MIT CEEPR

MIT Center for Energy and Environmental Policy Research

Working Paper Series

Policies for Electrifying the Light-Duty Vehicle Fleet in the United States

CASSANDRA COLE, MICHAEL DROSTE, CHRISTOPHER R. KNITTEL, SHANJUN LI, AND JAMES H. STOCK

SEPTEMBER 2021

CEEPR WP 2021-014

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Policies for Electrifying the Light-Duty Vehicle Fleet in the United States[*]

Cassandra Cole[†] Michael Droste[‡] Christopher Knittel[§] Shanjun Li[¶] James H. Stock[||]

September 8, 2021

Abstract

The decarbonization of the light-duty vehicle (LDV) fleet in the United States is an important policy priority for the coming decades. This paper investigates the potential for government policy to accelerate the transition of the LDV fleet to electric vehicles. We consider several forms of government policy: subsidized construction of charging stations, refundable tax credits for electric vehicles, and a tradable permit system for vehicle manufacturers. Our objective is to evaluate forms of these policies that are capable of achieving a target 50% sales share of zero-emissions vehicles by 2030. Our results indicate that charging station subsidies are extremely effective relative to alternative proposals, as measured by impact for a given fiscal expenditure.

Keywords: Decarbonization, Electric Vehicles, Consumer Subsidies, Charging infrastructure

JEL Classification: H23, L62, R41

---

[*] We are thankful for useful comments from Jim Archsmith, Susan Helper, Ken Gillingham, Jing Li, Erich Muehlegger, David Rapson, Catherine Wolfram, and participants in the 2021 NBER Workshop on Economics of Transportation in the 21st Century.

[†] Harvard University. Email: ccole@g.harvard.edu

[‡] Harvard University. Email: mdroste@fas.harvard.edu

[§] MIT Sloan. Email: knittel@mit.edu

[¶] Cornell University. Email: sl2448@cornell.edu

[||] Corresponding author. Harvard University. Email: james_stock@harvard.edu

1 Introduction

The decarbonization of the light duty vehicle (LDV) sector is a major policy priority in the United States. In 2019, 58% of U.S. transportation carbon emissions arose from the operation of LDVs. The Biden administration has declared a target of 50% new vehicle sales in 2030 comprising zero-emissions vehicles: battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and hydrogen fuel cell vehicles.[1] The UK government has announced a ban on the sale of new gasoline and diesel cars and vans in 2030, with hybrid cars and vans phased out by 2035.

Major automakers have announced ambitious plans for expanding their production of electric vehicles. Ford will invest $22 billion through 2025 in electrifying transportation, including producing fully electric versions of its vans and pickup trucks. GM plans to produce 30 new electric vehicle models by the end of 2025, transition to producing only EVs by 2035, and become carbon neutral by 2040, while simultaneously investing in battery technology. By the end of the decade, Volkswagen plans to launch approximately 70 BEV and 60 hybrid models, including 20 BEVs and more than 30 hybrids already in production. All three companies have also committed to expanding EV charging infrastructure.

As automakers increase their production of electric vehicles and components (i.e. electric batteries), replacing conventional internal combustion engine (ICE) vehicles with EVs appears to be the most promising pathway for decarbonizing LDVs in the near future. Moreover, doing so appears increasingly economically feasible: prices of lithium-ion battery packs decreased by 16% annually between 2017 and 2019[2], with average battery prices reaching $137/kWh and reports of some battery packs reaching less than $100/kWh in 2020. Yet deep EV penetration is not a certainty, and policy may play an important role in expediting and supporting the transition. To this end, a variety of policies have been proposed to spur electrification of the US EV fleet. Broadly, these include building charging infrastructure, subsidizing the costs of purchasing or driving EVs, and regulatory approaches that use existing legal authorities of the Environmental Protection Agency (EPA) to regulate CO2 emissions and the Department of Transportation (DOT) to regulate fuel economy.

In order to evaluate this suite of policies for expediting electrification of the LDV fleet, we use a joint model of charging station supply and EV demand. Our model is modified from Zhou and Li (2018) and Springel (forthcoming) and adopts parameter values drawn from the literature. We then simulate the diffusion path of EVs under different policy scenarios including refundable tax credits, charging station subsidies, and tradeable allowances.

We vary the size of the subsidies and total program budgets for both vehicles and charging

---

[1] See the While House press release on 08/05/2021 titled "President Biden Announces Steps to Drive American Leadership Forward on Clean Cars and Trucks".

[2] Kapoor, MacDuiffie, and Wilde (2019) at https://mackinstitute.wharton.upenn.edu/2020/electric-vehicle-battery-costs-decline/

stations to obtain the share of battery EVs, the reduction in greenhouse gases, and total governmental outlays.

The rest of the paper is organized as follows. Section 2 describes our model. Section 3 describes the policies that we consider. Section 4 describes the results of our simulations. Section 5 concludes.

2 Model

This section describes our baseline model of the demand for electric vehicles. Our model has two main components: a discrete choice model of electric vehicle demand, and an entry/exit model of charging station supply. We calibrate our model using parameter estimates from related literature, and use it to evaluate a suite of policies that can expedite the electrification of the U.S. light-duty vehicle fleet.

2.1 Electric Vehicle Demand

We model the demand for electric vehicles with a multinomial logit framework. There are two vehicle classes: cars and (light-duty) trucks, where trucks include SUVs and minivans. Within each vehicle class, consumers choose between an electric vehicle (EV) and a conventional vehicle with an internal combustion engine (ICE) to maximize utility. The baseline model allows switching between fuel types within each vehicle class but not between classes. That is, the share of each class is held fixed. Time is discrete and indexed by t. Consumers, indexed by i, choose to purchase an EV or ICE within their class that maximizes their utility.

The (indirect) utility of consumer i from purchasing an EV in vehicle class j (car or truck) at time t relative to an ICE is:

$$u_{ijt} = \alpha_j + \beta_p ln(P_{jt}) + \beta_2 \ln(N_t^{L2}/Q_{t-1}) + \beta_3 \ln(N_t^{L3}) + \psi_{jt} + \epsilon_{ijt} = \bar{u}_{jt} + \epsilon_{ijt}, \tag{1}$$

where P_{jt} is the price of EV normalized by the price of ICE (i.e., the price ratio of the two fuel types within vehicle class j). The term on vehicle price highlights the role of relative vehicle price in EV diffusion: as the EV prices decrease, e.g., due to the reduction in battery cost, consumers are more like to adopt EVs.

N_t^{L2} and N_t^{L3} represent the stock of level 2 and level 3 electric charging stations available at time t. The second and third terms in this equation capture an indirect network externality for EVs: consumer utility from EVs increases with the size of the charging network. The network size of level 2 and level 3 stations enters the utility differently. The effect of level 2 charging stations decreases with the EV stock, capturing the congestion effect in these slow charging stations.

The drift term ψ_{jt} captures preference for other vehicle attribute differences between EVs and

ICE vehicles. These include observable but unmodeled attributes such as acceleration (typically better for EVs than ICEs), battery range, and length of time to charge an EV, and unobserved attributes such as consumer awareness of EVs and consumer attachment to the sound and feel of an ICE. The final term in (1), ϵ_{ijt}, is an idiosyncratic taste shock, and is assumed to have i.i.d. type-I extreme value distribution across consumers and over time. With the distributional assumption on ϵ_{ijt}, the EV sales share for vehicle class j in period t is given by:

$$s_{jt} = \frac{\exp(\bar{u}_{jt})}{1 + \exp(\bar{u}_{jt})}, \tag{2}$$

where $\bar{u}_{jt}$, the deterministic utility, is defined in Equation (1). The price elasticity of EV demand of class j is given by $\eta_p = (1 - s_{jt})\beta_P$. Similarly, the elasticity of EV demand with respect to level 2 and 3 charging station supply is $\eta_2 = (1 - s_{jt})\beta_2$ and $\eta_3 = (1 - s_{jt})\beta_3$, respectively.

