Environmental Science & Technology

Article

Cite This: *Environ. Sci. Technol.* XXXX, XXX, XXX−XXX

pubs.acs.org/est

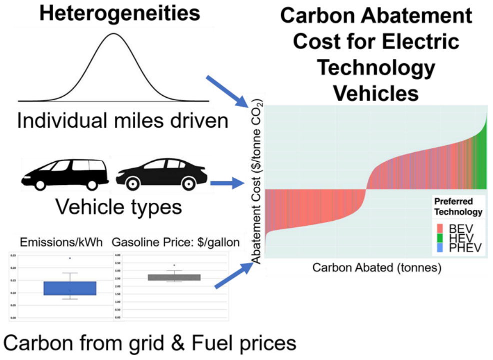
Heterogeneity in Economic and Carbon Benefits of Electric Technology Vehicles in the US

Ranjit R. Desai,*[†,$] Roger B. Chen,[‡] Eric Hittinger,[§] and Eric Williams[†]

[†]Golisano Institute for Sustainability, Rochester Institute of Technology, Rochester, New York 14623, United States
[‡]Department of Civil and Environmental Engineering, University of Hawaii, Manoa, Honolulu, Hawaii 96822, United States
[§]Department of Public Policy, College of Liberal Arts, Rochester Institute of Technology, Rochester, New York 14623, United States

Supporting Information

ABSTRACT: To broadly contribute to sustainable mobility, electric technology vehicles (hybrid, electric, and plug-in-hybrid) must become more price competitive with internal combustion vehicles. This study assesses the economic and carbon benefits of electric technology vehicles in the U.S., accounting for household-by-household behavioral variability and geographical differences in fuel and electricity prices. This finer resolution provides insight into subsets of the population for whom adoption is economically or environmentally favorable, allowing us to construct marginal abatement cost curves for CO_2 that account for geographic, behavioral, and stock heterogeneities. Currently, low gasoline prices and high initial expense means that, without subsidies, few consumers benefit financially from electric technology vehicles (1.7% of drivers). However, improved technology dramatically and nonlinearly increases both the number of consumers that benefit and corresponding carbon emissions that could be abated without government subsidy. Our results clarify cost targets that electric vehicle technology must achieve in order to deliver net financial and subsidy-free environmental benefits.



INTRODUCTION

Transportation is a necessity of daily life but also accounts for a large share of greenhouse gas (GHG) emissions in the United States (U.S.) and the world. In the U.S., the transport sector emits 1782 million metric tonnes of CO_2e (MMT CO_2e) (28% of all U.S. emissions) with 60% of that due to light-duty vehicles (i.e., private transport).[1,2] Globally, transportation accounts for 23% of energy-related greenhouse gas emissions and 92% of total oil consumption.[3] For these reasons, decarbonization of transportation is a critical part of controlling atmospheric GHG concentrations. Furthermore, the current Intergovernmental Panel on Climate Change (IPCC) report recommends "rapid and far-reaching" efforts in the transport sector to limit global warming to 1.5 °C[4,5] as well as to achieve the 2 °C target set in the Paris Accords.[6]

Electric Technology Vehicles (ETV) are a leading solution for decarbonizing transportation.[7−9] In this paper, the term Electric Technology Vehicle (ETV) is used to include Hybrid Electric Vehicles (HEV), Battery Electric Vehicles (BEV), and Plug-in Hybrid Electric Vehicles (PHEV). An electric drivetrain, common to all three types, improves efficiency. Batteries provide flexibility to run vehicles on electricity derived from different fuel mixes, ideally low carbon ones. Governments around the world have been investing significantly to encourage consumers to adopt electric vehicles.[10] In the U.S., for example, the federal government provides tax credits up to $7500 for the purchase of BEVs and PHEVs.[11]

Despite considerable government investment and societal attention given to electric vehicles, there are critical unanswered questions. An important one is what economic benefits do Electric Technology Vehicles deliver to consumers? However, there is as yet no analysis accounting for both the behavioral and spatial heterogeneity in the answer. There is substantial variability in driving patterns, preferred vehicle type, and gasoline and electricity prices. In the U.S., the average annual distance driven, as estimated from the National Household Travel Survey (NHTS) for this work, is 11700 miles with a large standard deviation of 10040 miles.[12] Moreover, consumers own vehicles of different makes, models, and types of vehicles from other consumers, e.g., 52% drive passenger cars and station wagons and 21% drive Sport Utility Vehicles (SUVs). Gasoline and electricity prices vary by location. In 2017, the average gasoline price in the U.S. was $2.53 per gallon with a standard deviation of $0.12 per gallon.[13] South Carolina had the lowest gasoline price of $2.13 per gallon, whereas Hawaii had the costliest gasoline at $3.09 per gallon. Similar variations can be seen in electricity prices. The average electricity price in the U.S. was 10.3 cents per kWh with a standard deviation of 3.3 cents. Residents of Louisiana paid 7.5 cents per kWh compared to

Received: May 14, 2019
Revised: November 7, 2019
Accepted: November 13, 2019
Published: November 13, 2019

DOI: 10.1021/acs.est.9b02874
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

those in Hawaii who paid 24 cents per kWh.[14] The above heterogeneities are expected to give rise to substantial variability in fuel savings from purchasing an electric technology vehicle.

Currently, the most resolved analysis of the economic benefits of electric vehicles is at the city level.[15−17] Results indicate that an average driver gets economic benefits in 3 of 14 U.S. cities with the highest subsidies, from current electric vehicles (EV).[15] Other prior economic studies of benefits are at the state level.[18,19] However, individual variations in driving patterns within cities and states must be accounted for. Also, as electric technology vehicles are part of national energy strategies, a national-level analysis of economic benefits to consumers is overdue. We address this gap with a case study of the U.S. using individual responses regarding vehicle ownership and usage from the National Household Travel Survey (NHTS).[12] The NHTS includes annual miles driven on a particular vehicle which is calculated using one-day travel activity, odometer reading of the vehicle, user-reported annual miles driven, and demographic information on the primary user of the vehicle.[20]

While a national analysis of the economic benefits of current Electric Technology Vehicles (with and without subsidy) is certainly useful, it is also important to consider technological progress. Motivations behind the U.S. EV subsidy include an expectation that the subsidy will support future cost reductions of the emerging technology. Recent price reductions in vehicle batteries support optimism that EV technology will continue to improve.[21−23] We thus also analyze how the population of U.S. consumers that benefit from electric technology vehicles grows as technology costs fall. In addition, the economic benefits from electric technology vehicles are sensitive to gasoline and electricity prices. Temporal variability in gasoline prices is particularly high due to volatility in the global market for crude oil.

