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Carbon abatement costs are negative for many electric vehicles across U.S. cities

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Abstract

Electric vehicles are a critical technology for reducing greenhouse gas (GHG) emissions in the transportation sector. Price is a major barrier for widespread electric vehicle adoption. Here we conduct a life cycle assessment and a total cost of ownership (TCO) analysis of conventional internal combustion engine vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles, and battery electric vehicles across five vehicle classes, with five different charging strategies, in 20 U.S. cities. We find that battery electric vehicles have the lowest life cycle GHG emissions of any powertrain across all vehicle classes, locations, and charging strategies. In contrast, the powertrain with the lowest TCO depends on the class, location, and charging pattern. By quantifying both GHG emissions and TCO, we calculate the abatement cost of different vehicle choices – the emissions reductions per dollar spent. We find that small and midsize battery electric vehicles have negative carbon abatement costs over their lifetimes in most locations. These vehicles have both lower GHG emissions and lower total cost than conventional alternatives. For larger vehicles the locations with a negative abatement cost are limited; however, the abatement cost remains below most social cost of carbon estimates, suggesting electrification is a cost-effective GHG reduction strategy.

Introduction

Electric vehicles (EVs) have dramatically lower lifecycle greenhouse gas (GHG) emissions than conventional gasoline vehicles[1–4]; consequently, EV adoption is a primary strategy for decarbonizing the road transportation sector[5,6]. Worldwide, adoption of EVs is expected to continue accelerating. But in the U.S., EV adoption has lagged behind other countries[7], despite technological advances[8]. Within the U.S., adoption rates vary widely by location and for different consumers and applications[9]. EV prices are one of the most highly cited barriers for consumers[10–12]. On average, new EVs have higher retail prices than conventional alternatives. However, when the total cost of ownership (TCO) is considered, EVs are cost competitive in some situations[13].

Life cycle assessment (LCA) has been used to compare GHG emissions of different vehicle powertrains. This includes emissions from the materials, manufacturing, and disposal of the vehicle itself (the vehicle cycle) and emissions from operating the vehicle, including direct emissions from combustion and upstream emissions from fuel production (the fuel cycle). Such comparisons are complicated by the fact that vehicle emissions vary by vehicle class, location, driving patterns, charging patterns, and EV range[14]. In general, emissions reductions enabled by electrification are proportional across vehicle classes, though the absolute emissions savings are greater for larger vehicles[15]. Across locations, emissions vary due to differences in temperature (impacting vehicle fuel economy), and the mix of electricity generating resources that power the local electric grid[16–21]. Driving patterns impact emissions by affecting a vehicle's fuel economy[2]. Charging patterns impact emissions because the carbon intensity of the electric grid varies in time as well as by location[22].

Similarly, TCO studies have shown that the total cost of a vehicle also depends on the powertrain[23], class[24], location[25,26], driving pattern[27], and charging pattern[28,29]. TCO includes upfront costs (down payment, taxes, fees), recurring costs (fuel, insurance, maintenance, repairs, financing, fees), and end-of-ownership costs (scrappage or resale). Location affects costs for fuel (gasoline and electricity), insurance, taxes, and fees.

Both LCA and TCO studies depend on assumptions regarding system boundaries and the parameters used to characterize vehicles (e.g., fuel economy) and their operation (e.g., lifetime mileage). Though many studies have investigated emissions and cost independently, few have assessed both[2,30–33]. Modeling cost and emissions simultaneously allows for the abatement cost to be obtained[34], which is an important metric for policy makers. Woodley et al. found that BEV vs ICEV abatement costs in U.S. states ranged from \$76/ton to \$583/ton, with an average value of \$192/ton, and they suggest this cost is too high for effective GHG abatement[34].

Abatement costs can also be compared with the social cost of carbon (SCC) to evaluate societal costs and benefits of actions or policies. Estimates of the SCC have increased over time[35] and vary widely based on distributional weighting[36], discount rates[37,38], and which damages are included[39]. Prior to its repeal under the current U.S. administration, the U.S. EPA in December 2023 finalized an estimate of \$190/tonne CO_2, to be used in regulatory impact analyses[40]. This was a sizable increase from the previous U.S. government value (\$51/tonne), though other recent assessments estimate much higher values (e.g., \$283/tonne[41], \$1,013/tonne[42]).

The major contributions of this study are:

a) assessing vehicles life cycle GHG emissions and total cost of ownership using consistent assumptions and parameters across both models,
b) including variation in both cost and emissions depending on powertrain, class, location, driving pattern, and charging pattern,
c) using these results to evaluate breakeven times (i.e., how long it takes for cost or emissions savings to be realized),
d) evaluating the cost effectiveness (i.e., abatement cost), on an individual basis, of reducing GHG emissions through vehicle electrification, and
e) identifying locations and situations where there are tradeoffs between cost and emissions, and "win-wins" where cost and emissions can be reduced simultaneously.

We find that vehicle electrification results in life cycle GHG emissions savings across all vehicle classes and in all 20 cities we investigated. On average, battery electric vehicle (BEV) emissions are 37% of the emissions of a conventional internal combustion engine vehicle (ICEV) of the same vehicle class. Compared to an ICEV, a BEV has a lower total cost of ownership in some locations depending on the vehicle class. For small vehicles (compact and midsize sedans), the BEV has a lower TCO in almost all locations. For SUVs, the BEV has a lower TCO in some cities, and for pickup trucks the BEV has a higher TCO in all cities.

BEVs have higher upfront emissions and costs than conventional vehicles. For GHG emissions, BEVs break even with ICEVs within 2 years. For TCO, BEVs break even as early as 7 years for smaller vehicles but may not break even during the vehicle's lifetime for pickup trucks. For smaller vehicles (sedans and small SUVs), we find that BEVs compared to ICEVs have a negative abatement cost, representing a win-win where both cost and GHG emissions are reduced. For larger vehicles there is a tradeoff between cost and emissions (on average $41/tonne for a midsize SUV and $130/tonne for a pickup truck); however, the cost of this tradeoff is generally lower than SCC estimates. By charging during off peak hours, abatement costs can be reduced, and more locations and vehicle classes become "win-wins" where cost and emissions can be reduced simultaneously.

Results

Here we compare internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), plug in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs) across five vehicle classes, for five different charging strategies, in 20 U.S. cities. To evaluate abatement costs, we first present results for GHG emissions and TCO individually.

Greenhouse Gas Emissions and Total Cost of Ownership

Increasing degrees of vehicle electrification (ICEV to HEV to PHEV to BEV) results in decreased life cycle GHG emissions. For conventional ICEVs and HEVs, most of the GHG emissions come during the pump-to-wheel (PTW) portion of the use phase (i.e., from the combustion of gasoline). For electric vehicles GHG emissions are produced upstream in the well-to-pump (WTP) phase, from generation sources used to produce electricity. Electric vehicles have higher vehicle cycle emissions than conventional vehicles (**Fig. 1a**). In addition to electrification, downsizing to smaller vehicle classes decreases GHG emissions (**Fig. 1c**); however, the impact of electrification is greater than the impact of downsizing. This result is consistent across vehicle classes, charging strategies, and locations.

