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Prepared under Task No. VTP2.0100

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Abstract

With the aim of reducing greenhouse gas emissions associated with the transportation sector, policymakers are supporting a multitude of measures to increase electric vehicle adoption. The actual amount of emissions reduction electric vehicles provide is dependent on when and where drivers charge the vehicles. This analysis contributes to our understanding of the degree to which a particular electricity grid profile, the vehicle type, and charging patterns impact CO_2 emissions from light-duty, plug-in electric vehicles. We present an analysis of anticipated emissions resulting from both battery electric and plug-in hybrid electric vehicles for four charging scenarios and five electricity grid profiles. A scenario that allows drivers to charge electric vehicles at the workplace yields the lowest level of emissions for the majority of electricity grid profiles. However, vehicle emissions are shown to be highly dependent on the percentage of fossil fuels in the grid mix, with different vehicle types and charging scenarios resulting in fewer emissions when the carbon intensity of the grid is above a defined level. Restricting charging to off-peak hours results in higher total emissions for all vehicle types, as compared to other charging scenarios.

Table of Contents

Introduction and Background

With the aim of reducing greenhouse gas emissions associated with the transportation sector, decision makers at the national, state, and local levels are supporting a multitude of policy measures to increase adoption of light-duty electric vehicles (DOE 2015; DeShazo 2015; ICCT 2015; Zhou 2015). The actual emission-reduction benefits associated with plug-in electric vehicles (PEVs) in a specific location are dependent on multiple factors, such as the electricity generation fuel mix, the time of day charging, and the vehicle type. Using a wide variety of methodologies and assumptions, numerous studies have investigated the impact of these different factors on emissions (Hacker 2007; Parks 2007; Anaire 2012; Kelly 2012; RAP/ICCT 2013; Nunes 2014; Tulpule 2014; Nealer 2015; Wood 2015; Jochem 2016).

A 2012 Union of Concerned Scientists (UCS) study concludes that emissions from electric vehicles are less than those of an average conventional vehicle, regardless of mix of fuels used to generate the electricity on which they are charged (Anair 2012). While the authors of the study acknowledge the impact of location and time of day that charging occurs, they do not specifically calculate PEV emissions for different grid mixes, stating:

> Because the hourly variations in emissions intensity are not consistent across regions, times of day, or seasons, it is not practical to develop general consumer guidelines on when the lowest emissions intensity will occur throughout the day. For now, we recommend that EV consumers use their regional grid emissions, averaged over the course of the year, as a guide to estimating their personal EV global warming emissions.

Several studies have quantified the importance of location and time of day when estimating PEV emissions. Tulpule (2013) concludes that day charging with solar-powered charging stations in Ohio could realize CO_2 emissions reductions of up to 90% versus home charging during evening hours. Jochem et al. (2015) finds that total life-cycle external costs of PEVs are highly dependent on the electricity mix and the charging strategy employed.

While a commonly used methodology bases emissions estimates on the annual average electricity generation mix (Hacker 2007), an alternative approach bases calculations on the electricity fuel source that is on the margin (meaning the electricity load that PEVs add to the existing load).[1] Holland et al. (2015) take this approach, finding significant variation in the marginal emissions associated with PEVs in different locations, thus reinforcing the notion that electricity grid mix has a notable impact on emissions. The authors also point out the potential for the transfer of the emissions benefits of EVs from one location to another, as a result of regional electricity imports and exports. Parks et al. (2007) and Denholm et al. (2013) also use the marginal emission methodology. Both studies conclude that the availability of daytime charging increases the percentage of miles that plug-in hybrid electric vehicles (PHEVs) drive on electricity and results in greater petroleum displacement.

[1] As pointed out in the Union of Concerned Scientists study, these calculations based on the marginal fuel source provide insight into the impact of large-scale PEV deployment on electricity grids, but basing calculations on the average electricity generation mix may be more suitable to inform policy and consumer decision-making.

The analysis described in this paper investigates the emissions impacts by time of day and charging scenario for five different electricity grid mixes and multiple vehicle types. We investigate both PHEVs and BEVs that are charged using either slow (level 1) or fast (level 2) charging equipment at varying times of day. The electricity grids on which the vehicles are charged differ in their carbon intensities. Each grid is characterized by an hourly generation profile for an entire week. Seasonal variations are not captured because the profiles represent the average fuel mix over the course of a year.[2]

A strength of our methodological approach is the consideration of not only the emissions associated with charging electric vehicles on a particular electricity grid, but also the emissions associated with the non-electric miles driven. This includes the miles that PHEVs drive in gasoline mode, and those trips that battery electric vehicle (BEV) drivers are required to make in a conventional vehicle (CV). As such, we are able to provide a more complete representation of total emissions associated with PEV-owner travel. Including CV emissions enables this analysis to capture the more nuanced story of PEV use.