The carbon benefits of Electric Technology Vehicles depend on the electrical grid they use to charge. Running an EV from coal-generated electricity can actually increase emissions.[24,25] There is considerable geographical variability in grid mixes and ensuing carbon benefits in switching from gasoline to EVs. This dependence of EV carbon reductions on location has been studied in detail. Prior results for the U.S. have shown that the regional variation in grid mixes and average miles driven significantly affect the emissions from EV usage.[25−29] For example, Graff-Zivin et al. found substantial variation in the marginal emissions of electricity varying with respect to location and time-of-use,[24] e.g., the upper Midwest region showing three times higher marginal emission rates compared to the western U.S.

An analysis of EV emission benefits should account for the life cycle,[25,27−32] though some studies limit their focus to the use phase.[24,33−35] Manufacturing ETVs is carbon intensive compared to conventional vehicles,[25,28,30,36] thus the inclusion of manufacturing tends to decrease the carbon benefits of ETVs. Note that the literature indicates a wide range of estimates of emissions from vehicle manufacturing; there are also indications that these emissions may be falling over time, in particular for battery manufacturing.[31,37,38] The upstream emissions for producing and distributing gasoline are significant and higher than those for electricity (2400 g CO_2e/gallon for gasoline versus 72.5 g CO_2e/kWh for electricity[29]). Accounting for upstream emissions for fuel production thus increases the relative carbon benefits of ETVs.

Our work addresses an important question: What is the cost-effectiveness of electric technology vehicles as a carbon mitigation option considering that economic and grid emission benefits vary by behavior and location? We address this question by modifying the usual Carbon Marginal Abatement Cost Curve (MACC) (\$/$MTCO_2e$) to account for heterogeneity. The marginal abatement cost curve (MACC) is often used by policy analysts,[39,40] and typically shows abatement cost (e.g., \$/$MTCO_2e$) and total abatement potential ($MTCO_2e$) for a given set of interventions. Interventions are ordered from least to highest cost of mitigation. Prior MACC analyses represent technology in terms of an average user, neglecting heterogeneity. This is reasonable when assessing 100% adoption of a technology. However, given observed behavioral heterogeneity (e.g., Sekar et al., 2016[41]), it is important to consider mitigation paths in which technologies are adopted by subgroups that benefit the most. Consider an example of a technology intervention with a net economic cost to the average consumer. It may be that the population divides into one group that saves money with the technology and another that does not. Considerable carbon savings with negative cost may be possible considering adoption by the first group. Segmenting the population according to relative benefits can thus upend the understanding of the carbon mitigation costs of a technology. We will show that this is the case for electric technology vehicles in the U.S.

Using the usual aggregated approach, marginal abatement costs for carbon have been assessed in the transportation sector.[42−44] For example, New York City projected marginal abatement costs for battery electric vehicles at \$80 per $MTCO_2e$ in 2020 and −\$10 per $MTCO_2e$ in 2030, and for PHEVs, \$90 per $MTCO_2e$ in 2020 and −\$10 per $MTCO_2e$ in 2030.[42] The transition from positive to negative cost between 2020 and 2030 is due to assumptions about the cost reduction of electric technology vehicles. Morisugi et al. calculated the abatement costs in the U.S. for different CO_2 emission tax levels to be \$234−399 per $MTCO_2e$ with a CO_2 emission tax of \$100 per $MTCO_2e$ for the transportation sector.[43] These previous studies have not included behavioral heterogeneity in estimating carbon abatement costs.

The model presented in this paper characterizes the economic and carbon implications of an electric technology vehicle purchase. Other relevant work has studied other aspects of vehicle choice, such as whether fuel efficiency affects consumers' purchase decisions.[45−49] And, against the popular belief that fuel economy standards help consumers financially,[47] studies have found that consumers do not correctly value high energy-efficient investments.[46] Personal vehicle purchases are well-studied, often using discrete choice models.[50,51,60,52−59] These studies show that vehicle purchase decisions depend on several factors, including economics. As we are limited by data used for this study, we focus on Total Cost of Ownership, which captures the capital and operating costs associated with a purchase of a vehicle.[61,62] While understanding the conditions under which and the rate at which consumers would actually purchase electric technology vehicles is critical, we consider a narrower question for a number of reasons. First, economic and carbon savings are important decision variables and, as described above, have not yet been properly assessed. Second, public policies such as the federal tax subsidy for electric vehicles should be assessed for potential to deliver direct public and private benefits aside from the decision calculus of consumers.[63−65] This is particularly true for electric vehicles as consumer decisions will depend on what fleet of electric technology vehicles is brought to the market, the outcome of which is difficult to predict and depends partly on