The purchase price of a vehicle is the largest contributor to its lifetime cost, followed by insurance, fuel, maintenance, and repairs. Smaller contributions are made by financing (interest), taxes, and various fees (**Fig. 1b**). Electrification can result in lower (e.g., compact sedan) or higher (e.g., pickup truck) TCO depending on the vehicle class; however, reducing vehicle size uniformly reduces TCO (**Fig. 1d**).

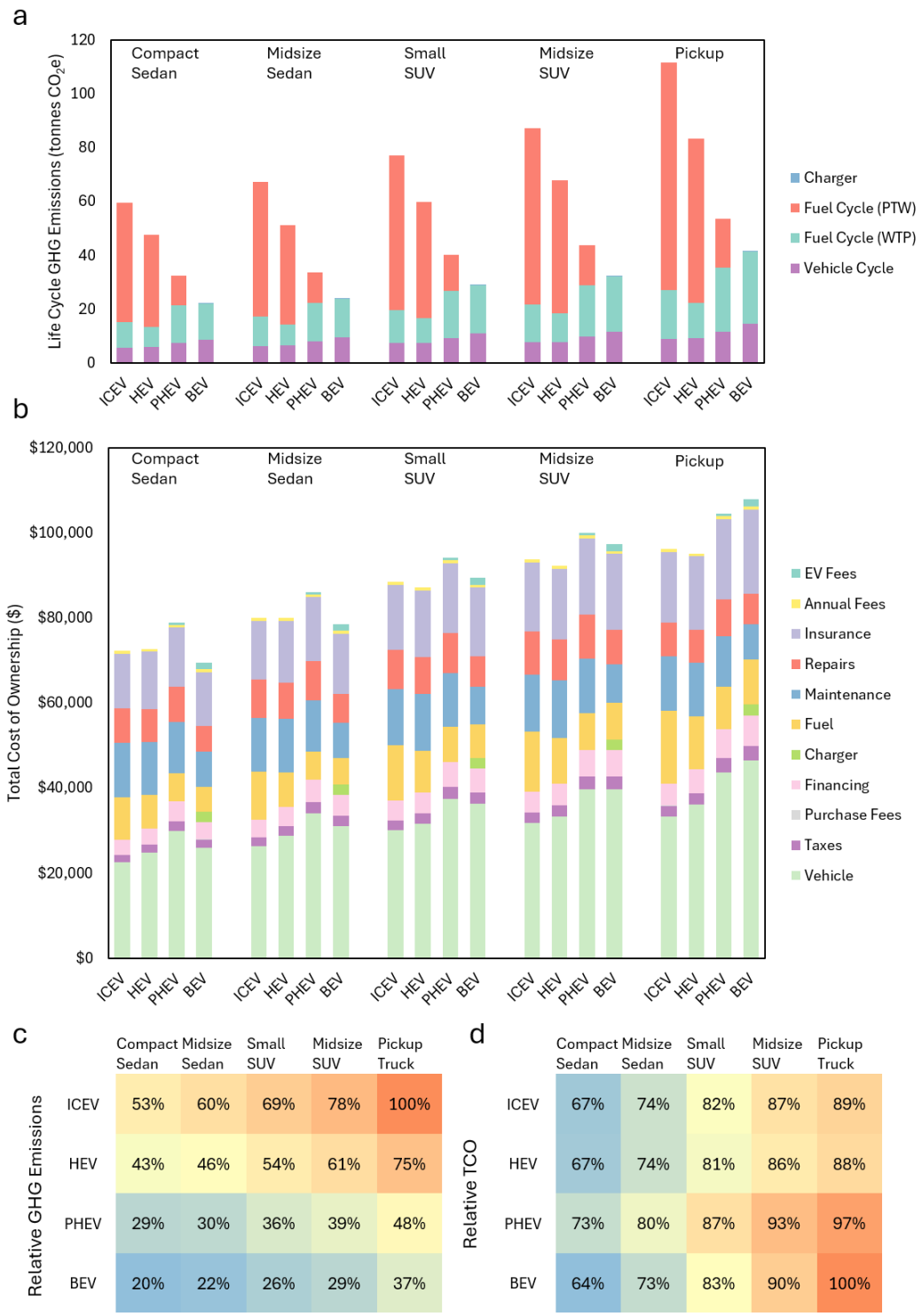


Fig. 1. Life cycle greenhouse gas emissions and total cost of ownership by component

a-d, *Over the entire vehicle lifespan, the life cycle greenhouse gas emissions broken down by stage (a), the total cost of ownership broken down by cost component (b), the life cycle GHG emissions relative to the highest emitting vehicle (c), and the total cost of ownership relative to the most costly vehicle (d), for internal combustion engine vehicles (ICEV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), and battery electric vehicles (BEV) of each vehicle class using U.S. average values for emissions and cost inputs. See Supplemental Note 1 for results for each city.*

Regional Variation

Life cycle GHG emissions of ICEVs and HEVs are relatively constant across locations, whereas emissions of PHEVs and BEVs vary greatly due to the local electric grid and projections of the future grid mix in each location. For example, a small SUV BEV in Cleveland (37 tonnes CO_2e) has approximately 2.6 times the GHG impact as the same vehicle in Seattle (14 tonnes CO_2e) (**Fig. 2a**). Even with the most carbon intensive grid, BEVs have lower GHG emissions than PHEVs, HEVs, and ICEVs.

TCO varies by city across all powertrains due to differences in fuel, insurance, taxes, and fees. Interestingly, the three most expensive cities for ICEVs are the three most expensive for BEVs (Los Angeles, San Francisco, and Detroit), and the three least expensive cities for ICEVs are the three least expensive cities for BEVs (Charlotte, Cleveland, and Portland) (**Fig. 2b**). Furthermore, cities with the largest cost savings when comparing a BEV to an ICEV are not cities with the highest gasoline prices or cities with the lowest effective electricity prices, because many cities with high gasoline prices also have high electricity prices (e.g., San Francisco, Los Angeles), and many cities with low electricity prices also have low gasoline prices (e.g., Dallas, Houston, Charlotte, Cleveland).

Taking the difference in total cost of ownership shows the cities in which BEVs are most cost competitive (**Fig. 3a,b**). The cities where BEVs have the largest cost savings compared to ICEVs are Seattle, Chicago, Miami, and Phoenix, each of which have average to high gasoline prices, and low to average electricity prices. Chicago, Miami, and Phoenix also have some of the lowest annual fees for BEVs. Seattle has one of the highest annual BEV fees, but the gasoline to electricity cost difference is large enough that Seattle still has the greatest total cost savings. The cities with the smallest savings (or largest cost advantage for ICEVs) are Philadelphia and Boston, which have the highest effective electricity prices outside of California, and average gasoline prices. Notably, Boston is one of the few cities in our sample without time-of-use electricity prices, whereas Philadelphia, which has similar on-peak electricity prices as other cities, has one of the highest off-peak electricity rates.