2.2 Charging Station Supply

Our model of charging station supply is built on a static firm entry exit/model in the spirit of Zhou and Li (2018) and Springel (forthcoming), which itself builds on a literature dating back to Bresnahan and Reiss (1991).

Firms make an entry/exit decision to either build a charging station or not. Firms that build a charging station in period t receive a discounted stream of future profits. An entering firm pays a fixed cost of C_{2t} to build a level-2 charging station and C_{3t} to build a level-3 charging station at the prevailing technology.

The value of a firm entering the market for level k ($k = 2, 3$) charging stations in period t is:

$$V_t^k = -C_t^k + \pi_t^k + \frac{1}{1+r}\pi_{t+1}^k + \frac{1}{(1+r)^2}\pi_{t+2}^k \cdots$$

where $\pi_t^k(N_t^k, Q_t)$ denotes the profit accruing to the firm operating a level k charging station in period t as a function of the size of charging station network N^k and EV stock Q. δ is the discount factor.

In a free-entry equilibrium, the firms are indifferent between investment at time t and $t+1$. This implies:

$$\pi_t^k(N_t^k, Q_t) = C_t^k - \frac{1}{1+r}C_{t+1}^k.$$

That is, the cost differential in charging investment from one period to the next (i.e., the benefit of waiting) should be equal to the profit in the current period (i.e., the cost of waiting). Assume the following functional form for the period profit function:

$$\pi_t^k(N_t^k, Q_t) = exp(\kappa_k)(N_t^k)^\gamma Q_t,$$

This gives rise to the following equations characterizing the supply of charging stations:

$$\ln\left(N_t^k\right) = \kappa_{\mathrm{k}} + \gamma \ln\left(Q_t\right) - \gamma \ln\left(\tilde{C}_t^{\mathrm{k}}\right)$$

where the κ terms are constants. Q represents the stock of electric vehicles in period t, N represents the stock of charging stations, and $\tilde{C}_t^{\mathrm{k}} = C_t^{\mathrm{k}} - \frac{1}{1+r} C_{t+1}^{\mathrm{k}}$.

We assume that charging station costs follow an exogenous law of motion:

$$C_t^k = C_0^k \cdot \left(0.5 + 0.5 e^{\zeta \cdot t}\right),$$

where C_0^k denotes the cost in 2020. The parameter $\zeta < 0$ captures a deterministic reduction in costs, where we have assumed the long-run cost asymptotes to 50% of the cost of a 2020 charging station for simplicity.

2.3 Vehicle Pricing

Our model assumes an exogenous path for the relative price of EVs with respect to ICEs, denoted P_{jt} . The relative price includes the cost of purchasing a vehicle, maintenance costs, fuel costs. We model this with a "bottom-up" approach based on Lutsey and Nicholas (2019).

The price of a vehicle depends on that vehicle's sticker price, maintenance costs, and fuel costs. We use information from Lutsey and Nicholas (2019) to produce forecasts for maintenance costs per mile and sticker price. We forecast fuel economy for ICE and EV cars and SUVs, relying on current and proposed fuel standards.

2.4 Calibration

This section describes the calibration procedure we use to perform policy experiments with our model. Table 1 describes the parameters in our model, their calibrated values, and provides a note on their source. Select parameters are discussed below.

As our model holds the total number of cars fixed and the relevant price is the relative price of ICE vs. EVs (within a category), we must choose between using estimates of own- or cross-price demand elasticity in calculating our demand coefficient. We follow the literature in using EV own-price elasticity of demand. In particular, we choose $\eta_p = -2.5$ as an approximate median of existing elasticity estimates, emphasizing those studies which examine network effects between EV and charging station stocks: Springel (forthcoming) finds an average EV demand elasticity between -1.5 and -2.1 in Norway. Using U.S. data, Xing et al. (2021) estimate an own-price elasticity for BEVs of -2.751; Zhou and Li (2018) find an average own-price elasticity of -1.024; Li (2016) estimates an own-price elasticity of -2.7; Li et al. (2017) provide estimates ranging from -0.817 to -1.378 with an estimate of -1.288 in their GMM specification. Muehlegger and Rapson (2019) find an elasticity of -3.3 for low- and middle-income households in California.

Existing literature does not separately estimate charging station elasticities for level 2 and level 3 chargers, so we set the two parameters (η_2 and η_3) equal to one another. We choose to be conservative with regards to the impact of charging infrastructure on EV adoption by setting $\eta_2 = \eta_3 = 0.37$ based on Springel (forthcoming), while other estimates in the literature tend to be higher. Li et al. (2017) estimate a charging station elasticity of 0.84, Zhou and Li (2018) estimate an elasticity ranging from 0.4 to 1.4 across specifications, and the parameter estimates in Xing et al. (2021) imply an elasticity of 0.26.

We choose a similarly conservative value for annual charging station cost declines. Analysis by the Rocky Mountain Institute finds annual hardware cost declines of approximately 12% on average from 2010 to 2019; we adjust this downward to 4% annual cost declines to conservatively factor in soft costs which we do not expect to decline as quickly as hardware costs. Analogously, we choose annual battery cost declines of 9% by adjusting downward recent estimates of 13% to 17% (Ziegler and Trancik (2021)).

According to the charging station database from the Alternative Fuel Data Center (AFDC), the average number of ports (”plugs”) is 2 in level-2 stations and 4 in level-3 stations. Assuming a full installed cost (including parts and labor) of $2,000 and $50,000 per port for level 2 and level 3, respectively, we set level 2 station cost to $4,000 and level-3 station cost to $200,000.

We calibrate three sets of parameters. First, we calibrate the intercepts in the charging station supply equations to match full-penetration ratios of charging stations to EVs. In particular, we set κ_2 such that the full-penetration L2/EV ratio is 0.1. Likewise, we set κ_3 such that the full-penetration EV/L3 ratio is 60,000. Last, we calibrate the drift term in our law of motion for EV preference so that our forecasted EV penetration is 20% by 2030.

2.5 No-Policy Baseline

There is considerable disagreement over the level of EV penetration absent government policy. The purpose of this paper is to project policy impacts, not to make no-policy forecasts of EV penetration. We therefore calibrate our no-policy baseline to have 20% EV penetration in 2030, a value chosen to fall midway between conservative projections including the Energy Information Administration’s no-policy projection of 3.8% by 2030 and substantially more aggressive projections like IHS Markit Sales Based Powertrain Forecast’s 36.6% penetration in 2030 (these figures include PHEVs and BEVs). We implement this baseline by choosing the drift parameter in the ψ_t process so that the mean (over Monte Carlo simulations) EV penetration rate in 2030 is 20%.

Table 1: Benchmark Parameter Values and Sources

Name	Value	Notes
A. Vehicle Demand Parameters		
η_p	-2.5	Price elasticity of EV demand at initial market share s_0 (see text)
η_2	0.37	Elasticity of EV demand w.r.t. level-2 charging
η_3	0.37	Elasticity of EV demand w.r.t. level-3 charging
ρ_c	0.1072	Charging station (annual) exit rate; BEA depreciation rate for general industrial equipment
ρ_v	$\frac{1}{11.5}$	Vehicle (annual) scrappage rate; Based on Polk data average age of vehicles on the road
$\bar{Q}$	17	FRED light weight vehicle sales, millions annually
ψ_g	-	Calibrated: drift in unobserved EV attributes and tastes
B. Charging Station Supply Parameters		
γ	0.671	Elasticity of charging station supply with respect to EV stock
C_0^2	4,000	Level 2 charging station cost in 2020 ($), 2 ports (see text)
C_0^3	200,000	Level 3 charging station cost in 2020 ($), 4 ports (see text)
ζ	-0.04	Charging station cost growth (see text)
r	0.03	Annual discount rate
κ_2	-	Calibrated: full penetration L2/EV ratio = 0.1
κ_3	-	Calibrated: full penetration EVs/L3 ratio = 150k 4-plug chargers
C. Price Forecast Parameters		
e_{car}	3.2	Mi/kWh EV car avg: Chevy Bolt, adjusted down for cold weather
e_{suv}	2	Mi/kWh EV suv/lt truck average
f_{car}	27.5	EPA estimate of real-world fuel economy for cars
f_{suv}	22.4	EPA estimate of real-world fuel economy for SUVs
v	2,924,053	Million vehicle miles traveled (VMT) for LDVs, 2019; FHWA
B_g	-0.09	Battery cost growth (see text)
v_g	-0.0091	Growth of VMT (AEO 2021 reference case)
Gas prices	-	Energy Information Administration Annual Energy Outlook 2021

Notes: This table describes the baseline calibrated parameters in our model. Parameter values are drawn from existing academic literature and professional forecasts.

