AEA Papers and Proceedings 2023, 113: 316–322
https://doi.org/10.1257/pandp.20231063

GLOBAL EV PENETRATION: POLICIES, SUBSIDY PASS-THROUGH, AND CONSUMER PREFERENCE

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

By Cassandra Cole, Michael Droste, Christopher Knittel, Shanjun Li, and James H. Stock*

The decarbonization of light-duty vehicles (LDVs) is a major policy priority in the United States, as LDV operations accounted for 58 percent of transportation emissions of carbon dioxide (CO_2) in the United States in 2019. The Biden administration has set a target that 50 percent of new vehicle sales in 2030 be zero-emissions vehicles. As automakers have announced ambitious plans for expanding their production of electric vehicles (EVs) and investing in charging infrastructure, replacing conventional internal combustion engine (ICE) vehicles with EVs is the most promising pathway for decarbonizing LDVs in the near future, and doing so appears increasingly economically feasible. Yet deep EV penetration, even if socially optimal, is not a certainty given the presence of network externalities between charging stations and vehicles, or the so-called "chicken and egg problem." Therefore, public policies could play an important role in expediting the transition. To this end, two recent acts of the US Congress, the Infrastructure Investment and Jobs Act of 2021 (IIJA) and the Inflation Reduction Act of 2022 (IRA), provide subsidies and tax incentives to promote EV sales and the deployment of EV charging infrastructure.

We estimate the effects of the main IIJA and IRA charger and EV provisions on EV new sales market share, greenhouse gas emissions, and government expenditures. We estimate the costs of these policies, measured in dollars per ton of CO_2 abated, which can be compared to their social benefits in reduced emissions.

Our analysis shows that the provisions of the IIJA and the IRA would increase the 2030 EV share of new LDV sales by 18 percentage points, reduce US CO_2 emissions by 80 million metric tons in 2030, and have costs of approximately \$95 per ton of CO_2 abated, well below the most recent Environmental Protection Agency estimate of the social cost of carbon (SCC) of \$190 per ton. We also estimate the total (undiscounted) fiscal cost of these policies to be \$451 billion through 2031, an order of magnitude greater than the official Congressional cost estimate of \$15.6 billion[1] (Congressional Budget Office 2022).

I. Model

Our model consists of a discrete choice model of EV demand and an entry/exit model of charging station supply calibrated using parameter estimates from the literature.

*Cole: Harvard University (email: ccole@g.harvard.edu); Droste: Harvard University (email: mdroste@fas.harvard.edu); Knittel: MIT and NBER (email: knittel@mit.edu); Li: Cornell University and NBER (email: sl2448@cornell.edu); Stock: Harvard University and NBER (email: james_stock@harvard.edu). We are thankful for helpful 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. The authors acknowledge partial funding support from DOT-NSF project 36363.03.01.00 administered by NBER.

†Go to https://doi.org/10.1257/pandp.20231063 to visit the article page for additional materials and author disclosure statement(s).

[1] \$10.6 billion for sections 13401, 13402, and 13404 of CBO (2022), plus \$5 billion for the IIJA's National Electric Vehicle Infrastructure Program.

A. *Electric Vehicle Demand*

We model the demand for EVs with a multinomial logit framework that focuses on drive train choice for two otherwise similar vehicles—for example, the Ford F-150 and its EV version, the F-150 Lightning. There are two vehicle classes: cars and light-duty trucks, including sport-utility vehicles (SUVs) and minivans. The model holds the share of each class fixed for simplicity. Within each class, consumers indexed by i choose between an EV and an ICE vehicle to maximize utility. The baseline model allows switching between fuel types within each vehicle class but not between classes. There is an outside option with utility normalized to zero. Time is discrete and indexed by t. 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

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

where P_{jt} is the ratio of the EV price to the ICE price within class j. N_t^{L2} and N_t^{L3} represent the stock of level 2 and level 3 electric charging stations available at time t. Their inclusion captures an indirect network externality for EVs: consumer utility from EVs increases with the size of the charging network. Unlike level 3 (fast) charging stations, the effect of level 2 charging stations decreases with the EV stock, Q_{t-1}, capturing the congestion effect for slow charging stations.

The drift term ψ_{jt} captures preferences 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 the length of time to charge an EV, as well as unobserved attributes such as consumer awareness of EVs and consumer attachment to the sound and feel of an ICE. The final term in equation (1), ϵ_{ijt}, is an idiosyncratic taste shock and is assumed to have an i.i.d. type I extreme value distribution across consumers and over time.

