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## LETTER

# The role of pickup truck electrification in the decarbonization of light-duty vehicles

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## Abstract

Electrification can reduce the greenhouse gas (GHG) emissions of light-duty vehicles. Previous studies have focused on comparing battery electric vehicle (BEV) sedans to their conventional internal combustion engine vehicle (ICEV) or hybrid electric vehicle (HEV) counterparts. We extend the analysis to different vehicle classes by conducting a cradle-to-grave life cycle GHG assessment of model year 2020 ICEV, HEV, and BEV sedans, sports utility vehicles (SUVs), and pickup trucks in the United States. We show that the proportional emissions benefit of electrification is approximately independent of vehicle class. For sedans, SUVs, and pickup trucks we find HEVs and BEVs have approximately 28% and 64% lower cradle-to-grave life cycle emissions, respectively, than ICEVs in our base case model. This results in a lifetime BEV over ICEV GHG emissions benefit of approximately 45 tonnes CO<sub>2</sub>e for sedans, 56 tonnes CO<sub>2</sub>e for SUVs, and 74 tonnes CO<sub>2</sub>e for pickup trucks. The benefits of electrification remain significant with increased battery size, reduced BEV lifetime, and across a variety of drive cycles and decarbonization scenarios. However, there is substantial variation in emissions based on where and when a vehicle is charged and operated, due to the impact of ambient temperature on fuel economy and the spatiotemporal variability in grid carbon intensity across the United States. Regionally, BEV pickup GHG emissions are 13%–118% of their ICEV counterparts and 14%–134% of their HEV counterparts across U.S. counties. BEVs have lower GHG emissions than HEVs in 95%–96% of counties and lower GHG emissions than ICEVs in 98%–99% of counties. As consumers migrate from ICEVs and HEVs to BEVs, accounting for these spatiotemporal factors and the wide range of available vehicle classes is an important consideration for electric vehicle deployment, operation, policymaking, and planning.

## 1. Introduction

Rapid decarbonization of all sectors of the economy is required to limit climate change and avoid potentially catastrophic impacts [1]. Transportation is currently the largest greenhouse gas (GHG) emitting sector in the U.S., contributing 29% of U.S. emissions [2]. To reduce these emissions, a wide variety of technologies and policies have been proposed, with no single technology or policy sufficient to achieve the reduction needed to meet mitigation targets [3, 4].

Electrification is among the most prominent of the many actions being considered to decarbonize the transportation sector.

Light-duty vehicles (LDVs) are responsible for 58% of U.S. transportation emissions [5]. There has been significant growth in the adoption of light-duty battery electric vehicles (BEVs) [6], yet EVs only represented 2% of new vehicle sales in the U.S. in 2020 [7]. Many barriers remain, including upfront vehicle cost, charging infrastructure availability, range anxiety [8], and the comparatively few vehicle types

available [9]. Yet, the market is diversifying rapidly. As of 2020, there were 50 light-duty BEV and plug-in hybrid electric vehicle (PHEV) models commercially available in the U.S., with 130 models anticipated by 2023 [10]. While the heterogeneity of electric vehicle consumers has been investigated [11], the heterogeneity within the electric LDV market has not [12]. The vast majority of research attention has been focused on the environmental benefits of electric sedans compared to their internal combustion engine vehicle (ICEV) or hybrid electric vehicle (HEV) counterparts; however, sedans and station wagons made up only 31% of 2020 U.S. LDV sales [13]. U.S. EPA reports that trucks were 56% of 2020 U.S. LDV sales (39% truck SUVs, 14% pickups, 3% vans) [13]. Furthermore, the percentage of sedans in the LDV fleet has been decreasing, while the percentages of SUVs and trucks are increasing [13].

Using life cycle assessment (LCA), the GHG implications of vehicle electrification have been shown over a wide range of conditions, including vehicle model [14], vehicle range [15], electric grid generation mix [16], electric grid emissions factor [17], ambient temperature [18], battery degradation [19], driving patterns [20], charging patterns [21], and the many combinations of these factors [22, 23]. Some vehicle LCAs focus on use-phase emissions (also known as fuel cycle or well-to-wheels, WTW, emissions) [16, 18, 19, 21, 24–35], while others also incorporate vehicle cycle emissions (vehicle materials, part manufacturing, assembly, and disposal) [17, 22, 23, 36–59]. Vehicle LCAs also vary in their handling of GHG emissions associated with electricity production (average vs. marginal emissions factors, historic or projected emissions, regional variation, temporal variation) [60], vehicle assumptions (e.g. lifetime) [61] and the impact of temperature on vehicle fuel economy. However, studies that explicitly make such comparisons for vehicle classes other than sedans (e.g. ICEV SUV vs. BEV SUV) are rare [42, 43, 50, 51]. Only one study includes electric pickup trucks [52] and it has significant modeling differences from our study (supplemental note 1 available online at [stacks.iop.org/ERL/17/034031/mmedia](https://stacks.iop.org/ERL/17/034031/mmedia)).

Here we conduct an LCA of pickup trucks and compare the implications of pickup truck electrification to those of sedan and SUV electrification. We focus on GHG emissions, though vehicle electrification also has important implications for material use [62] and local air quality [63]. Both vehicle cycle and fuel cycle contributions are included (i.e. cradle-to-grave). We compare three different model year 2020 powertrain options (ICEV, HEV, and BEV) for three vehicle classes (midsize sedan, midsize SUV, and full-size pickup truck), accounting for differences in fuel economy, annual mileage, vehicle production, and vehicle lifetime across vehicle classes. Sensitivity analyses are conducted using different BEV

ranges (battery sizes), drive cycles, and BEV lifetimes, and for projected model year 2030 vehicles. We show the heterogeneity in life cycle GHG emissions across the U.S., accounting for regional variation in grid mixes and ambient temperatures, both with greater regional detail than previous studies [17–19, 22–24, 29, 30, 35, 36, 42, 56, 57, 64]. Finally, the impacts of charging BEVs at different times of the day and with different grid decarbonization scenarios are investigated.