2.6 Uncertainty and Monte Carlo Simulations

There are multiple sources of uncertainty underlying this model. Some of the parameters in Table 1 are econometric estimates and have sampling variability. Other parameters are engineering estimates or cost estimates obtained from historical data and there is uncertainty both about their current values and about projecting them forward. Because the model is nonlinear, these sources of uncertainty enter and interact in complex ways.

To obtain a rough estimate of the combined effect of this uncertainty on the policy objects of interest, we use Monte Carlo analysis with 1,000 draws. In each simulation, we simulate the model with parameters centered on the values described in Table 1. Standard deviations for the random draws are from empirical standard errors for parameters from the literature when available, from models estimated for this purpose (oil prices), or are judgmental based on ranges of estimates in the literature.

The shaded bands in our graphs communicate 80% and 90% uncertainty bands, obtained by taking quantiles of the distribution of endogenous variables. Details are available from the authors upon request.

3 Policies

We consider how our model is affected by three types of government policies meant to spur the adoption of electric vehicles.

The first policy we consider is government-subsidized production of new charging stations. Specifically, we assume a cost-sharing program in which the government subsidizes an exogenous fraction τ_k of level k charging stations. The government pays this percentage subsidy to each charging station built until the federal budget allocation is spent, at which point the program ends. We assume that a requirement of the federal subsidy is that subsidized charging stations be maintained so that the total number of charging stations does not fall after the subsidy program ends.

Second, we consider a rebate for the purchase of electric vehicles. This policy reduces the sticker price of electric vehicles, reducing the price of EVs relative to ICEs. In practice this could be achieved by a point-of-sale rebate to the consumer, a point-of-sale dealer rebate, or a refundable tax credit, assuming they are equal in size and salience. We consider a program with two distinct levels: an initial EV subsidy rate that prevails over the period 2022-2025, and a follow-up subsidy rate that prevails from 2026 until spending on this program exceeds an exogenous threshold. At this point, the program is assumed to 'phase out' over a two-year period.

The last policy we consider sets both the fuel efficiency of ICE vehicles and mandates the fraction of EVs sold, both by class of vehicle. This policy instrument is intended to reflect a regulatory path consistent with existing law, in which the Department of Transportation regulates fuel economy of ICEs and the EPA regulates emissions. Under this hypothetical policy, because ICE fuel economy is determined by DOT authorities and increases slowly post-2027. EPA authority is over the fraction of zero-emission vehicles sold, and that authority is implemented through a zero-emission vehicle (ZEV) standard. The standard is calibrated to start at 11.3% in 2024 for cars, and two years later for SUVs and to hit 50% in 2030 (for cars and SUVs combined). The hypothetical ZEV standard is implemented through a tradable permit system. Each ZEV produced yields its manufacturer a tradable permit, or ZEV credit. Each vehicle (ZEV or ICE) sold requires c (with $c < 1$) ZEV credits to be retired with the government. To limit the price impact of the standard, we allow for a ceiling on the price of the ZEV credits. We assume that ZEV credit costs and subsidies are fully passed through to consumers.

For each policy, we compute the non-discounted total fiscal cost of the policy through 2030. Carbon dioxide emissions trajectories by year under the no-policy baseline and under a candidate policy are computed using ICE fuel efficiencies by year and EV emissions induced on the margin from the additional electricity demand from the EVs. EV marginal power sector emissions were computed using the results discussed above from Stock and Stuart (2021).

4 Results

4.1 Main Results

The simulation results are summarized in Table 2. The columns of results present the EV sales share achieved by 2030 and emissions reduction in 2030 relative to the no-policy baseline. The second columns of results provide fiscal detail: total fiscal spending, spending on the charging station cost-share program, spending on the EV rebate program, and the amount of rebate spending which is inframarginal, that is, which goes to consumers who would have purchased an EV even if the neither the charging station nor rebate programs were in place. In the table, the first set of columns describes the policies: the federal fraction of the charging station cost-share, the total charging station budget, the initial EV rebate, the EV rebate from 2026 through the end of the full program when the EV new sales share reaches 50% and the program is phased down, and the ZEV mandate price cap.

The first row (row 0) summarizes the no-new-policy baseline. Row A1 provides results for a charging station subsidy policy only, with allocation of \$7.5B and cost-share rate of 67%. Row A2 considers an EV rebate program with values chosen roughly to approximate the rebate in the Clean Energy for America Act, specifically with initial rebate value of \$10,000 through 2025 and rebate value \$11,000 from 2026 until the new sales share of EVs is 50%, at which point the rebate steps down over two years by 25% then by 50%. Row A3 simulates simultaneous implementation of the \$7.5B charging station program and the \$10,000/\$11,000 rebate program. Row A4 simulates the effect of the charging station program and a ZEV regulation with a \$10,000 ZEV credit price cap, but no EV rebate.

The E block in Tables 2 and 3 considers combinations of charging station and rebate policies for which the total fiscal cost (the two policies combined) is in the range of \$155B-\$160B, but with no ZEV regulation. The F block considers the same set of policies, but in concert with a ZEV regulation with a \$10,000 cap on the ZEV credit. The G blocks consider different charging station-only possibilities.

The tables suggest the following results.

1. The \$7.5B charging station policy alone has a substantial effect on EV sales, increasing the EV share from approximately 20% under the no-policy case to just under 30%. However, that charging station policy alone falls far short of 50% EV penetration.

2. The expansive EV rebate program based on the Clean Energy for America Act by itself, and in concert with the charging station, induces significant additional EV sales, but those policies too fall short of the 50% sales target. The total cost of the pair of policies is large, estimated to be approximately \$450 billion using the mean of the Monte Carlo simulations.

3. The \$7.5B charging station subsidy, combined with the ZEV mandate, achieves penetration comparable to the rebate program alone, but that combination also falls short of the 50% 2030 sales share target.

4. Fiscal spending on charging stations is more effective than spending on rebates. Focusing on the E block, for which the total fiscal cost is held approximately constant at \$156-160B, shifting \$33B from the rebate program to the charging station program (that is, moving from the highest-rebate package E1 to the lowest-rebate package E6) increases the EV penetration share from 34% to 55%. Along with this increase in EV penetration is an approximate doubling in CO2 abatement, relative to the no-policy case. Figure **??** summarizes this key finding. The vertical axis is the estimated share of EVs in 2030, while the horizontal axis is the share of the fiscal budget used to subsidize charging stations, as opposed to subsidizing vehicles. The blue line represents the results block E; the red line represents the results in block F. The Figure illustrates that EV penetration has a nearly linear relationship with respect to the share of the budget allocated to charging stations.[3]

5. Augmenting the fiscal programs with a regulatory ZEV mandate increases EV penetration.

6. The EV rebate programs all involve substantial inframarginal transfers to individuals who would have purchased an EV under the no-policy baseline. For example, in the E suite of policies, inframarginal transfers range from 28% in the lowest-rebate case (E6) to 42% in the highest-rebate case (E7).

7. The marginal returns on charging station spending, as measured both by incremental EV sales penetration and by emissions reductions in 2030, declines slowly with the level of spending. As seen in the upper panels of Figures 3 and 4, diminishing marginal returns start to appear only around \$20B of total cost.

