC, the cognitive burden is negligible, and the individual does not have to worry about their supplier interfering in charging, even if direct charging control is rare. Households with wholesale power prices may be more risk-tolerant or have more demand-side flexibility (and load control) than the average household. As a result, they are willing to accept SMC offerings like daily optimization and grid-strain events to shift charging and help the power grid.

Household income is crossed with an attitudinal variable that signals the importance of managed charging in reducing one's power bill. The more important saving money through smart charging is to households making $50,000 to $74,999 annually (pre-tax), the less likely they are to accept SMC for night or daily optimization relative to other choices, signaling that SMC is not viewed as a money-saving option.

The addition of attitudinal variables significantly improves the modeling specification. Individuals who increasingly do not want to think about how their PEV charges once plugged in prefer SMC-night only to other options, even UMC. Perhaps respondents are willing to allow their local power company to stagger charging at night to manage grid conditions because they do not care when or how their vehicle charges at night, relative to UMC with non-aware charge staggering that can create peaks of EV demand at night (*31*).

Individuals who increasingly agree that SMC has more risks than benefits are more likely to choose UMC or "never" accept a managed charging program. The sign for UMC is negative relative to unmanaged charging, even if not statistically significant. In other words, if an individual believes that SMC has more risks than benefits, they are unlikely to accept or even consider any managed charging program, even a user-managed program. Smart charging can reduce the curtailment of VRE and make the grid more reliable by increasing demand-side flexibility. The more important the SC benefit of maximizing VRE, the more likely an individual is to accept SMC offerings or consider SMC (maybe). The more important the SC benefit of increasing the reliability of the power grid is to an individual, the more willing they are to accept or consider accepting smart charging; however, SMC-daily optimization is not statistically significant in this sample.

The next set of variables are built environment indicators from the U.S. EPA's SLD (*27*). Individuals residing in areas with a higher annual average concentration of fine particulate matter are more receptive to UMC and SMC-daily optimization. As the power sector retires coal power plants and adds VRE capacity, the transportation sector (i.e., ICEVs) will account for a higher share of total air pollution. People residing in areas with cleaner air may be less motivated to participate in smart charging programs to reduce air pollution from power plants; however, other motivating factors may be present. Individuals living close to more heavily used highways are likely exposed to higher levels of air and noise pollution and may relate congestion on roads to congestion on transmission lines. A positive and significant relationship exists between traffic proximity and volume with SMC-grid strain only. The Gini index is a correlation coefficient that measures income inequality, where 0 represents complete equality and 1 represents complete inequality. Individuals living in neighborhoods with higher income inequality are hesitant to choose SMC and need more information. Individuals may hesitate to accept SMC because they perceive a free-rider effect of PEV drivers not allowing SMC but benefiting from the actions of other altruistic PEV drivers.

Lastly, households were asked how convenient it would be to install a charger at home if there was not already one. Individuals that believe it is extremely inconvenient to install a charger at home

in their current location and are now told they have a BEV-250 vehicle with a charger at home may be willing to accept SMC-daily optimization or grid strain only offerings, provided they can get past the home charging barrier. Creating EV-ready building codes, subsidizing EV installation, and developing inclusive utility investment programs to address disparities in residential charging access are solutions that can capture these willing SMC users (*32–34*).

This model implies that BEV ownership and retail energy prices are critical factors that explain smart charging preferences; however, ICEV households paying flat energy prices can still prefer smart charging programs to unmanaged charging. To understand the importance of BEV ownership and wholesale-indexed electricity prices, the estimated model was used to predict the preferred alternatives for all adults if these variables were all independently true or false. If all households had a BEV, the probability of respondents choosing UMC would increase by nearly 44 percentage points, while unmanaged charging would fall by nearly 55 percentage points. If all households paid wholesale energy prices, the predicted probability of choosing unmanaged charging would fall by 48 percentage points. Figure 4 shows the change in the probability of the preferred PEV smart charging choice if all households owned or leased a BEV, relative to having no BEVs. Similarly, the figure shows the scenario where all households paid wholesale-indexed energy rates relative to households paying all other retail rate types.