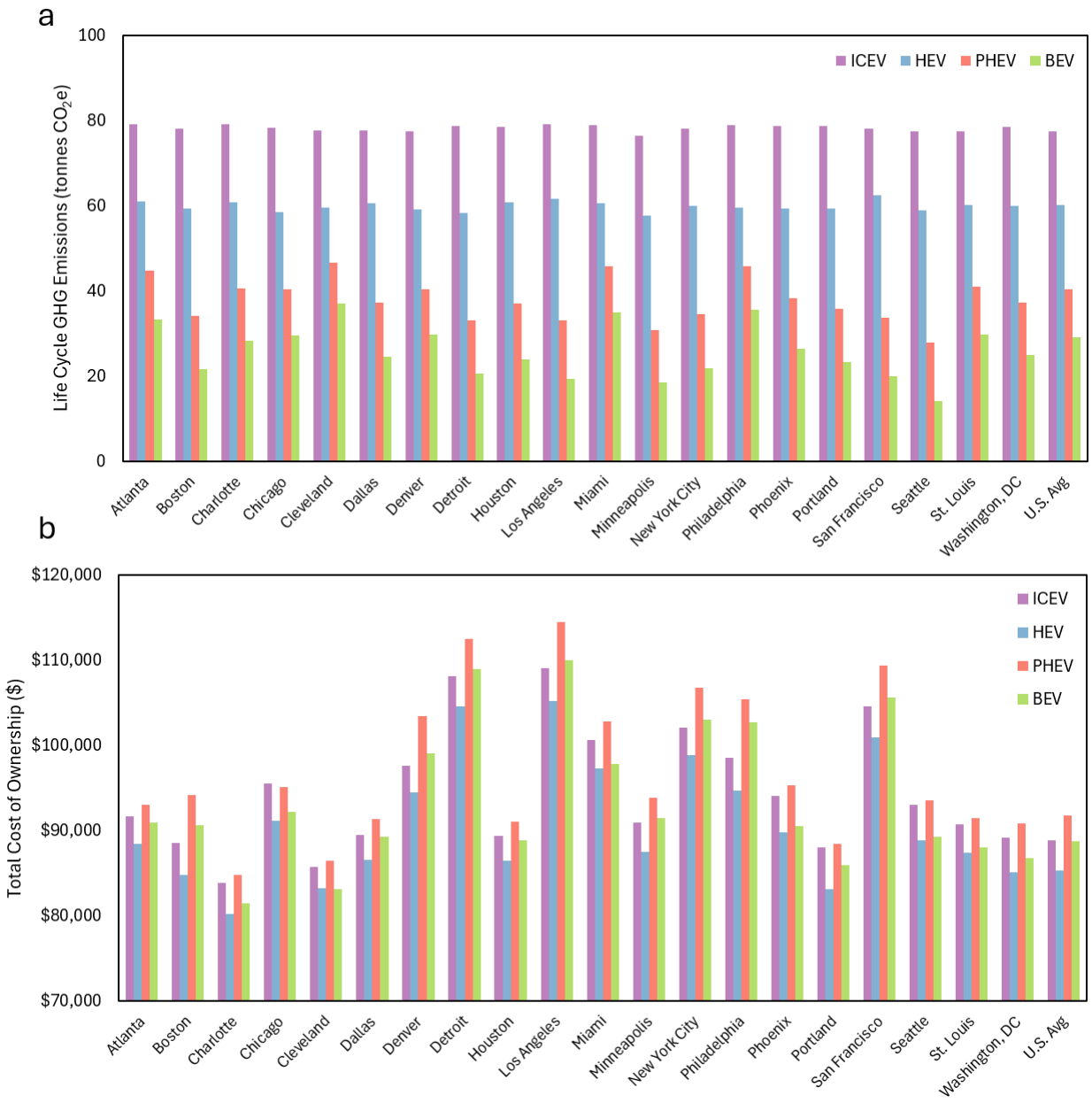


Fig. 2. Life cycle greenhouse gas emissions and total cost of ownership by location
a-b*, Over the entire vehicle lifespan, the life cycle greenhouse gas emissions (a) and the total cost of ownership (b) for internal combustion engine vehicles (ICEV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), and battery electric vehicles (BEV) for a small SUV. See Supplemental Note 1 for other vehicle classes (compact sedan, midsize sedan, midsize SUV, and pickup truck).*

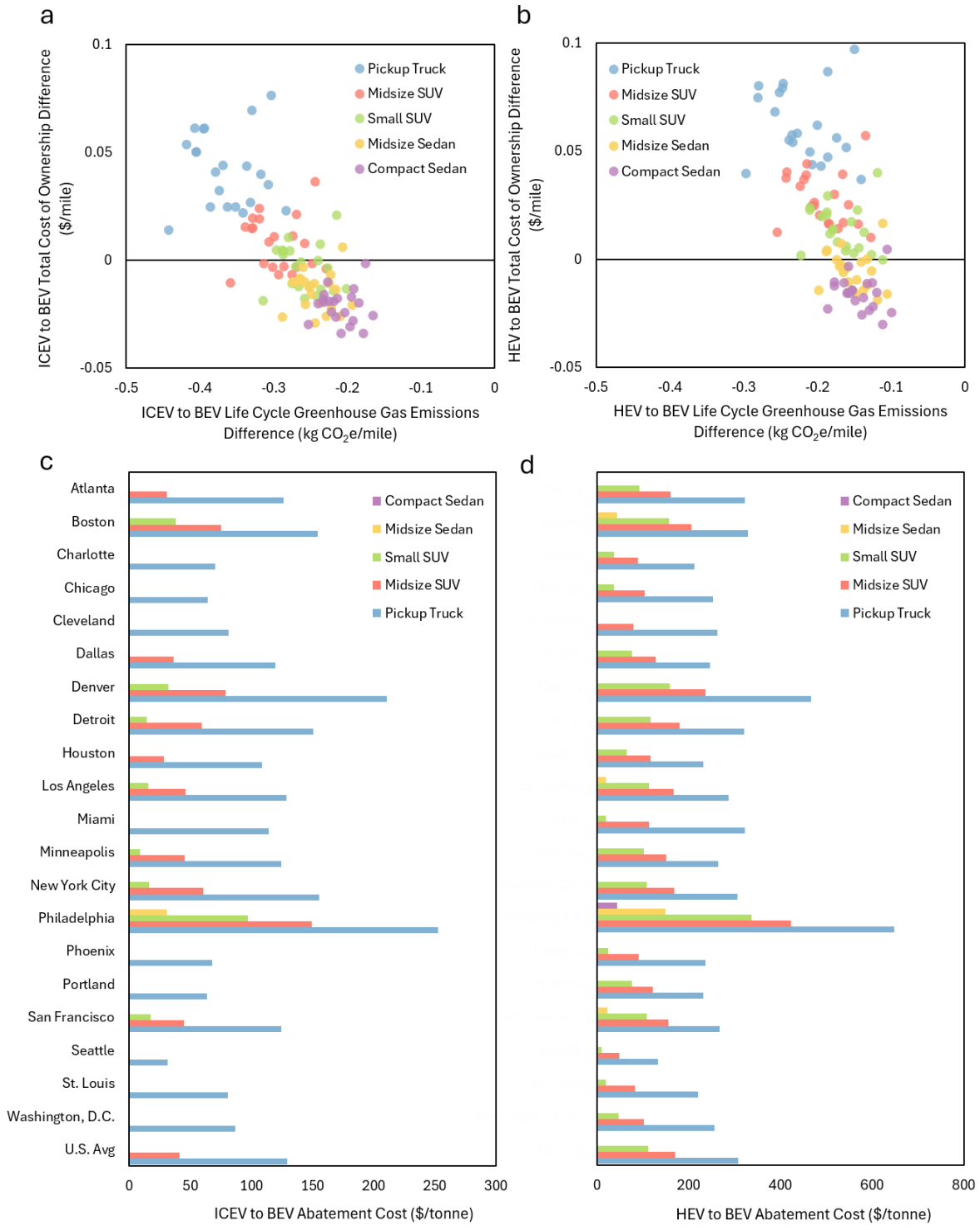


Fig. 3. Difference in cost and emissions, and abatement cost of vehicle transitions ***a-d,*** *The difference in life cycle greenhouse gas emissions and total cost of ownership (a, b) and abatement cost (c, d) when comparing an internal combustion engine vehicle (ICEV) and a battery electric vehicle (BEV) (a, c) and an hybrid electric vehicle (HEV) and a battery electric vehicle (b, d) of each vehicle class in each of the 20 cities investigated. Bars are not shown for vehicle classes with negative abatement costs in c and d, as the metric no longer measures cost-effectiveness when costs are negative.*

