energies

MDPI

Supplemental Information for Research Article:

Future Costs of Electric Vehicles: Effects of Technological Progress and Consumer Heterogeneity

Ranjit R. Desai [1,+], Eric Hittinger [2] and Eric Williams [3,*]

[1] National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401.; Ranjit.Desai@nrel.gov
[+] Ranjit R. Desai is with the National Renewable Energy Laboratory (NREL), Golden, CO, USA. This work was completed before R.R.D. joined NREL and was not funded by NREL or the U.S. Department of Energy.
[2] Department of Public Policy, College of Liberal Arts, Rochester Institute of Technology, Rochester, NY 14623; eshgpt@rit.edu
[3] Golisano Institute for Sustainability, Rochester Institute of Technology, Rochester, NY 14623.
[*] Correspondence: exwgis@rit.edu

Citation: Desai, R.R.; Hittinger, E.; Williams, E. Interaction of Consumer Heterogeneity and Technological Progress in the US Electric Vehicle Market. *Energies* **2022**, *15*, 4722. https://doi.org/10.3390/10.3390/en15134722

Academic Editor: Donato Morea

Received: 3 June 2022
Accepted: 22 June 2022
Published: 28 June 2022

1. Methods

1.1 Calculation of Expected Duration of Ownership

We calculate the expected duration of ownership. A lifetime of a vehicle differs from the expected duration of ownership because different consumers use their vehicles for a different number of years before switching and/or selling vehicles. The NHTS provides the number of months a vehicle owned. We use these observed durations to generate a distribution for how long owners have currently owned their vehicle. This duration differs from the actual duration of ownership before vehicle disposal or retirement.

The survival rate is calculated for each year i.e., the percentage of vehicles using their vehicle past the respective year, conditional upon the consumers have used their vehicles until that year (i.e., how long they have currently owned their vehicle).

The survivor function is shown in Equation S1, n_j is the number of consumers using their vehicles past duration t_j, and $h_j$is the number of consumers who sold their vehicles in the duration t_j. It is estimated by setting the estimated conditional probability of using the vehicle past t_j equal to the observed relative frequency of completion at t_j.The distribution is shown in Figure S1 and it depicts how frequently the consumers replace their vehicles.

$$\hat{S}(t_j) = \prod_{j=1}^{j} (n_j - h_j)/n_j \qquad \textit{Equation S1}$$

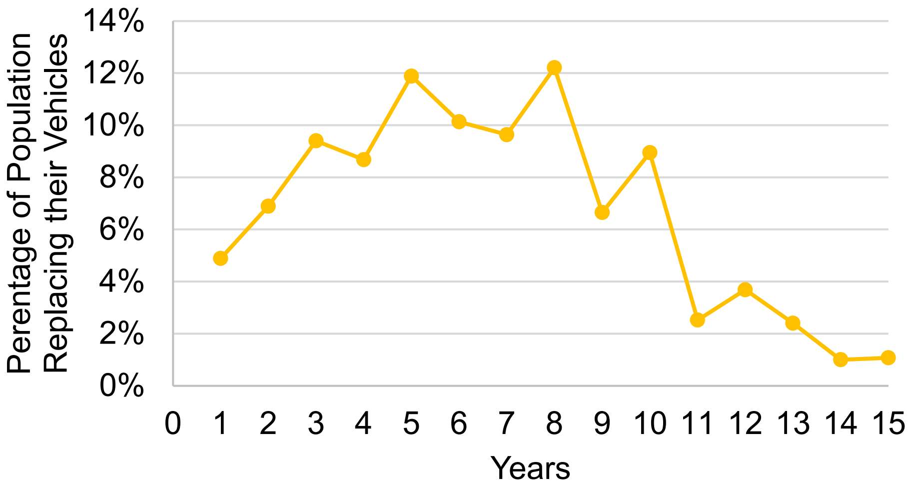

Figure S1: Distribution of Population Replacing their Vehicles in respective years

To calculate the expected duration of ownership (n), given a consumer has used their vehicle for 'x' number of years, we build the new distribution with the remaining probabilities by determining the conditional survival probability given that the vehicle own year (currently owned duration) is not complete, assuming the maximum lifetime is assumed to be fifteen years.

We primarily use the National Household Travel Survey (NHTS) vehicle fleet as the main input for our vehicle-level analysis. The NHTS collects vehicle attributes and use characteristics for households in the national sample. The detailed methodological framework is shown in figure 1 of the main text. To calculate marginal abatement cost of each electric technology vehicle (HEV or BEV or PHEV), we need total cost of ownership (indicated by Equation 1 in the main text) of an ETV and the amount of emissions saved by a particular ETV. To determine the total cost of ownership we need initial capital cost. The calculations for initial capital costs are dependent on the vehicle's type of propulsion technology (electric vs. plug-in hybrid), class (Sedan vs SUV), make and model (Honda vs Toyota and Civic vs Camry). The dataset includes households' state of residence, used in indicating the resolution of geographical heterogeneity, i.e., determine state-specific electricity emissions, and fuel and electricity prices. The information about the intensity of vehicle use and the lifetime of a particular vehicle is a source of behavioral heterogeneity. The vehicles differ from each other in terms of make, model, and type of a vehicle (source of stock heterogeneity), which we have considered in our model. The following section explains how we generate the technology variants for each vehicle class.

1.2 Defining Consumer Vehicle Options for Internal Combustion Engine and Electric Technology Vehicles

The NHTS dataset contains information on the make, model and type of each vehicle in the sampled vehicle fleet. We use this information to estimate the initial capital cost and mileage. If consumers decide to switch and adopt a more energy efficient vehicle, assuming the consumers stay consistent, meaning the consumers stick to their current class type, make and model, they face four options: 1. Latest Conventional Vehicle, 2. Hybrid Engine Vehicle, 3. Battery Electric Vehicle and 4. Plug-in Hybrid Electric Vehicle. Currently, in the market, we do not have hybrid, battery electric and plug-in hybrid technology variants for every vehicle type, make and model in the NHTS vehicle fleet. For example, we do not have a battery electric truck or a battery electric Dodge Charger available in the real-world market. Therefore, we calculate the cost of the technology in addition to the price of its conventional variant. For example, in case of Dodge Charger, we calculate how much additional amount a particular consumer has to pay in get a HEV or BEV or PHEV variant which will have a comparable performance as that of a sedan (as Dodge Charger is a sedan).