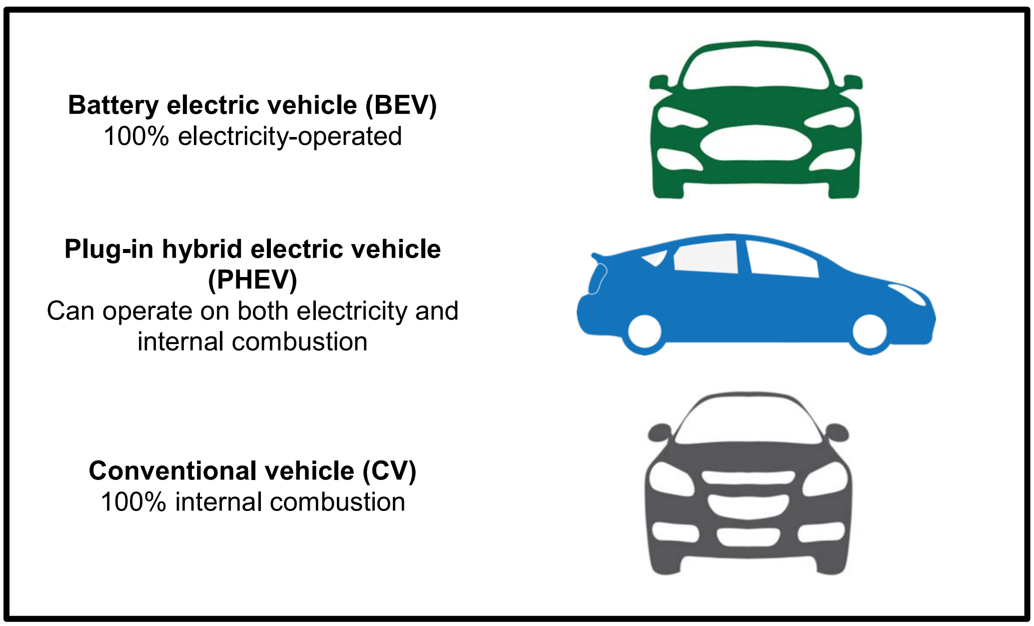

Figure 1. Descriptions and symbols for vehicles studied

[2] The vehicles modeled represent efficiencies anticipated for 2025.

Methodology

Electricity Grid Profiles

For this study, we modeled five different electricity grids with a variety of fuel mixes. The grids broadly represent regions across the United States and their different levels of carbon intensity. The profiles were generated using the production cost model PLEXOS (Energy Exemplar 2015), which simulates the least-cost dispatch of the electric power system, taking into account hourly variations in demand and numerous operational constraints. PLEXOS models electricity dispatch from generating units at intervals as short as five minutes. This analysis simulated hourly dispatch intervals for an entire year, for each of five grids. These results were aggregated to produce annual average hourly profiles (shown in Figure 1). The main analysis is based on a 'standard scenario,' which assumes moderate renewable energy build-out and accounts for currently planned closures of coal facilities and anticipated growth in natural gas generation (Brinkman 2015; Bloom et al. 2016). In addition, a sensitivity analysis (presented in a later section) was conducted for cases with high and low percentages of renewable energy.

Figure 2 shows the five grid profiles used in the main analysis, which represent a broad spectrum of low to high carbon intense grids. Although the example of the low carbon grid is composed largely of renewable energy, a grid with nuclear, hydropower, or other emissions-free generation sources would yield similar results.