Abatement Cost

Abatement cost represents the cost paid to achieve a reduction in emissions. In this context a negative abatement cost means there is a cost savings and an emissions savings (a "win-win"), while a positive abatement cost shows a trade-off (there is a positive cost paid to achieve emissions reductions). As shown in **Fig. 3a**, the emissions difference between a BEV and an ICEV is negative for all vehicle classes in all cities and is more negative for larger vehicle classes. The cost difference is negative for smaller vehicle classes but positive for larger vehicle classes. When comparing a BEV and an HEV, the emissions difference remains negative for all vehicle classes in all cities, but by a lesser amount (**Fig. 3b**), and the cost difference is negative for fewer cities.

Of the 20 cities evaluated, switching from an ICEV to a BEV has a negative abatement cost in all 20 cities for a compact sedan, 19 cities for a midsize sedan, 12 cities for a small SUV, 9 cities for a midsize SUV, and zero cities for a pickup truck (bars are not shown for city-vehicle combinations with negative abatement costs). U.S. average abatement costs are negative for compact sedans, midsize sedans, and small SUVs, $41/tonne for midsize SUVs and $130/tonne for pickup trucks (**Fig. 3c**). Applying a carbon tax at the EPA estimated SCC of $190/tonne would result in a negative abatement cost in all but two locations (Denver and Philadelphia) for one vehicle class (pickup truck). Abatement costs are much higher when comparing an HEV and a BEV, because an HEV has lower costs and lower emissions than an ICEV. However, the abatement cost is still negative in most locations for compact and midsize sedans (**Fig. 3d**).

These abatement costs are much lower than those estimated by Woodley et al.[34,43] This difference stems from a variety of factors, but chief among them are 1) lower purchase price differences between ICEVs and BEVs, as the price gap has shrunk over time, and 2) updated projections of electric grid decarbonization over the lifetime of the vehicles.

Breakeven Time

BEVs have a higher initial GHG burden than other powertrains, primarily due to the Li-ion battery. BEVs have lower emissions while in operation, though the degree depends on the carbon intensity of the local electric grid. Thus, BEVs breakeven with other powertrains after a certain amount of time (or miles); after that time BEVs have lower life cycle emissions. Similarly, BEVs generally have higher upfront purchase costs, and lower costs in operation due to lower fuel, maintenance, and repair costs. Lower operating costs are sometimes, but not always, sufficient to make up for the initial higher cost burden (i.e., the breakeven time may exceed the vehicle's lifetime). Thus, BEVs will break even on cost for some vehicle classes in some locations.

For GHG emissions, BEVs break even with ICEVs of the same vehicle class within 2 years (**Fig. 4a**). The GHG breakeven time is approximately the same regardless of vehicle class. Even with the substantial variation in GHG emissions, this holds true across all 20 cities we investigated.

For TCO, the breakeven time depends heavily on the vehicle class. With U.S. average values, the breakeven times are 10 years (compact sedan), 12 years (midsize sedan), 15 years (small SUV), and longer than the vehicle's lifetime for a midsize SUV or pickup truck (**Fig. 4b,c**).

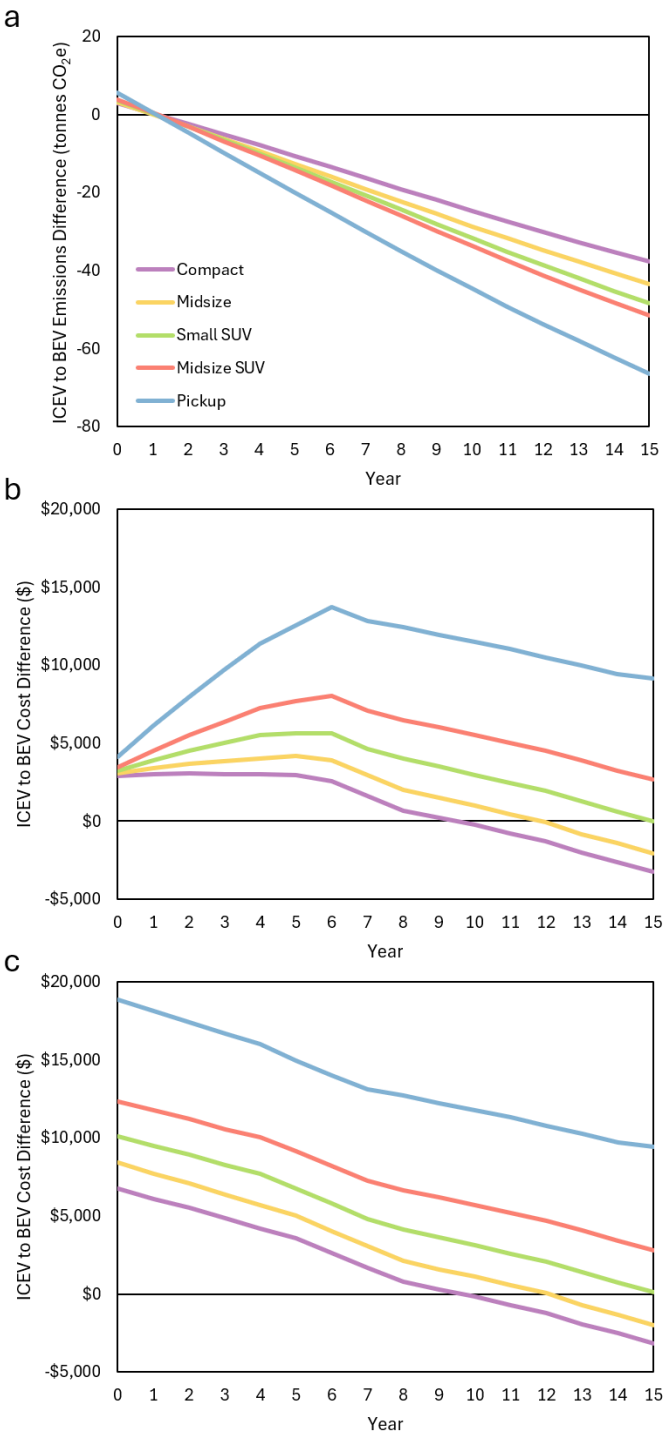


Fig. 4. Life cycle greenhouse gas emissions and total cost of ownership breakeven times a-c, *The time required to break even in terms of greenhouse gas emissions (a), and total cost of ownership with financing (b) and without financing (c), when comparing an internal combustion engine vehicle (ICEV) to a battery electric vehicle (BEV). Calculated by taking the cumulative emissions or cost each year for the ICEV and subtracting the cumulative emissions or cost each year for the BEV of the same vehicle class, using U.S. average values. See Supplemental Note 1 for results for each city.*

Charging Strategies

Both cost and emissions vary with time. Previous studies generally use average regional electricity prices[2,31]. Here we pair hourly prices from utilities with different consumer charging behaviors. This method results in substantially different charging costs than using average prices[13]. We obtain hourly electricity prices from rate plans from electric utilities in each city. Of the 20 cities, 15 have time-of-use programs that charge different per kWh rates depending on the time of day. We apply five different charging strategies with different amounts of home and public charging, and off-peak, part-peak, and on-peak charge timing to reflect consumers with differences in price sensitivity or charging access (**Fig. 5e**). Our base cases uses 80% home charging (of which 50% is off-peak, 25% is part-peak, and 25% in on-peak) and 20% public charging (of which 50% is level 2 charging and 50% is DC fast charging).