---

[3] The ideal experiment would hold the fiscal costs exactly fixed across the scenarios. However, we note that the government budgets are actually smaller as we move rightward in the figure, implying that if we kept budgets exactly fixed, the EV shares would be even greater as we increase the share of the budget for charging stations.

4.2 Sensitivity analysis

We consider two sets of sensitivity checks. The first uses a more optimistic baseline assumption of EV penetration in 2030, specifically using the IHS Markit 2030 forecast instead of the average of the EIA and IHS Markit forecasts. The second uses the baseline penetration forecast of Table 2, however chooses a lower elasticity for charging stations, and higher price elasticity by setting η_2=η_3 = 0.2 and η_P = -3.5 in the discrete choice demand framework.[4] These parameters were chosen specifically to examine the sensitivity of our main findings of the relative effectiveness of fiscal spending on charging stations over rebates. The results are summarized in Tables 3 and 4, respectively, and the results for the charger-only policies are given in the second and third panels, respectively, of Figures 3 and 4.

First consider the higher-penetration baseline case (Table 3 and middle panels of Figures 3 and 4). Under this scenario, more charging stations are built endogenously under the baseline, so there are more inframarginal transfers on charging stations and charging station costs per ton are higher than in the benchmark case. Still, spending on charging stations remains substantially more effective, per fiscal dollar, than spending on rebates: reallocating \$33B from the high-rebate case (E1) to charging stations increases penetration by 19 percentage points while saving, on net, \$20B (because the 50% sunset threshold for the rebate program is reached earlier).

As expected, the charger subsidy program has reduced effectiveness in the low-charger/high price elasticity case (Table 4 and bottom panels of Figures 3 and 4), compared to the benchmark case. Still, reallocating \$30B to chargers in E1 increases 2030 EV penetration by 9 percentage points while reducing fiscal expenditures by \$20B. In this scenario, the rebate-only policy achieves the 50% target at a cost of approximately \$430B. It is worth noting that the already-effective ZEV policy is even more effective under these parameters because, for a given tradeable permit price, a great shift in EV sales is induced by the higher price elasticity.

4.3 Uncertainty

We illustrate the uncertainty of the policy effects, as estimated by the Monte Carlo simulations, for the highest- and lowest-rebate policies of the fiscally comparable policies in the benchmark case (E1 and E6) in Figure 5, and the same policies paired with the ZEV mandate in Figure 6. Each figure shows the distribution of the estimated change, by year, in the EV sales share induced by the indicated policy (note that this is the change in sales share, not the level of sales share, which is the sum of the baseline share in Figure 2 and the change). Evidently there is a considerable range of estimated EV sales shares. Comparing the upper and lower panels of each plot shows that the more

---

[4] The lower bound estimate in the literature on the EV demand elasticity with respect to charging station is 0.26 in Xing et al. (2021). The upper bound estimate of own-price elasticity for EVs (in magnitude) is -3.3 in Muehlegger and Rapson (2019) focusing on lower- and middle-income households. As EVs penetrate the market deeper and an average EV buyer likely have a lower income, the price sensitivity among these consumers should be higher.

charger-intensive policy shifts up the full distribution of impacts. Holding constant the charger and rebate policies, imposing the ZEV mandate serves to place a floor on the distribution of the effects, so that the ZEV mandate drives EV penetration even in those simulated situations in which the other two policies are less effective.

5 Discussion

Our results emphasize two important findings. First, there is a great deal of heterogeneity (in terms of impact on EV penetration per dollar of government expenditure) across the policies we study. Second, none of the three policies we study in isolation is capable of reaching 50% EV penetration in the market for new vehicles without a very large price tag; instead, a combination of policies is likely to provide the most impact on EV penetration.

Why do our results indicate that charging station subsidies are so effective? There are two reasons. First, for individuals who cannot install their own chargers, for example because they park on a street or live in an apartment building, buying and EV simply isn't an option, regardless of how deep the subsidy is. For them, providing additional charging stations makes it possible to purchase an EV. Even for consumers who have their own personal charging stations, the current low density of on-the-road level 3 chargers makes long-distance travel challenging at best. For them, additional level 3 chargers reduce range anxiety and make it possible to use EVs in the way that drivers now use ICEs. Second, much of spending on tax credits is inframarginal; it consists of transfers to individuals who would have purchased an electric vehicle whether or not the tax credit we study exists. And although individuals are highly response to changes in the relative price of cars or electric vehicles, an appreciably large subsidy for EV purchases would amount to hundreds of billions of dollars in government transfers.

This analysis makes many simplifications and has limitations. While in practice EV sales rebates could be capped at specific vehicle prices to potentially better target marginal consumers, this model does not permit that level of nuance. Additionally, there are many potential extensions of the model which may prove significant and have not been incorporated here; allowing consumer choice between cars and SUVs, incorporating more evidence on the nuances of level 2 vs. level 3 charging station supply and demand, and simply making the charging station model more granular all have the potential to provide policy-relevant insight. Addressing these limitations is a topic for ongoing research.

References

Bresnahan, Timothy and Peter Reiss, "Entry and competition in concentrated markets," *Journal of Political Economy*, 1991, *99*, 977–1009.

Li, Jing, "Compatibility and Investment in the U.S. Electric Vehicle Market," 2016. Working paper.

Li, Shanjun, Lang Tong, Jianwei Xing, and Yiyi Zhou, "The Market for Electric Vehicles: Indirect Network Effects and Policy Impacts," *Journal of the Association of Environmental and Resource Economists*, 2017, *4* (1), 89–133.

Lutsey, Nic and Michael Nicholas, "Update on electric vehicle costs in the United States through 2030," 2019. Working paper.

Muehlegger, Erich and David S. Rapson, "Subsidizing Mass Adoption of Electric Vehicle: Quasi-Experimental Evidence from California," 2019. Working Paper.

Springel, Katalin, "Network Externality and Subsidy Structure in Two-Sided Markets: Evidence from Electric Vehicle Incentives," *American Economic Journal: Economic Policy*, forthcoming.

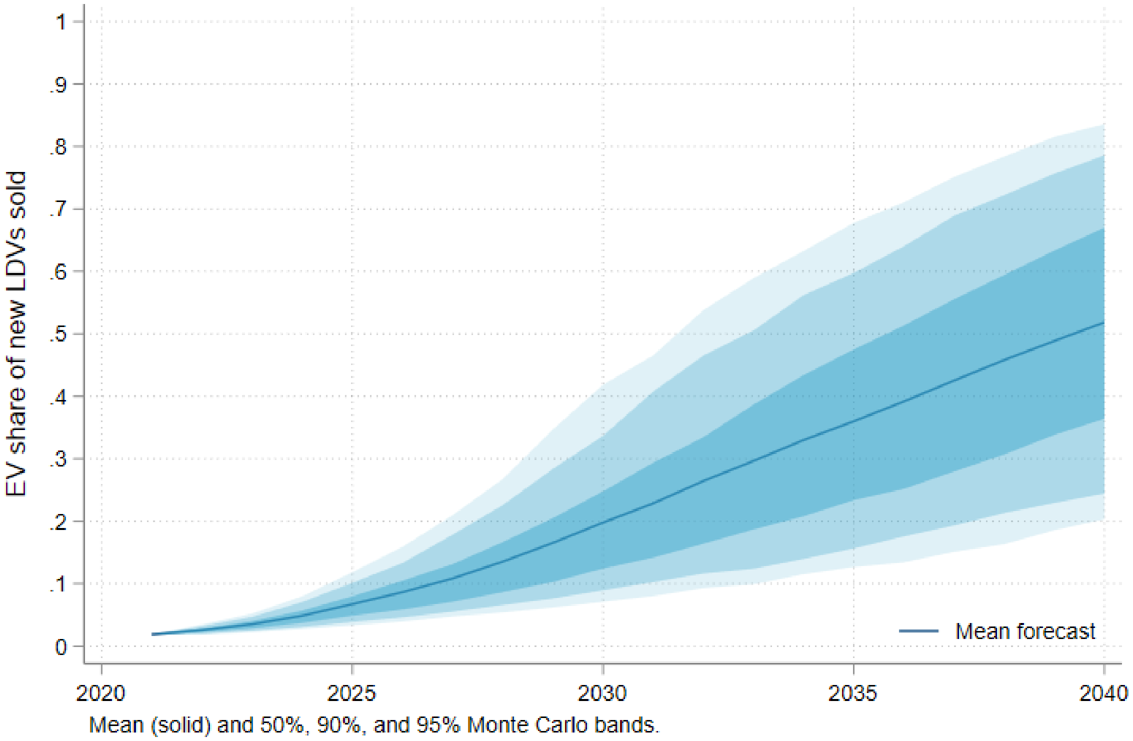
Stock, James H. and Daniel Stuart, "Robust Decarbonization of the US Power Sector: Policy Options," 2021. NBER Working Paper 28677.