The EV sales share for vehicle class j in period t is given by

$$(2)\qquad s_{jt} \; = \; \frac{\exp\left(\bar{u}_{jt}\right)}{1 + \exp\left(\bar{u}_{jt}\right)},$$

where $\bar{u}_{jt}$, the deterministic utility, is defined in equation (1). The price elasticity of EV demand of class j is given by $\eta_p = \left(1 - s_{jt}\right)\beta_P$. The elasticity of EV demand with respect to level k charging station supply is $\eta_k = \left(1 - s_{jt}\right)\beta_k$.

B. *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 (2021), which build 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 station in period t receive a discounted stream of future profits. An entering firm pays a fixed cost of C_{kt} to build a level k charging station at the prevailing technology. In a free-entry equilibrium, the firms are indifferent between entering at time t and $t+1$. This implies that 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):

$$(3)\qquad \pi_t^k\left(N_t^k, Q_t\right) \; = \; C_t^k - \frac{1}{1+r} C_{t+1}^k.$$

$\pi_t^k\left(N_t^k, Q_t\right)$ denotes the current profit at period t accruing to the firm operating a level k charging station as a function of the size of charging station network N^k and EV stock Q. r is the discount rate. We assume the following functional form for the period profit function, where the profit from a charging station is increasing in the quantity of EV stock and decreasing in the number of other charging stations:

$$(4)\quad \pi_t^k\left(N_t^k, Q_t\right) \; = \; \left(\exp\left(\kappa_k\right)/\left(N_t^k\right)\right)^{\frac{1}{\gamma}} Q_t.$$

This gives rise to the following equation characterizing the supply of level k charging stations:

$$(5)\quad \ln\left(N_t^k\right) \; = \; \kappa_k + \gamma \ln\left(Q_t\right) - \gamma \ln\left(\tilde{C}_t^k\right),$$

where the κ terms are constants, Q represents the stock of EVs in period t, N represents the stock of charging stations, and $\tilde{C}_t^k \; = \; C_t^k - \frac{1}{1+r} C_{t+1}^k$. We assume that charging station costs follow an exogenous law of motion:

$$(6)\qquad C_t^k \; = \; C_0^k \cdot \left(0.5 + 0.5\, e^{\zeta \cdot t}\right),$$

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

C. *Vehicle Pricing*

We assume 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, the cost of installing a home charger if done, maintenance costs, and fuel costs. We model this with a "bottom-up" approach based on Lutsey and Nicholas (2019). That is, the price of a vehicle depends on the vehicle's sticker price, maintenance costs, and fuel costs. We use information from Lutsey and Nicholas (2019) to forecast 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.

D. *Calibration*

Table A1 in the online Appendix lists the parameters in our model and their calibrated or assumed values, and provides a note on their source. Select parameters are discussed below.

We hold the total number of cars fixed, so the relevant price is the relative price of ICE versus EVs (within a category). We follow the literature in using estimates for the EV own-price elasticity of demand to define the demand coefficient on the price ratio. We choose $\eta_p = -2.5$ as an approximate median of existing estimates.[2] Existing literature generally does not separately estimate charging station elasticities for level 2 and level 3 chargers, with the exception of Sommer and Vance (2021), who, using German data, find a substantially higher but imprecisely estimated elasticity for level 3 stations. We conservatively set $\eta_2 = \eta_3 = 0.37$ based on Springel (2021).[3]

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 percent on average from 2010 to 2019; we adjust this downward to 4 percent annual cost declines to conservatively factor in soft costs, which we do not expect to decline as quickly as hardware costs. Similarly, we choose annual battery cost declines of 9 percent by adjusting downward recent estimates of 13 percent to 17 percent (Ziegler and Trancik 2021).

Using Alternative Fuels Data Center data indicating that the average number of ports is two in level 2 stations and four in level 3 stations, and assuming a full installed cost of \$2,000 and \$100,000 per port for level 2 and level 3, respectively, we set level 2 station cost to \$4,000 and level 3 station cost to \$400,000.

Three parameters are calibrated. We set 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, and we set κ_3 such that the full-penetration number of level 3 stations is 60,000 based on the observed number of gas stations. We calibrate the drift term in our law of motion for EV preference (ψ_{jt}) so that our forecasted EV penetration aligns with IHS Markit's projection for 2030. Our goal is not to accurately forecast EV penetration absent new policy but to project policy impacts relative to the baseline. We implement the baseline by choosing the drift parameter in the ψ_{jt} process so that the mean EV penetration rate in 2030 over Monte Carlo draws is 36.6 percent.