The different charging strategies have a limited impact on the GHG emissions of the BEVs (**Fig. 5a**). One interesting comparison is Portland and San Francisco. Portland's rate structure incentivizes charging overnight, even though emissions are higher in those hours. In comparison, San Francisco maintains off-peak pricing through the middle of the day (when there is abundant solar energy) and has on-peak pricing in the evening, which incentivizes charging during hours with a lower emissions intensity.

Charging strategies have a notable impact on TCO (**Fig. 5b**). In general, using more home charging and charging during off-peak times reduces TCO. Boston, San Francisco, Los Angeles, and Philadelphia are exceptions, because on-peak home charging prices are higher than level 2 public charging prices, leading to lower costs when public charging replaces on-peak home charging. In some cities (e.g. Atlanta, Charlotte, Cleveland, Dallas, Houston) the difference between the 'all public charging' and 'no public charging' scenarios changes the BEV from the most expensive (higher than ICEV, HEV and PHEV) to the least expensive powertrain. Changing charging strategies makes a substantial difference for the abatement cost and can change the abatement cost from positive to negative for some vehicle classes (**Fig. 5c** and **Fig. 5d**). For example, when switching from 'occasional' public charging to 'rare' public charging the number of cities with a negative abatement cost for a small SUV increases from 12 to 18.

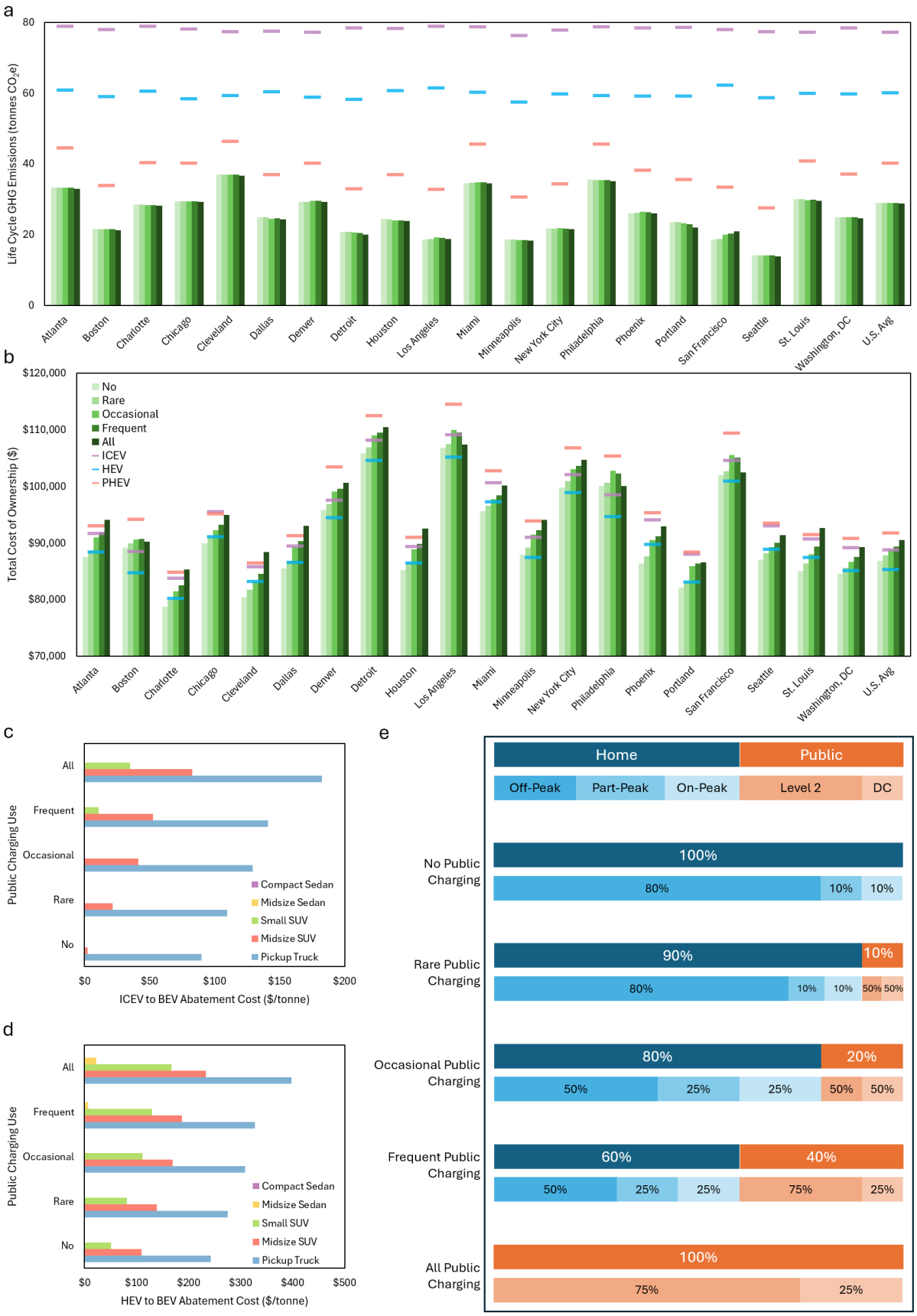

a
Life Cycle GHG Emissions (tonnes CO_2e)
0
20
40
60
80
Atlanta
Boston
Charlotte
Chicago
Cleveland
Dallas
Denver
Detroit
Houston
Los Angeles
Miami
Minneapolis
New York City
Philadelphia
Phoenix
Portland
San Francisco
Seattle
St. Louis
Washington, DC
U.S. Avg
b
Total Cost of Ownership ($)
$70,000
$80,000
$90,000
$100,000
$110,000
$120,000
No
Rare
Occasional
Frequent
All
ICEV
HEV
PHEV
c
Public Charging Use
All
Frequent
Occasional
Rare
No
Compact Sedan
Midsize Sedan
Small SUV
Midsize SUV
Pickup Truck
$0
$50
$100
$150
$200
ICEV to BEV Abatement Cost ($/tonne)
d
Public Charging Use
$0
$100
$200
$300
$400
$500
HEV to BEV Abatement Cost ($/tonne)
e
Home
Public
Off-Peak
Part-Peak
On-Peak
Level 2
DC
No Public Charging
100%
80%
10%
10%
Rare Public Charging
90%
10%
80%
10%
10%
50%
50%
Occasional Public Charging
80%
20%
50%
25%
25%
50%
50%
Frequent Public Charging
60%
40%
50%
25%
25%
75%
25%
All Public Charging
100%
75%
25%