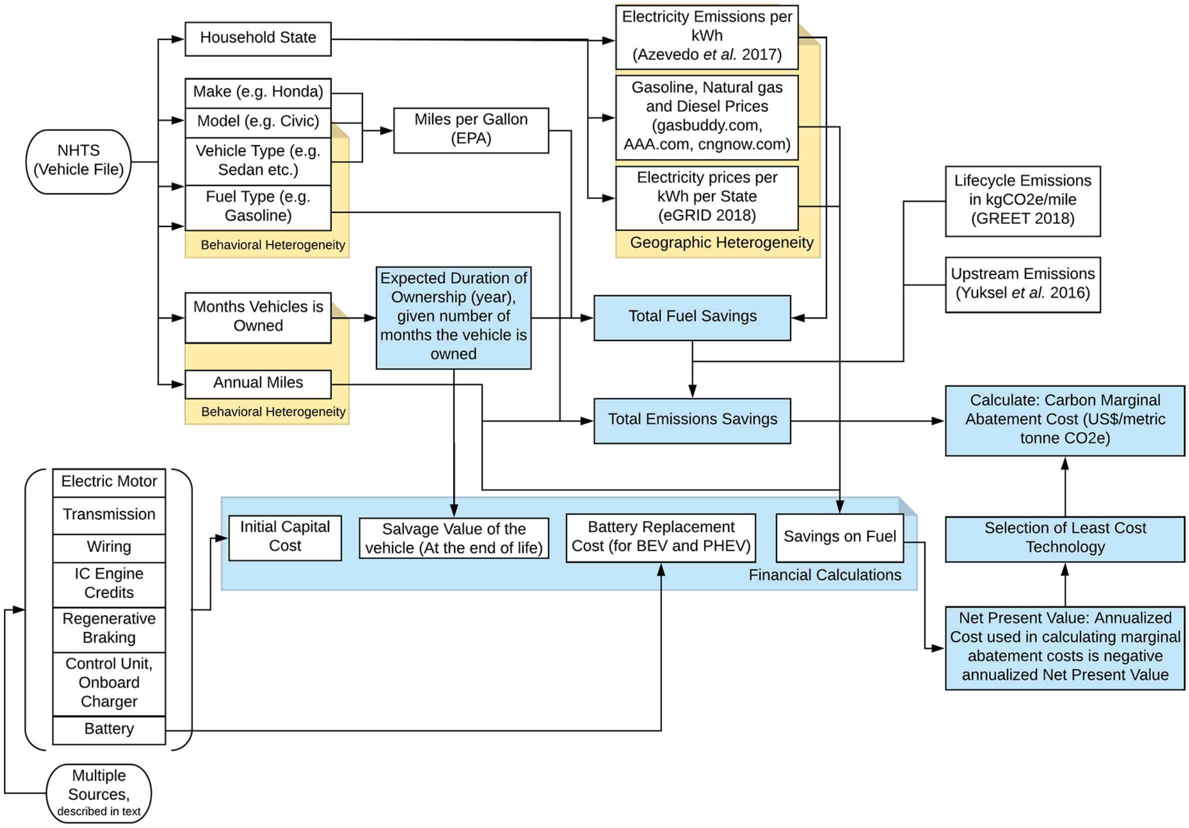


Figure 1. Methodological framework. The diagram shows the flow of data and calculations and indicates data sources used, such as the National Household Travel Survey[12] and others.[2,28,29,66−72] Blue backgrounds refer to model calculations; yellow backgrounds show types of heterogeneity analyzed.

policy decisions. While decision science should be brought to bear to understand electric vehicle technology adoption, there is a complementary role from a purely accounting economic perspective. Third, it is important to understand how technological progress and variations in fuel prices affect trade-offs between conventional gasoline and electric technology vehicles. The marginal abatement curve framework explored here can deliver useful, if bounded, answers to this question.

To summarize the work, we first develop a model assessing economic benefits of electric technology vehicles (hybrid, plug-in hybrid, electric) that accounts for *individual-level differences* in miles driven, type of vehicle owned (sedan, SUV, minivan and truck), and lifetime ownership preferences in the U.S. The model also considers *state-level differences* in gasoline and electricity prices and includes upstream carbon emissions associated with vehicle and fuel production. The National Household Travel Survey (NHTS) is used as the primary data source, which includes vehicle holdings characteristics for each surveyed household (a total of 309000 households and 143000 vehicles). Next, the net economic benefits (or costs) are calculated to replace each existing internal combustion vehicle with a comparable electric technology vehicle. Consumers are assumed to choose a HEV, PHEV, or BEV depending on which provides the greatest private economic benefit. This distinguishes subpopulations into groups that benefit economically from electric technology (and hence negative abatement costs) and those who do not. The economic analysis is followed by a state-by-state marginal emissions model to obtain a carbon abatement cost curve resolved consumer-by-consumer. We then consider how economic benefits and carbon abatement costs evolve with lower battery and related technology prices as well as higher gasoline prices. This is analyzed both with and without the current federal tax credit for electric and plug-in hybrid vehicles.

■ METHODS

Figure 1 shows the overall methodological framework. A detailed explanation appears in the Supporting Information but is summarized here. The National Household Travel Survey (NHTS) sample vehicle fleet is used as the main input for the vehicle-level analysis. NHTS reports the households' state of residence, used in modeling geographical heterogeneity with state-specific electricity emissions and fuel and electricity prices. The NHTS data set also reports make, model, and type of the vehicle (used to estimate the initial capital cost and mileage), number of months the vehicle is currently owned (used to estimate the expected duration of ownership of the vehicle), and number of miles driven annually (behavioral heterogeneity) for each household vehicle. In evaluating purchase of an electric technology vehicle, we assume consumers keep the same make, model, and type as their previous vehicle. Four technology options are considered: (1) updated conventional vehicle, (2) hybrid electric vehicle, (3) battery electric vehicle, and (4) plug-in hybrid electric vehicle. The meaning of *updated conventional vehicle* is the 2018 version of the model the consumers currently own. The economic and carbon implications of purchasing an ETV by comparing the ETV with the updated conventional vehicle are then assessed.

The current vehicle market does not offer ETV analogues for every available model. With this said, the suite of available ETV models is expanding rapidly. For example, there were 11 new ETV models offered in 2018 compared to 2017.[2] This evolving market presents a challenge for modeling ETV adoption. Considering only currently available ETVs would properly reflect today's options but would misrepresent choices even a few years later. Thus, we assume a developed ETV market in which there is a reasonable analogue ETV option for any current vehicle model. Therefore, ETV choice is modeled as a differential technology "upgrade" to currently sold conventional vehicles. This leads to modeling incremental cost additions of each technology type (HEV or BEV or PHEV) for each vehicle class (sedan, SUV, van, and truck). Using prior models of ETV characteristics and costs,[73−76] technical and performance specifications are designed and *additional costs* for ETVs are estimated based on a model conventional vehicle for each vehicle class. The cost model accounts for batteries, other electric vehicle (EV) systems such as electric motor, transmission and integration, control unit, onboard charging unit, regenerative breaking, and wiring, as well as credits for removing mechanical components of internal combustion engines for EVs. The battery cost and electric motor costs are scaled with respect to the battery size and power requirements for each vehicle type and are based on the International Council on Clean Transportation (ICCT) report.[77] We use a battery cell price of $230 per kWh, in line with various estimates for the year 2018 from previous studies[78−80] and reports such as Bloomberg New Energy Finance (BNEF)[81] and the Joint Technical Support Document from the U.S. Environmental Protection Agency (US-EPA).[82] In addition to capital costs, an industry markup factor of 1.46 is assumed for all vehicle components.[83]

We model operation of a vehicle in terms of annual miles driven by an individual consumer. Note that this neglects temporal variability in vehicle use, i.e., consumers driving more or less on individual days, as well as the complexity of multivehicle households choosing different vehicle types for different trips. We treat BEV range in terms of delivering average daily miles, e.g., a 100-mile range vehicle can meet demand for consumers traveling less than 365 × 100 = 36500 miles per year. We consider two BEV designs for each vehicle type, 100 and 150 miles of range, respectively. Consumers who drive more than 150 miles daily can only choose HEV or PHEV technologies. For PHEVs, it is assumed that a consumer will first operate on electricity until the battery is drained and then switch to gasoline. For both BEV and PHEV, we assume charging is available and done at the state average residential rate. Also, we neglect the effect that differences in temperature[29] and terrain have on the relative performance of ETVs and conventional vehicles. The detailed cost model is presented in Table S2 in the Supporting Information (SI) and in the attached SI excel sheet.