II. Policies

The IIJA contains two subsidy programs for EV chargers: \$5 billion in grants to states for subsidizing EV chargers along interstate highways and other major travel corridors with an 80 percent federal cost share, and \$2.5 billion for alternative fuel infrastructure (including EV chargers, hydrogen, and natural gas, with 50 percent in low-income locations). The IRA contains a 30 percent tax credit through 2032

[2] These include estimates of −1.5 to −2.1 in Norway (Springel 2021); of −1.23 (Li et al. 2017), −1.02 (Zhou and Li 2018), −2.7 (Li 2016), and −2.75 (Xing, Leard, and Li 2021) in the United States; and of −3.3 for low- and middle-income households in California (Muehlegger and Rapson 2018).

[3] Some other estimates in the literature are higher: 0.84 in Li et al. (2017), 0.4–1.4 in Zhou and Li (2018), 0.54 in Sommer and Vance (2021) for level 2, and 0.26 in Xing, Leard, and Li (2021).

for chargers installed in census tracts (i) with a poverty rate of at least 20 percent, (ii) with median household income below 80 percent of the state median, or (iii) in a nonurban area (which we define as at least 50 percent nonurban), conditions satisfied by 99.6 percent of census tracts.

The IRA replaces the existing federal EV purchase tax credit with a credit of $3,750 if an increasing fraction of battery minerals are sourced from free trade agreement countries, plus $3,750 if an increasing fraction of the battery value is assembled in North America, subject to a cap on the consumer's income ($300,000 for married filing jointly; 96.1 percent of households qualify) and on the vehicle price. Starting in 2024, this credit is transferable to a dealer, so it is in effect a point-of-sale rebate. The IRA also introduces a $4,000 tax credit for purchasing a used EV from a dealer, with stricter income and sales price caps than the new EV tax credit.

The availability and incidence of these incentives is difficult to estimate ex ante. We assume that IIJA will fund $5 billion of level 3 chargers and between $0 and $2.5 billion of level 2 chargers, both with an 80 percent federal cost share. Concerning new sales incentives, if the marginal cost of qualified mining and battery manufacturing is the same as the nonqualified counterparts, then all new EVs would eventually qualify, and the tax incentive would largely be passed on to the consumer. On the other hand, if qualifying sourcing incurs additional marginal cost, the $7,500 credit would in part cover those higher production costs, and the consumer could see only a fraction of the tax credit. Similarly, if used EVs are in fixed supply, the used EV tax credit theoretically would accrue to the seller, although in practice the incidence might be shared among the seller, dealer, and used EV buyer. We address these uncertainties by considering several tax credit scenarios.

We compute the total fiscal cost of each policy. CO_2 emissions trajectories by year under each policy are computed using Corporate Average Fuel Economy standards and EV emissions induced on the margin from the additional electricity demand from the EVs. EV marginal power sector emissions are computed using simulation results from Stock and Stuart (2021).

III. Results

The simulation results are summarized in Table 1. Columns 1–4 describe the policies: the total charging station budget, whether the IRA charging station 30 percent tax credit is in place (expiring in 2032), and the EV sales rebate accruing to the consumer and paid by the government. Columns 5–7 present the EV sales share achieved in 2030, the emissions reductions achieved in 2030 relative to the baseline, and the discounted private resource costs per ton of CO_2 abated over the lifetime of the policy. Column 8 provides total fiscal spending through 2031; the online Appendix presents spending on the charging station cost-share program, the EV rebate program, and inframarginal rebates—that is, rebates that go to consumers who would have purchased an EV if the neither the charging station nor rebate programs were in place.

The first row (row 0) summarizes the pre–IIJA/IRA baseline (no policy). Block I simulates various provisions of the IIJA and the IRA. Scenario I1 implements the IIJA as an 80 percent subsidy to new level 3 charging stations every year until total government spending reaches $5 billion; I2 adds an additional $2.5 billion for level 2 chargers. I3 implements the 30 percent charging subsidy from the IRA alone. I4 implements the charging provisions of the IIJA and the IRA. I5 through I8 implement the IRA rebate for new EV purchases under varying assumptions. In I5, the consumer receives only one of the two $3,750 rebates and none of the used EV purchase credit. In I6, the consumer receives $3,750 plus the present discounted value of the used EV purchase credit. I7 and I8 assume that the consumer receives the full $7,500 credit, with no pass-through of the used EV credit in I6 and full pass-through of the present-discounted $4,000 in I7. Taking I6 as our benchmark IRA rebate implementation, I9 combines this with the 30 percent charging station subsidy, and I10 additionally adds the $5 billion in IIJA subsidies. I10 is our benchmark scenario for the combined impact of the IIJA and the IRA.