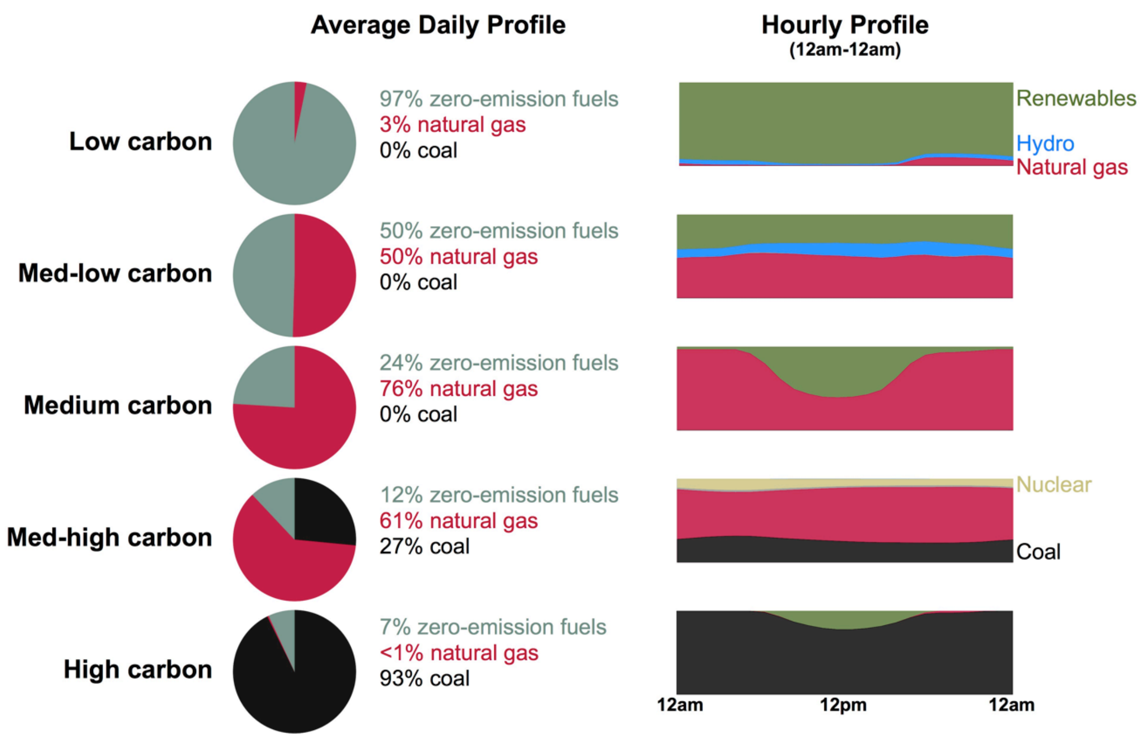

Figure 2. Modeled grid profiles representing varying levels of carbon intensity

Source: Brinkman (2015)

Calculating Electrical Load from EV Charging

We calculated the hourly electrical load profiles associated with EV charging for 28 different scenarios (7 vehicle types and 4 charging scenarios). NREL's Battery Lifetime Analysis and Simulation Tool for Vehicles (BLAST-V) model was used to generate the hourly electrical loads over an entire week for each scenario (NREL 2015a). BLAST-V incorporates data on behavioral driving tendencies of EV drivers based on actual observations into its simulations to determine scenario-specific hourly vehicle load demand (NREL 2015b). Publicly available data from the California Department of Transportation 2010-2012 Household Travel Study was used to characterize travel (NREL 2015b; Nutstats Research Solutions 2013). Inputs to the BLAST-V model included the vehicle type, the types and locations of charging infrastructure available to drivers, and the set of trips requested by the drivers. The vehicle type and charging infrastructure available to the driver was varied in each BLAST-V run, while the set of trips requested by drivers remained constant. Outputs of each BLAST-V run included the number of electric miles, the number of non-electric miles, and the kilowatt-hours needed for charging for each hour of the week. Non-electric miles are those that PHEVs drive in gasoline mode, and those trips that BEV drivers are required to make in a conventional vehicle.

Figure 3 depicts the seven vehicle types modeled, which include both PHEVs and BEVs. The figure also indicates the range the vehicles are assumed to be capable of traveling on a full charge under the standard U.S. Environmental Protection Agency's urban dynamometer driving schedule (unadjusted estimates). The vehicle range was adjusted in BLAST-V by approximately 30% to account for real-world effects including speed, acceleration rate, ambient temperature, and cabin heating and cooling (EPA 2006). Given the amount of data gathered from the multiple runs and the similarity of many of the conclusions across vehicle ranges, we present the detailed results for only the BEV200 and the PHEV30 in some cases.

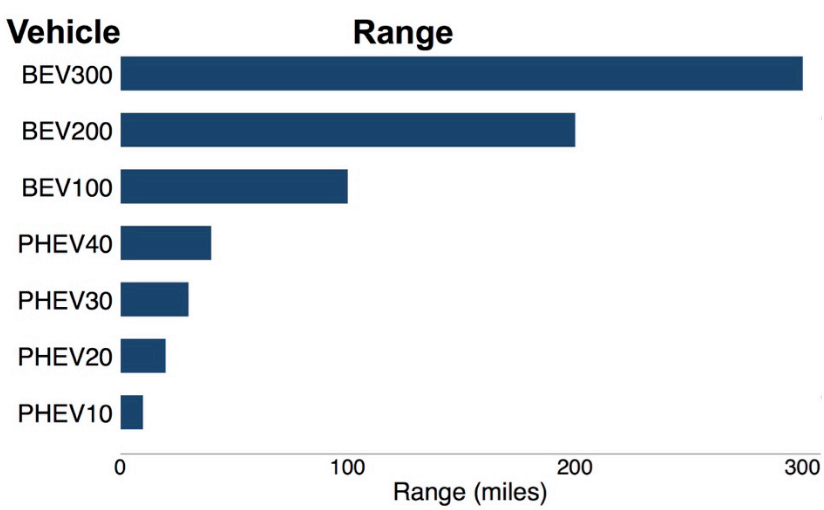

Figure 3. Vehicle types and ranges modeled

The four charging scenarios simulated represent a variety of situations, with three home-only charging scenarios and one home-plus-workplace charging scenario.[3] In the home charging

[3] Public charging stations were not made available to the vehicles during BLAST-V simulation.

scenarios, drivers were either allowed charge their vehicle whenever they were home (also known as opportunity charging) with a Level 1 or Level 2 charger,[4] or were restricted to charging between midnight and 1 p.m. with a Level 2 charger. This 'time-restricted' charging scenario represents the incentives that utilities are increasingly offering EV owners to charge during off-peak hours.[5] Table 1 summarizes the five different charging scenarios modeled for each vehicle type in this study.

Note that smart charging is not included in any of the charging scenarios. While research has shown that charging infrastructure that incorporates advanced controls can be a potentially important mechanism to manage load from PEV charging to reduce system impacts and emissions (Garcia-Villalobos 2014), uncontrolled charging is likely to remain the standard for some time.