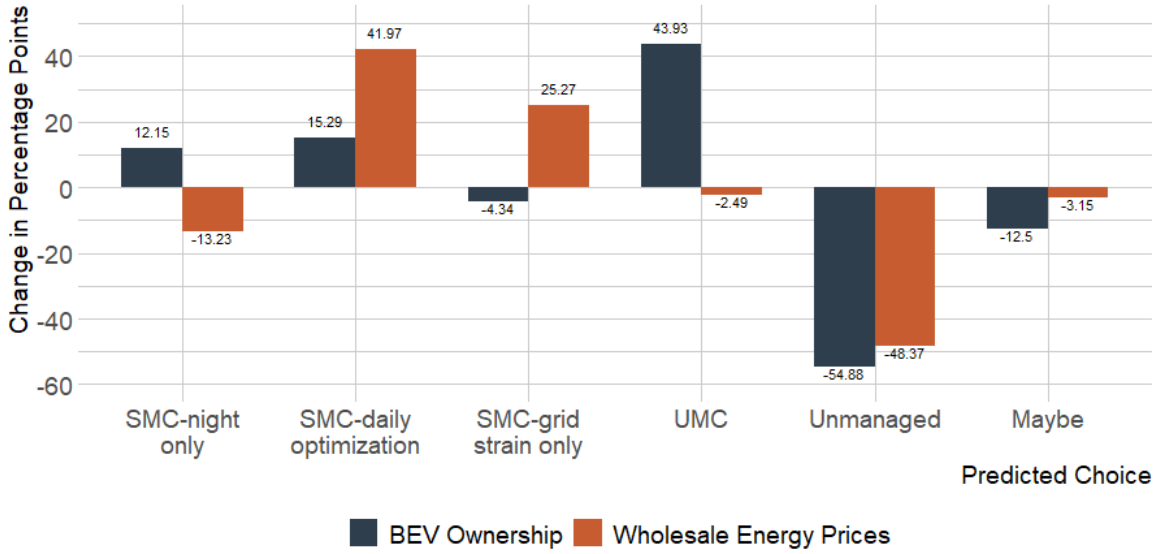

Figure 4 Predicted shifts in preferred alternatives with shifts in BEV ownership and wholesale-index energy price indicator variables (0% to 100%)

Financial Incentives for Supplier-Managed PEV Smart Charging

After individuals selected their preferred PEV charging program, they were told to assume they participated in an SMC program. Again, they had the same information (e.g., they drive a BEV with a range of 250 miles and can charge at home at a speed providing up to 20 miles of recouped range for every hour of charging). Respondents selected the preferred one-time bill credit for participating in an SMC program using a slider scale, from $0 to $200, with the option to mark "more than $200." Respondents were provided with the details shown in Figure 5.

Your local power company gives you a one-time bill credit ($) if you participate in an EV smart charging program. The power company studies your EV charging patterns for one month and creates a custom charging schedule for you. This allows the power company to charge EVs at a lower cost without impacting your travel needs. Details:

- For overnight charging, you allow the power company to charge your EV whenever, so long as you receive a full charge by the morning. Your vehicle is charged sometime between the hours of 10 PM and 6 AM.
- For daytime charging, the power company can interrupt charging during extreme events (no more than 5 times a year). Otherwise, your charging is not affected.
- Must stay enrolled in the program for at least 1 year to receive the one-time credit.

What is the smallest one-time bill credit ($) you would accept to allow your local power company to modify your EV charging when plugged in?

Figure 5 Survey prompt on minimum financial incentives for participating in PEV smart charging programs

The range in one-time bill credit was adjusted down from the potential per-vehicle value of smart charging found in the literature, which primarily centers on the California market, where electricity prices are higher than the national average (*7*). While all respondents selected their preferred one-time credit to accept SMC, not everyone is willing to accept SMC, let alone UMC. Due to the declining marginal value of managed charging with increasing PEV penetration (*35*), it may be advantageous for power suppliers to study the value of smart charging locally and use price discrimination to reward those offering the highest value.