We first identify make, model and fuel type of each vehicle in the dataset. For miles per gallon (or fuel efficiency), we have compiled a list of highest selling vehicles in the U.S. (added in the supplementary Excel sheet) with respect to vehicle types (Car, Van/Minivan, SUV, Truck) [1]. This list has the number of units sold for a particular vehicle make and model for 2017. The detailed vehicle list is attached in the supplementary information Excel sheet. The recent fuel efficiencies (miles per gallon) for each of these vehicles are taken from the U.S. Environmental Protection Agency (EPA) [2]. These mileages are for new Internal Combustion Engine (ICE) vehicles. We match each NHTS observation (i.e., make and model) with its corresponding U.S. EPA rated mileage. So that we can compare the electric technology vehicles with the latest conventional vehicles. For models which are not on this EPA list of highest-selling vehicles (for example, Jaguar XF), we have assigned a generic mileage for each vehicle type which is calculated as a weighted average of the number of units sold and mileage of highest sold vehicles.

For technical specifications and performance characteristics by vehicle type—sedan, SUV, van/minivan/station wagon, pickup truck, we have also generated non-existing technology variants. The power and performance characteristics of base conventional vehicles are assumed to be similar to vehicles with high market shares—for example, Toyota Camry [3], Honda CRV [4], Toyota RAV4 [5], Honda Odyssey [6], Ford 150 [7]. Table S1 shows the technical specifications (power and battery capacity) and performance characteristics (miles per gallon or miles per charge) of the technology variants. The gasoline mileage (mpg) for hybrid and plug-in hybrid are assumed to be 27.5% more efficient than the conventional versions [8,9]. The electric mileages (miles per charge) are assumed and calculated as the average mileage for available electric (3.71 miles per kWh) and plug-in electric vehicles (3.14 miles per kWh) in the market (the calculations are shown in supplementary Excel sheet). For each vehicle class, we assume the battery efficiency drops as much as their conventional counterparts' fuel efficiency drops. For example, if the gasoline mileage drops by 21% from a sedan (32 miles per gallon i.e., mileage of a generic sedan) to an SUV (25.4 miles per gallon i.e., mileage of a generic SUV), then for electric variants the electric efficiency also drops by 21% from sedan (3.71 miles per kWh) to a SUV (2.95 miles per kWh). As the BEVs in the market have wide ranges (miles per charge or full battery capacity), we have modeled two BEV versions for each vehicle type with 100- and 150-mile ranges. The consumers who drive more than 150 miles daily—assumed maximum range of BEV—would have only HEV and PHEV technologies available to feasibly choose from.

Table S1 Technical Specifications and Performance Characteristics of Non-existing Technology Variants [8–11]

		Technical Specifications				Performance	
Vehicle Type	**Technology**	**Battery Capacity (kWh)**	**ICE Power (kW)**	**Electric Motor (kW)**	**Total Power (kW)**	**Mileage (miles per gallon)**	**Range (miles per charge or full battery capacity)**
Sedan	CONVENTIONAL		131		131	34	
Sedan	HEV	1	102	29	131	43	
Sedan (Short Range)	BEV-100	27		131	131		100
Sedan (Long Range)	BEV-150	40		131	131		150
Sedan	PHEV-40	13	85	46	131	43	40
SUV	CONVENTIONAL		142		142	30	
SUV	HEV	1.5	111	31	142	38	
SUV (Short Range)	BEV-100	34		142	142		100
SUV (Long Range)	BEV-150	51		142	142		150
SUV	PHEV-40	16	92	50	142	38	40
Van/Minivan/ Station Wagon	CONVENTIONAL		209		209	22	
Van/Minivan/ Station Wagon	HEV	1.5	163	46	209	28	
Van/Minivan/ Station Wagon (Short Range)	BEV-100	40		209	209		100
Van/Minivan/ Station Wagon (Long Range)	BEV-150	60		209	209		150
Van/Minivan/ Station Wagon	PHEV-40	19	136	73	209	28	40
Truck	CONVENTIONAL		243		243	18	
Truck	HEV	1.5	190	53	243	23	
Truck (Short Range)	BEV-100	42		243	243		100
Truck (Long Range)	BEV-150	62		243	243		150
Truck	PHEV-40	20	158	85	243	23	40

1.3 Salvage Value

The Salvage Value is a value of a vehicle in a used car market at the end of the expected duration of ownership. It is estimated as a function of years of ownership. R. Raustad has generated an equation to estimate depreciation percentage (is shown in Figure S2) as a function (With R^2=0.9997) of years of ownership of the vehicles [12]. The author has collected data from Edmunds.com for several makes and models. The equation to calculate the depreciation percentage is as shown in Equation S2. The consumer receives the salvage value at the end of expected duration of ownership (n), therefore we have accounted it as the present value of future money, as shown in Equation S4.