## 2. Methods

### 2.1. Vehicle cycle

Key vehicle parameters are obtained from the Autonomie model [65], which simulates vehicle energy consumption for a wide range of vehicle classes, powertrain options, and levels of future technology development. We compare three vehicle classes (midsize sedans, midsize SUVs, and full-size pickup trucks) across three different powertrain options (ICEV, HEV, and BEV). We include two performance categories (base and premium) to represent a range of options available in the market. The premium options are heavier, have slightly poorer fuel economy, and for the BEV options, have slightly larger batteries. For BEVs, we assume a 300-mile range as our base case. The median EV range for 2020 BEV models in the U.S. was 259 miles, although several vehicles with ranges of 300 miles or more are available [66]. We have rounded up this value, based on the assumption that the ranges of future vehicles will be larger. For each vehicle class, the BEV option is significantly heavier than the ICEV and HEV options primarily due to the Li-ion battery. The outputs we use from Autonomie are vehicle weight, battery size, and fuel economy (table 1). These representative parameters are compared with values for actual vehicles in the U.S. market in supplemental note 1.

To calculate the materials, manufacturing, and end-of-life phase emissions, we use the GREET 2021 model [67, 68], developed by Argonne National Laboratory. We modified the sedan, SUV, and pickup truck options within GREET with the year in which the vehicle is produced, using the vehicle parameters from Autonomie (see supplemental note 2). Vehicle cycle emissions include the production of all vehicle components (body, powertrain, transmission, chassis, traction motor, generator, electronic controller), fluids used over the lifetime of the vehicle (e.g. 39 oil changes and 19 windshield fluid refills), vehicle batteries (lead-acid batteries in all three powertrains, and Li-ion traction batteries in the HEVs and BEVs), and the assembly and disposal of the vehicle. We do not include replacement of the Li-ion battery over the vehicle's lifetime, nor do we include battery second life, which could lower the emissions attributable to the battery's production for its primary use [69].

**Table 1.** Vehicle parameters.

Vehicle class	Powertrain	Curb weight (kg)		Battery size (kWh)		Fuel economy (MPG or Wh/mile)	
		Base	Premium	Base	Premium	Base	Premium
Midsize sedan	ICEV	1437	1539	—	—	31.4	27.7
	HEV	1502	1595	1.7	2.2	46.7	42.3
	BEV-300	1642	1720	74.3	78.3	236.3	248.1
Midsize SUV	ICEV	1669	1873	—	—	26.8	24.0
	HEV	1758	1947	2.0	2.7	38.1	35.0
	BEV-300	1993	2167	98.9	102.0	318.1	332.1
Fullsize pickup truck	ICEV	2104	2321	—	—	21.4	20.3
	HEV	2150	2371	2.9	3.4	31.0	29.4
	BEV-300	2454	2693	119.7	123.9	388.6	405.5

## 2.2. Use phase

The use phase emissions of any vehicle depend on the vehicle miles traveled, fuel economy of the vehicle and the GHG emissions intensity of its energy source. For the ICEV and HEV options, the annual mileage and the WTW GHG emissions intensity of gasoline are divided by the fuel economy.

$$\text{GHG}_{\text{ICEV,HEV}} = \sum_{y=2022}^{y+L_v} M_{v,y}/\text{FE}_g \times \text{CI}$$

The annual emissions are added starting in year  $y$  through the lifetime of the vehicle  $L_v$ , where  $M_{v,y}$  is the mileage vehicle  $v$  is driven in year  $y$  [miles],  $\text{FE}_g$  is the fuel economy of the gasoline powered (ICEV or HEV) vehicle [miles/gallon], and  $\text{CI}$  is the WTW carbon intensity of gasoline (10.67 kg CO<sub>2</sub>e/gallon) [67]. This value represents the combustion emissions and the upstream emissions of gasoline production.

Use phase emissions for BEVs are calculated similarly. The only difference is the WTW carbon intensity of gasoline is replaced by the WTW carbon intensity of charging the vehicle, which includes the grid emissions factor and a charging efficiency (85% for the base case). Unlike the carbon intensity of gasoline, which remains constant throughout the vehicle's lifetime, the grid emissions factor is updated throughout the vehicle lifetime, starting in 2022.

$$\text{GHG}_{\text{BEV}} = \sum_{y=L_v}^{y=2022} M_{v,y} \times \text{FE}_e \times \text{EF}_y \times \eta$$

where  $\text{FE}_e$  is the fuel economy of an electric (BEV) vehicle [ $\frac{\text{Wh}}{\text{mile}}$ ],  $\text{EF}_y$  is the emissions factor in year  $y$  [ $\frac{\text{kg CO}_2\text{e}}{\text{kWh}}$ ], and  $\eta$  is the charging efficiency. We account for operating differences between each vehicle class. We use data from the 2017 National Household Travel Survey [70] to determine the average annual vehicle miles traveled,  $M_{v,y}$ , for each vehicle class. Vehicle lifetime mileage projections from Zhu *et al* [71] are then used to determine the lifetime of each vehicle in years,  $L_v$ . The Zhu *et al* projections are used as they

account for differences in vehicle class and the trend towards longer lifetimes in newer vehicles. This results in lifetimes of 17.0 years (184 000 miles) for 2020 sedans, 17.8 years (205 000 miles) for 2020 SUVs, and 18.6 years (206 000 miles) for 2020 pickups.

We obtain grid emissions factors from NREL's Cambium resource, which provides projections of emissions factors, cost, generation, and other data for 134 balancing areas in the United States on an hourly basis from 2020 to 2050. We use the projected average emissions factor (AEF) of the U.S. electricity grid updated biennially for the lifetime of the vehicle, obtained from Cambium's mid-case standard scenario [72].

## 2.3. Sensitivity analyses

As 'range anxiety' is a commonly cited barrier to EV adoption [73], increasing vehicle range has been a key objective for vehicle manufacturers. Larger batteries are needed to increase range, which results in higher emissions in both the vehicle cycle and use phase, the latter due to the adverse effect of the additional battery weight on fuel economy. We consider the emissions using BEV ranges of 200 and 400 miles, in addition to the base case of 300 miles (see supplemental note 3 for vehicle parameters for sensitivity analyses). The vehicle weights and battery sizes are used to calculate production phase emissions using GREET. The vehicle fuel economy values are used to calculate use-phase emissions.

