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

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The decarbonization of the light duty vehicle (LDV) sector is a major policy priority in the United States as LDV operations account for 58% of transportation emissions of carbon dioxide (CO_2) in the U.S. in 2019. The Biden administration has declared a target of 50% of new vehicle sales in 2030 comprising zero-emissions vehicles. As automakers have announced ambitious plans for expanding their production of 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 is not a certainty, and public policies could play an important role in expediting the transition. To this end, two recent Acts of the U.S. Congress, the Infrastructure Investment and Jobs Act of 2021 (IIJA) and the Inflation Reduction Act of 2022 (IRA) provide subsidies and tax incentives to prmote EV sales and deployment of EV charging infrastructure.

In this paper, we use discrete choice model of EV adoption to 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. In addition, we estimate the costs of these policies, measured in dollars per ton of CO2 abated, which can be compared to their social benefits in reduced emissions. a variety of policies have been proposed to spur electrification of the US EV fleet. Included among these are fiscal policies subsidizing charging stations and consumer EV purchases. To evaluate these policies, we use a joint model of charging station supply and EV demand. In brief, we estimate that the modeled provisions of the IIJA and IRA increase the 2030 EV share of new LDV sales by 17 percentage points, reduce U.S. CO2 emissions by 60 million metric tons in 2020, and have costs of approximately $93 per ton of CO2 abated, well below the most recent Environmental Protection Agency estimate of the Social Cost of Carbon (SCC) of $190/ton. We also estimate the total (undiscounted) fiscal cost of these policies to be $384 billion through 2031, an order of magnitude greater than the official Congressional cost estimate of $10.6 billion (CBO 2022).

I. Model

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

A. 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 including SUVs and minivans. The model holds the share of each class fixed for simplicity. Within each vehicle class, consumers indxed 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 and its utility is normlized to be 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:

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

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 sta-

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tions 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, capturing the congestion effect for 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 the 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 Equation (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 k charging station supply is $\eta_k = (1-s_{jt})\beta_k$.

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 themselves 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.

The value of a firm entering the market for level k 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 entering 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). 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:

$$\pi_t^k(N_t^k, Q_t) = (exp(\kappa_k)/(N_t^k))^{\frac{1}{\gamma}} Q_t,$$

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

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

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% of the cost of a 2020 charging station.

C. 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, 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 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 vs. 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, emphasizing those studies which examine network effects between EV and charging station stocks. These include estimates of -1.5 to -2.1 in Norway (Springel, 2021); -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 US; and -3.3 for low- and middle-income households in California (Muehlegger and Rapson, 2019).

Existing literature does not separately estimate charging station elasticities for level 2 and level 3 chargers. We conservatively set $\eta_2 = \eta_3 = 0.37$ based on Springel (2021), while some other estimates in the literature are higher: 0.84 in Li et al. (2017), 0.4-1.4 in Zhou and Li (2018), and 0.26 in Xing, Leard and Li (2021).

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. Similarly, we choose annual battery cost declines of 9% by adjusting downward recent estimates of 13% to 17% (Ziegler and Trancik, 2021).

Using AFDC data indicating that the average number of ports is 2 in level-2 stations and 4 in level-3 stations and assuming a full installed cost 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.

Three parameters are calibrated. First, 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 EV/L3 ratio is 60,000 based on the observed ratio of gas stations to ICE vehicles. Finally, we calibrate the drift term in our law of motion for EV preference ($\psi_j t$) so that our forecasted EV penetration is 36/6% to align with IHS Markit's projection for 2030. Our goal is not to accurately forecast EV penetration in the no-policy baseline, but to project policy impacts relative to that baseline. We implement the 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 36.6%.

II. Policies

The IIJA contains two subsidy programs for EV chargers: $5B of grants to states for subsidizing EV chargers along interstate highways and other major travel corridors, and $2.5B for alternative fuel infrastructure (including EV chargers, hydrogen, and natural gas), with 50% in low- income locations. The IRA contains a 30% tax credit for new chargers through 2030, for chargers installed in census tracts with 1) a poverty rate of at least 20%, 2) a median household income below 80% of the state median household income, or 3) in a non-urban area (which we define as at least 50% non-urban), conditions satisfied by 99.6% of census tracts.

The IRA replaces the existing federal EV purchase tax credit with a tax credit of $3750 if an increasing percent of battery minerals are sourced from free trade agreement countries plus $3750 if an increasing percent 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% of households qualify) and on the vehicle price. Starting 2024, this credit is transferable to a dealer so is in effect a point-of-sale rebate. In addition, the IRA introduces a $4000 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 $5B of Level 3 chargers and between 0 and $2.5B of Level 2 chargers, with a cost share. Concerning new sales incentives, if the marginal cost of qualified mining and battery manufacturing is the same as the non-qualified 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 $7500 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. Carbon dioxide emissions trajectories by year under each policy are computed using CAFE fuel efficiency 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 III. Columns 1-6 describe the policies: the federal fraction of the charging station cost-share, the total charging station budget, whether the IRA charging station 30% tax credit is in place (expiring 2032), and the EV sales rebate accruing to the consumer and paid by the government. Columns 7-9 present the EV sales share achieved by 2030, emissions reductions achieved in 2030 relative to the baseline, and the cost per ton of CO_2 abated over the lifetime of the policy. Columns 10-13 provide fiscal detail: total fiscal spending through 2031, 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 if the neither the charging station nor rebate programs were in place.