Table 1. Charging Scenarios Modeled

Scenario Name	Where can you charge?	When can you charge?	Charging Technology/Speed
Home L1	Only at home	Anytime	Level 1
Home L2	Only at home	Anytime	Level 2
Time Restricted	Only at home	Midnight-1 p.m. only	Level 2
Workplace	At Home & work	Anytime	Level 2

As mentioned above, the BLAST-V model calculates the number of electric miles and non-electric miles driven for each scenario. The same trips are taken in every scenario, and thus the same numbers of miles are driven. However, because of the technical differences in the vehicles, the method BLAST-V uses to determine the ratio of electric to non-electric miles differs for the BEV and PHEVs.

For the BEV scenarios, when a journey is requested, a BEV owner must choose whether to drive their BEV or a CV. The BLAST-V model assumes that owners choose to drive their BEV if the trip is comfortably within the vehicle's range at its current state of charge. If the current state of charge is insufficient to make the trip, the owner drives a CV. The same number and length of trips are taken for every scenario; it is assumed that drivers do not forego a trip simply because they cannot make it using their BEV.

[4] Level 1 chargers are standard for all vehicles and do not require any specialized equipment. They use 120 volt, alternating current and a standard household plug, however a dedicated circuit is necessary. Level 2 chargers supply 240 volt, alternating current. They require the installation of specialized charging equipment and a dedicated 40 amp circuit. Level 2 chargers typically take about half of the time of a Level 1 charger to fully charge a depleted battery.
[5] The Alternative Fuels Data Center database lists at least 18 utilities that have special time-of-use rates for owners of electric vehicles (http://www.afdc.energy.gov/fuels/laws/ELEC). One study found that EV owners with time-of-use pricing generally began charging their vehicles around midnight, when lower rates are available (Ecotality and Idaho National Laboratory 2013).

For the PHEV scenarios, the PHEV operates in electric mode until the vehicle exceeds the battery's range at its current state of charge, at which time it switches to gasoline mode, which results in non-electric miles.

Calculating Emissions Associated with the Scenarios

The level of emissions associated with each charging scenario is based on the carbon intensity of the electricity grid at the specific time of day the vehicles are charged, the emissions associated with burning gasoline, the ratio of electric-to-gasoline miles driven, and the efficiencies of the vehicles.

To calculate emissions for electric miles driven, each electricity generation fuel source was assigned an emission factor (lbs CO_2/kWh) (see Figure 4) and the methodology employed by Brinkman (2015). There are two emissions factors for natural gas; one represents the more efficient heat rate of combined cycle plants. These emissions factors were applied to the electricity mixes for each of the five grid profiles studied to arrive at the hourly carbon intensity for each profile.

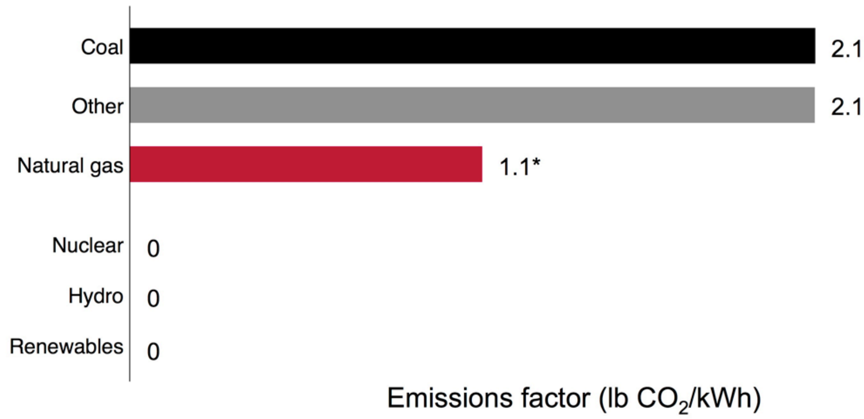

Figure 4. Emissions factors of fuel sources

Source: Brinkman (2015)

*Natural gas emission factor is the average of combustion turbine and combined cycle emission factors.

The emissions associated with the non-electric miles are a function of the vehicle efficiency, which differs between BEVs and PHEVs. For the PHEV scenarios, the emissions associated with the non-electric miles are assumed to be 0.29 lb CO_2/mile (based on the 66.8 mpg efficiency anticipated for 2025).[6] The emissions associated with the miles driven in the conventional vehicle are assumed to be 0.48 lb CO_2/mile (based on a 40.8 mpg efficiency anticipated for 2025).[7] Figure 5 illustrates the methodologies used to calculate emissions from both the BEV and PHEV scenarios.

[6] Modeling is based on a 2025 vehicle efficiency rating of 66.8 mpg (the anticipated PHEV vehicle fuel economy according to the U.S. Department of Energy [DOE] and the Government Performance and Results Act [GPRA]) and an emissions factor of 8.91 kg (19.64 lb) CO_2/gallon gasoline (EIA 2013).

[7] Modeling is based on a 2025 vehicle efficiency of 40.8 mpg (the anticipated conventional vehicle fuel economy according to DOE/GPRA) and an emissions factor of 8.91 kg (19.64 lb) CO_2/gallon gasoline (EIA 2013). Current year vehicles that are still on the road in 2025 were not modeled.