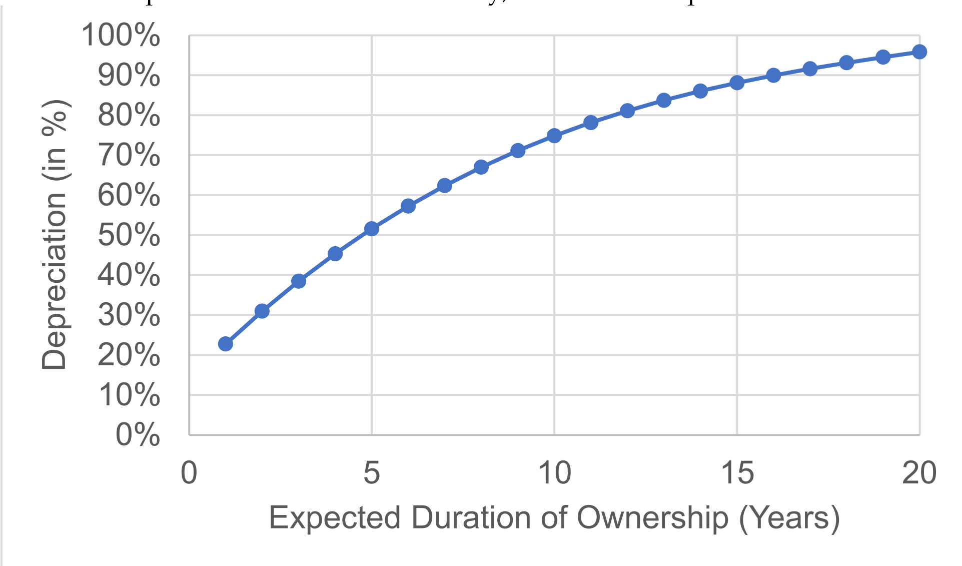

Figure S2: Depreciation Percentage at a function of Expected Duration of Ownership (Years)

$$Depreciation\ Percentage = (6 \times 10^{-5})\, n^3 - (0.0038)\, n^2 + (0.093)\, n + 0.1384 \quad \text{Equation S2}$$

$$Salvage\ Value\ of\ a\ vehicle\ (\$) = Depreciation\ Percentage \times Initial\ Capital\ Cost(\$) \quad \text{Equation S3}$$

$$Discounted\ Salvage\ Value\ at\ the\ end\ of\ duration\ of\ ownership = Salvage\ Value\ of\ a\ vehicle \times (1+r)^{-n} \quad \text{Equation S4}$$

1.4 Battery Replacement Cost

For HEVs, the battery replacement costs are not considered, as the battery typically lasts for the lifetime of the vehicle. For BEVs and PHEVs, the battery replacement costs are considered only if the expected battery life is less than 15 years—the assumed maximum duration of ownership of the vehicle. The life of the battery is estimated as a function of the number of charging-discharging cycles and depth of discharge [12,13] (Equation S5 & S6 in the SI). For BEVs and PHEVs, a battery replacement cost at the end of life, and life of the battery is estimated as a function of number of charging-discharging cycles and depth of discharge [12,13]. The battery lifetime is calculated as shown in Equation S5 and Equation S6. E. Wood *et al.* calculated the power level of 70% of the peak power can be achieved with the depth of discharge of 80% and charging-discharging cycles of 3,500 [13]. Therefore, to calculate battery lifetime, we assume the depth of discharge 80%, and 3,500 charging-discharging cycles. Thus, for example, the battery of 27 kWh with efficiency 3.71 miles per kWh, depth of discharge 80%, and 3,500 charging-discharging cycles can provide 280,476 miles in its lifetime, and with 18,000 annual miles, the battery life would be

15.6 years. Using this battery lifetime, the discounted battery replacement cost is calculated. For the consumers who have battery lifetime more than the expected duration of ownership, and when these consumers sell their vehicles, and the buyer of this used vehicle would need to replace the degraded battery shortly after. Therefore, to compensate for this battery use, we consider that the previous owner still pays for the battery replacement. To account for this cost, we reduce the discounted salvage value by the amount the consumer would have paid to replace the battery by saving annually until the end of the expected duration of ownership.

$$\begin{aligned} &Maximum\ Miles\ in\ battery's\ lifetime\ (miles) \\ &= Battery\ Capacity\ (kWh) \\ &\times Battery\ Efficiency\ (miles\ per\ kWh) \\ &\times\ Depth\ of\ Discharge\ (80\%) \\ &\times No.of\ Charging\ Discharging\ Cycles\ (3500) \end{aligned} \quad \text{Equation S5}$$

$$Battery\ Lifetime\ (\ years) = \frac{Maximum\ Miles\ in\ battery's\ lifetime}{Annual\ Miles} \quad \text{Equation S6}$$

1.5 Fuel Savings

Based on the State of residence of the driver, each vehicle is assigned average state electricity prices from the U.S. Energy Information Agency [14]. Fuel prices are also assigned with respect to the corresponding fuel type and U.S. State [15–17]. The fuel savings for each ETV are calculated and discounted for the expected duration of ownership, as shown in Equation S7-Equation S12 in SI. For both BEV and PHEV, we assume charging is available and done at the state average residential rate.

Finally, we calculate the discounted fuel savings. The first step of calculating the fuel savings is to identify the fuel and electricity costs for each consumer. Using the household's State of residency, each observation is assigned electricity emissions per kWh (of generation) from the U.S. Energy Information Agency [14] as well as the conventional fuel prices [15–17]. As all the calculations are done in comparison with the conventional vehicle, first annual fuel costs of conventional vehicles are calculated (Equation S7). Then the fuel costs of each of the technology variant are calculated for each vehicle type. The fuel costs for HEVs are calculated like that of a conventional vehicle (Equation S8). For BEVs, first the annual electricity consumption is calculated using the maximum range of the vehicle and then the cost of electricity consumption (i.e. the fuel cost) is calculated (Equation S9). For PHEVs, the fuel costs are calculated similar to that of BEVs, and it is assumed that the consumer first uses the electric energy and once the battery runs out (i.e. maximum range of PHEV) the vehicle is run on gasoline (Equation S10). The annual fuel savings are calculated for each of the technology variants (Equation S11) and then converted to discounted fuel savings (present value of annuity) for the total expected duration of ownership (Equation S12). All these cost components are discounted at an assumed discount rate (r) of 7%. For each consumer, we select *the least total cost to the consumers* (i.e. the highest Net Present Value) electric technology vehicle. The annualized Costs are shown in Equation 1 as negative annualized Net Present Value.