Xing, Jianwei, Benjamin Leard, and Shanjun Li, "What Does an Electric Vehicle Replace?," *Journal of Environmental Economics and Management*, May 2021, *107*, 102432.

Zhou, Yiyi and Shanjun Li, "Technology Adoption and Critical Mass: The Case of the U.S. Electric Vehicle Market," *The Journal of Industrial Economics*, 2018, *66* (2), 423–480.

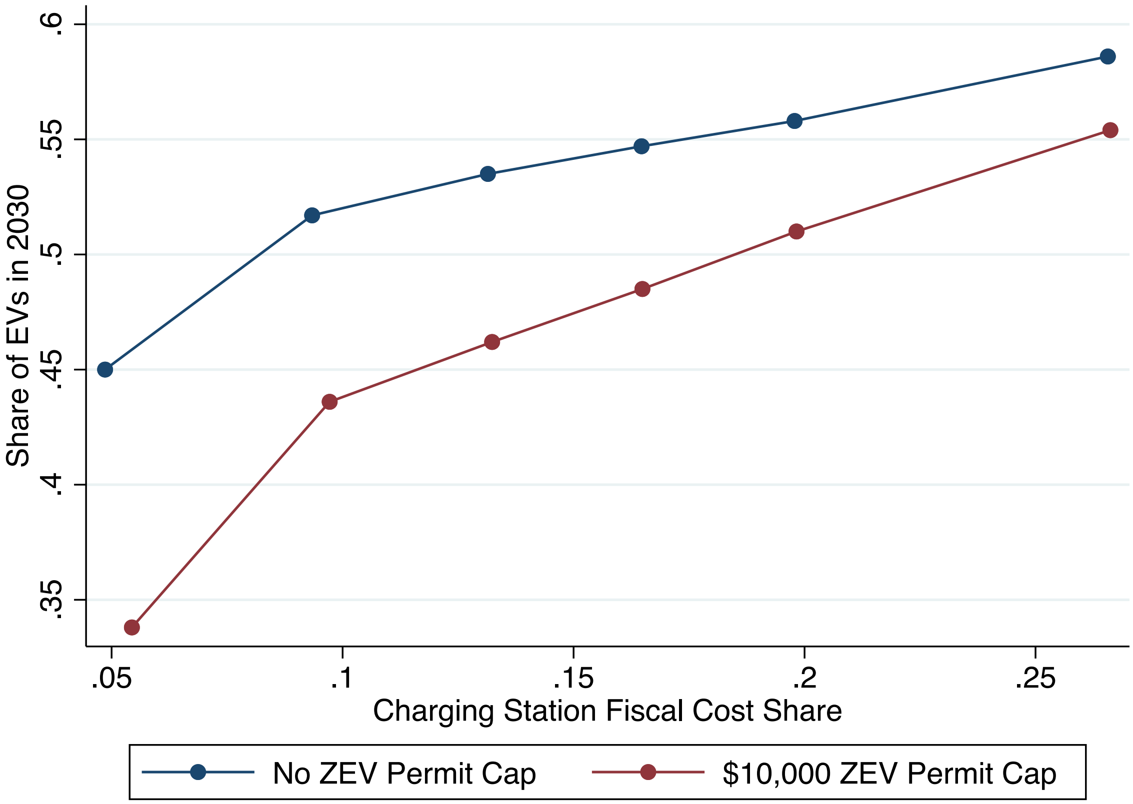
Ziegler, Micah S. and Jessica E. Trancik, "Re-examining rates of lithium-ion battery technology improvement and cost decline," *Energy & Environmental Science*, 2021, *14*, 1635–1651.

Figure 1: Baseline Electric Vehicle Share of New Vehicles Sold



Notes: This figure plots our baseline forecast of the EV sales share of new vehicles sold through 2050. The shaded area indicates a 90 percent confidence interval obtained via Monte Carlo simulation, as described in the main text.

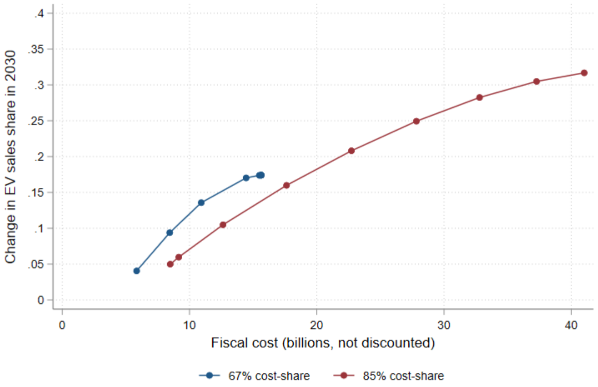
Figure 2: Baseline Electric Vehicle Share of New Vehicles Sold



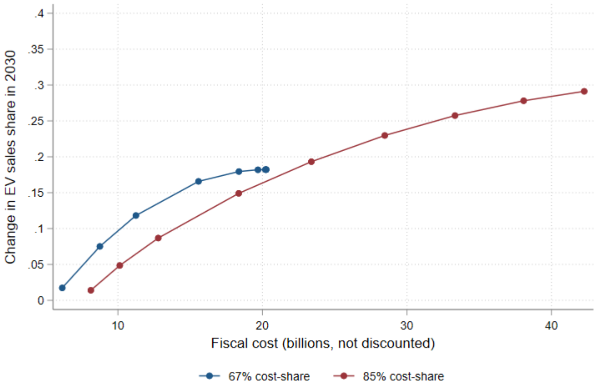
Notes: This figure plots the results of Scenarios E (blue line) and F (red line) in Table 2. The vertical axis is the estimated share of EVs in 2030, while the horizontal axis is the share of the fiscal budget used to subsidize charging stations, as opposed to subsidizing vehicles.