The E block in Table 1 considers combinations of charging station and rebate policies, for which the total fiscal cost (the two policies combined) is in the range of $263 billion to $275 billion. The table suggests the following results.

TABLE 1—MAIN SIMULATION RESULTS

	Policies				EV share and emissions			Fiscal costs through 2031 ($B, not discounted) (8)
	Station subsidies		EV sales rebate					
	Budget ($B) (1)	IRA (2)	Rebate (3)	Expenditures (4)	EV sales share by 2030 (5)	Δ CO_2 in 2030 (mmt) (6)	Cost per ton CO_2 avoided (7)	
0	—	—	—	—	0.366	—	—	—
I1	5	—	—	—	0.442	−31	97	6
I2	7.5	—	—	—	0.439	−40	107	9
I3	—	0.3	—	—	0.422	−15	90	4
I4	5	0.3	—	—	0.469	−42	102	10
I5	—	—	3,604	6,872	0.433	−20	63	286
I6	—	—	6,410	6,872	0.490	−37	66	332
I7	—	—	7,208	10,476	0.506	−43	67	528
I8	—	—	10,014	10,476	0.565	−63	71	608
I9	—	0.3	6,410	6,872	0.546	−54	80	382
I10	5	0.3	6,410	6,872	0.577	−80	95	451
E1	8	—	4,400	4,400	0.480	−64	100	263
E2	15	—	3,900	3,900	0.561	−86	107	273
E3	25	—	3,500	3,500	0.643	−99	110	275
E4	28	—	3,400	3,400	0.658	−100	110	273
E5	30	—	3,250	3,250	0.665	−100	111	265
E6	40	—	3,100	3,100	0.679	−110	113	263

Note: In I2, the budget is split between $5 billion for level 3 stations and $2.5 billion for level 2 chargers.

(i) The IIJA's charging station policy alone has a substantial effect on EV sales, increasing the EV share by 7.3 percentage points for the case in which the $2.5 billion program is fully spent on charging stations.

(ii) The comprehensive EV rebate and charging station program based on the IRA induces significant additional EV sales, by 18 percentage points (I9 versus 0).

(iii) The total cost of the IIJA and the IRA is large, estimated to be $451 billion in our benchmark specification (I10). This is an order of magnitude greater than the official $15.6 billion estimated cost of these provisions (Congressional Budget Office 2022). The arithmetic is straightforward. As a back-of-envelope estimate, suppose that the 2030 50 percent EV share is achieved, so 8.5 million more EVs are sold, and that the average tax credit (taking into account credits for both new and used EVs) is $10,000; then total expenditures are $85 billion in 2030 alone.

(iv) Spending on charging stations is more effective than spending on rebates. In the E block, for which the total fiscal cost is held approximately constant at $263 billion to $275 billion, shifting $30 billion 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 48 percent to 68 percent. Along with this increase in EV penetration is a near doubling in CO_2 abatement relative to the no-policy case.

(v) All policy combinations in Table 1 pass a cost-benefit test using the most recent EPA estimate of the SCC ($190 per ton). For example, in the benchmark IIJA/IRA implementation (I10), the estimated cost of the policy is $95 per ton of CO_2 abated.

(vi) The EV rebate programs involve substantial inframarginal transfers to those who would have purchased an EV even in the baseline. For example, in the E block, inframarginal transfers range from 40.3 percent of government spending in the lowest-rebate case (E6) to 57.0 percent of government spending in the highest-rebate case (E1).

A. *Sensitivity Analysis*

We consider three sets of sensitivity checks, with full simulation results included in the online Appendix. The first matches the EIA's projection of a 3.8 percent EV share in 2030. The second uses a baseline assumption of 20 percent in 2030. The last uses the baseline penetration of Table 1 but chooses a lower elasticity for charging stations and a higher price elasticity by setting $\eta_2 = \eta_3 = 0.2$ and $\eta_P = -3.5$ in vehicle demand. These parameters were chosen to examine the sensitivity of our findings of the relative effectiveness of fiscal spending on charging stations over rebates.