$$Fuel\ Cost\ for\ Conventional\ Vehicles\ (\$) = \frac{Annual\ Miles}{Mileage\ (miles\ per\ gallon)} \times Fuel\ Price\ (\$/gallon) \quad \text{Equation S7}$$

$$Fuel\ Cost\ for\ HEVs\ (\$) = \frac{Annual\ Miles}{Mileage\ (miles\ per\ gallon)} \times Fuel\ Price\ (\$/gallon) \quad \text{Equation S8}$$

$$\text{Fuel Cost for BEVs } (\$) = \frac{\text{Annual Miles}}{\text{Electric Mileage (miles per kWh)}} \times \text{Fuel Price } (\$/kWh) \quad \text{Equation S9}$$

$$\text{Fuel Cost for PHEVs } (\$) = \left[\frac{\text{Range of PHEV (miles)}}{\text{Electric Mileage (miles per kWh)}} \times \text{Fuel Price } (\$/kWh) + \frac{(\text{Annual Miles}/365 - \text{Range of PHEV})}{\text{Mileage (miles per gallon)}} \times \text{Fuel Price } (\$/gallon) \right] \times 365 \quad \text{Equation S10}$$

$$\text{Annual Fuel Savings } (\$) = \text{Fuel Cost of conventional vehicles}(\$) - \text{Fuel Cost of Electric Technology Vehicle}(\$) \quad \text{Equation S11}$$

$$\text{Discounted Fuel Savings } (\$) = \text{Annual Fuel Savings} \times \left[\frac{1-(1+r)^{-n}}{r} \right] \quad \text{Equation S12}$$

1.6 Initial Capital Costs

Before calculating the initial capital costs, we define the consumer vehicle options because the consumers do not have ETV analogous to their current conventional vehicle. We define the technical specifications such as power and performance characteristics, mileage (miles per kWh for BEVs and miles per gallon for HEVs and PHEVs) for each vehicle type (sedan, SUV, van/minivan/station wagon, pickup truck). These specifications are added in Table S1 and the SI excel sheet.

The BEV range (total miles can be traveled using one completely charged battery) is limited and must be accounted for in designing vehicles and their use by consumers. Given the wide ranges in miles per charge, we modeled two BEV versions for each vehicle type with 100 and 150 miles of range. Consumers who drive more than 150 miles daily may only choose HEV and PHEV technologies. For PHEVs, we assume that a consumer will first operate on electricity until the battery is drained and then switch to gasoline.

The initial capital cost is a part of the Financial Model as well as the Technology Progress Model. In the Financial Model, it is a part of the *Total Cost of Ownership*. However, it is in the Technology Progress Model the per-unit price of the battery cell and the non-battery EV technology costs are decided. Therefore, the initial capital costs are dictated by the Technology Progress Model.

1.6.1 Non-Battery EV Technology Costs

Although most published literature claims that the cost of the battery is the most significant additional cost component, we believe that the non-battery components are also equally—if not more, important—and depending on the assumed cost model, sometimes costlier than the battery in a vehicle. And the relevance of non-battery costs in ETVs will only grow as battery costs continue their rapid decline. Importantly, the net financial benefits of BEVs depend strongly on the additional cost of ETVs. However, there is a dearth of recent, updated, and detailed bottom-up cost breakdowns for BEVs and PHEVs. There are a few studies with bottom-up cost estimates for the cost of ETVs and/or the additional cost of the technology variants that we leverage.

As an example, the additional cost calculated for a BEV sedan with a 100-mile range as per the High Non-Battery Cost Model is $10,745, including the battery, non-battery EV technologies, ICEV credits, and markup factor. Similarly, a PHEV sedan with a 40-mile range would cost $7,883 more than a comparable ICEV. All outputs of this model, by vehicle model and specification, are provided in an excel sheet in the Supporting Information.

For example, a 100-mile range sedan BEV would have additional costs of $7,437, differing from the $10,745 for the High Non-battery Cost output despite identical assumptions about battery and motor size. This includes 27 kWh of battery and the powertrain costs for 131 kW of power output (with $14.1 per kW and 935.1 fixed costs for the Low Non-battery Cost Model) as well as markup factor and ICEV credits. Similarly, a PHEV sedan with a 40-mile range has an additional cost of $3,239. Both these costs are significantly lower than the High Non-Battery Cost Model estimates. These calculations, as well as those for other vehicle types, are attached in the excel sheet in the SI.

For this work, the experience curve has been implemented for two technologies: Battery Cells and Non-battery EV Technologies. The ETVs encompass both Li-ion battery technology as well as non-battery EV components like the electric motor. With the increase in the number of ETVs allocated, these technologies go through the experience curve and collectively decrease the capital cost of the ETVs. The battery cell prices fall with each installed battery cell, and the non-battery EV technology prices decrease with each unit purchased of BEV or PHEV. However, the decrease in the prices is calculated using two different learning rates: Learning Rate for Battery (LR_B) and a lower Learning Rate for Non-Battery EV components (LR_{NB}).

1.6.2 Learning Rate for Battery (LR_B)

Nykvist et al. estimated the LR_B for Li-ion battery cell cost as 6-8% in 2015 using multiple sources of battery cell prices, but this work includes a significant amount of grey literature [18]. However, later the same authors Nykvist *et al.* re-estimated the learning rate to be 17% [19] in their latest work (published 2019). BNEF reported the LR_B to be 19% and has used this figure in their analyses, but the report does not provide a source [20,21]. In addition to these studies, a recently published estimate based on economies of scales by Kittner et al. shows the LR_B to be 17.3% [22]. Moreover, Schmidt *et al.* reported the LR_B to be 16% [23]. We use a baseline value of LR_B of 17% for our model, in line with these studies, and run the model for modified values.