We calculate the Total Cost of Ownership (TCO) of an ETV in comparison with the latest conventional vehicle, accounting for factors shown in eq 1. A discount rate of 7% is assumed for this work. It is common to use 7% as the discount rate in total cost of ownership calculations.[15,84−88] Moreover, the discount rate of 7% is also suggested by the Office of Management and Budget.[89,90] The duration of car ownership for each consumer is calculated based on ownership data from NHTS. The NHTS does not report vehicle lifetimes; we derive an expected duration of ownership through random generation conditional upon the probability distribution of lifetime and survivor function given how long consumers have owned their current car; see Figure S1 in the SI. Note that the duration of car ownership varies (also shows the behavioral heterogeneity) by consumer (7 years average with standard deviation of 3.6 years). Duration determines the vehicle lifetimes used in calculating total cost of ownership and the salvage value.

$$\begin{aligned}&\text{Total cost of Ownership}\\&\quad= \text{Initial Capital cost} - \text{Discounted Fuel Savings}\\&\qquad+ \text{Discounted Battery Replacement cost}\\&\qquad- \text{Discounted Salvage Value}\end{aligned} \tag{1}$$

Battery replacement cost, given that current HEV batteries typically last the lifetime of the vehicle, are applied only to BEVs and PHEVs when the battery life is estimated to be less than 15 years (i.e., the maximum life of the vehicles assumed in this study). For BEVs and PHEVs, the life of the battery is estimated as a function of number of charging−discharging cycles and depth of discharge[91,92] (eqns S6 and S7 in the SI). The Salvage Value (or resale value of the used vehicle) is estimated as a function of years of ownership (eqns S3− S5 in the SI).[92]

Average fuel and electricity prices for each vehicle are based on the state of residence of the consumer. Average state electricity prices are from the U.S. Energy Information Agency,[72] and gasoline prices are also assigned with respect to the corresponding fuel type and U.S. State.[66−68] The fuel savings for each ETV is calculated and discounted for the expected duration of ownership as shown in eqns S8−S13 in the SI. Once the total cost of ownership is calculated for each ETV in comparison with a conventional vehicle, a *least total cost to the consumer* (i.e., the highest Net Present Value) option (preferred technology) is selected for a particular consumer. The resulting Net Present Value of purchasing an ETV is converted to Annualized Cost (US$) using an individual's lifetime ownership.

To estimate annual emissions during vehicle operation, we combine annual miles driven with fuel efficiency and marginal emission factors for electricity (MEF in $\text{kgCO}_2\text{e/kWh}$) for each state (based on state of residence) from the latest work of Azevedo et al. 2017.[69] We also account for life cycle stages of vehicle manufacturing and upstream emissions to produce gasoline and electricity. For vehicle manufacturing, we use the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model developed by the Argonne National Laboratory.[70] Emissions to manufacture an ETV or conventional vehicle are amortized over the vehicle life (to yield $\text{gCO}_2\text{e/mile}$) and converted to annual manufacturing emissions ($\text{MTCO}_2\text{e/year}$) using annual miles driven. See eqns S14−S18 in SI for details. Upstream emissions for producing gasoline ($\text{gCO}_2\text{e/gallon}$) and electricity ($\text{gCO}_2\text{e/kWh}$) are estimated using average values from Yuksel et al. 2016,[29] who used other studies to estimate these emission factors.[28,29,70,71] The final result combining operation, manufacturing, and upstream fuel emissions is an Annual Emissions Savings from adopting an ETV compared to a conventional vehicle (MTCO_2e). Note that savings from adopting ETVs can be negative when grid electricity is very carbon intensive. As will be seen in results, however, if consumers choose the ETV type (hybrid, EV, or PHEV) that yields maximum economic value, this results in carbon savings always being positive. The carbon marginal abatement cost (US$ per MTCO_2e) for purchasing an ETV compared to a conventional vehicle is the ratio of Annualized Vehicle Cost and Annualized Emissions Savings (Equation S19 in SI).

DOI: 10.1021/acs.est.9b02874
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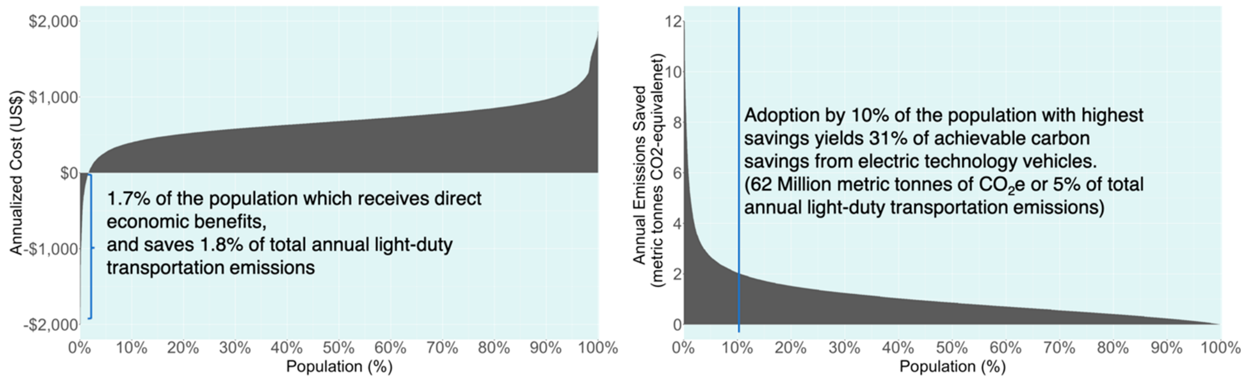

Figure 2. Unsubsidized annualized cost (US$/year) and annual emissions saved (MTCO$_2$e) from switching from conventional to an electric technology vehicle, per vehicle owned by U.S. consumers, ordered from lowest to highest cost (highest to lowest emissions savings). The left figure shows that 1.7% of the population, having negative annualized costs, directly benefits financially. The right image shows how annual emissions savings vary by person, driven primarily by heterogeneity in annual mileage.