Driving patterns also impact the use phase emissions of all three vehicle classes. We compare 100% city driving, 100% highway driving, and our base case, a 43/57 city/highway split, which is an estimate of real-world performance [13]. The fuel economy for the Urban Dynamometer Driving Schedule (UDDS) and the Highway Fuel Economy Test (HWFET) are adjusted to represent the on-road fuel economy of city and highway driving according to the formulas developed by U.S. EPA [74] and used by Elgowainy *et al* [75] (supplemental note 4).

In the base case, we assume that the BEV and the ICEV and HEV alternatives have the same lifetime to compare across powertrains. In practice, BEV

lifetimes may differ from the ICEV or HEV lifetimes for a variety of reasons including battery degradation, more or less aggressive driving patterns, and different responses to ambient conditions. We test scenarios where the BEV lasts 20% more or 20% fewer miles than the average for its vehicle class, while the ICEV and HEV options remain at the base level for their vehicle classes. The same annual vehicle miles traveled (VMT) profile is used for each vehicle, so vehicles with more lifetime miles will also have longer lifetimes in years.

In addition to model year 2020 vehicles, we perform the same analysis for model year 2030 vehicles with low and high levels of technological development, based on projections from Autonomie [65]. The charging efficiency is increased to 88%, and the emissions factors are projected starting in 2030 through the lifetime of the vehicle. All other procedures are unchanged from the base case.

#### 2.4. Regional variation

While BEVs have lower GHG emissions than HEVs and ICEVs on average across the U.S., in practice there is considerable regional heterogeneity. Three major factors are considered to account for variation in operating emissions of vehicles across the U.S.: drive cycle, grid emissions factors, and ambient temperatures (which impacts the fuel economy of all three vehicle powertrains). Variability in drive cycle is accounted for by assigning each county a ratio of urban to highway driving, using the six categories in the 2013 NCHS Urban-Rural classification scheme [76]. The variability in grid emissions is included using 134 electricity balancing areas (BAs) within the contiguous U.S., provided by Cambium [72]. To account for the impact of temperature on fuel economy we use average monthly temperatures for each county for 2016–2020 from NOAA [77] and calculate temperature dependent fuel economy adjustment factors, following the work of Wu *et al* [23] (see supplemental note 5).

#### 2.5. Time of charging and grid decarbonization

For BEVs, we introduce the time-of-day at which charging takes place as an additional parameter, as grid emissions factors vary by time of day as well as location. Using hourly data from Cambium, AEFs are calculated for three charging schemes: midday charging (10 am–2 pm), evening charging (5 pm–9 pm), and overnight charging (12 am–4 am). We show each scheme independently (one scheme used for the whole lifetime of the vehicle). Further emissions reductions are made possible through an alternative scenario in which the least emitting charging scheme is chosen for each year (supplemental note 6).

In addition to optimizing the time-of-day of charging, BEV emissions can be further reduced by rapid grid decarbonization. The base case is a

business-as-usual scenario which includes policies in place as of June 2020 with no projected policy changes [78], resulting in a grid that is 50% less carbon intensive in 2035 compared to 2005 [79]. We include two additional scenarios from Cambium: 95% decarbonization by 2050 and 95% decarbonization by 2035 (compared to 2005 levels). We show the impact of time-of-day optimization and different grid scenarios independently and as combined occurrences.

### 3. Results

Using the vehicle weights and battery sizes from table 1, we use the GREET2021 model [67, 68] to calculate the vehicle cycle emissions of each vehicle. Across all three vehicle classes, the BEV has roughly double the GHG emissions in the vehicle cycle, due to emissions for battery production (figure 1).

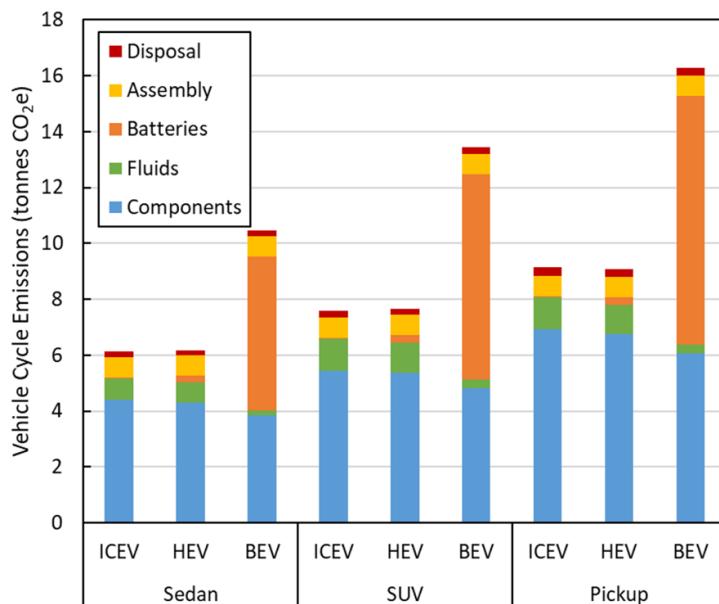
Once the vehicle cycle and the use-phase emissions are added together, we compare the lifetime GHG emissions of each vehicle (figure 2). BEVs have higher production emissions than HEVs and ICEVs but have lower in-use emissions. The intersections of lines of similar color in figure 2 represent the time it will take for a BEV to break even with its ICEV and HEV alternatives. For BEVs and ICEVs the break-even time is 1.2–1.3 years for sedans, 1.4–1.6 years for SUVs, and 1.3 years for pickup trucks (figure 2(a)), based on the average annual VMT for each vehicle class. For BEVs and HEVs the breakeven time is 2.2–2.4 years for sedans, 2.5–2.7 years for SUVs, and 2.2–2.4 years for pickup trucks (figure 2(b)).

On a per-mile basis, electrifying an ICEV pickup to a BEV pickup results in life cycle GHG emissions savings of 345–366 g CO<sub>2</sub>e/mile, electrifying an ICEV SUV results in savings of 273–315 g CO<sub>2</sub>e/mile, and electrifying an ICEV sedan results in savings of 244–285 g CO<sub>2</sub>e/mile. There can also be benefits to switching to a different vehicle class or downsizing within a vehicle class [80], though the emissions reduction is significantly less than the emissions reduction enabled by electrification (figure 3).