1.6.3 Learning Rate for Non-Battery EV Components (LR_{NB})

Similar to batteries, the literature has a wide variation for learning rate (LR_{NB}) for non-battery EV components for ETVs. Weiss *et al.* have shown that the experience curve and/or learning rate studies are still not conducted for several energy-related technologies, including, but not limited to, electric motors and entire motor systems [24,25]. Therefore, we looked at several studies about the LR_{NB} for the non-battery EV components. Most of these learning rates are for a particular component in the EV drivetrain and/or referenced from other studies as well as, in some cases, to personal communications, often lacking primary data from manufacturers. Unsurprisingly, there is considerable variation in the LR_{NB} estimated and/or assumed by different studies. For example, Pasaoglu *et al.* have used 10% of LR_{NB} for EV components based on the experience curve for energy technologies, because the authors assume that the drivetrain technology is a matured technology [26–28]. OPR van Vliet *et al.* and Contestabile *et al.* have assumed 5% *LR* for powertrain components [29,30]. Weiss *et al.* have proposed that the powertrain components have the same *LR* as that of the batteries and hence assumed that the LR_{NB} for the non-battery components to be 17% [31]. In a recent publication, Safari *et al.* estimated that the cost of "electrification" for mid-size BEVs has LR as 15+/-1% [32]. The LR_{NB} varies significantly in these studies and has uncertainty about the source. Therefore, for our study, we have assumed 5% as the LR_{NB} for BEVs and PHEVs for non-battery EV components. It is based on the Ricardo-AEA report, which was prepared by using a survey of manufacturers conducted by Delphi [33], a method that we find to be logical and close to primary data sources.

1.7 Efficiencies for Batteries and ICEVs

With the increasing demand for EVs and an increase in EV penetration, the battery chemistry is improving, which positively impacts the battery efficiency. The battery cells are getting denser and will be able to hold more charge in the future. This will enable the EV manufacturers to produce longer-range EVs as well as smaller batteries for shorter range EVs [34–37]. In our model, we have accounted for this EV technology development as a yearly 2% decrease in battery cell capacity (kWh) for the new vehicles to achieve the assumed 100-mile and 150-mile ranges, irrespective of the type of the vehicle [38].

We also assume that the fuel efficiency of the ICEVs is going to improve mainly due to the implementation of Corporate Average Fuel Economy (CAFE) standards as well as the introduction of new technologies. The University of Michigan Transportation Research Institute (UMTRI) has consolidated sales-weighted data about the fuel-economy rating (window sticker) of purchased new vehicles for October 2007 through December 2017 [39]. As per the dataset in 2007, the fuel efficiency is 20.2 miles per gallon (mpg), and at the end of 2017, it is 25.2 mpg. We have used this dataset of the ten years to generate a linear trend and used the same trend to project the fuel efficiencies in the future. This resulted in an ICEV sedan having fuel efficiencies of 39.8 mpg in 2040. We further used these projected fuel efficiencies to estimate the percentage increase in fuel efficiency compared to the 2017 fuel efficiency. These calculated annual increase in fuel efficiencies were then used to forecast the fuel efficiencies for other ICEV vehicle types such as SUV as well as the fuel efficiencies for BEVs (miles per kWh) and PHEVs. This resulted in BEVs having a fuel efficiency of 9.57 miles per kWh in 2040 compared to 3.71 miles per kWh in 2017. The assumption is that the battery efficiency (miles per kWh) also increases similar to that of the ICEVs' fuel efficiency (miles per gallon) because some technologies such as rolling resistance will be benefitting the ETVs as well. The dataset is added in the SI Excel sheet.

ICEV Cost Premium: In the final rulemaking for 2017-2025 of the CAFE standards published in 2012, the U.S. Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) analyzed the possible technologies which would benefit ICEVs by increasing the fuel efficiency (miles per gallon) and achieve the CAFE standards for manufacturers. These technologies include Engine Friction Reduction, Variable Valve Timing (VVT)-Intake Cam Phasing, VVT-Dual Cam Phasing, Discrete Variable Valve Lift (DVVL), Continuous Variable Valve Lift (CVVL), Electrical/Electro-hydraulic Power Steering, and Lower Rolling Resistance Tires. Some of these technologies cannot be used simultaneously, and some would have higher impacts depending on the size of the ICEVs. While each of these technologies would improve fuel efficiency, the manufacturing costs of the ICEVs would be expected to increase [40]. There is significant uncertainty related to when/if these technologies will be part of ICEV design as well as which of these technologies will be part of a particular vehicle, as it depends upon automobile manufacturers' decisions, vehicle size and type, and the ignition system of the vehicle. Several analyses (for example, the ICCT [38] and BNEF [34]) looking at future EV adoption have assumed cost increments for ICEVs with time. We have used these published reports to estimate the increase in real capital cost of ICEVs over time [34,38,40–42], which we refer to as the '*ICEV Cost Premium*.' The BNEF report estimates the cumulative average growth rate (CAGR) for ICEV price increases to be 0.70% for sedans. As per Brennan JW *et al.*, the CAGR for the ICEV price increase is 0.46% [41]. We have averaged these two CAGRs and assumed that the price of ICEVs increases by 0.6% each year for the scenarios where we apply the ICEV Cost Premium. For sedans, the current price of a comparable ICEV is $24,380 in our model, resulting in an annual price rise of $142. This price rise is in line with the other estimates published in various reports, such as the ICCT and NRC [34,38,40–42]. Because our cost model calculates the cost difference between an ICEV and an ETV (and not the absolute price of either), ICEV cost premiums must be estimated indirectly. For non-sedan vehicle types, this annual price rise is scaled with respect to the ratio of power ratings. For example, for an SUV, the designed power rating (described in technical specifications) is 142 kW, and it is 1.08 times that of a sedan (131 kW). Therefore, the annual price increase for an SUV is $154. The calculations and final estimates are described in the SI excel sheet.

2. Results

The detailed modeling approach described above is necessary to create a model that can realistically examine whether and how heterogeneity and technological progress can interact to create cascading diffusion of EVs from an initial group of consumers to the larger pool. The disaggregation of consumers into 200,000 different groups, based on NHTS survey data, provides the basis for the behavioral and geographic heterogeneity that drives the feedback between adoption and lower prices in later periods. To demonstrate the importance of heterogeneity, Figure 2 (in the main text) shows the evolution of battery cell prices over time (which is a function of adoption) with and without consideration of consumer heterogeneity. Figure 3 shows the base case market share of technologies if the inherent heterogeneities are considered. With these assumptions (High non-battery costs with ICEV cost premiums), BEV adoption grows from a few percent of the market to 90+% of the market over 15 years.