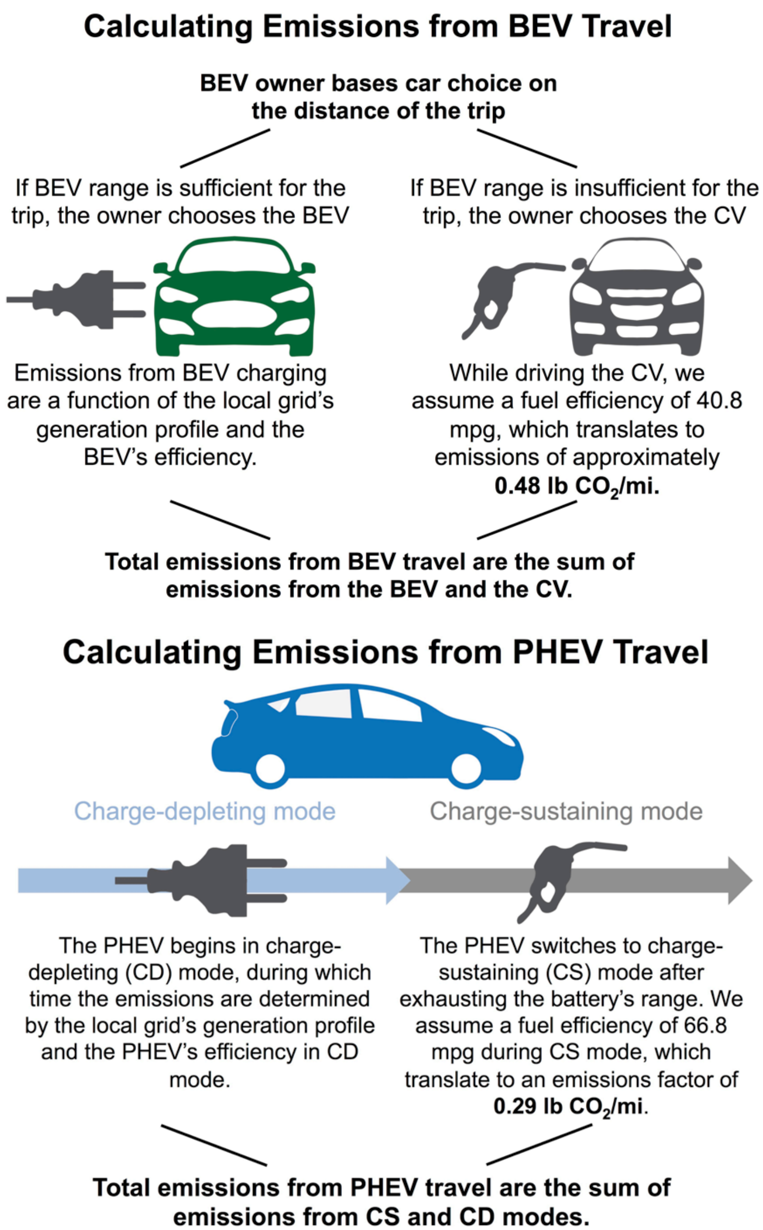

Figure 5. Methodologies used to calculate emissions from BEVs and PHEVs

Figure 6 shows the distribution of electric miles and non-electric miles, by vehicle type and charging scenario, as calculated by the BLAST-V model. It indicates that BEV scenarios generally result in more miles driven on electricity than the PHEV scenarios. We also see that the Home L2 and Workplace scenarios result in the greatest number of miles driven on electricity, and the lowest mileage driven on gasoline. This is true for every vehicle model. The faster charging afforded by the Level 2 chargers and the greater frequency of charging afforded by the availability of workplace charging allow BEV owners to charge more over the course of a typical day and drive their BEV for more electric miles. Likewise, more charging afforded by fast home charging and workplace charging allows PHEV drivers to operate their vehicle in electric mode for a higher proportion of their total mileage.