#### 3.1. Sensitivity analyses

##### 3.1.1. Vehicle range

The 200-mile range BEVs have approximately 11% lower lifetime emissions than the 300-mile range BEVs, a decrease of 14–21 g CO<sub>2</sub>e/mile across the three vehicle classes. The 400-mile range BEVs have 16%–17% higher lifetime emissions than the 300-mile range BEVs, an increase of 22–32 g CO<sub>2</sub>e/mile. Approximately 64%–76% of this effect is due to battery production, with the remainder resulting from in-use efficiency changes due to the additional vehicle weight. As larger vehicles require greater additional battery capacity to achieve the same increase in range, the absolute impact of increasing BEV range is greatest for pickup trucks. However, the emissions



**Figure 1.** Vehicle cycle emissions for base models.

of even the highest emitting BEV (premium, 400-mile range pickup) remain lower than the HEV and ICEV options of any vehicle class (figure 4(a)).

### 3.1.2. Drive cycle

For ICEVs, the fuel economy is greater on highways than in an urban setting. Conversely, HEVs and BEVs are more efficient with urban driving patterns. Therefore, cities are particularly well suited for BEV adoption [33]. Regardless of vehicle class (sedan, SUV, and pickup), BEV and HEV powertrains yield the greatest benefits for city driving. However, even with 100% highway driving, a BEV has much lower GHG emissions than a HEV or ICEV (figure 4(b)). Additionally, the drive cycle is less influential for BEVs than it is for ICEVs and HEVs across all vehicle classes, and generally more significant for larger vehicles across powertrains. For BEVs, the differences in emissions between 100% city and 100% highway driving (base and premium model average) are 15 g CO<sub>2</sub>e/mile for sedans, 26 g CO<sub>2</sub>e/mile for SUVs, and 35 g CO<sub>2</sub>e/mile for pickup trucks. For HEVs the differences are 22, 35, and 54 g CO<sub>2</sub>e/mile, and for ICEVs the differences are -83, -61, and -64 g CO<sub>2</sub>e/mile for sedans, SUVs, and pickup trucks, respectively.

### 3.1.3. BEV lifetime

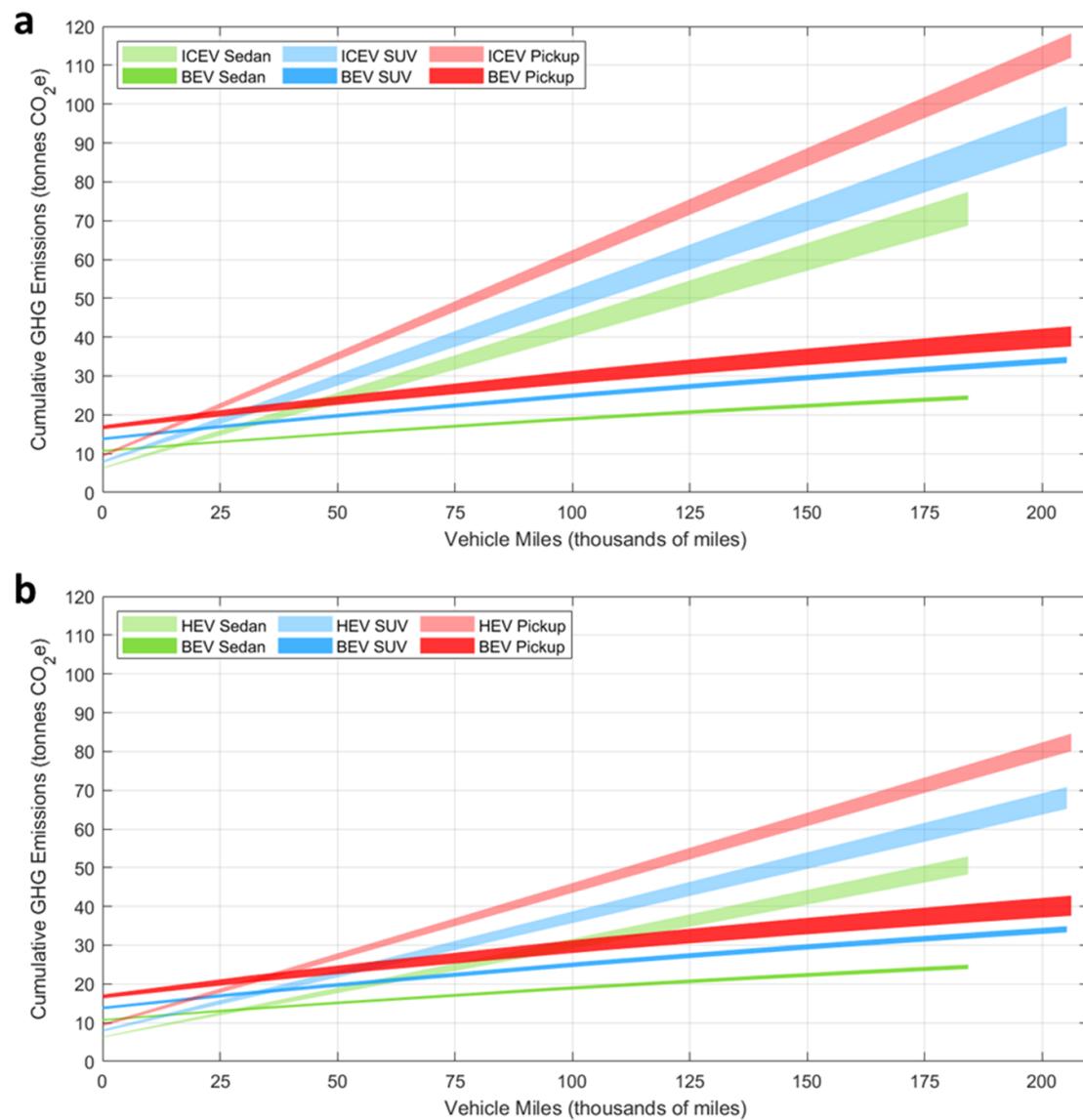
A 20% greater BEV lifetime results in a 9%–11% decrease in per mile emissions (12–19 g CO<sub>2</sub>e/mile) due to a reduced contribution of vehicle production emissions. Likewise, there is a 13%–14% increase in per-mile emissions (17–28 g CO<sub>2</sub>e/mile) when BEV lifetime is reduced by 20%. Even with the reduced lifetime, the BEV has lower per mile GHG emissions than the ICEV or the HEV alternatives (figure 4(c)).