As discussed in the methodology, early adopters replace their current vehicles by ETVs in the initial years of the simulation, which increases the cumulative capacity of the technology. This increased capacity feeds into technological progress, and the price of the technology decreases. In the subsequent year, more consumers can benefit by moving to ETVs than the previous year, therefore the ETV adoption increases, which increases the cumulative capacity of batteries, reducing the price of the technology even further. As can be seen in Figure 2 and Figure 3, when the model accounts for heterogeneities, the battery cell price reduces as a result of substantial adoption of ETVs (mainly BEVs), and this adoption is a result of decreased battery cell price as a result of technology progress. Without heterogeneity (Figure 2), there are no early adopters, and ETV technology only begins to improve when ICEV Cost Premium makes private economics of ETVs more attractive to the average consumer. In both cases, the ICEV cost premium is included, which means that conventional vehicles get more efficient as well as more expensive with the time. In this work, we have defined the High Non-Battery Cost Model with ICEV Cost Premium as the base case scenario. However, the effects of this assumption are interrogated extensively below.

2.1 High Non-Battery Cost Vs. Low Non-Battery Cost Model

As explained in the Financial Model section (Section 2.1), the additional cost of technology includes both battery and non-battery costs. While there is a reasonably strong consensus on battery costs, this is not true about the non-battery costs. Furthermore, the differences are not trivial with regards to the effect on model output: assuming low versus high non-battery costs can result in a qualitatively different expectation of how the BEV market may evolve. Figure 3 shows the additional costs of a BEV-100 sedan under high and low non-battery cost models and with/without ICEV Cost Premiums, at a gasoline price of $2.60 per gallon. The initial cost gap between these two models is $3,300, which tends to be approximately maintained despite very different adoption rates (discussed below).

To better understand the context of the trends in the additional cost, note that the solid blue line in Figure 2 represents the base case. Figure 2 and Figure 3 show the corresponding battery cell price reduction (with a solid blue line), and the related market share of technologies (i.e., an increase in the share of ETVs). Comparing the two models with ICEV Cost Premium (i.e., the solid lines in Figure 3, the capital cost difference between ICEVs and BEVs decreases rapidly and crosses zero after 10 years in the Low Non-Battery Cost Model. This process takes an additional 14 years in the High Non-battery Cost Model. Therefore, we emphasize that the assumption to choose one model over another substantially affects the future outlook for technology adoption. If one assumes the lower model, then one can reasonably believe that BEVs can cost-effectively replace the incumbent ICEV technology over 10-15 years. If you consider the high non-battery cost model, this is delayed by an additional 10-15 years. We also highlight that the ICEV Cost Premium plays a significant role in this process, even though it seems like a minor modeling point. If we assume that ICEVs experience no changes in inflation-adjusted capital costs (versus a 0.6% increase each year for the base case), then the model suggests that BEVs may never dominate the market. Obviously, this adds to the uncertainty in studying the adoption of ETVs.

2.2 Impact of Fuel Prices

For the High Non-Battery Cost Model with higher gasoline prices ($2.60 per gallon and $5.20 per gallon), the reduction in battery cell price is faster and substantial. The maximum reduction happens in the case of the High Non-Battery Cost Model and gasoline price of $5.20 per gallon, where the battery cell price reduces to $49 per kWh (reduction of 79%). This suggests that if gasoline becomes more expensive, the majority of consumers will enjoy financial benefits from ETVs, potentially leading to a substantial replacement of the incumbent ICEVs by ETVs. The Low Non-Battery Cost Model makes the ETVs more attractive financially compared to ICEVs at higher gasoline prices, and even when the battery cell prices are high.