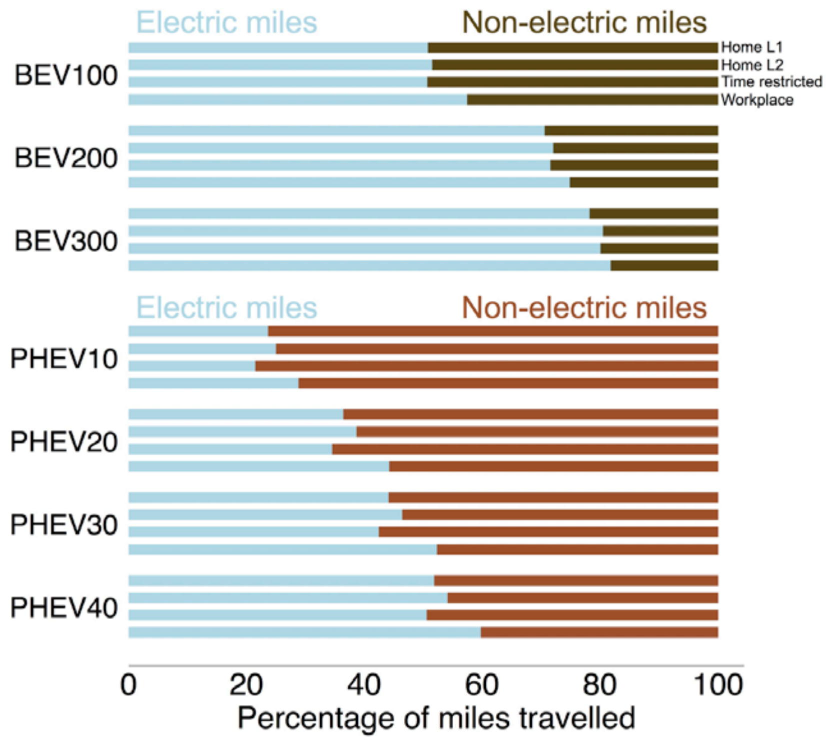

Figure 6. Distribution of electric versus non-electric miles traveled, by vehicle type and charging scenario

Note: Non-electric miles for BEVs result from the use of a conventional vehicle to make trips that would not be possible in the BEV due to the state-of-charge at the time the trip was requested. The non-electric miles for the PHEVs result from the use of the PHEV in gasoline mode (also known as charge-sustaining mode). Because of the difference in efficiency of the CV and the PHEV, the emissions associated with a BEV non-electric mile are higher than the emissions of the PHEV non-electric mile.

Electricity Load Profiles Associated with EV Charging

Figures 7 and 8 show the annual average load profiles for the four charging scenarios modeled, for the BEV200 and the PHEV30. The load shapes were not significantly different for the other vehicle ranges. In addition, there is little difference between the load shapes of the BEVs as compared to PHEVs. The main difference is the higher overall load of the BEV.

Three of the charging scenarios show a clear peak during the evening hours. However, note that the load shape for the time-restricted scenario clearly indicates the lack of charging between 1pm and midnight. Load is very high (6,200 kilowatts) at midnight (when charging is initially allowed) and drops sharply as vehicles become fully charged. The load ramps up again in the morning before dropping to zero at 1 p.m. (when charging restrictions begin).

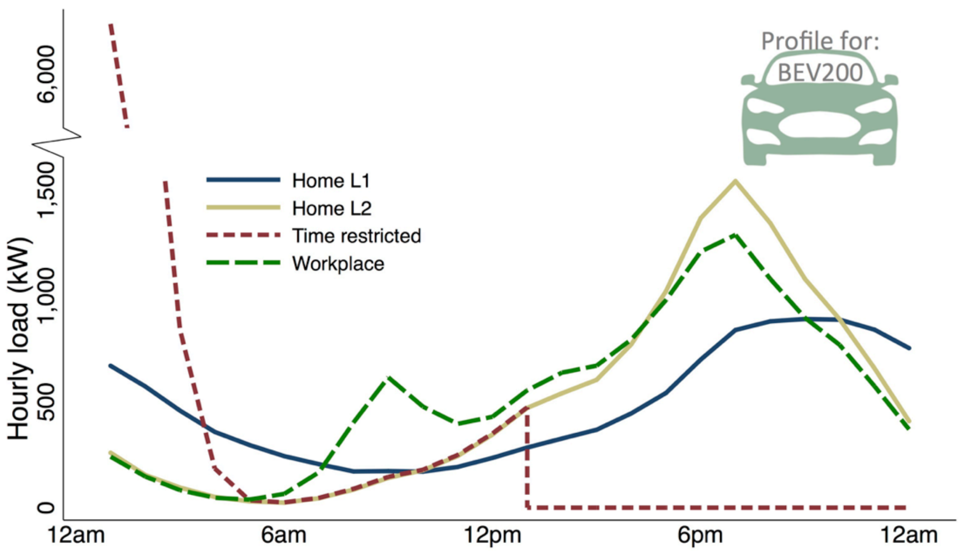

Figure 7. BEV load profile by scenario

Note: The scale in the figure is capped at 1,500 kW for presentation purposes (the time restricted scenario peaks at 6,200 kW at 12 a.m.).

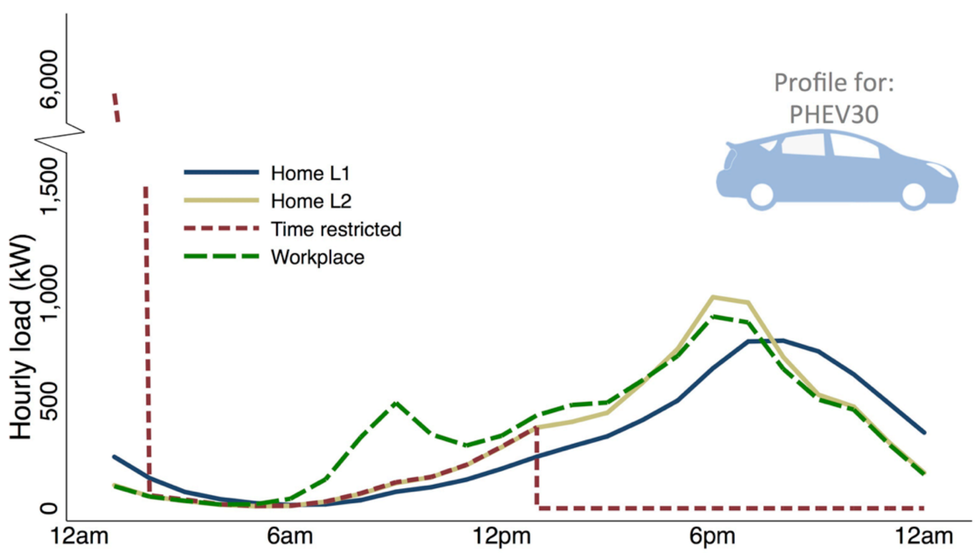

Figure 8. PHEV load profile by scenario

Note: The scale is capped at 1,500 kW for presentation purposes (the time restricted scenario peaks at 5,700 kW at 12 a.m.).