The first row (row 0) summarizes the pre-IIJA/IRA (no policy). Block I simulates various implementations of the IIJA and IRA. Scenarios I1 implements the IIJA as an 80% 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% charging subsidy from teh IRA alone. I4 through I7 implement the IRA rebate for new EV purchases under varying assumptions. In I4, the consumer receives only one of the two $3750 rebates and none of the used EV purchase credit. In I5, the consumer receives $3750 plus the present discounted value of the used EV purchase credit. I6 and I7 assume the consumer receives the full $7500 credit, with no pass-through of the used EV credit in I6 and full pass-through of the present-dscounted $4000 in I7. Taking I5 as our benchmark IRA rebate implementation, I8 combines this with the 30% charging station subsidy and I9 additionally adds the $5 billion in IIJA subsidies. I9 is our benchmark scenario for the combined impact of the IIJA and IRA.

The E block in Table III considers combinations of charging station and rebate policies for which the total fiscal cost (the two policies combined) is in the range of $244B-$265B. The tables suggest the following results.

1) The IIJA's charging station policy alone has a substantial effect on EV sales, increasing the EV share by 3.8 percentage points for the case in which the $2.5 billion program is fully spent on charging stations.

2) The comprehensive EV rebate and charging station program based on the IRA induces significant additional EV sales, by 17.1 percentage points (I8 vs. 0).

3) The total cost of the IIJA and IRA is large, estimated to be $384 billion in our benchmark specification (I9). This is an order of magnitude greater than the official $10.6 billion estimated cost of these provisions (Congressional Budget Office 2022).

4) 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 $244-265B, shifting $35B 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 49% to 65%. Along with this increase in EV penetration is a doubling in CO_2 abatement, relative to the no-policy case.

5) All policy combinations in table III pass a cost-benefit test using the most recent EPA

TABLE 1—MAIN SIMULATION RESULTS

	Policies						EV share & Emissions			Fiscal costs through 2031 ($B, not discounted)			
	Station cost share				EV sales rebate								
	Level 2	Level 3	Budget ($B)	IRA	Rebate	Expenditures	EV Sales Share by 2030	Δ CO_2 in 2030 (mmt)	Cost per ton CO_2 avoided	Total	Chargers	Rebates	Inframarginal Rebates
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
0	-	-	-	-	-	-	0.372	-	-	-	-	-	-
I1	-	0.8	5	-	-	-	0.392	-15	114	7	7	-	-
I2	0.8	0.8	8	-	-	-	0.410	-26	122	11	11	-	-
I3	-	-	-	0.3	-	-	0.429	-15	97	7	7	-	-
I4	-	-	-	-	3420	6511	0.436	-18	66	268	-	268	117
I5	-	-	-	-	5917	6511	0.486	-34	69	307	-	307	202
I6	-	-	-	-	6840	10115	0.505	-40	70	500	-	500	234
I7	-	-	-	-	9337	10115	0.557	-58	73	568	-	568	319
I8	-	-	-	0.3	5917	6511	0.543	-51	84	357	9	348	202
I9	-	0.8	5	0.3	5917	6511	0.548	-60	93	384	14	370	202
E1	0.7	0.7	8	-	4700	4700	0.486	-49	93	255	10	245	160
E2	0.7	0.7	15	-	4000	4000	0.545	-66	102	249	17	232	137
E3	0.7	0.7	25	-	3750	3750	0.610	-79	108	265	27	237	128
E4	0.8	0.8	28	-	3500	3500	0.619	-85	112	260	31	229	120
E5	0.8	0.8	30	-	3250	3250	0.619	-91	116	253	34	219	111
E6	0.9	0.9	40	-	2750	2750	0.651	-103	123	244	46	198	94

estimate of the SCC ($190/ton). For example, in the enchmark IIJA/IRA implementation (I9) the estimated cost of the policy is $93 per ton of CO_2 abated.

6) 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 38.5% of government spending in the lowest-rebate case (E6) to 62.7% of government spending in the highest-rebate case (E1).

A. *Sensitivity analysis*

We consider two sets of sensitivity checks, with full simulation results included in the online appendix. The first uses a baseline assumption of 20% EV penetration in 2030. The second uses the baseline penetration of Table III but 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. 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.

Under the lower penetration baseline scenario, fewer charging stations are built endogenously under the baseline, so there are fewer inframarginal transfers on charging stations and charging station costs per ton are higher than in the benchmark case. 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.

As expected, the charger subsidy program has reduced effectiveness in the low-charger/high price elasticity case 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.

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 prior studies so their joint distributions are not available. In the online appendix, we report uncertainty estimates that treat these sources of uncertainty as independent and compute standard errors for the estimated policy effects by Monte Carlo simulation. There is considerable uncertainty around the projected penetration rates, for example in the benchmark no-policy case the 90% Monte Carlo band for 2030 penetration is 10.6% to 72.7% (mean of 36.6%). The uncertainty associated with the marginal policy effects (which controls for baseline uncertainty) is less, for example our benchmark estimate of the combined effect of the IIJA and IRA has a 90% Monte Carlo uncertainty band of 9.8% to 23.0%, with mean of 17.4%.

IV. Discussion

We find that the combined EV provisions of the IIJA and IRA substantially expedite the transition to EVs, at a cost per ton well below the EPA's recent estimate of the Social Cost of Carbon. Among these provisions, we find that those subsidizing charging stations is substantially more effective in boosting EV sales and reducing CO2 emissions than those subsidizing new and used EV sales. The North American content provisions of the IRA and the uncertain incidence of the used EV tax credit further complicate estimating the effect of the EV purchase tax credits in the IRA.

Our finding that charging station subsidies are especially effective derives from elasticity estimates in the literature, but 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 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. Moreover, 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, 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: 977–1009.

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

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." Working paper.

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

Springel, Katalin. 2021. "Network Externality and Subsidy Structure in Two-Sided Markets: Evidence from Electric Vehicle Incentives." *American Economic Journal: Economic Policy*, , (4): 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." *The Journal of Industrial Economics*, 66(2): 423–480.

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