Figure 3: Increase in 2030 EV sales share for charger-only policies

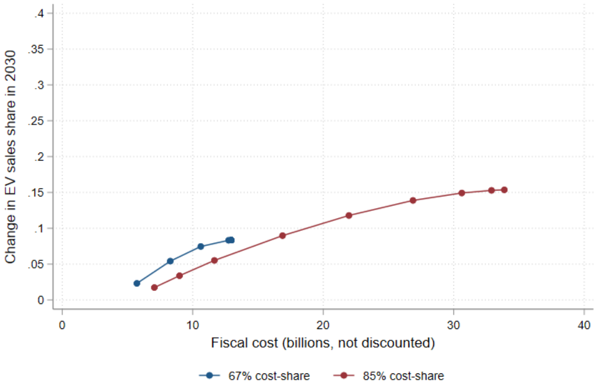
(a) Benchmark



(b) High EV penetration



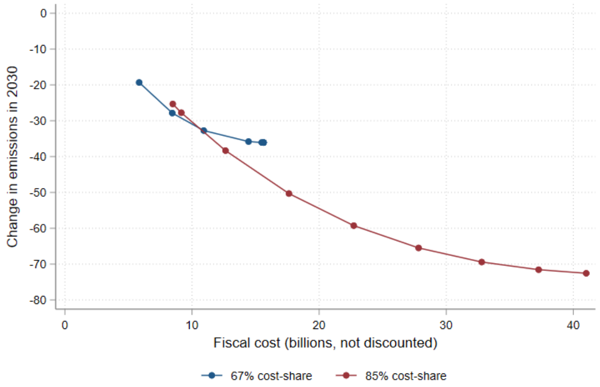
(c) Low charger elasticity



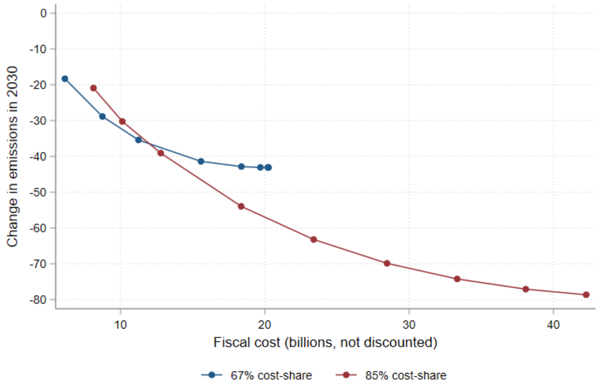
Notes: Difference in EV 2030 sales share in 2030, relative to the no-policy baseline, as a function of the charger budget for charger-only policies, for 67% and 85% cost-share programs, for benchmark case (upper), higher EV penetration case (middle), and low charger elasticity case (lower).

Figure 4: CO2 Emissions abated for charger-only policies

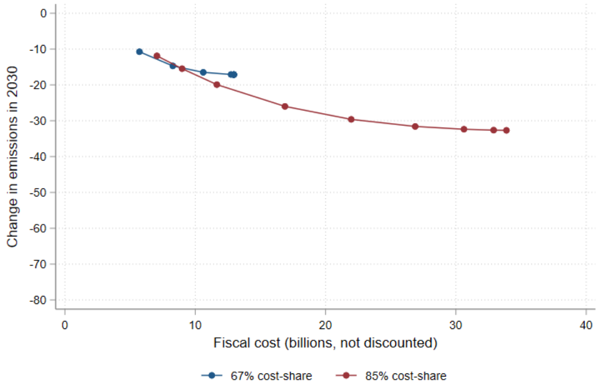
(a) Benchmark



(b) High EV penetration



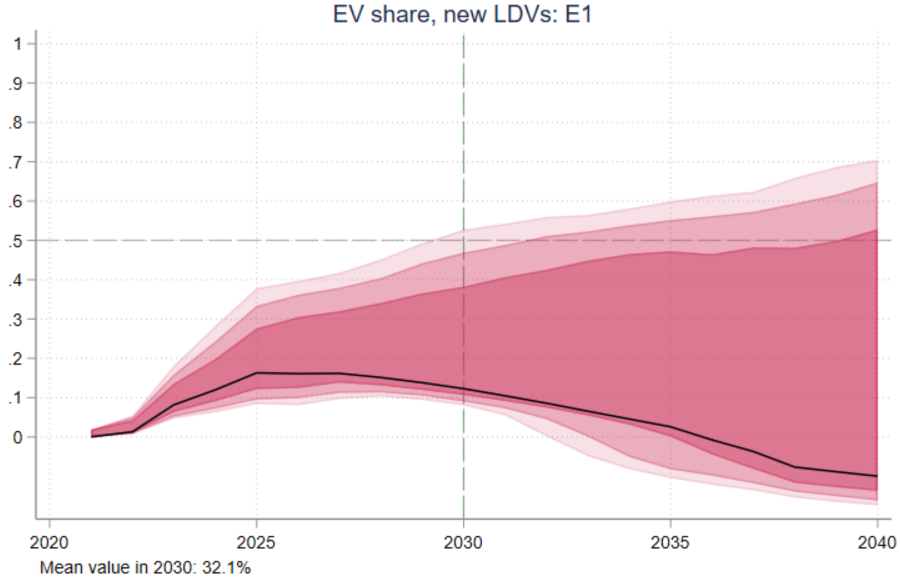
(c) Low charger elasticity



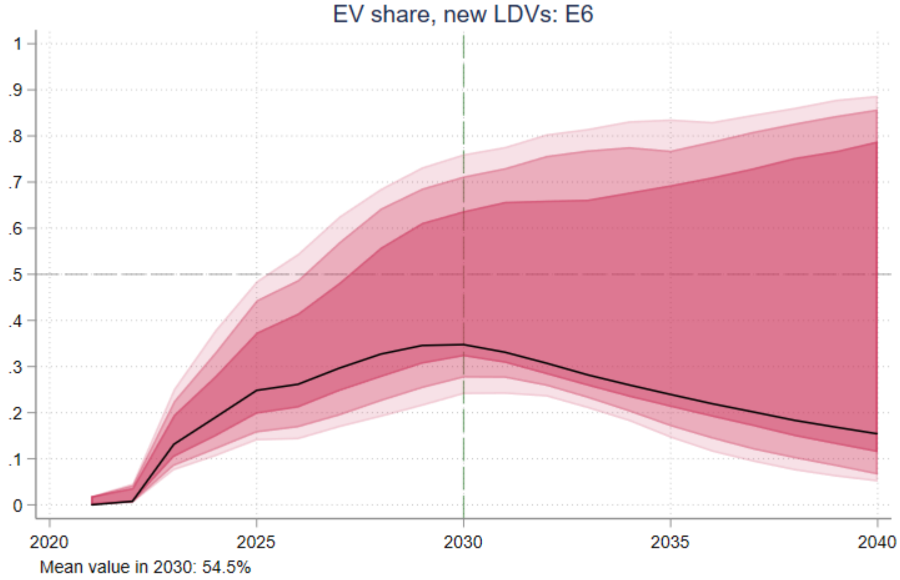
Notes: Difference in CO2 emissions in 2030, relative to the no-policy baseline, as a function of the charger budget for charger-only policies, for 67% and 85% cost-share programs, for benchmark case (upper), higher EV penetration case (middle), and low charger elasticity case (lower).