Fig. 5. Difference in cost and emissions depending on charging strategies
a-e, *For five different charging strategies, the life cycle greenhouse gas emissions for a small SUV (a) and the total cost of ownership for a small SUV in each city (b). For the same five charging strategies the abatement cost when comparing an ICEV and a BEV (c), the abatement cost when comparing an HEV and a BEV (d), using U.S. average values. For each charging strategy, the percentages of home (divided into off-peak, part-peak, and on-peak) and public (divided into level 2 and DC) charging (e). See Supplemental Note 1 for results for other vehicle classes (a,b), and different cities (c,d).*

Sensitivity Analysis

A smaller battery reduces both cost and emissions for BEVs. A 200-mile range BEV has a lower TCO than an ICEV of the same vehicle class across all classes and in all cities, with the exception of a pickup truck in Philadelphia (**Fig. 6a**). A 400-mile range BEV has a higher TCO than an ICEV of the same vehicle class across all classes and in all cities (**Fig. 6b**). Regardless of battery size, BEVs have lower life cycle GHG emissions than comparable ICEVs.

Fuel prices can have a large impact on TCO. Gasoline prices in May 2026 were approximately 25% higher than the 2021-2025 May average. With a 25% increase in gasoline prices, BEVs have a lower TCO than ICEVs (and thus a negative abatement cost) in all 20 cities for compact and midsize sedans, 19 cities for small SUVs, 18 cities for midsize SUVs, and 7 cities for pickup trucks (**Fig. 6c**). If electricity prices were 25% higher than the rates currently available in each city, BEVs would have a lower TCO in 18 cities for compact sedans, 13 cities for midsize sedans, and 8 cities for small SUVs. BEVs would have a higher TCO in all cities for midsize SUVs and pickup trucks (**Fig. 6d**).

How the electric grid changes over time will impact BEV GHG emissions. Our base case from Cambium[44] is the "high renewable electricity cost, low natural gas price" scenario. This is scenario with the slowest rate of grid decarbonization. We also test the "midcase" scenario and the "low renewable electricity cost, high natural gas price" scenarios, which have faster rates of grid decarbonization (**Fig 6e** and **Fig. 6f**). However, since the electricity cost is based on current rate plans, TCO, and therefore the number of cities where the BEV TCO is lower than an ICEV, are unchanged from the base case. The U.S. average abatement costs for switching an ICEV to a BEV pickup truck are $130/tonne, $127/tonne, and $121/tonne, showing that on average the impact of different grid scenarios is relatively small.

Two other parameters, vehicle miles traveled (VMT) and discount rate, have a substantial impact on the results. With a higher annual and lifetime VMT, the cost savings of a BEV compared to alternatives is greater, resulting in lower abatement costs, and more vehicle classes with negative abatement costs (**Fig. 6g**). Similarly, a lower discount rate (i.e., valuing future costs similarly to costs in the present) enhances the cost savings of BEVs, as they generally have higher upfront costs and lower recurring costs (**Fig. 6h**).

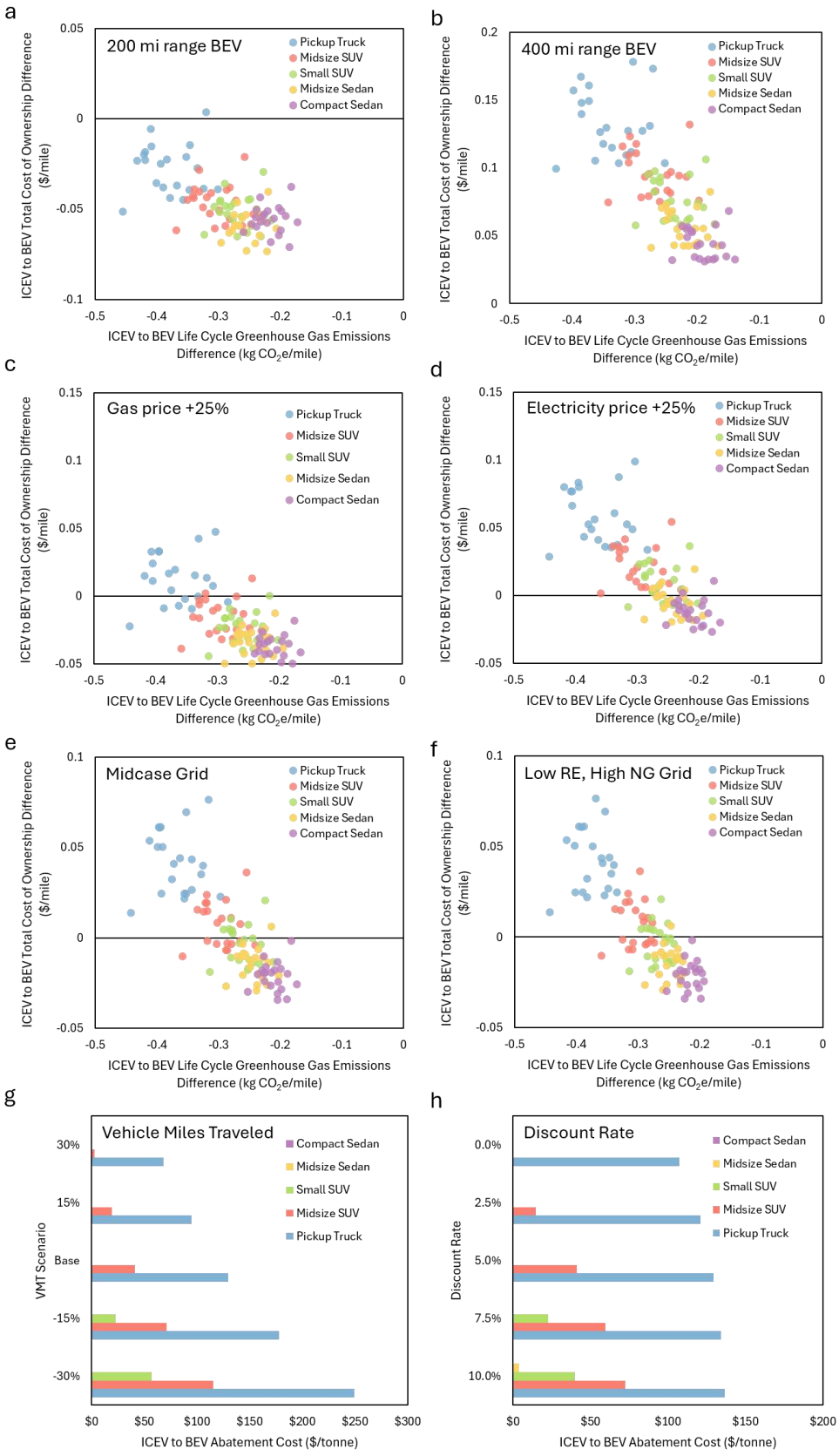

a
200 mi range BEV
Pickup Truck
Midsize SUV
Small SUV
Midsize Sedan
Compact Sedan
ICEV to BEV Total Cost of Ownership Difference ($/mile)
ICEV to BEV Life Cycle Greenhouse Gas Emissions Difference (kg CO2e/mile)
b
400 mi range BEV
c
Gas price +25%
d
Electricity price +25%
e
Midcase Grid
f
Low RE, High NG Grid
g
Vehicle Miles Traveled
VMT Scenario
30%
15%
Base
-15%
-30%
ICEV to BEV Abatement Cost ($/tonne)
h
Discount Rate
0.0%
2.5%
5.0%
7.5%
10.0%