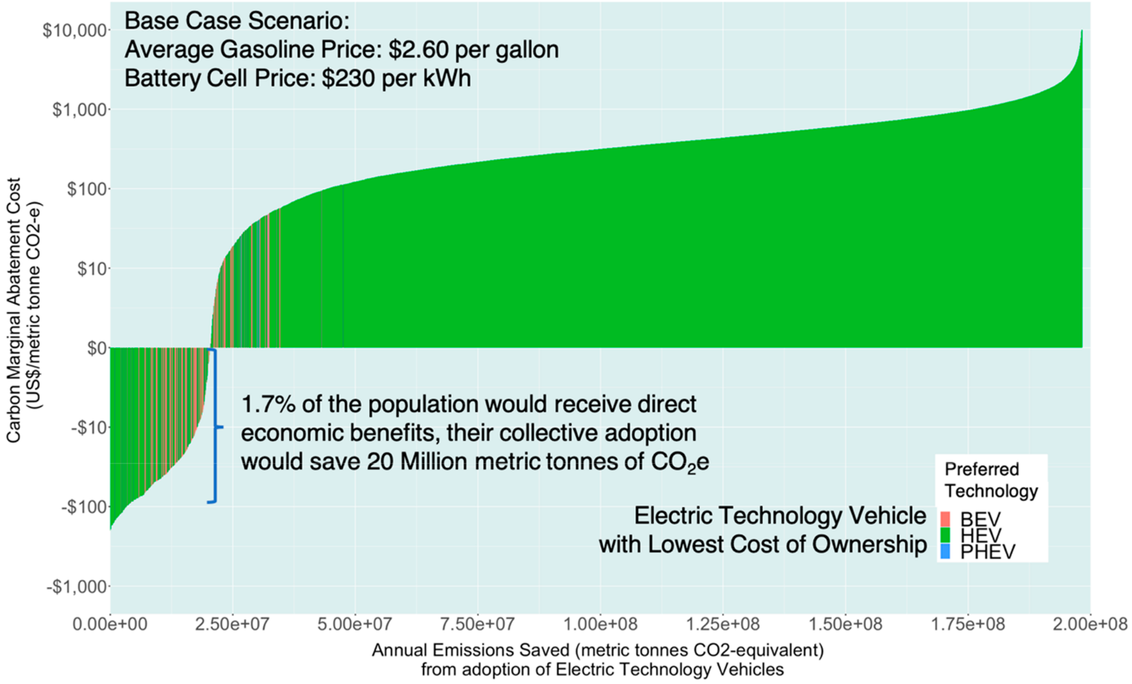

Figure 3. Carbon marginal abatement cost curve (MACC) for electric technology vehicles (ETVs) with current prices and no subsidy (base case scenario). The figure shows a series of narrow rectangles, ordered from lowest to highest height, with log scale. Each rectangle reflects an individual response to the National Household Travel Survey; the number of corresponding consumers varies by weight (with mean of 680). Rectangle height is the cost of abatement of one metric tonnes (MT) of CO$_2$e. Negative marginal cost represents consumers who financially benefit (save money) from buying an electric technology vehicle. The width of each rectangle is the amount of carbon emissions saved in a year from this household group switching to its least cost electric technology vehicle; the width of the *x*-axis reflects every personal vehicle in the U.S. being replaced by an ETV. Note that this base case scenario does not account for current federal tax credits for PHEV and EV of up to US$ 7500 or state/local subsidies (BEV, Battery Electric Vehicle; HEV, Hybrid Electric Vehicle; PHEV, Plug-in Hybrid Electric Vehicle).

■ RESULTS

The first set of outputs produces distributions of economic and carbon implications of electric technology vehicle adoption. Summary results of this analysis are shown in Figure 2. Annualized cost includes amortized purchase cost, fuel expenses (gasoline and electricity), battery replacement, and resale value when the vehicle is replaced. Annual emissions savings are calculated by assuming the vehicle is driven in the state of purchase, subtracting the emissions from gasoline used in a conventional vehicle from emissions due to electricity consumed by the electric technology vehicle (and gasoline for hybrid and PHEV models). The model assumes that the consumer chooses between hybrid, electric, or plug-in hybrid electric depending on which has the lowest annualized costs. If the 10% of consumers with highest emissions savings move to an electric technology vehicle, this can potentially save over 62 MMT (i.e., 5% of the total light-duty transportation emissions).

We next calculate the carbon marginal abatement cost curve (MACC), shown in Figure 3. The figure shows carbon abatement costs and corresponding emissions savings assuming each household purchases the electric technology vehicle (HEV, EV, or PHEV) with least total cost of ownership. Using results

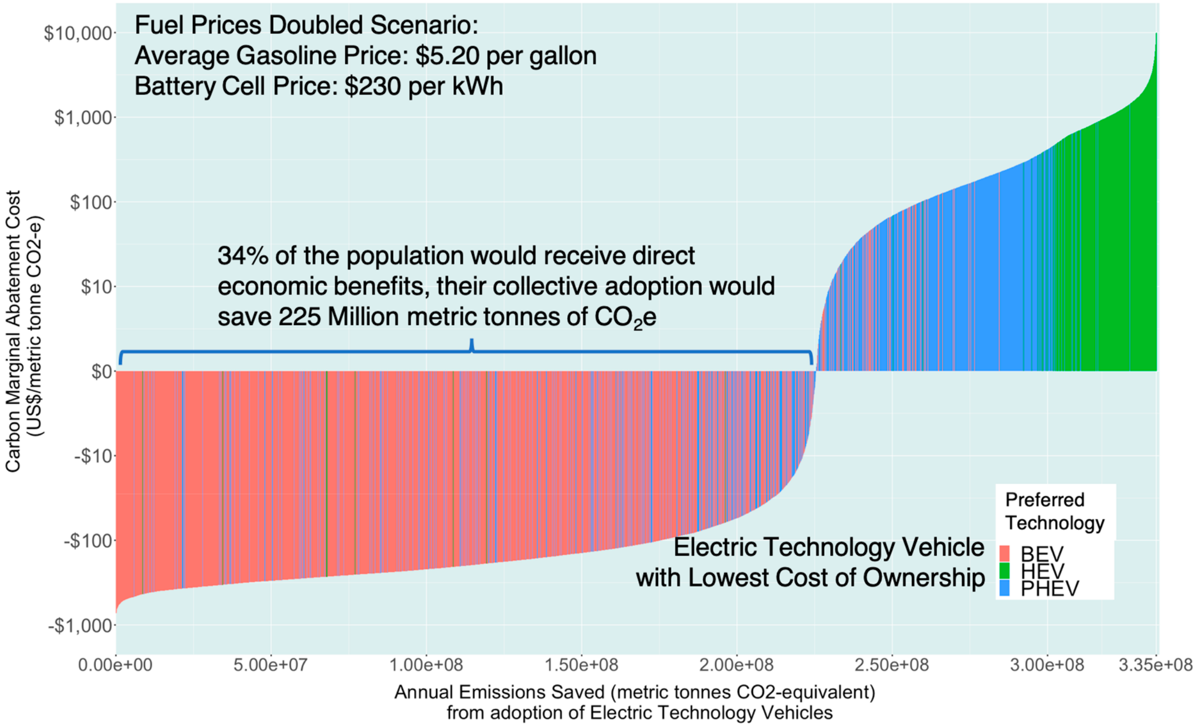

Figure 4. Carbon marginal abatement cost curve (MACC) for electric technology vehicles (ETVs) with doubled gasoline price ($5.20 per gallon) and current vehicle prices; 34% of the population saves money (negative abatement cost) from ETVs; their adoption would yield 67% of achievable carbon savings from electric technology vehicles. Note that both axes have different ranges from Figure 3. With doubled fuel prices, some consumers save much more, resulting in a wider range on the negative *y*-axis. BEV and PHEV emerge as more often preferred compared to the base case (current fuel and technology prices, no subsidy), with their adoption resulting in larger carbon savings (*x*-axis scale increase) compared to HEV dominated adoption in Figure 3 (BEV, Battery Electric Vehicle; HEV, Hybrid Electric Vehicle; PHEV, Plug-in Hybrid Electric Vehicle).

shown in Figure 2 for individual households, Emissions Saved becomes a width on the *x*-axis for that household ($MTCO_2e$). The *y*-axis shows carbon mitigation cost ($\$/MTCO_2e$), found by dividing Annualized Cost by Annual Emissions Saved. These bars are then reordered from lowest to highest carbon abatement costs. We define the term “Free Carbon” as the amount of carbon mitigated if all consumers that save economically would purchase an ETV.