### 3.1.4. Future vehicle technology development

Future vehicles have higher battery energy density, improved powertrain efficiency, and are lighter. In future years, BEV lifetime emissions as a percentage of ICEV emissions remains relatively constant. BEV pickup emissions as a percentage of ICEV pickup emissions are 36% for 2020 vehicles, 32% for 2030 vehicles in the low technology development scenario, and 36% for 2030 vehicles in the high technology development scenario (figure 4(d)). The pace of future vehicle technology improvement is not expected to greatly affect these comparisons without significant grid decarbonization.

## 3.2. Regional variation

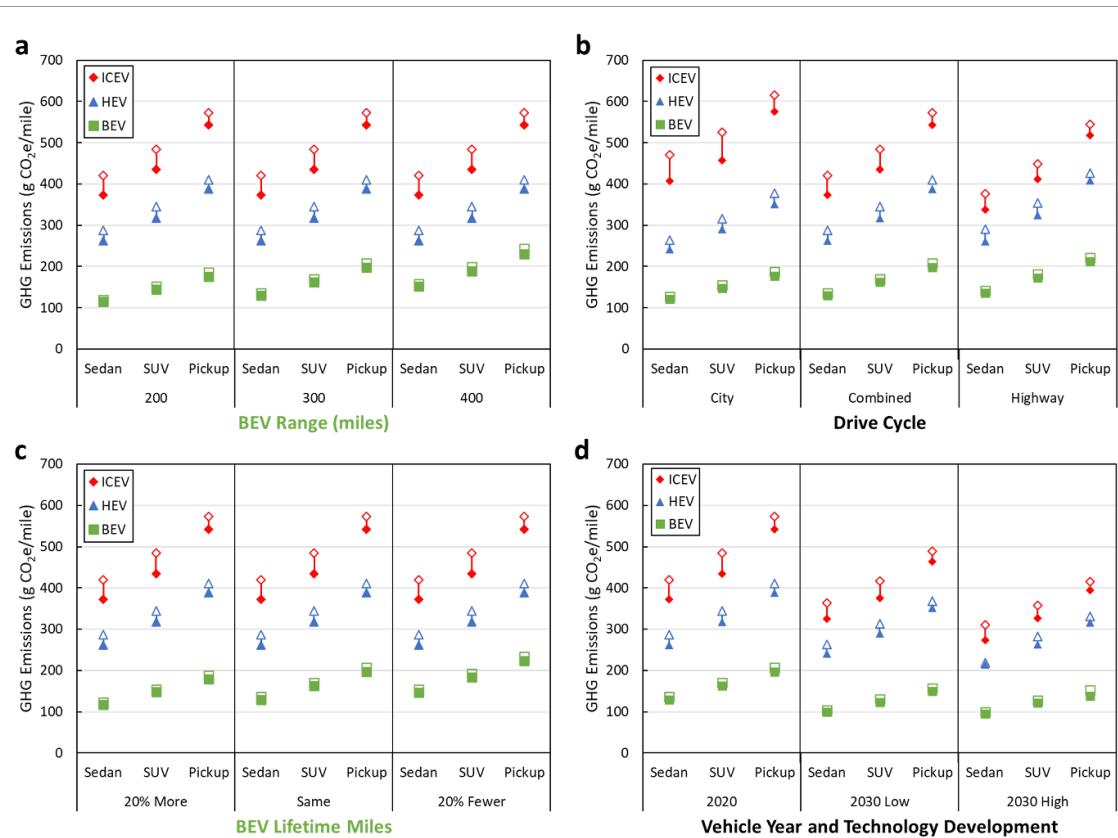
Accounting for local drive cycles, temperatures, and grid emissions gives the following emission ranges for our base model vehicles (units of g CO<sub>2</sub>e/mile): ICEV sedan, 344–450; HEV sedan, 223–378; BEV sedan, 57–394; ICEV SUV, 416–513; HEV SUV, 271–465; BEV SUV, 65–525; ICEV pickup truck, 519–649; HEV pickup truck, 330–581; and BEV pickup truck, 79–644 (figure 5). BEV emissions range from 13% to 118% of ICEV emissions and from 14% to 134% of HEV emissions across all U.S. counties. The highest BEV emissions occur in a few Mountain State areas with high use of coal for electricity generation, while the lowest occur in regions with high contributions of hydro, nuclear, wind, and solar (e.g. Pacific coast states, Northeast, and west Texas). Using a population-weighted average across all U.S. counties, BEV emissions are approximately 36% of ICEV emissions and approximately 51% of HEV emissions for all three vehicle classes, similar to the U.S. average results summarized in figure 3.



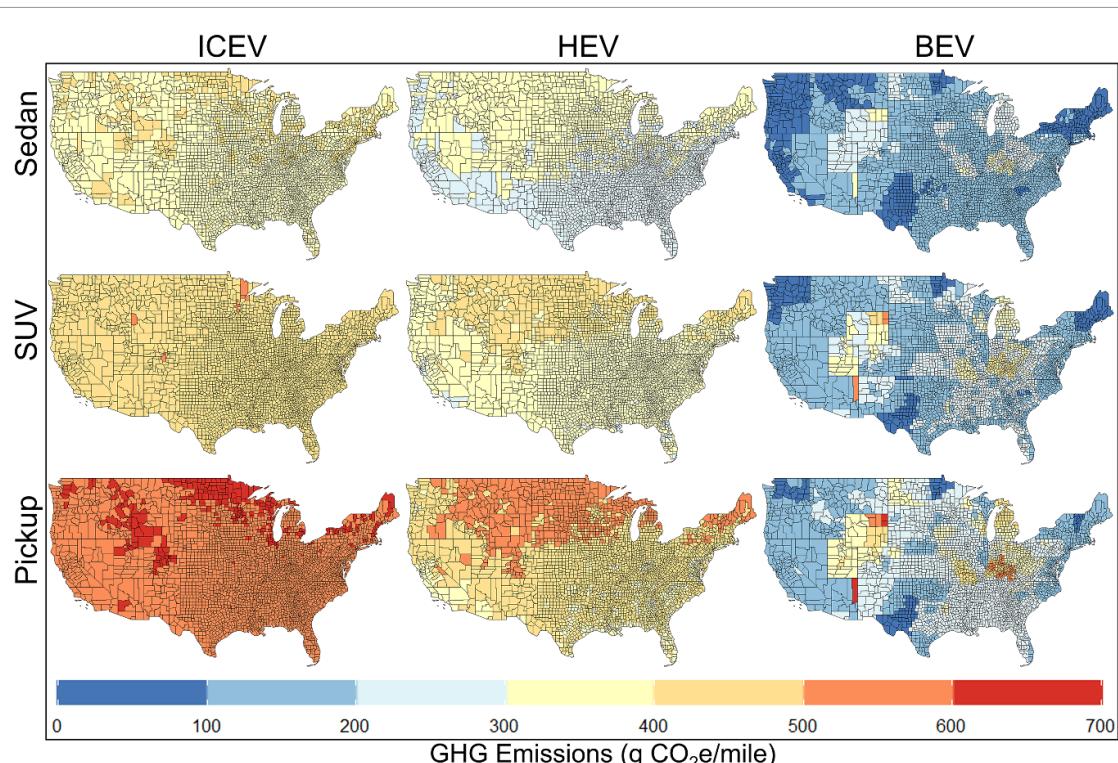
**Figure 2.** Cumulative greenhouse gas emissions versus vehicle mileage for (a) internal combustion engine and battery electric sedans, SUVs, and pickup trucks, and (b) hybrid electric and battery electric sedans, SUVs, and pickup trucks. The lower and higher limits of each range are results for base and premium models, respectively.