Figure 5: EV share under policies E1 and E6, benchmark case

(a) Benchmark



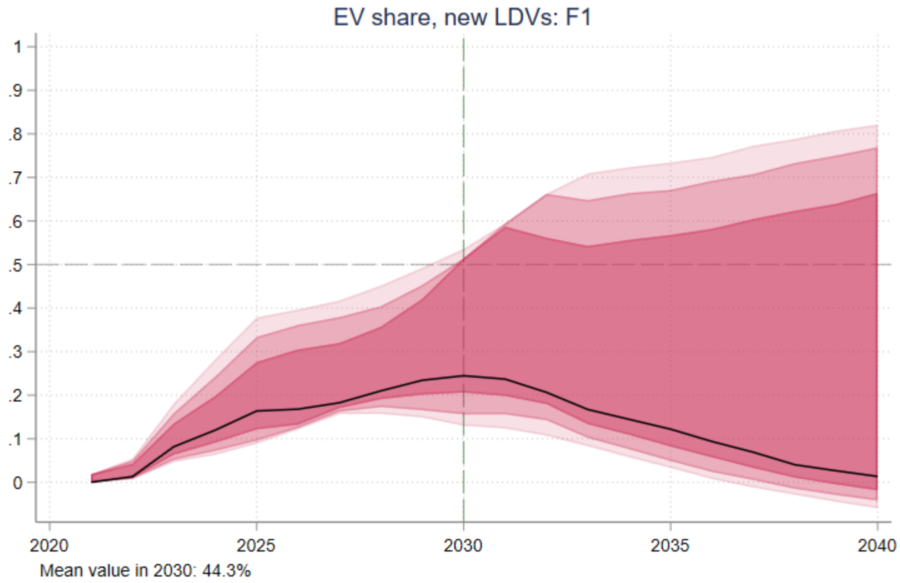
(b) High EV penetration



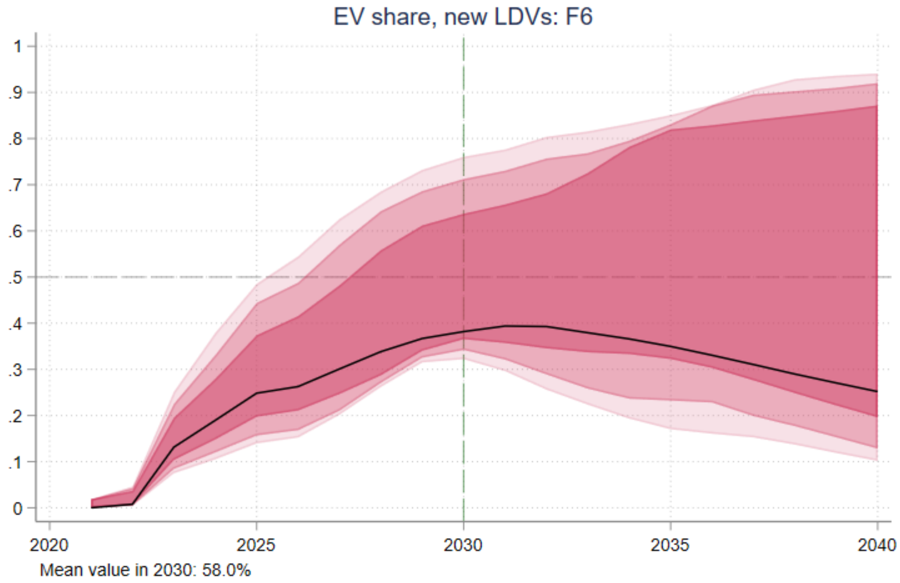
Notes: Panel (a) corresponds to E1 and Panel (b) corresponds to E6 in Table 2. E1: charging station cost-sharing by government at 67% with a cap of \$7.5 billion on total charging subsidy; EV sales rebate at \$6,000 from 2022-2025, and then \$3,900 from 2026 on. E6: charging station cost-sharing at 85% with a cap of \$40 billion on total charging subsidy; EV sales rebate at \$3,900 from 2022-2025, and then \$2,100 from 2026 on.

Figure 6: EV share under policies F1 and F6, benchmark case

(a) Benchmark



(b) High EV penetration



Notes: Panel (a) corresponds to F1 and Panel (b) corresponds to F6 in Table 2. F1: charging station cost-sharing by government at 67% with a cap of \$7.5 billion on total charging subsidy; EV sales rebate at \$6,000 from 2022-2025, and then \$3,900 from 2026 on; ZEV price cap at \$10,000. F6: charging station cost-sharing at 85% with a cap of \$40 billion on total charging subsidy; EV sales rebate at \$3,900 from 2022-2025, and then \$2,100 from 2026 on; ZEV price cap at \$10,000.

Table 2: Simulation Results: Benchmark case

	Policies					**EV share & Emissions**		**Fiscal costs ($B, not discounted)**			
	Station cost share		EV sales rebate		ZEV permit price cap ($)	EV Sales Share by 2030	ΔCO2 in 2030 (mmt)	Total	Of which:		
	Percent	Budget ($B)	2022 - 2025	2026+					Chargers	Rebates	Inframarginal Rebates
0	-	-	-	-	-	0.199	-	-	-	-	-
A1	0.67	7.5	-	-	-	0.293	-28	8	8.4	-	-
A2	-	-	10,000	11,000	-	0.426	-46	347	-	347	154
A3	0.67	7.5	10,000	11,000	-	0.459	-75	457	8.9	448	144
A4	0.67	7.5	-	-	10,000	0.412	-44	9	8.7	-	-
E1	0.67	7.5	6,000	3,900	-	0.338	-44	158	8.6	149	63
E2	0.67	15.0	5,500	3,500	-	0.436	-55	160	15.6	145	56
E3	0.70	25.0	5,000	3,250	-	0.462	-59	158	20.9	137	51
E4	0.75	28.0	5,000	2,750	-	0.485	-66	158	26.0	132	45
E5	0.80	30.0	4,600	2,400	-	0.510	-74	156	31.0	125	39
E6	0.85	40.0	3,900	2,100	-	0.554	-87	158	42.2	116	32
F1	0.67	7.5	6,000	3,900	10,000	0.450	-57	178	8.6	169	63
F2	0.67	15.0	5,500	3,500	10,000	0.517	-64	174	16.2	157	56
F3	0.70	25.0	5,000	3,250	10,000	0.535	-67	170	22.4	148	51
F4	0.75	28.0	5,000	2,750	10,000	0.547	-73	167	27.4	139	45
F5	0.80	30.0	4,600	2,400	10,000	0.558	-79	162	32.1	130	39
F6	0.85	40.0	3,900	2,100	10,000	0.586	-90	162	43.0	119	32
G672	0.67	5.0	-	-	-	0.240	-19	6	5.8	-	-
G673	0.67	7.5	-	-	-	0.293	-28	8	8.4	-	-
G674	0.67	10.0	-	-	-	0.335	-33	11	10.9	-	-
G675	0.67	15.0	-	-	-	0.370	-36	14	14.4	-	-
G676	0.67	20.0	-	-	-	0.373	-36	15	15.5	-	-
G677	0.67	25.0	-	-	-	0.373	-36	16	15.6	-	-
G678	0.67	30.0	-	-	-	0.373	-36	16	15.6	-	-
G679	0.67	35.0	-	-	-	0.373	-36	16	15.6	-	-
G6710	0.67	40.0	-	-	-	0.373	-36	16	15.6	-	-
G852	0.85	5.0	-	-	-	0.249	-25	8	8.5	-	-
G853	0.85	7.5	-	-	-	0.259	-28	9	9.2	-	-
G854	0.85	10.0	-	-	-	0.304	-38	13	12.6	-	-
G855	0.85	15.0	-	-	-	0.359	-50	18	17.6	-	-
G856	0.85	20.0	-	-	-	0.407	-59	23	22.7	-	-
G857	0.85	25.0	-	-	-	0.449	-65	28	27.8	-	-
G858	0.85	30.0	-	-	-	0.482	-69	33	32.8	-	-
G859	0.85	35.0	-	-	-	0.504	-72	37	37.3	-	-
G8510	0.85	40.0	-	-	-	0.516	-73	41	41.0	-	-

Notes: The first row reports the no-new-policy baseline, the remaining rows report alternative policy scenarios. No-policy EV share penetration is calibrated to average of EIA AEO 2021 reference case and IHS (August 2021) projections for 2030. Parameter values are given in Table 1