A relatively small population, 1.7% of all drivers with very high annual mileage, benefits economically from electric technology vehicles. It can be seen that most consumers currently prefer hybrids over BEV and PHEV if forced to switch from a conventional internal combustion vehicle. The estimated “free carbon” in the base case scenario is 20 million metric tonnes (MMT) CO_2e or 1.8% of the total light-duty transportation emissions in the U.S. To provide context for these numbers, note that switching the entire U.S. vehicle fleet to ETVs would decrease light-duty vehicle emissions in the U.S. by 198 MMT, or 17%, assuming current electricity generation mixes around the country (the right end of the *x*-axis of Figure 3). The consumers who directly benefit financially from ETVs have an average carbon abatement cost of −$45 per $MTCO_2e$ with an average annual mileage of 51600 miles. Compare this to consumers who do not save money: they have an average abatement cost of $5500 per $MTCO_2e$ and drive an average of 11000 miles annually. Large savings on fuel consumption by the first group enables these consumers to recover their high initial capital costs. Note that the average U.S. consumer drives 11700 miles annually, thus consumers getting financial benefits from an ETV drive over four times the national average. We have included additional analyses of considering only the use phase (i.e., excluding upstream emissions and manufacturing emissions for vehicles) as well as sensitivity analysis for interest rates in the SI.

The MACC in Figure 3 is constructed with 2017 fuel and technology prices. However, these prices are expected to change with time. Therefore, two alternative scenarios are examined: (i) First, a doubled fuel price scenario and (ii) second, a scenario with 75% decrease in battery cell prices (i.e., $58 per kWh, down from $230 per kWh). Figure 4 shows the MACC with current technology prices, but fuel prices are doubled (average fuel price of $5.20 per gallon) compared to the base case scenario (average fuel price of $2.60 per gallon). As the fuel prices increase, the consumers are better off buying more expensive BEV or PHEV choices, as they recover these initial high capital costs through savings in fuel consumption. It can be seen that the technology of choice switches to BEV or PHEV instead of HEV (relative to base case scenario) due to electricity being a cheaper fuel. HEVs are still the best ETV choice for drivers with low mileage (lowest capital costs), who are generally on the right side of the figure. Abatement costs are as low as −$10,000 per $MTCO_2e$. Note that abatement cost is a ratio, so large magnitudes can come from a large numerator, a small denominator, or both. For example, a consumer who saves $2870 annually by purchasing a BEV with a carbon reduction of only 0.28 $MTCO_2e$ has an abatement cost of −$10,200 per $MTCO_2e$.

In the doubled fuel price scenario (average fuel price $5.20 per gallon), the number of consumers benefiting from electric technology vehicles grows to a 34% share. The “free carbon” is 225 million $MTCO_2e$ or 20% of total light-duty transportation emissions. The consumers who benefit financially drive an average of 19800 miles annually, and the consumers who do not

DOI: 10.1021/acs.est.9b02874
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

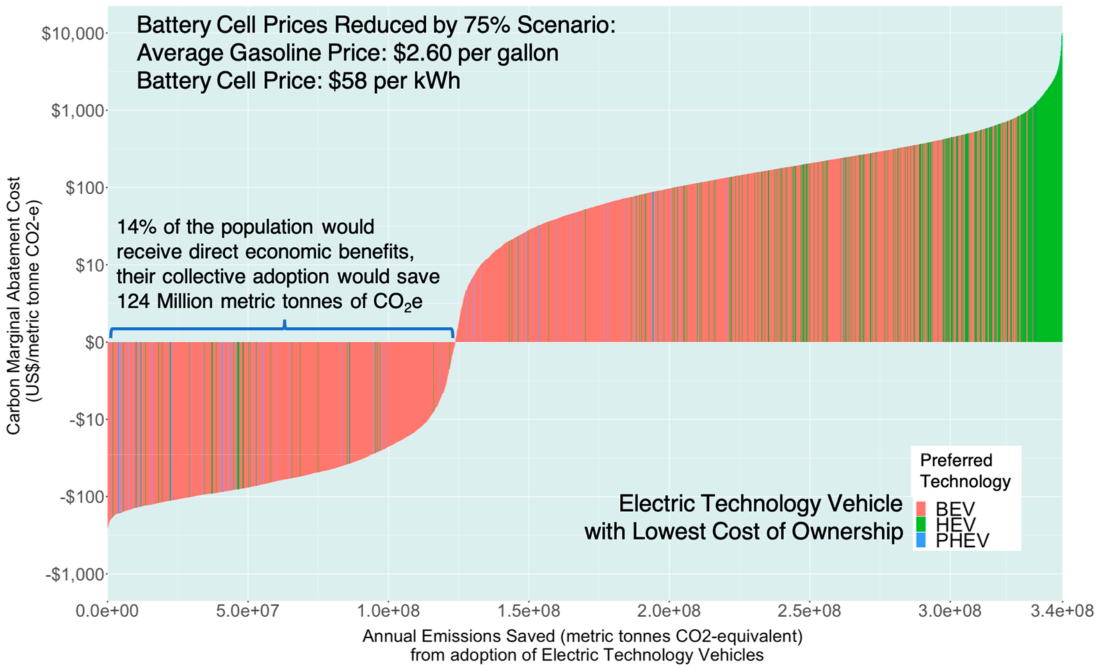

Figure 5. Carbon marginal abatement cost curve (MACC) for electric technology vehicles (ETVs) with current gasoline price and battery cell cost of \$58 per kWh (25% of the current battery cell prices of \$230 per kWh). Adoption by the 14% of population that benefits financially (negative abatement cost) yields 36% of achievable carbon savings from electric technology vehicles. Note that both axes have different ranges from the base in Figure 3 (current fuel and technology prices, no subsidy). Some consumers save much more with lower battery prices, resulting in a wider range on the negative *y*-axis. BEV and PHEV emerge as more often preferred compared to the base case, with their adoption resulting in larger carbon savings (*x*-axis scale increase) compared to HEV dominated adoption in Figure 3 (BEV, Battery Electric Vehicle; HEV, Hybrid Electric Vehicle; PHEV, Plug-in Hybrid Electric Vehicle).