	ICEV	HEV	BEV
Pickup	543-573 100%	388-410 72%	182-207 35%
SUV	435-485 82%	317-345 59%	162-170 31%
Sedan	373-420 71%	262-287 49%	129-136 24%

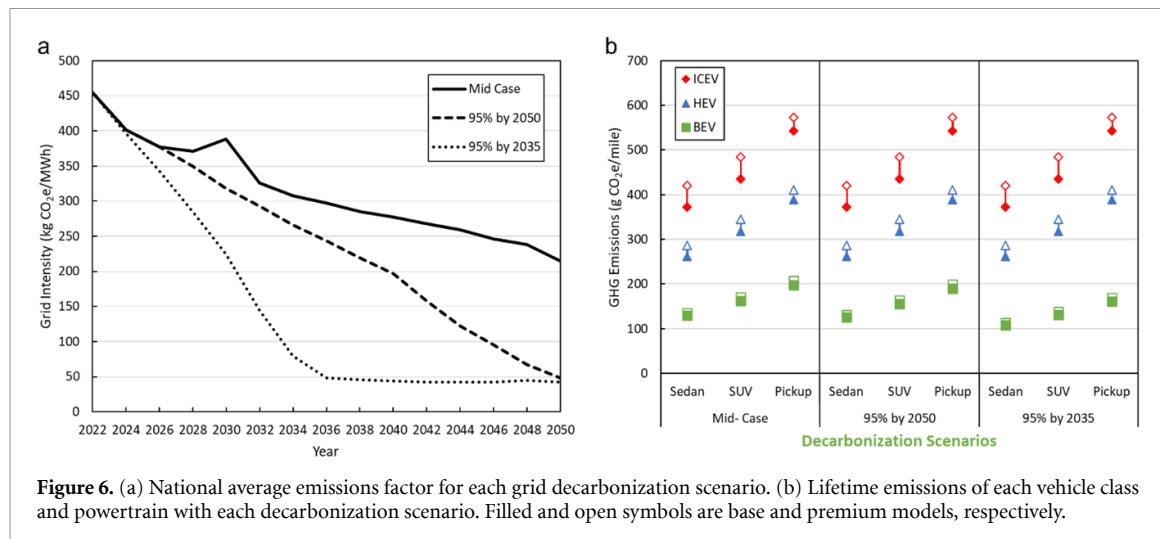
**Figure 3.** Lifetime cradle-to-grave GHG emissions (base and premium models) for each combination of vehicle class and powertrain in g CO<sub>2</sub>e/mile and average GHG emissions as a percentage of ICEV pickup truck emissions.



**Figure 4.** Lifetime emissions of each vehicle class and powertrain, (a) using 200-, 300-, and 400-mile ranges for the BEV options, (b) with city (UDDS), combined (43/57 city/highway split) and highway (HWFET) adjusted drive cycles, (c) using a BEV lifetime of 20% more and 20% less than the ICEV and HEV options, and (d) with current and future vehicles with different levels of technology development. Filled and open symbols are base and premium models, respectively.



**Figure 5.** Life cycle GHG emissions for each vehicle class and powertrain, accounting for differences in grid emissions for electricity balancing areas and county-level differences in drive cycle and temperature effect on fuel economy.



**Figure 6.** (a) National average emissions factor for each grid decarbonization scenario. (b) Lifetime emissions of each vehicle class and powertrain with each decarbonization scenario. Filled and open symbols are base and premium models, respectively.

For sedans, the BEV is the least emitting option in 2983 counties and the HEV is the least emitting option in 125 counties (out of 3108 counties in the contiguous United States). For SUVs, the BEV and HEV are the least emitting options in 2930 and 178 counties, respectively. For pickups, the BEV and HEV are the least emitting options in 2948 and 168 counties, respectively. The ICEV is the least emitting option in zero counties. The rare situation in which the ICEV emits less than the BEV occurs in only 3, 53, and 35 counties for the sedan, SUV, and pickup, respectively.

We also calculate the difference in emissions from switching from an ICEV or HEV to a BEV in each county. Using a population-weighted average across all counties, switching from an ICEV to a BEV saves 260, 285, and 368 g CO<sub>2</sub>e/mile for sedans, SUVs, and pickup trucks respectively. Switching from an HEV to a BEV saves 133, 158, and 196 g CO<sub>2</sub>e/mile for sedans, SUVs, and pickup trucks respectively (supplemental note 7). These savings are somewhat larger for premium vehicles (supplemental note 8).