Analysis of Emissions Associated with Miles Driven on Electricity

The following analysis figures (Figures 9–13) provide detailed results for the five generation profiles and four charging scenarios studied. The layout of the figures elucidates the relationships between the multiple variables of interest and allows us to compare of the hourly generation profile and CO_2 intensity of the grid with the hourly load and cumulative grid-based CO_2 emissions for each charging scenario. Note that Figures 9–13 only include the emissions resulting from the miles driven on electricity. They do *not* include emissions resulting from non-electric miles; these are presented separately in subsequent sections.

On a low-carbon grid (Figure 9), CO_2 intensity spikes during the evening 'peak hours' between 6 p.m. and midnight. This spike results in higher grid-based emissions for charging scenarios that have high loads in the evening hours (e.g., Home L2 and Workplace charging). However, the emissions from electricity miles are low in all charging scenarios, because of the minimal use of carbon-based fuels. On low-carbon grids, conventional vehicle miles have a significantly higher carbon intensity than electric miles, favoring the charging scenarios that allow for more miles driven on electricity (i.e., Workplace charging).

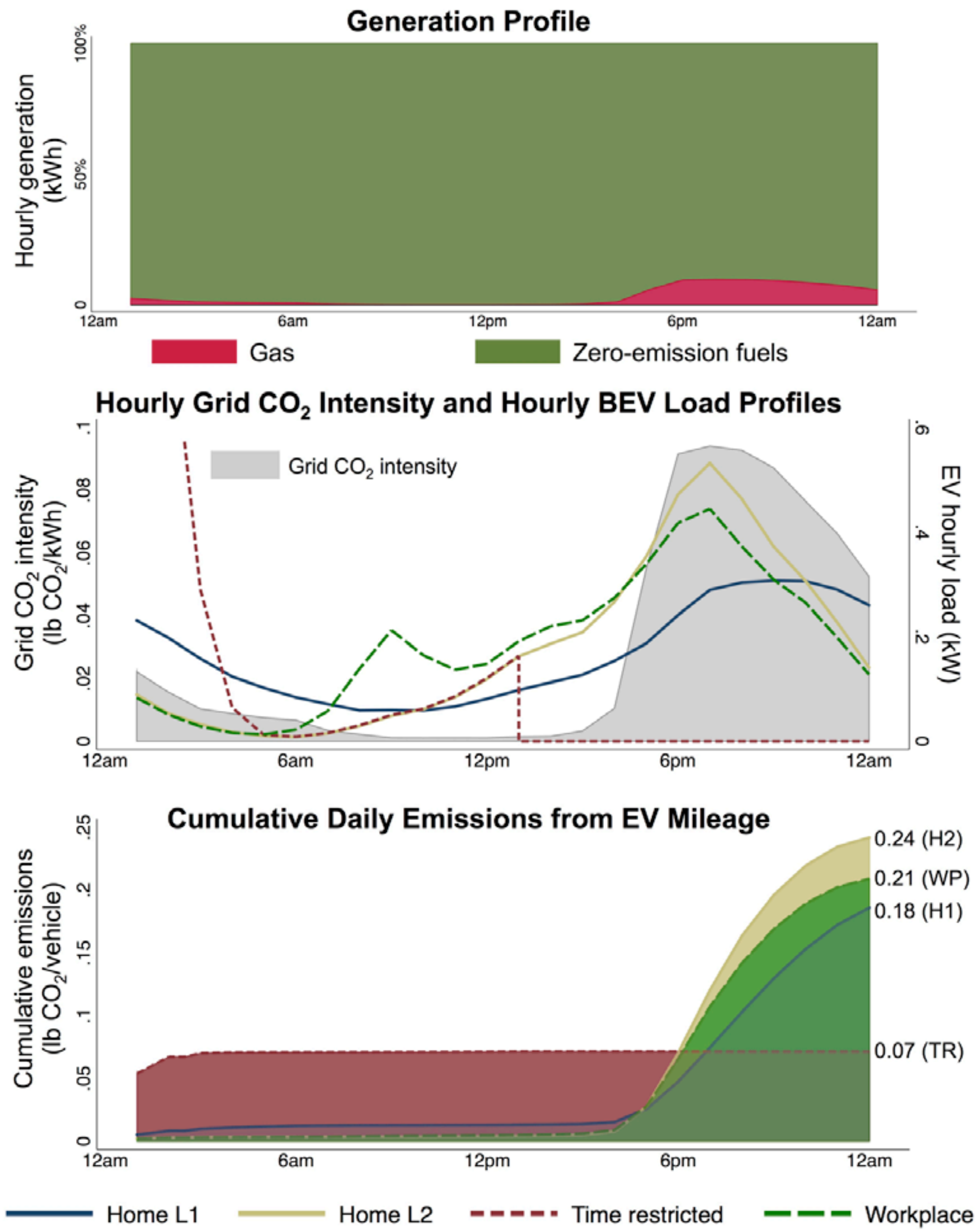

Figure 9. Analysis figure for low carbon grid

Note: Figure based on BEV emissions.