Fig. 6. Sensitivity Analyses
a-h, *Difference in life cycle GHG emissions and total cost of ownership when comparing an ICEV to a BEV with a 200 mi-range (a), and a BEV with a 400 mi-range (b). Difference in life cycle GHG emissions and total cost of ownership when comparing an ICEV to a BEV with 25% higher gasoline prices (c), and 25% higher electricity prices (d). Difference in life cycle GHG emissions and total cost of ownership when comparing an ICEV to a BEV with the Cambium 'midcase' grid scenario (e), and the Cambium 'Low renewable electricity cost and high natural gas price' grid scenario (f). ICEV to BEV abatement cost for scenarios with different annual and lifetime vehicle miles traveled (g), and discount rates (h). See Supplemental Note 1 for abatement costs for a-f.*

Discussion

This study shows that BEVs are the least carbon intensive powertrain across all vehicle classes and across a wide range of locations and charging and driving patterns. Compared to conventional ICEVs, small and midsize BEVs have a lower total cost of ownership in most locations. With elevated gasoline prices (e.g., prices at the time of writing in May 2026) and for drivers that travel above average annual distances, BEVs have a TCO advantage in almost all locations for all vehicle classes excluding pickup trucks. For BEVs with smaller (i.e., 200-mile range) battery sizes, the TCO advantage can be expanded to all vehicle classes. Thus, there are a large proportion of consumers for whom a BEV represents a "win-win" with both lower cost and lower GHG emissions. This differs from past results due to the compounding effects of both an increase in the emissions reduction from ICEVs to BEVs, as the electric grid and future grid projections have gotten less carbon intensive over time[1], and a reduction (and in some cases a reversal) of the TCO difference between ICEVs and BEVs, largely driven by reductions in BEV price[13,34].

This analysis reveals several ways to increase the cost-competitiveness of BEVs. For electric utilities, introducing rate plans with off-peak hours, or reducing prices during off-peak hours to enhance the incentive to charge during those times can make BEVs more cost competitive. For cities, increasing the availability of home charging for renters and in multi-unit dwellings can help consumers avoid higher cost public charging. At the state level, fees for BEVs, while small compared to the TCO of a vehicle, can make a difference in whether or not a BEV is a cost saving option for consumers. Consumers themselves can lower their costs by using off-peak hours and avoiding public charging.

Abatement cost is a function of both the cost difference and emissions difference between vehicles. Time-of-use charging can lower charging cost, but we found it has relatively little impact on GHG emissions. It could have an impact on emissions if structured differently – but most current time-of-use rate structures do not have a strong correlation between off-peak hours and low-emitting hours. Nevertheless, it does reduce the abatement cost, by reducing the cost of charging, making BEVs a cost and emissions saving option in many locations.

Even where there is cost and emissions savings, breakeven times are very different and may not be worth it for all owners, depending on their ownership period. Therefore, strategies to reduce the initial cost of BEVs (ranging from technological advances lowering battery prices to subsidies from the government) remain important for adoption. We did not include subsidies in our analysis, though many cities included do offer subsidies (primarily at the state level) which would lower abatement costs and breakeven times.

There are several limitations to this study. We considered a vehicle's entire lifetime, which means we did not consider vehicle resale. This would impact results, particularly for consumers with short vehicle ownership periods, as BEVs show higher depreciation rates in the first few years of vehicle lifetime[45]. The locations we investigated are all large urban centers; rural areas may have different travel patterns and insurance and fuel prices. However, Miotti and Trancik showed that emissions reductions for a BEV versus an ICEV are almost as large in rural areas as urban areas[2]. We also did not consider future charging capabilities like vehicle to home charging, which could reduce both cost and emissions[46]. Additionally, electricity rate structures are likely to change as the electric grid evolves, especially as more variable renewable technologies are added. Finally, we limited our analysis to cost and GHG emissions and did not evaluate the important impacts of vehicle electrification on local air quality[47,48]. Despite these limitations, our results have important implications for consumers, manufacturers, and policy makers. We show not only that electric vehicles reduce GHG emissions substantially compared to conventional vehicles, but also that they reduce emissions cost-effectively, and for many consumers, with cost savings.

Methods

We estimate the life cycle GHG emissions and total cost of ownership for five different vehicle classes (compact, midsize sedan, small SUV, midsize SUV, pickup truck), four powertrains (ICEV, HEV, PHEV, BEV), in 20 different cities (Atlanta, Boston, Charlotte, Chicago, Cleveland, Dallas, Denver, Detroit, Houston, Los Angeles, Miami, Minneapolis, New York City, Philadelphia, Phoenix, Portland (OR), San Francisco, Seattle, St. Louis, Washington, D.C.) as well as using U.S. average values. Cities were selected based on metropolitan statistical area (MSA) population as well as proximity to other cities, to increase geographic diversity.

Parameters

Vehicles used in this study are synthetic vehicles from Argonne National Laboratory's Autonomie model[49]. We use model year 2025 vehicles, the base (rather than premium) performance category, and the low technology development scenario. Key parameters for each vehicle are the mass, battery size, fuel economy, and manufacturer's suggested retail price (MSRP). Key parameters related to the vehicle's operation are annual and lifetime miles driven, which are obtained from NHTSA and the Transportation Energy Data Book[50]. For full details of model parameters, and a comparison with real vehicle makes and models, see **Supplemental Note 2**.

Life Cycle GHG Emissions Model

First, we calculate the vehicle cycle emissions (emissions from materials and manufacturing the vehicle itself, as well as component and fluid replacement over the lifetime of the vehicle). We use parameters from Autonomie (vehicle curb weight, battery capacity, battery energy density) and input these into the GREET model[51,52]. We use NMC622 as the battery chemistry for PHEVs and BEVs, and do not include replacement of the Li-ion battery during the vehicle's lifetime.

Next, we calculate the fuel cycle emissions (emissions from operating the vehicle) over the lifetime (L) of the vehicle. The total emissions are represented by **Equation 1**:

$$GHGs = VC + \sum_{y=2026}^{2026+L} \sum_{m=1}^{12} \mu_l * \left(M_{m,y} * \frac{FE_{c,p,l,m}^{elec}}{\eta_C} * \frac{CI_{l,m,y}^{elec}}{\eta_{TD}} \right) + (1 - \mu_l) * \left(M_{m,y} * FE_{c,p,l,m}^{gas} * CI^{gas} \right) \quad (1)$$

VC represents the vehicle cycle emissions. μ_l is the utility factor (percentage of driving in electric mode), which is 0 for ICEVs and HEVs, 1 for BEVs, and 0.69 for the 50-mile range PHEV. $M_{m,y}$ represents the miles driven in each month of each year. $FE_{c,p,l,m}^{elec}$ and $FE_{c,p,l,m}^{gas}$ represent the fuel efficiency (in Wh/mile and gallons/mile respectively) for each class (c), and powertrain (p), for each location (l), for each month (m). The fuel economies are adjusted to account for regional differences in temperature and different ratios of city to highway driving. $CI_{l,m,y}^{elec}$ is the carbon intensity of the electric grid in each location (l) for each month (m) of each year (y) in kg CO_2e/MWh. CI^{gas} is the carbon intensity of gasoline including upstream emissions of fuel production and distribution (10.5 kg CO_2e/gallon), η_C is the charging efficiency (90%), and η_{TD} is the efficiency of electricity transmission and distribution (95%).