### 3.3. Time of charging

We compare three common charging schemes: midday charging (10 am–2 pm), evening charging (5 pm–9 pm), and overnight charging (12 am–4 am). Compared to the previous method (annually averaged emissions factors for each county), charging at specific times can lead to an 86% decrease to a 74% increase in emissions for individual counties. As a population-weighted average, midday charging results in an 8% decrease, evening charging results in a 3% increase, and overnight charging results in a 1% increase in emissions. This reflects the fact that on a population-weighted basis midday emissions are generally lower than average. These scenarios assume midday, evening, or overnight charging is used for the vehicle's entire lifetime. Updating the optimal charging scheme each year (e.g. overnight charging

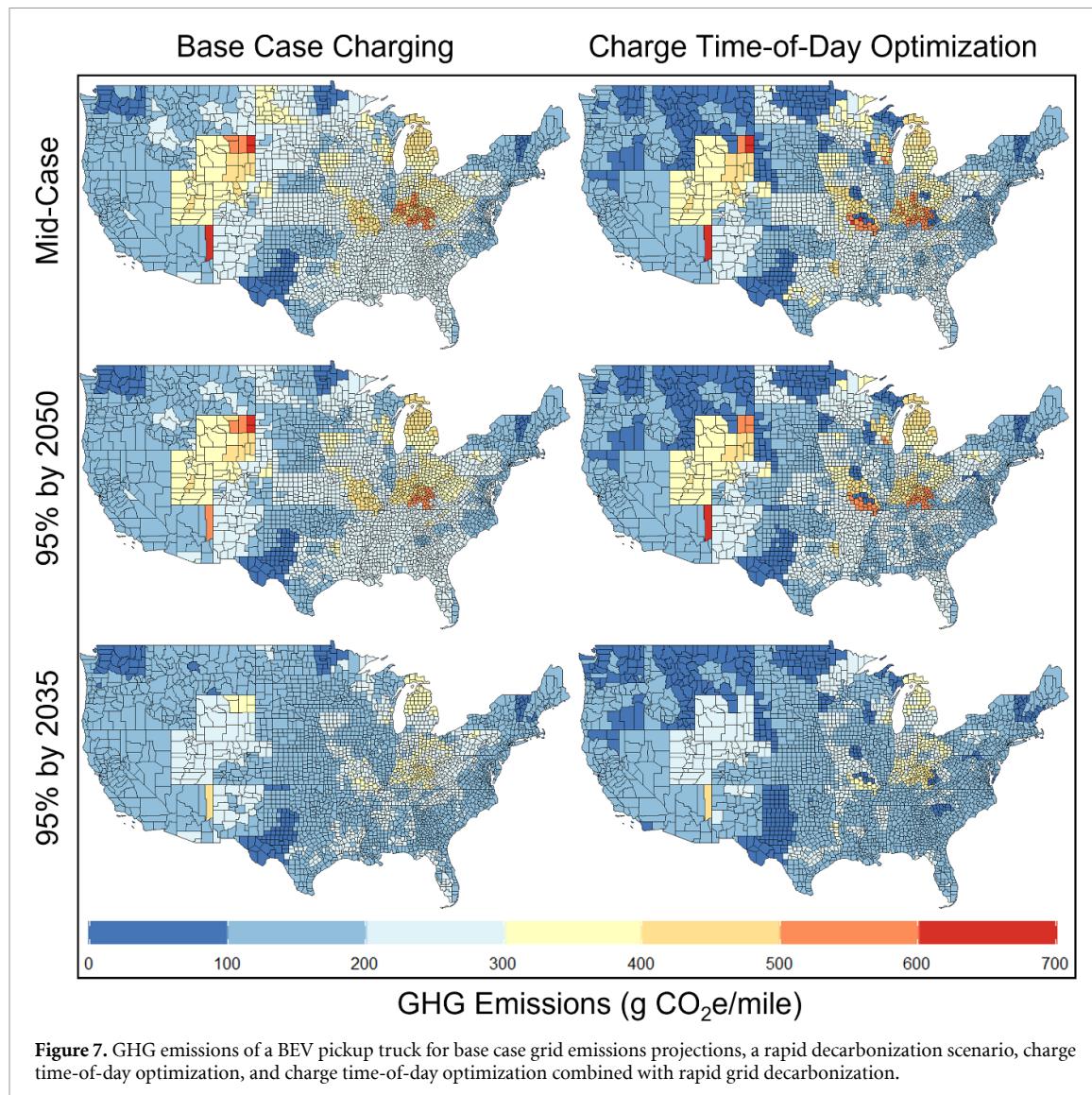
in 2025, evening charging in 2026, etc.) allows for further reductions in emissions. If this is done for each county, there is a population weighted average decrease of 11%.

### 3.4. Grid decarbonization

In our base case scenario, which uses Cambium's mid case projections, the average emissions factor across the U.S. is reduced to 50% of 2005 levels by 2035. The two other scenarios shown in Cambium are 95% decarbonization by 2050 and 95% decarbonization by 2035. (figure 6(a)). In each decarbonization scenario model year 2020 vehicles are used and are operated starting in 2022 through the lifetime of the vehicle.

Using U.S. average emissions, a 95% reduction in grid emissions intensity by 2050 results in a 3% decrease in emissions for BEV sedans (4 g CO<sub>2</sub>e), a 4% decrease in emissions for SUVs (6 g CO<sub>2</sub>e), and a 4% decrease in emissions for pickup trucks (8 g CO<sub>2</sub>e) compared to the baseline scenario (figure 6(b)). At a county level, BEV pickup truck emissions range from a 5% increase to a 19% decrease from the baseline scenario. This is because emissions in the mid-case scenario and the 95% decarbonization by 2050 scenario do not diverge significantly until late in each vehicle's lifetime.

In the 95% decarbonization by 2035 scenario, BEV sedan emissions are reduced by 17% (21–23 g CO<sub>2</sub>e), SUV emissions are reduced by 19% (31–32 g CO<sub>2</sub>e), and pickup emissions are reduced by 19% (37–38 g CO<sub>2</sub>e) compared to the base scenario. At a county level, BEV pickup truck emissions range from a 0% change to a 44% decrease from the base scenario. In this case, average BEV pickup GHG emissions are reduced to 29%, rather than 36% as in the base case, of their ICEV counterparts. This limited impact is due to the time delay required for the benefits of grid decarbonization to become significant, and vehicle cycle emissions (57, 65, and 79 g CO<sub>2</sub>e/mile for sedans, SUVs, and pickups, respectively). These reflect values



for vehicles that begin operating in 2022; larger reductions would be seen for future vehicles, which will have a larger proportion of their lifetime operating with a cleaner grid and have lower production-phase emissions. Additionally, differences in emissions across vehicle classes are reduced with a less carbon-intensive grid.