Table 3: Simulation Results: Higher penetration case

	Policies					**EV share & Emissions**		**Fiscal costs ($B, not discounted)**			
	Station cost share		EV sales rebate		ZEV permit price cap ($)	EV Sales Share by 2030	ΔCO2 in 2030 (mmt)	Total	Of which:		
	Percent	Budget ($B)	2022 - 2025	2026+					Chargers	Rebates	Inframarginal Rebates
0	-	-	-	-	-	0.374	-	-	-	-	-
A1	0.67	7.5	-	-	-	0.449	-29	9	8.7	-	-
A2	-	-	10,000	11,000	-	0.594	-51	395	-	395	231
A3	0.67	7.5	10,000	11,000	-	0.610	-77	431	9.1	422	188
A4	0.67	7.5	-	-	10,000	0.511	-38	9	8.8	-	-
E1	0.67	7.5	6,000	3,900	-	0.500	-47	182	9.0	173	94
E2	0.67	15.0	5,500	3,500	-	0.594	-61	179	16.1	163	80
E3	0.70	25.0	5,000	3,250	-	0.629	-66	176	23.7	152	73
E4	0.75	28.0	5,000	2,750	-	0.645	-73	173	28.1	145	64
E5	0.80	30.0	4,600	2,400	-	0.659	-80	167	31.9	135	54
E6	0.85	40.0	3,900	2,100	-	0.694	-92	163	42.9	120	43
F1	0.67	7.5	6,000	3,900	10,000	0.551	-54	193	9.0	184	94
F2	0.67	15.0	5,500	3,500	10,000	0.627	-66	186	16.5	169	80
F3	0.70	25.0	5,000	3,250	10,000	0.659	-71	182	24.4	158	73
F4	0.75	28.0	5,000	2,750	10,000	0.670	-77	178	28.8	149	64
F5	0.80	30.0	4,600	2,400	10,000	0.679	-83	170	32.5	138	54
F6	0.85	40.0	3,900	2,100	10,000	0.708	-94	165	43.4	122	43
G672	0.67	5.0	-	-	-	0.391	-18	6	6.1	-	-
G673	0.67	7.5	-	-	-	0.449	-29	9	8.7	-	-
G674	0.67	10.0	-	-	-	0.492	-35	11	11.2	-	-
G675	0.67	15.0	-	-	-	0.540	-41	16	15.6	-	-
G676	0.67	20.0	-	-	-	0.553	-43	18	18.4	-	-
G677	0.67	25.0	-	-	-	0.556	-43	20	19.7	-	-
G678	0.67	30.0	-	-	-	0.556	-43	20	20.2	-	-
G679	0.67	35.0	-	-	-	0.556	-43	20	20.3	-	-
G6710	0.67	40.0	-	-	-	0.556	-43	20	20.3	-	-
G852	0.85	5.0	-	-	-	0.388	-21	8	8.1	-	-
G853	0.85	7.5	-	-	-	0.423	-30	10	10.1	-	-
G854	0.85	10.0	-	-	-	0.461	-39	13	12.8	-	-
G855	0.85	15.0	-	-	-	0.523	-54	18	18.4	-	-
G856	0.85	20.0	-	-	-	0.567	-63	23	23.4	-	-
G857	0.85	25.0	-	-	-	0.604	-70	28	28.5	-	-
G858	0.85	30.0	-	-	-	0.631	-74	33	33.3	-	-
G859	0.85	35.0	-	-	-	0.652	-77	38	38.1	-	-
G8510	0.85	40.0	-	-	-	0.665	-79	42	42.3	-	-

Notes: The first row reports the no-new-policy baseline, the remaining rows report alternative policy scenarios. No-policy EV share penetration is calibrated to HIS (August 2021) projections for 2030. Parameter values are given in Table 1.

Table 4: Simulation Results: Low charger/high price elasticity case

	Policies					**EV share & Emissions**		**Fiscal costs ($B, not discounted)**			
	Station cost share		EV sales rebate		ZEV permit price cap ($)	EV Sales Share by 2030	ΔCO2 in 2030 (mmt)	Total	Of which:		
	Percent	Budget ($B)	2022 - 2025	2026+					Chargers	Rebates	Inframarginal Rebates
0	-	-	-	-	-	0.202	-	-	-	-	-
A1	0.67	7.5	-	-	-	0.256	-15	8	8.3	-	-
A2	-	-	10,000	11,000	-	0.518	-68	428	-	428	154
A3	0.67	7.5	10,000	11,000	-	0.520	-83	484	8.9	475	147
A4	0.67	7.5	-	-	10,000	0.437	-39	9	8.7	-	-
E1	0.67	7.5	6,000	3,900	-	0.329	-37	149	8.4	140	67
E2	0.67	15.0	5,500	3,500	-	0.377	-41	145	15.1	130	60
E3	0.70	25.0	5,000	3,250	-	0.382	-41	138	18.6	119	56
E4	0.75	28.0	5,000	2,750	-	0.385	-42	133	22.9	110	50
E5	0.80	30.0	4,600	2,400	-	0.396	-45	129	28.3	101	44
E6	0.85	40.0	3,900	2,100	-	0.415	-49	128	37.9	91	38
F1	0.67	7.5	6,000	3,900	10,000	0.487	-54	175	8.5	166	67
F2	0.67	15.0	5,500	3,500	10,000	0.508	-55	166	16.3	150	60
F3	0.70	25.0	5,000	3,250	10,000	0.512	-55	159	21.2	138	56
F4	0.75	28.0	5,000	2,750	10,000	0.513	-56	151	25.9	126	50
F5	0.80	30.0	4,600	2,400	10,000	0.516	-58	145	31.5	114	44
F6	0.85	40.0	3,900	2,100	10,000	0.523	-60	142	41.6	100	38
G672	0.67	5.0	-	-	-	0.225	-11	6	5.7	-	-
G673	0.67	7.5	-	-	-	0.256	-15	8	8.3	-	-
G674	0.67	10.0	-	-	-	0.276	-16	11	10.6	-	-
G675	0.67	15.0	-	-	-	0.285	-17	13	12.7	-	-
G676	0.67	20.0	-	-	-	0.285	-17	13	13.0	-	-
G677	0.67	25.0	-	-	-	0.285	-17	13	13.0	-	-
G678	0.67	30.0	-	-	-	0.285	-17	13	13.0	-	-
G679	0.67	35.0	-	-	-	0.285	-17	13	13.0	-	-
G6710	0.67	40.0	-	-	-	0.285	-17	13	13.0	-	-
G852	0.85	5.0	-	-	-	0.219	-12	7	7.1	-	-
G853	0.85	7.5	-	-	-	0.236	-15	9	9.0	-	-
G854	0.85	10.0	-	-	-	0.257	-20	12	11.7	-	-
G855	0.85	15.0	-	-	-	0.292	-26	17	16.9	-	-
G856	0.85	20.0	-	-	-	0.320	-30	22	22.0	-	-
G857	0.85	25.0	-	-	-	0.341	-32	27	26.9	-	-
G858	0.85	30.0	-	-	-	0.351	-32	31	30.6	-	-
G859	0.85	35.0	-	-	-	0.355	-33	33	32.9	-	-
G8510	0.85	40.0	-	-	-	0.355	-33	34	33.9	-	-

Notes: The first row reports the no-new-policy baseline, the remaining rows report alternative policy scenarios. No-policy EV share penetration is calibrated to average of EIA AEO 2021 reference case and HIS (August 2021) projections for 2030. Parameter values are given in Table 1, with the modification that the charger elasticity (η_2 and η_3) is set to 0.2 and the price elasticity (η_P) is set to -3.5.

MIT CEEPR

MIT Center for Energy and Environmental Policy Research

Since 1977, the Center for Energy and Environmental Policy Research (CEEPR) has been a focal point for research on energy and environmental policy at MIT. CEEPR promotes rigorous, objective research for improved decision making in government and the private sector, and secures the relevance of its work through close cooperation with industry partners from around the globe. Drawing on the unparalleled resources available at MIT, affiliated faculty and research staff as well as international research associates contribute to the empirical study of a wide range of policy issues related to energy supply, energy demand, and the environment.

An important dissemination channel for these research efforts is the MIT CEEPR Working Paper series. CEEPR releases Working Papers written by researchers from MIT and other academic institutions in order to enable timely consideration and reaction to energy and environmental policy research, but does not conduct a selection process or peer review prior to posting. CEEPR's posting of a Working Paper, therefore, does not constitute an endorsement of the accuracy or merit of the Working Paper. If you have questions about a particular Working Paper, please contact the authors or their home institutions.

MIT Center for Energy and
Environmental Policy Research
77 Massachusetts Avenue, E19-411
Cambridge, MA 02139
USA

Website: ceepr.mit.edu

MIT CEEPR Working Paper Series is published by the MIT Center for Energy and Environmental Policy Research from submissions by affiliated researchers.

Copyright © 2021
Massachusetts Institute of Technology

For inquiries and/or for permission to reproduce material in this working paper, please contact:

Email ceepr@mit.edu
Phone (617) 253-3551
Fax (617) 253-9845