Under both low-penetration baselines, spending on charging stations remains substantially more effective per fiscal dollar than spending on rebates: moving from the high-rebate case (E1) to the high–station subsidy case (E6) increases the EV share by 21 percentage points in the 20 percent baseline and 4.4 percentage points in the 3.8 percent baseline. Even under the lowest (3.8 percent) baseline, our estimate of the combined costs of the IRA and the IIJA is $130 billion.

As expected, the charger subsidy program has reduced effectiveness in the low-charger/high–price elasticity case. Still, reallocating $30 billion to charging stations from E1 to E6 increases 2030 EV penetration by 9.2 percentage points while reducing fiscal expenditures by $27 billion. In this scenario, the benchmark estimate for the IRA and the IIJA costs $444 billion.

B. *Uncertainty*

These point estimates are subject to estimation uncertainty associated with the model parameters, such as the elasticities, and projection uncertainty, such as for oil price projections. The parameters are taken from various studies, so their joint distributions are not available. In the online Appendix, we present uncertainty estimates that treat the parameters as independent using Monte Carlo simulations. There is considerable uncertainty around the projected penetration rates—for example, in the benchmark no-policy case, the 90 percent Monte Carlo band for 2030 penetration is 10.6 percent to 72.7 percent. The uncertainty associated with the marginal policy effects (which controls for baseline uncertainty) is less. Our benchmark estimate of the combined effect of the IIJA and the IRA has a 90 percent uncertainty band of 12.3 percent to 27.2 percent, with a mean of 21.1 percent.

IV. Discussion

We find that the combined EV provisions of the IIJA and the IRA substantially expedite the transition to EVs, at a cost per ton well below the EPA's recent estimate of the SCC. Subsidizing charging stations is considerably more effective in boosting EV sales and reducing carbon emissions than subsidizing EV sales is. The North American content provisions and the uncertain incidence of the used EV tax credit complicate analysis of the tax credits in the IRA.

Our finding that charging station subsidies are especially effective derives from elasticity estimates in the literature, but it also makes sense intuitively. For individuals who cannot install their own chargers—for example, because they park on a street or live in an apartment building—if public charging is unavailable, then buying an EV simply isn't an option, regardless of how deep the subsidy is. For them, providing additional charging stations enables EV ownership. 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. Additional level 3 chargers reduce range anxiety and make it possible to use EVs in the way that drivers now use ICEs. Moreover, much of the spending on tax credits is inframarginal: it consists of transfers to individuals who would have purchased an EV whether or not the tax credit we study exists, reducing the efficiency of purchase subsidies.

This analysis makes many simplifications and has limitations. Most notably, the model operates at the level of drive train choice and sweeps all other vehicle characteristics into unobserved shift parameters; a modest extension would allow choice between cars and SUVs, while a more granular approach would operate at the choice of vehicle model and would project new EV models that will be coming out over this decade. The model does not incorporate ICE bans proposed or adopted by several states, which would shift the baseline to deeper penetration, nor does it incorporate lags in EV production capacity as factories are built and supply chains are developed. Importantly, the charger component of the model does not address the critical question of charger location. Addressing these limitations is a topic of ongoing research.

REFERENCES

Bresnahan, Timothy, and Peter Reiss. 1991. "Entry and Competition in Concentrated Markets." *Journal of Political Economy* 99 (5): 977–1009.

Congressional Budget Office. 2022. *Summary: Estimated Budgetary Effects of H.R. 5376, the Inflation Reduction Act of 2022*. https://www.cbo.gov/publication/58455.

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

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

Lutsey, Nic, and Michael Nicholas. 2019. "Update on Electric Vehicle Costs in the United States through 2030." Unpublished.

Muehlegger, Erich, and David S. Rapson. 2018. "Subsidizing Mass Adoption of Electric Vehicle: Quasi-Experimental Evidence from California." NBER Working Paper 25359.

Sommer, Stephan, and Colin Vance. 2021. "Do More Chargers Mean More Electric Cars?" *Environmental Research Letters* 16: 064092.

Springel, Katalin. 2021. "Network Externality and Subsidy Structure in Two-Sided Markets: Evidence from Electric Vehicle Incentives." *American Economic Journal: Economic Policy* 4 (13): 393–432.

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

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

Zhou, Yiyi, and Shanjun Li. 2018. "Technology Adoption and Critical Mass: The Case of the U.S. Electric Vehicle Market." *Journal of Industrial Economics* 66 (2): 423–80.

Ziegler, Micah S., and Jessika E. Trancik. 2021. "Re-examining Rates of Lithium-Ion Battery Technology Improvement and Cost Decline." *Energy & Environmental Science* 14: 1635–51.