2.3 Learning rate of batteries

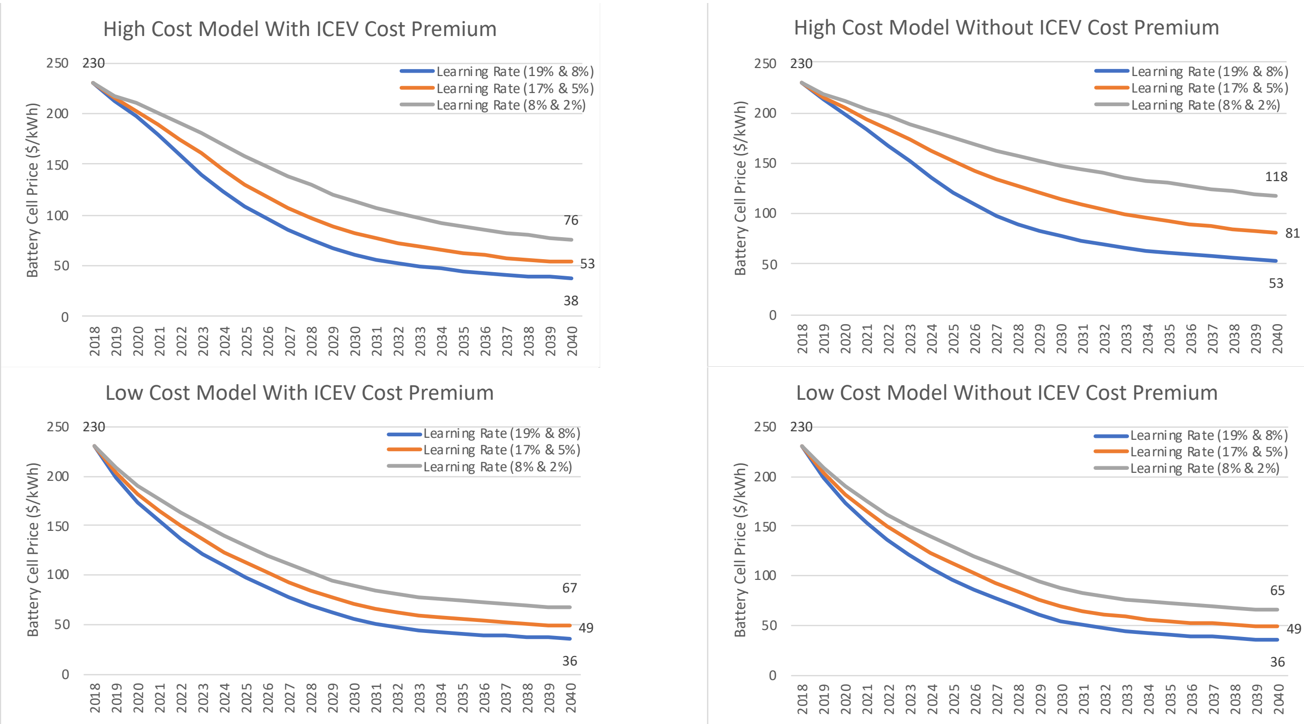

Figure S3: Progression of Battery Cell Price ($ per kWh). The base case represents 17% learning rate for batteries and 5% for non-battery technologies. Sensitivity Analyses with Optimistic (for battery 19%, and for non-battery technology 8%) and Pessimistic (for battery 14%, and for non-battery technology 2%) cases of learning rate of battery cell. The Learning Rate of 17% represents the base case scenario. With Optimistic cases, the ETVs adoption is accelerated and with pessimistic cases the adoption is slower than the base case scenario in both high as well as low-cost models.

2.4 Charging Constraint

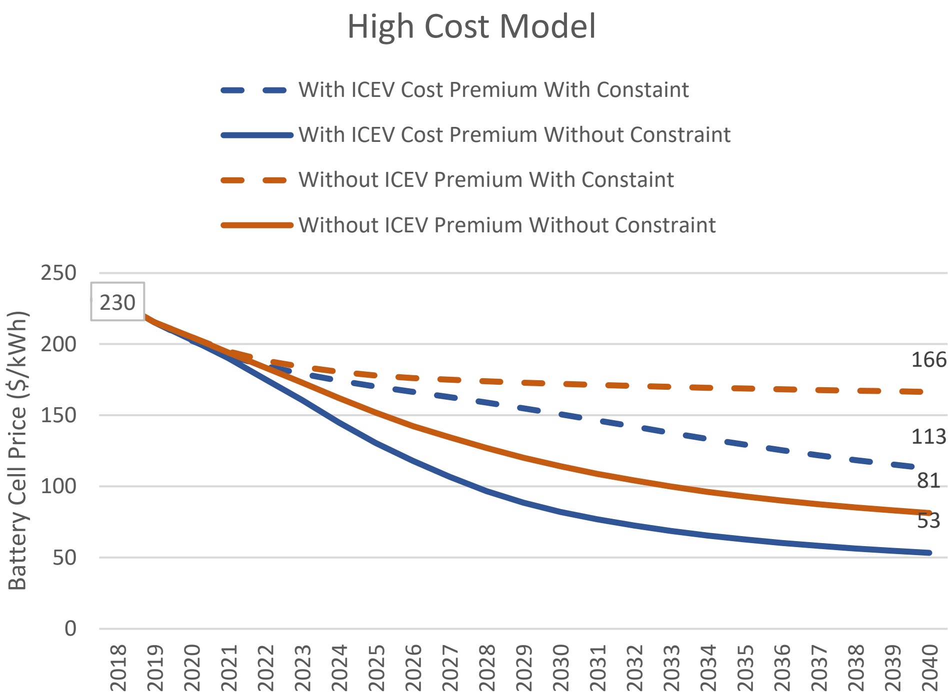

Figure S4. Progression of Battery Cell Price ($ per kWh) for High-Cost Model with and without ICEV Cost Premium, and with and without availability/access to the Charging Stations to 50%. With the charging availability constraint, the adoption of ETVs slows down, and vice versa.

References

1. GoodCarBadCar.net Auto Sales Data | Canada & the USA | GoodCarBadCar.Net Available online: http://www.goodcarbadcar.net/ (accessed on 1 January 2018).
2. U.S.-EPA Fuel Economy Available online: https://www.fueleconomy.gov/ (accessed on 27 February 2018).
3. Toyota Toyota Camry:Ebrochure.
4. Honda Honda CRV:Specifications.
5. Toyota Toyota RAV4:Specifications.
6. Honda Honda Odyssey:Specifications.
7. Ford Fond 150:Specifications.
8. Kromer, M.A.; Heywood, J.B. *Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet*; Cambridge, Massachusetts, 2007;
9. Kromer, M.A.; Heywood, J.B. *Electric Powertrains : Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet*; Cambridge, Massachusetts, 2007;
10. N.R.C. *Transitions to Alternative Vehicles and Fuels*; Washington, D.C., 2013;
11. N.R.C. *Transitions to Alternative Vehicles and Fuels: Appendix F*; Washington, D.C., 2013;
12. Raustad, R. *Electric Vehicle Life Cycle Cost Analysis*; Cocoa, FL, 2017;
13. Wood, E.; Alexander, M.; Bradley, T.H. Investigation of Battery End-of-Life Conditions for Plug-in Hybrid Electric Vehicles. *Journal of Power Sources* **2011**, *196*, 5147–5154, doi:10.1016/j.jpowsour.2011.02.025.
14. U.S.-EIA State Electricity Profiles Available online: https://www.eia.gov/electricity/state/%0A (accessed on 1 January 2018).
15. www.AAA.com Gas Prices Available online: http://gasprices.aaa.com/state-gas-price-averages/ (accessed on 1 January 2018).
16. CNG-Now Average CNG Price By State Available online: http://www.cngnow.com/average-cng-prices/Pages/default.aspx (accessed on 1 January 2018).
17. GasBuddy.com GasBuddy.Com Available online: http://www.gasbuddy.com/USA (accessed on 13 February 2018).
18. Nykvist, B.; Nilsson, M. Rapidly Falling Costs of Battery Packs for Electric Vehicles. *Nature Climate Change* **2015**, *5*, 329–332, doi:10.1038/nclimate2564.
19. Nykvist, B.; Sprei, F.; Nilsson, M. Assessing the Progress toward Lower Priced Long Range Battery Electric Vehicles. *Energy Policy* **2019**, *124*, 144–155, doi:10.1016/j.enpol.2018.09.035.
20. Curry, C. *Lithium-Ion Battery Costs and Market*; 2017;
21. Morsy, S. *BNEF Long Term EV Outlook*; 2017;
22. Kittner, N.; Lill, F.; Kammen, D.M. Energy Storage Deployment and Innovation for the Clean Energy Transition. *Nature Energy* **2017**, *2*, 1–6, doi:10.1038/nenergy.2017.125.
23. Schmidt, O.; Hawkes, A.; Gambhir, A.; Staffell, I. The Future Cost of Electrical Energy Storage Based on Experience Rates. *Nature Energy* **2017**, *6*, 17110, doi:10.1038/nenergy.2017.110.
24. Weiss, M.; Junginger, M.; Patel, M.K.; Blok, K. A Review of Experience Curve Analyses for Energy Demand Technologies. *Technological Forecasting and Social Change* **2010**, *77*, 411–428, doi:10.1016/j.techfore.2009.10.009.
25. Gielen, D. Energy Technology Perspectives 2008: Scenarios and Strategies for CO 2 Emissions Reduction. *International Journal of Gas Turbine, Propulsion and Power Systems* **2010**, *3*, 1–9.