People who previously said they would be willing to cede control to their power company for the benefit of the community (SMC-daily optimization) and during grid-strained days (SMC-grid strain only) are willing to accept a lesser one-time credit—an average of $96.33 and $99.57, respectively (Figure 6). Those that would only permit control during grid strain (SMC-grid strain only) ask for an average of $100.38. The three groups that previously preferred SMC do not ask for high one-time bill credits—9.3% to 20.0% of these respondents selected the checkbox for "more than $200," versus 23.9% to 38.9% of respondents choosing the non-SMC choices. Although SMC may entail higher administrative and technical costs than UMC, the value to utilities is higher, and the supplier may have a greater return on investment. Instead of paying UMC users an extra $26 to $30 per vehicle to participate in SMC, the power company may decide to shift more drivers from the unmanaged category to UMC.

Respondents answered how much money they would require each year for ongoing participation on top of the one-time incentive. The slider question was scaled down from $0 to $20, with an option to mark more than $20. Those who allow SMC-daily optimization require more annual compensation than those allowing SMC-grid strain only, which reflects the higher chance of intervention by the power company and possible inconvenience ($13.50 to $12.89). A higher share of individuals requires a yearly credit above the slider scale, which was set at $20 for this survey.

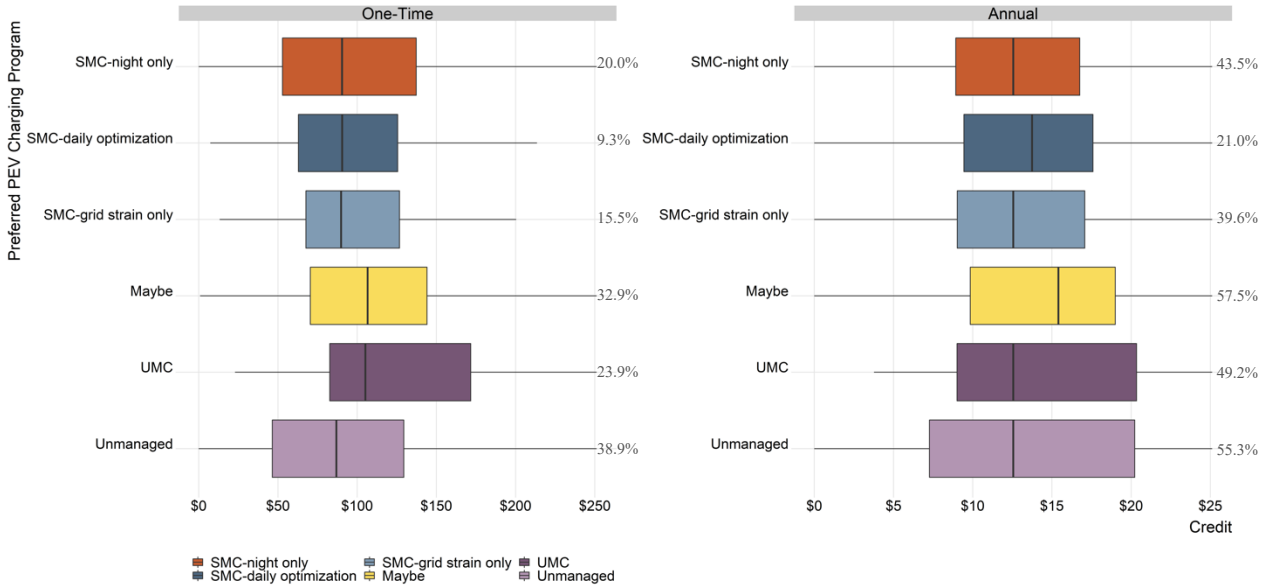

Figure 6 Preferred minimum one-time and annual bill credit for SMC participation (segmented by PEV charging preferences)

Note: Boxplot excludes those selecting the checkbox for "more than $200" or "more than $20." The percent of right-censored data by preferred charging style and bill-credit is provided to the right of each boxplot. Boxplot data shows population-weighted survey data which explains the whiskers that exceed the limits.