For the carbon intensity of the electric grid, we use projections from Cambium 2024[44]. The projections were made prior passage of the One Big Beautiful Bill Act (OBBBA), which removed renewable electricity tax credits that were part of the Inflation Reduction Act (IRA), so we use the scenario with the

slowest rate of decarbonization: the "Low Natural Gas Cost and High Renewables Cost" scenario. We use the long-run marginal emissions rate to account for operational and structural changes to the grid over the vehicle's lifetimes[53]. For each city we use emissions factors for each hour of the day for each month in their respective balancing areas. We then calculate a weighted average of the hourly emissions factors based on the percentage of charging taking place during off-peak, part-peak, and on-peak pricing hours in each location to obtain monthly emissions factors. The projections have a five-year time step, so we interpolate linearly between these steps. For full details of the GHG estimates see **Supplemental Note 3**.

Total Cost of Ownership Model

Our total cost of ownership model includes upfront costs (purchase, taxes, fees, and home charging) and recurring costs (fuel, insurance, financing, maintenance, repair, and recurring fees). We do not include a resale cost as we evaluate the vehicle over its entire lifetime. The upfront cost is shown in **Equation 2**:

$$Upfront\ Cost = DP_{c,p} + Tax_{c,p,l} + Fees_{c,p,l}^{purchase} + HC_{p,l} \quad (2)$$

Where $DP_{c,p}$ is the down payment for each class (c) and powertrain (p), $Tax_{c,p,l}$ represents taxes for each class and powertrain in each location (l), $Fees_{c,p,l}^{purchase}$ represents fees owed at the time of purchase, and $HC_{p,l}$ represents the cost of a home charger, which is applied only for BEVs. We do not include any federal, state, or city level subsidies for BEVs or chargers.

For the upfront cost we use a down payment of 10%. Taxes include state sales tax as well as county, city, and special purpose (e.g., local public transit) taxes as applicable. Fees include title and licensing fees. Home charger cost is based on inflation adjusted equipment and labor costs from Borlaug et al., and permitting fees[54]. We adjust labor costs based on the mean wage for electricians in each metro area.

Recurring costs are shown in **Equation 3:**

$$Recurring\ Cost = \sum_{y=2026}^{2026+L} \sum_{m=1}^{12} \frac{Fuel_{c,p,l,m,y} + Ins_{c,p,l,y} + Fin_{c,p,y} + Main_{p,y} + Rep_{c,p,y} + Fees_{c,p,l,y}^{ann}}{(1+d)^{(y-2026)}} \quad (3)$$

Which includes fuel, insurance, financing, maintenance, repairs, and annual fees for each combination of class, powertrain, location, month, and year. Future costs are discounted with a discount rate, d, of 5% in the base case.

Fuel cost is determined by the miles driven, the fuel efficiency of the vehicle, and the price of gasoline or electricity in each location (**Equation 4**).

$$Fuel_{c,p,l,m,y} = \sum_{y=2025}^{2025+L} \sum_{m=1}^{12} \mu * \left(M_{m,y} * \frac{FE_{c,p,l,m}^{elec}}{\eta_C} * EP_{l,m} \right) + (1-\mu) * \left(M_{m,y} * FE_{c,p,l,m}^{gas} * GP_{l,m} \right) \quad (4)$$

$EP_{l,m}$ is the electricity price in each location each month and $GP_{l,m}$ is the gasoline price in each location each month. Electricity prices are based on utility rate plans identified using the OpenEI Utility Rate Database[55], and verified with documents from the local electric utility in each location, which include different prices for on-peak, part-peak, and off-peak hours, different summer and winter prices, and in some cases different prices depending on monthly consumption. We also use location-specific prices for

level 2 and level 3 public charging. Gasoline prices are monthly averages from 2021-2025 for regular gasoline in each location.

We developed a formula for the insurance cost based on Liu et al., which adjusts the insurance cost based on powertrain and vehicle MSRP[23]. We add an adjustment based on VMT, based on Parker et al[26] and a location adjustment depending on the average insurance cost in each location. For the financing cost we use a 5% interest rate (a relatively low interest rate reflecting a consumer with a high credit score), and a 6-year loan term.

Maintenance costs are determined by the maintenance schedule in Argonne National Laboratory's BEAN model[24]. This schedule for replacement parts was created from original equipment manufacturer's (OEM's) suggested replacement schedule (e.g. new tires every 50,000 miles). The replacement schedule is applied to the annual mileage values used for each vehicle class to determine the costs in each year. Repair costs are also based on the BEAN model, and are a function of the powertrain, class, MSRP, and the vehicle's age.

Annual fees are taken from publicly available data (i.e., from state DOT or DMV websites). These include annual registration fees, and additional fees applied PHEVs and BEVs. These BEV fees range from $0 to $250 per year in different U.S. cities. Other recurring costs (e.g., parking, tolls, time-value costs for refueling or maintenance) are not included. For full details of the TCO model see **Supplemental Note 4**.

Charging Scenarios

We use five different charging scenarios with different percentages of public vs private charging and different percentages of off-peak, part-peak, and on-peak hours, where applicable. The 15 cities with time-of-use pricing generally incentivize charging overnight, though some locations have more unique rate structures that suit their environment (e.g., Phoenix has off-peak pricing between 10am and 3pm in the winter only, when there is high solar generation and low air conditioning demand). Effective electricity prices are determined by multiplying the price during the off-peak, part-peak, and on-peak hours by the percentage of charging assigned to that price period. The emissions are determined by taking the average emissions during the off-peak, part-peak, and on-peak hours in each location, and applying those emissions factors to the percentages used for each charging strategy. This method is representative of consumers that are primarily price-response, and not emissions-responsive, when deciding when to charge their vehicles.

Abatement Costs

Abatement costs are calculated by taking the difference in TCO between two powertrains and dividing by the difference in life cycle GHG emissions between two powertrains (**Equation 5**).

$$Abatement\ Cost = -1 * \frac{TCO_{p1} - TCO_{p2}}{GHG_{p1} - GHG_{p2}} \quad (5)$$

This gives a negative abatement cost when there is both a cost savings and an emissions savings for powertrain 2 compared to powertrain 1, and a positive abatement cost when there is a cost increase and an emissions savings for powertrain 2 compared to powertrain 1.

Data Availability

All data used in this study are publicly available and cited in the paper. Source data for all figures are provided with the paper and its Supplementary Information.

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Contributions

Conceptualization, data curation, methodology, formal analysis, visualization, writing – original draft, writing -review and editing: M.W. Funding acquisition, project administration, conceptualization, methodology, writing – review and editing: G.A.K.

Competing Interests

The authors declare no competing interests.

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