Combining charging time-of-day optimization with a decarbonizing grid yields greater benefits than either strategy when applied individually (figure 7). Using a population-weighted county average, optimized charging lowers BEV pickup emissions by 21 g CO<sub>2</sub>e/mile (11% decrease), using the 95% decarbonized by 2035 grid lowers BEV pickup emissions by 39 g CO<sub>2</sub>e/mile (16% decrease), and applying time-of-day optimization with that decarbonized grid leads to a savings of 54 g CO<sub>2</sub>e/mile (24% decrease).

#### 4. Discussion

This research quantifies the considerable GHG emission reductions that can be achieved from

transitioning to electrified powertrains across vehicle classes. Over the full life cycle using the U.S. annual average grid emissions factors, emissions of base model HEV and BEV sedans are 70% and 35% respectively of their ICEV counterpart; emissions of base model SUVs are 73% and 37% respectively of their ICEV counterpart, and emissions of base model HEV and BEV pickups are 72% and 34% of their ICEV counterpart. While the percentage difference in emissions for different powertrain options is similar across the three vehicle classes, switching an ICEV to a BEV results in greater absolute emissions reductions as vehicle size increases, due to the greater fuel consumption of larger vehicles. Over the lifetimes of the base models, BEV sedans, SUVs, and pickups emit approximately 45, 56, and 74 tonnes less CO<sub>2</sub>e than their ICEV counterparts.

These average values may be useful for an overall comparison between vehicle classes, but to accurately compare emissions for a specific consumer, location-specific data must be used. This is particularly important for BEVs, as grid emissions factors

vary greatly across the U.S., while the carbon intensity of gasoline does not. Additionally, BEV energy consumption is more temperature-sensitive than that of HEVs or ICEVs. Comparing individual counties with the lowest and highest emissions for pickup trucks (base or premium models), ICEV emissions range from 519 to 694 g CO<sub>2</sub>e/mile, HEV emissions range from 330 to 605 g CO<sub>2</sub>e/mile, while BEV emissions range from 79 to 668 g CO<sub>2</sub>e/mile. The impact of BEV adoption also depends on the vehicle that is replaced. Whether new BEVs replace ICEVs, HEVs, or any vehicles at all, and whether new BEVs replace other powertrains of the same vehicle class, will have a large impact on the emissions reduction potential and is an area worthy of additional study.

Choosing the best charging strategy (midday, evening, or overnight) can reduce BEV lifetime emissions by 11% on average. For sedans this reduces emissions by 15 g CO<sub>2</sub>e per mile, but for pickups emissions are reduced by 23–24 g CO<sub>2</sub>e per mile. Emissions could be further reduced by choosing to charge during the hours with the lowest carbon intensity for electricity generation throughout the entire day, rather than the three charging schemes assumed here, and by choosing the best charging times seasonally or even daily, rather than annually [81]. Policies or programs that incentivize charging during low-emitting hours could be applied at a regional level, as the optimal charging hours vary across the U.S. At a fleet level, other goals such as minimizing peak electrical load in a given region could also be incentivized [82].

Public concerns about BEVs having higher emissions than ICEVs or HEVs are largely unfounded, as BEVs outperform HEVs in 95%–96% of counties, and BEVs outperform ICEVs in 98%–99% of counties, even assuming modest progress towards grid decarbonization (i.e. the CO<sub>2</sub>-intensity of electricity production falls in half from 2005 levels by 2050). This suggests that policies at the federal level could be used to encourage BEV adoption throughout the U.S. and contribute directly to national carbon reduction targets and pledges. The large range in BEV emissions indicates that complementary policies at the state or local level could be implemented in well-performing regions to drive additional GHG reductions. Allocating BEV investments (e.g. charging infrastructure) according to the best performing counties may lead to greater GHG benefits in the near-term, but such campaigns should consider other social benefits including local air pollution effects and transportation accessibility and equity [83], and the long-term impact on BEV adoption. As seen in figure 4(d), ICEV to EV migration for current vehicles leads to similar GHG reduction as is expected for future vehicles. Therefore, policy to accelerate EV deployment should not be delayed until the grid decarbonizes more substantially. Rather, vehicle electrification and grid decarbonization should be pursued simultaneously, as the

benefit of each is increased by the development of the other.

Though vehicle electrification can substantially reduce GHG emissions, electrification alone is insufficient to decarbonize the transportation sector. Grid decarbonization and optimized charging schemes will increase the benefits of electrification. Even with electrification, rapid grid decarbonization, and optimized charging schemes, additional steps may be required to reduce transportation emissions and meet mitigation targets [4]. This could include decreasing VMT (e.g. decreasing travel demand through teleworking, increasing vehicle occupancy), improving fuel economy (vehicle lightweighting, aerodynamic design, improving rolling coefficient), vehicle downsizing (within and between vehicle classes), optimal trip assignment (matching vehicle to trip needs) [84], and shifting to alternative forms of transportation (walking, cycling, or public transportation) [85].

As shown here, larger vehicles have greater absolute emissions reduction potential from electrification. Non-financial consumer preferences [86] and different uses (commuting, hauling, towing) add complexity to comparisons between vehicle classes. While we used different lifetime and annual mileage for sedans, SUVs, and pickups, we used the same lifetime and annual mileage for ICEVs, HEVs, and BEVs of each vehicle class. This common basis was used to compare across the different powertrains; however, in practice these factors may vary by powertrain as well as vehicle class. Additionally, we used average emissions factors to compare vehicle emissions on an attributional basis. When investigating the consequential impact of large numbers of vehicles being electrified, marginal emissions factors may be more appropriate (supplemental note 9). Finally, social factors [87], economic factors [88], and other new technologies will interact with vehicle electrification, including automation and shared mobility services. These may result in rebound effects [89] (increasing annual mileage as fuel economy increases), induced demand [90] (from automation), and more or less charging flexibility (from vehicle sharing). While each of these topics have been investigated, a perspective that includes multiple vehicle classes representing the heterogeneity within the vehicle market may yield additional insight about the future of the transportation sector.

## Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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