A Tobit model, also known as a censored regression model, was developed to estimate the preferred one-time SMC and annual participation credit, since the survey used a slider scale with a checkbox for values exceeding the maximum sliding scale ($200 and $20 for one-time and annual credits, respectively. Tobit models assume normality and homoscedasticity in the distribution of residuals, and when heteroscedasticity is present, the results are biased (*36*, *37*). Residual plots with censored regression models indicated the data did not display homoscedasticity. Thus, Messner et al.'s heteroscedastic censored regression model with a logistic distribution was used (*38*). The left limit for the censored dependent variable was $0 and the right limit was $200 and $20, respectively.

$$y_i = \begin{cases} y_i^*, & y_L < y_i^* < y_U, \\ y_L, & y_i^* \leq y_L, \\ y_U, & y_i^* \geq y_U, \end{cases} \tag{1}$$

where y_L and y_U are the respective censoring limits (lower and upper) and y_i^* is the latent variable.

A subset of explanatory variables was first included when estimating the Tobit model. In subsequent steps, the covariates with the lowest statistical significance were removed using likelihood ratio tests, except for 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 (i.e., payments for SMC). Practical significance measures the change in payments due to a one-standard deviation change in each covariate. Covariates with standardized coefficients greater than 0.5 are considered "practically significant." Table 4 presents results on the one-time payments and annual payments.

Females that do not identify as Asian/Pacific Islander/Asian American, are between 18 and 24 years old, do not trust their power company to always guarantee a fully-charged EV, and perceive smart charging's benefit of increasing grid reliability as important (all other predictors constant), are estimated to have higher minimum one-time payments to allow their local power company to modify EV charging (i.e., SMC), while Asian American males who agree that EV owners should pay higher fees on power bills and are interested in long-range BEVs exclusively place a lower value on one-time bill payments to permit SMC. Perhaps those willing to pay additional monthly power fees that go to upgrade grid infrastructure and those preferring long-range BEVs are able to perceive their impact on the power grid and need less financial incentive to permit their local power company to modify their charging behavior.

Table 4: Minimum one-time and annual bill credit for SMC participation.

Bill Credit	Covariates	Coef.	Std. Coef.	Z-stat
One-Time	Intercept	84.607	--	10.25
	Male?	-5.050	-0.25	-1.27
	Asian/Pacific Islander/Asian American?	-15.174	**-0.75**	-2.82
	Age 18-24?	14.330	**0.71**	2.26
	Household Income ($150k and up)?	0.788	0.04	2.20
	Annual VMD (in 1,000 miles)	6.345	0.31	3.30
	Ideal BEV Range (in 25 miles)	-13.547	**-0.67**	-3.24
	Agree that EVs pay added fees on power bills to pay for grid upgrades?	-8.050	-0.40	-1.92
	Don't trust power company to always guarantee a fully-charged EV?	22.667	**1.12**	5.57
	Importance of smart charging increasing grid reliability	5.776	0.29	3.24
	N = 922 LL (all constants [AC]) = -5801.44, LL (final) = -5753.31 Pseudo R-Square = 0.008 AIC = 11528.62, BIC = 11583.10			
Annual	Intercept	13.086	--	17.07
	Male?	-0.807	-0.46	-2.20
	Age 18-24?	-1.019	**-0.58**	-2.02
	White Hispanic/Latino?	-2.003	**-1.14**	-1.44
	Household Income ($30k and under)?	-0.918	**-0.52**	-2.08
	Ideal BEV Range (in 25 miles)	0.768	0.44	4.38
	Agree the power grid can support the government's EV adoption goals?	-1.334	**-0.76**	-3.27
	Don't trust power company to always guarantee a fully-charged EV?	2.021	**1.15**	5.54
	Agree that smart charging is a net good for society?	0.833	0.47	2.01
	Importance of smart charging increasing grid reliability	0.421	0.24	2.48
	N = 922 LL (all constants [AC]) = -3341.23, LL (final) = -3289.91 Pseudo R-Square = 0.015 AIC = 6601.83, BIC = 6656.31			

Note: All Std. Coef., which are greater than 0.5, are in bold, and indicate practically significant predictors. Results are population weighted/sample corrected. VMD = Vehicle-miles driven.