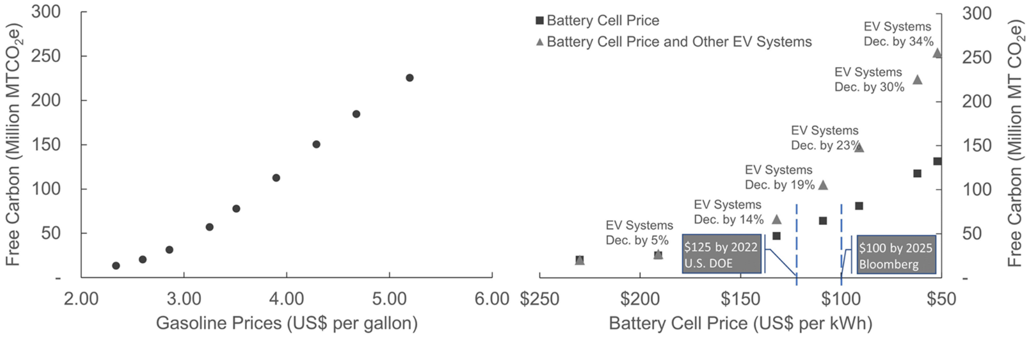

Figure 6. Impact of changes in price of gasoline, battery cells, and other electric vehicle systems on annual “free carbon”. Free carbon is carbon reduction achieved if all consumers that benefit economically from electric technology vehicles adopt them. As the fuel prices increase, the amount of free carbon saved increases nonlinearly. At lower gasoline prices, an increase of 50 cents per gallon saves 18 million MTCO$_2$e but the same increase at higher fuel prices saves 41 million MTCO$_2$e of emissions. Decreasing battery cell prices have a similar accelerating impact on free carbon. Moreover, if the prices of other EV systems (e.g., electric motors) decrease in step with battery cell prices (but at reduced rate), the amount of free carbon increases significantly and nonlinearly. For example, with battery cell price at \$52 per kWh, the free carbon is 132 million MTCO$_2$e; this combined with an EV systems price decrease of 34% increases the free carbon amount to 256 million MTCO$_2$e. (EV, Electric Vehicle; Dec., Decreased)

benefit financially drive about 62% less (7500 miles annually). The average mileage of consumers who benefit financially from ETVs (19800 miles) is now much closer to the national annual average mileage of 11700. This indicates that the pool of consumers that can benefit from these electric technology vehicles is broadened, from only extremely highly used vehicles to those with slightly higher than average annual usage. The average carbon abatement costs also change to −\$176 per MTCO$_2$e (relative to −\$45 in the base case) for financially benefiting consumers.

Figure 5 shows the MACC for electric technology vehicles with current fuel price but lower costs for battery cells: \$58 per kWh instead of the current \$230 per kWh, which represents significant technological progress in battery production. Several estimates project rapidly declining battery cell prices, such as \$125 per kWh by 2022 as per U.S. Department of Energy (DOE),[21] \$125 to \$150 per kWh by 2030 as per Union of Concerned Scientists (UCS),[22] and \$100 per kWh by 2025 as per Bloomberg.[23] The modeling here does not account for when these price targets will be achieved and instead describes economic and carbon benefits given an optimistic future battery price. Similar to the fuel price change scenario, consumers move away from hybrid vehicles but now with a stronger preference for battery electric vehicles (since batteries are cheaper) (Figure 4).

DOI: 10.1021/acs.est.9b02874

With decreasing battery cell prices, consumers now save money with both initial capital investment of a pure electric vehicle as well as fuel savings.

In the decreased battery cell price scenario, about 14% of the population benefits financially from ETVs, compared to 1.7% in the base case. The free carbon is 124 million $MTCO_2e$ or 11% of total light-duty transportation emissions. The consumers who benefit financially drive 26000 miles annually compared to the rest who do not benefit financially and drive 9300 miles. The lower battery prices also affect the carbon abatement costs for financially benefiting consumers. In this case, the average carbon abatement costs are −\$60 per $MTCO_2e$ (relative to −\$45 in the base case) for financially benefiting consumers and \$7900 per $MTCO_2e$ (relative to \$4900 in the base case) for the rest of the population.

Figure 6 shows summary results for free carbon for scenarios with different gasoline prices (left side) and lower costs of batteries and other ETV systems (right side). EV systems refer to the electric motor, transmission and integration, control unit, onboard charging unit, regenerative braking, and wiring. Notably, free carbon accelerates nonlinearly with increasing gasoline price and decreasing battery price. This is due to an accelerating share of the population that benefits from ETVs as the economics improve. To put the battery price scenarios in context, note that the DOE reports a battery cell price target for 2022 of \$125/kWh[20] and Bloomberg forecasts a cost of \$100/kWh for 2025.[22] Achieving these targets results in substantial increases in free carbon: 56−73 MMT versus 20 MMT today. Note that the full adoption of ETVs has the potential to save 382 MMT of carbon under the current grid mix, higher than savings shown in Figure 6. This is because the average consumer has yet to benefit economically from ETVs, even at these technology and gasoline prices.

CAVEATS

In this section, we recount modeling simplifications and postulate how accounting for these factors might affect results. Would accounting for neglected factors lower ETV mitigation costs/potential, increase them, or is the sign of the net effect not yet known? First, we assumed all consumers have access to charging; currently, this is true for only 50−60% of the population.[93,94] While charging infrastructure is growing, the rapidity and future extent of access is not known. Accounting for consumers without access to charging would limit adoption and thus lower mitigation potential. The degree of reduction is unclear, however: (1) Consumers without access to charging still have the option to purchase an HEV, and (2) there is a potential correlation between access to charging and longer driving distances and thus the benefits of owning an EV. Second, we assume the current electricity grid, but prices and carbon emissions will likely change. The sign of the net effect on results is, however, unknown. Carbon emissions may fall due to increased renewable adoption, but conversely, they could increase if charging is done at night when renewables are not on the grid. Third, we assumed that consumers with a daily mileage <100/150 miles would consider purchasing an EV with a range of 100/150 miles. Accounting for the complexities of how consumers would realize mobility demand when owning an ETV could increase or decrease adoption potential. On one hand, there are consumers who drive more than 100/150 miles per day who would consider an EV because there is an ICEV or HEV available in the household, or they may be willing to rent. On the other hand, there are consumers who drive less than 100/150 miles per day who would not purchase an EV due to the inconvenience of finding a vehicle on a high mileage day. Lastly, we assess ETVs through a purely economic lens. There are consumers that purchase an ETV even if they lose money and those who would not even if they could save. Moreover, a study by Jenn et al.[95] suggests that the United States Corporate Average Fuel Economy (CAFE) standards allow the automaker to sell more conventional vehicles for every ETV sold and therefore can result in increased carbon emissions. However, we do not incorporate such a fleet analysis in this work. Given these uncertainties, we do not assert precision in the numerical values of our results. However, our main purpose here is to demonstrate that comprehending consumer heterogeneity dramatically increases the carbon mitigation potential of ETVs. Heterogeneity has been neglected in previous analyses, and it is reasonable it will have a similar effect in future models that account for additional complexities.