26. Pasaoglu, G.; Honselaar, M.; Thiel, C. Potential Vehicle Fleet CO2 Reductions and Cost Implications for Various Vehicle Technology Deployment Scenarios in Europe. *Energy Policy* **2012**, *40*, 404–421, doi:10.1016/j.enpol.2011.10.025.
27. Pasaoglu, G.; Harrison, G.; Jones, L.; Hill, A.; Beaudet, A.; Thiel, C. A System Dynamics Based Market Agent Model Simulating Future Powertrain Technology Transition: Scenarios in the EU Light Duty Vehicle Road Transport Sector. *Technological Forecasting and Social Change* **2016**, *104*, 133–146, doi:10.1016/j.techfore.2015.11.028.
28. McDonald, A.; Schrattenholzer, L. Learning Rates for Energy Technologies. *Energy Policy* **2001**, *29*, 255–261, doi:https://doi.org/10.1016/S0301-4215(00)00122-1.
29. van Vliet, O.P.R.; Kruithof, T.; Turkenburg, W.C.; Faaij, A.P.C. Techno-Economic Comparison of Series Hybrid, Plug-in Hybrid, Fuel Cell and Regular Cars. *Journal of Power Sources* **2010**, *195*, 6570–6585, doi:10.1016/j.jpowsour.2010.04.077.
30. Contestabile, M.; Offer, G.J.; Slade, R.; Jaeger, F.; Thoennes, M. Battery Electric Vehicles, Hydrogen Fuel Cells and Biofuels. Which Will Be the Winner? *Energy and Environmental Science* **2011**, *4*, 3754–3772, doi:10.1039/c1ee01804c.
31. Weiss, M.; Patel, M.K.; Junginger, M.; Perujo, A.; Bonnel, P.; van Grootveld, G. On the Electrification of Road Transport - Learning Rates and Price Forecasts for Hybrid-Electric and Battery-Electric Vehicles. *Energy Policy* **2012**, *48*, 374–393, doi:10.1016/j.enpol.2012.05.038.
32. Safari, M. Battery Electric Vehicles: Looking behind to Move Forward. *Energy Policy* **2018**, *115*, 54–65, doi:10.1016/j.enpol.2017.12.053.
33. Hill, N.; Windisch, E.; Kirsch, F.; Horton, G.; Dun, C.; Energy, R.; Hausberger, S.; Matzer, C.; Graz, T.U.; Tepr, I.S.; et al. *Improving Understanding of Technology and Costs for CO2 Reductions from Cars and LCVs in the Period to 2030 and Development of Cost Curves (Ref: Ricardo/ED59621/Issue Number 3)*; Didcot, United Kingdom, 2016;
34. Soulopoulos, N. *When Will Electric Vehicles Be Cheaper than Conventional Vehicles?*; 2017;
35. The Boston Consulting Group *The Electric Car Tipping Point*; 2017;
36. Kuhlmann, K.; Wolf, S.; Pieper, C.; Xu, G.; Ahmad, J. *The Future of Battery Production for Electric Vehicles*; 2018;
37. Berckmans, G.; Messagie, M.; Smekens, J.; Omar, N.; Vanhaverbeke, L.; Mierlo, J. Van Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles up to 2030. *Energies (Basel)* **2017**, *10*, doi:10.3390/en10091314.
38. Wolfram, A.P.; Lutsey, N. *Electric Vehicles: Literature Review of Technology Costs and Carbon Emissions*; Washington, D.C., 2016;
39. UMTRI-(University of Michigan Transportation Research Institute) Sustainable Worldwide Transportation - Sales-Weighted Fuel Economy (Window Sticker) Available online: http://www.umich.edu/~umtriswt/EDI_sales-weighted-mpg.html (accessed on 15 November 2018).
40. EPA; NHTSA Joint Technical Support Document: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards. *Epa.Gov* **2012**, 602, doi:10.1007/s13398-014-0173-7.2.
41. Brennan, J.W.; Barder, T.E. Battery Electric Vehicles vs . Internal Combustion Engine Vehicles. *Arthur D Little* **2016**, 48, doi:10.1016/0375-9601(72)90803-1.
42. Kolwich, G. *Light-Duty Vehicle Technology Cost Analysis: European Vehicle Market | International Council on Clean Transportation*; Washington, D.C., 2013;

Abbreviations

BEV	Battery Electric Vehicle
BNEF	The Bloomberg New Energy Finance
CAFE	Corporate Average Fuel Economy
ETV	Electric Technology Vehicle
EV	Electric Vehicles
HEV	Hybrid Electric Vehicle
ICCT	The International Council on Clean Transportation
ICEV	Internal Combustion Engine Vehicle
kW	Kilowatt
kWh	Kilowatt-hour
NHTS	The National Household Travel Survey
NPV	Net Present Value
NRC	National Research Council
PHEV	Plug-in Hybrid Electric Vehicle
SUV	Sports Utility Vehicle
TCO	Total Cost of Ownership
VMT	Vehicle Miles Traveled
U.S.	The United States of America