Females that do not identify as White Hispanic/Latino, agree that smart charging is a net good for society, and perceive smart charging's benefit of increasing grid reliability as important (all other predictors constant), are estimated to have higher minimum annual payments to allow their local power company to modify EV charging (i.e., SMC), while young adults between 18 and 24 with a maximum household pre-tax income of $30,000 and agree the power grid can support the government's EV adoption goals place a lower value on annual bill payments to permit SMC.

Perhaps full-time working young adults making at most $15/hour who believe the power grid can support the government's ambitious EV adoption goals do not value charging flexibility as high as others or are not as financially driven as others in continuing to participate in an SMC program.

CONCLUSION AND POLICY IMPLICATIONS

This study used multinomial logit and Tobit models to understand the impact of demographics, travel characteristics, built-environment factors, and transportation-clean energy nexus opinions and values on Americans' preferred PEV charging program and desired payment for participating in an SMC program.

Results suggest that households paying time-varying power bills, like TOU, prefer UMC with an app or timer relative to other options. Households with wholesale-indexed rates may be more risk-tolerant and prefer SMC to optimize local grid conditions daily or only during grid strain days. Households with a BEV have experience charging their vehicle and may have a more informed stated preference regarding an SMC program, even though they are not widely available, unlike UMC programs. These households are willing to accept UMC and SMC for grid optimization and night-time interventions, but there was no statistically significant covariate for grid strain days. Individuals that believe it is extremely inconvenient to install a charger at home and are told to imagine they have a 250-mile-range BEV with a charger at home may be willing to accept SMC for daily optimization or grid strain days, but only if they can get past the home charging barrier. Cities need to ensure that buildings have the electrical wiring to support EV adoption, while power suppliers need to lower capital costs and regulatory barriers (e.g., permits) to support the retrofit of existing residences.

Attitudinal variables greatly improved model fit but are hard to measure in the real world to predict the adoption of managed charging programs. The results indicate that individuals who do not want to think about how an EV charges are more willing to accept night-only SMC, which can help avoid TOU-created electricity demand spikes from PEVs. The more important the benefit of maximizing renewables or increasing power grid reliability, the more likely an individual is to accept SMC offerings or consider SMC. Power companies could survey their customers annually or when sending out monthly bills to receive this attitudinal data. This information could allow them to tailor incentives to the local market to increase smart charging adoption while ensuring the cost of incentives is less than the added value.

Individuals that prefer SMC offerings may be more altruistic than those accepting UMC or those not willing to modify their charging behaviors, and they would expect less money for their participation in a future SMC program. Perhaps the lower payment is because they were already willing to participate in SMC and would not require additional compensation for less flexibility. Since individuals preferring UMC demand more compensation to participate in an SMC program, power companies could seek higher enrollment in UMC through lower off-peak prices rather than paying consumers to adopt SMC. Tobit models found that Asian American males who agree that EV owners should pay higher fees on power bills and are interested in long-range BEVs tend to accept smaller one-time bill credits to permit SMC. Perhaps individuals that perceive impacts of EVs on the power grid need less financial incentive to permit their local power company to modify future charging behavior. Females that do not identify as White Hispanic/Latino, agree that smart charging is a net good for society, and perceive smart charging's benefit of increasing grid reliability as important (all other predictors constant), are estimated to have higher minimum annual payments to allow their local power company to modify EV charging.

Our survey design centered on consumer flexibility in smart charging programs. When respondents were asked whether they would allow their local power supplier to directly control charging, the choices were not binary (i.e., yes or no). This choice structure is important since many individuals have two or more charging options today. Respondents were told that adjustments to PEV charging would not interfere with their travel needs and would be made based on historical data. Providing respondents with several alternatives in response to this question, namely never managed, unmanaged charging, UMC, and three SMC alternatives that were not rigid contracts (e.g., must be plugged in for 8 hours overnight at least three days a week), revealed nuanced preferences that other studies missed. The survey data on preferred one-time and yearly credits for SMC participation may indicate minimum incentive levels if power companies ignore individual preferences and uniformly alter PEV charging (i.e., contract-based PEV smart charging). Future surveys should continue to understand consumer needs and preferences through this approach to provide power companies with more flexible and low-cost smart charging options.

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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 the results and approved the final version of the manuscript.

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