We have, furthermore, tried to accommodate some of the caveats of the model through additional analyses. In the model, we have assumed a single markup factor for all ETV options. Therefore, in additional analysis, we estimated the carbon and economic benefits, if the markup factor is neglected for BEVs. The carbon emissions savings increase from 20 to 54 MMT, with 5% of the population directly receiving financial benefits versus 1.7% in the base case. We have also assumed that consumers charge their vehicles at their homes only once a day. However, if a level-2 charger and installation costs of \$6000[96,97] are added in the initial capital costs, the outlook for BEVs turns pessimistic. The carbon emissions savings (15 MMT) as well as the population receiving direct financial benefits (1.4%) both decrease compared to the base case. Currently, we have assumed that a consumer with an average daily mileage of less than and equal to 100 miles can opt for BEV-100. The NHTS daytrip analysis also reveals that 83% of the daily vehicle miles traveled (VMT) are under 60 miles and 95% is under 120 miles.[98] Therefore, as an additional sensitivity analysis, we assume that consumers with a maximum 80 mile daily mileage could opt for BEV-100, and similarly, consumers with a maximum 120-mile daily mileage could opt for BEV-150. In this scenario, the percentage of the population receiving direct financial benefits (1.5%) and carbon benefits (16 MMT) decreases from the base case.

DISCUSSION

An important conclusion of this work is that behavioral and geographic heterogeneity must be included in a proper assessment of the potential of electric technology vehicles to deliver economic and carbon benefits. We clarify how accounting for heterogeneity affects results in Table 1, which shows the percentage of the population who get direct financial benefits from ETVs and the corresponding amount of free carbon saved if these consumers adopt. If consumer behavior is treated as average (11700 miles driven year) and subsidies are removed, no consumer benefits from an ETV purchase. If heterogeneous consumer behavior is considered but geographical heterogeneity is ignored, only 1.5% of the population benefits financially, saving 16 MMT (second row). If all heterogeneities are considered, the base case result returns to 1.7% of the population financially benefiting from ETVs and 20 MMT of free carbon. If current tax credits are included (up to \$7500 for PHEV and BEVs) but only geographical heterogeneity is considered, the percentage of population benefiting increases from 0% to 7%, with a free carbon potential of 34

Table 1. Effect of Including Different Heterogeneities on Share of Population Benefiting from Electric Technology Vehicle Adoption and Free Carbon[a]

Behavioral Heterogeneity	Geographic Heterogeneity	Federal Tax Credits	Share of Population Receiving Direct Financial Benefits from Cost-Effective Adoption of Electric Technology Vehicles	Free Carbon (million $MTCO_2e$)
No	Yes	No	0%	0
Yes	No	No	1.5%	16
Yes	Yes	No	1.7%	20
No	Yes	Yes	7%	34
Yes	Yes	Yes	15%	97

[a] The first and second columns indicate what types of heterogeneity are considered; the third column indicates if federal tax credits are included. The fourth column shows the percentage of the population which directly receives financial benefits, and the fifth column shows corresponding free carbon gains. The first row shows the case if every vehicle is driven the 11700 annual miles of an average U.S. consumer, resulting in no consumers benefiting. The second includes individual variability in miles driven and vehicle types but neglects geographic heterogeneity, i.e., all consumers pay national average gasoline and electricity prices. The third row accounts for behavioral and geographic heterogeneity (the base case scenario). The fourth and fifth rows include federal tax subsidies.

MMT. However, it is important to note that although federal tax credits improve private finances for a consumer and increase "free carbon", federal subsidies actually represent a transfer from taxpayers to vehicle owners. Including the federal tax credit and both types of heterogeneity, the percentage of the population who benefits economically more than doubles to 15%, with the potential free carbon savings of 97 MMT. Note these 15% of consumers save far more emissions than the 10% of population shown in Figure 2, because the subsidy provokes a shift in preferred electric technology vehicle (e.g., HEV to BEV or PHEV), and hence corresponding emissions savings are higher, even for the same consumer.

Heterogeneity affects benefit−cost analyses of government policies to promote ETVs. For example, consider a 10% adoption of ETVs. If this 10% comes from average consumers, carbon reductions would be 1.13 $MTCO_2e$/vehicle (calculated from the base case for all users: 198 MMT are saved with 175 million ETVs). In contrast, if this 10% were individuals that benefit most economically from ETVs, annual carbon savings would be 3.1 times higher: 3.54 MT/vehicle. Valuing the carbon benefit of emissions reduction at \$40/$MTCO_2e$ (neglecting other societal benefits), these emissions savings deliver \$290 of benefit per vehicle assuming average consumers and \$920 of benefit per vehicle assuming that the "most benefiting" consumers adopt. Both assumptions (benefiting consumers and average consumers) are idealizations that do not capture the complexity of vehicle purchase decisions. The truth lies at an undiscovered point between adoption by those who benefit and adoption by the average consumer. But the critical policy point is this: the public benefits of promoting a technology depend on the heterogeneity of consumers' responses and better targeting can achieve more efficient results.

Note that neither average adoption nor beneficial adoption of ETVs leads to public benefits close to the \$7500 per vehicle currently spent on ETV subsidies. Viewed through the lens of current technology, the public cost of the ETV subsidy far exceeds its benefits.[36] However, much of the motivation for the subsidy is presumably derived from expectations of contribution to future cost reductions. Our results indicate the trajectory for growth in public benefits from lower technology costs. While we do not undertake a longer-term benefit−cost analysis of ETV subsidies, we note that it is conceivable to achieve positive net benefits, depending on how much expenditure is needed to promote cost reductions. If the elasticity of cost reductions as a function of technology investment is sufficiently high (e.g., high learning rate in an experience/learning curve), there is potential for "cascading diffusion", in which adoption by high-use subgroups enables cost reductions, making the technology attractive to other consumer tiers.[99,100] The knowledge of how this analysis would play out, accounting for behavioral and geographic heterogeneity, is needed for a plausible estimate.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.9b02874.

Methods, defining consumer vehicle options for internal combustion engine and ETVs, total cost of ownership, emissions savings (PDF)

Calculations and vehicle cost models (XLSX)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: Ranjit.Desai@nrel.gov.

ORCID

Ranjit R. Desai: 0000-0002-0722-7836

Eric Hittinger: 0000-0001-8439-4016

Present Address

$190 Lomb Memorial Dr. Rochester, NY 14623.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This research has been supported by the National Science Foundation, Environmental Sustainability Program (grant CBET #1605319).

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