The medium-low carbon grid (Figure 10) has a relatively steady CO_2 intensity throughout the 24-hour period. Because of this, the load shapes for the different charging scenarios have little impact on total emissions. The difference in total emissions between the scenarios in this case, is dependent more on the ratio between electric and non-electric miles. Workplace charging results in higher grid emissions because it allows for more miles driven on electricity, but when emissions from non-electric miles are considered, the scenario results in fewer total emissions than the others (see Figure 15).

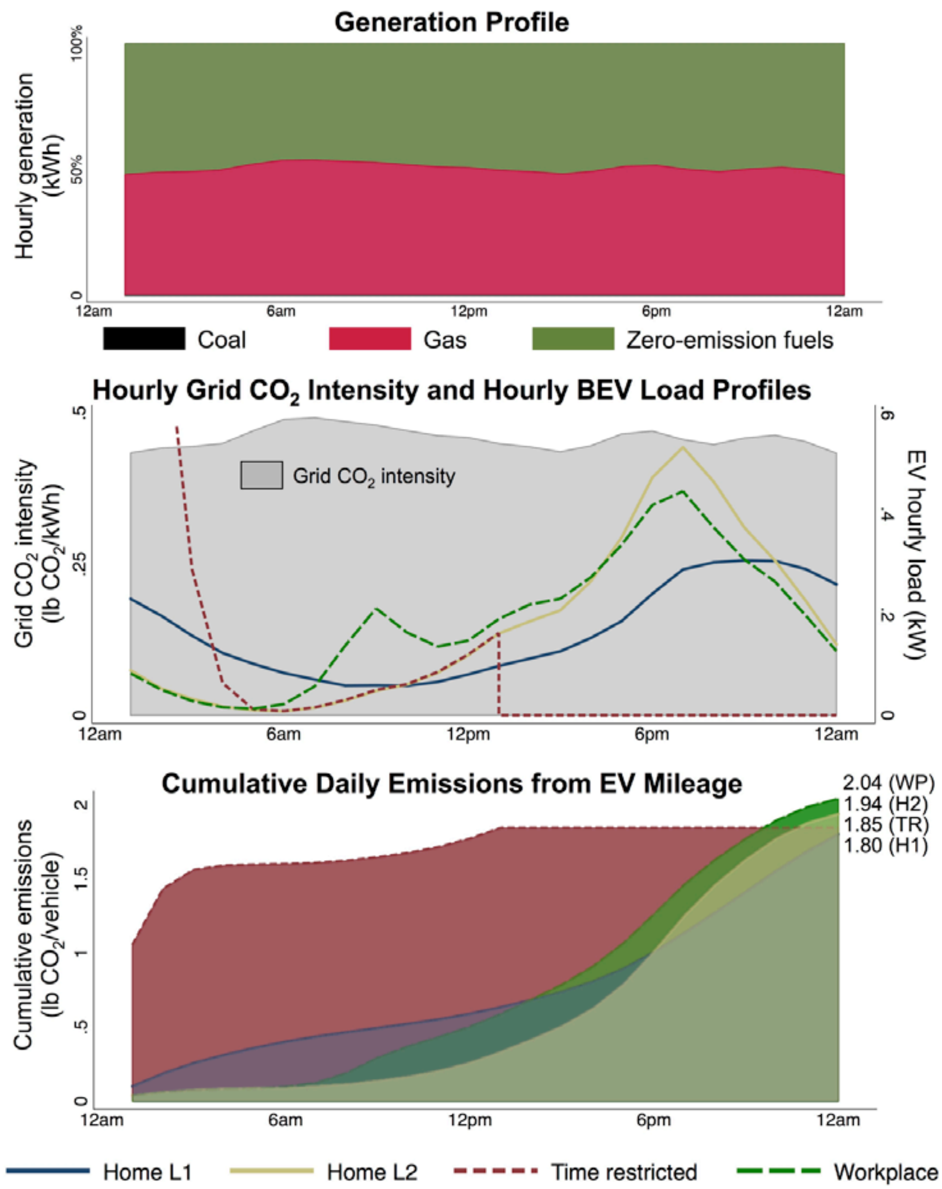

Figure 10. Analysis figure for med-low carbon grid

Note: Figure based on BEV emissions.

The medium carbon grid (Figure 11) has an obvious dip in carbon intensity during the mid-day hours, favoring charging scenarios that have a higher percentage of load between mid-morning and mid-afternoon. Home L1 and Workplace charging scenarios result in the lowest grid emissions in this scenario, followed closely by Home L2. Time restricted charging results in the highest grid emissions, since the majority of the load occurs between midnight and 6 a.m., when carbon intensity is high.

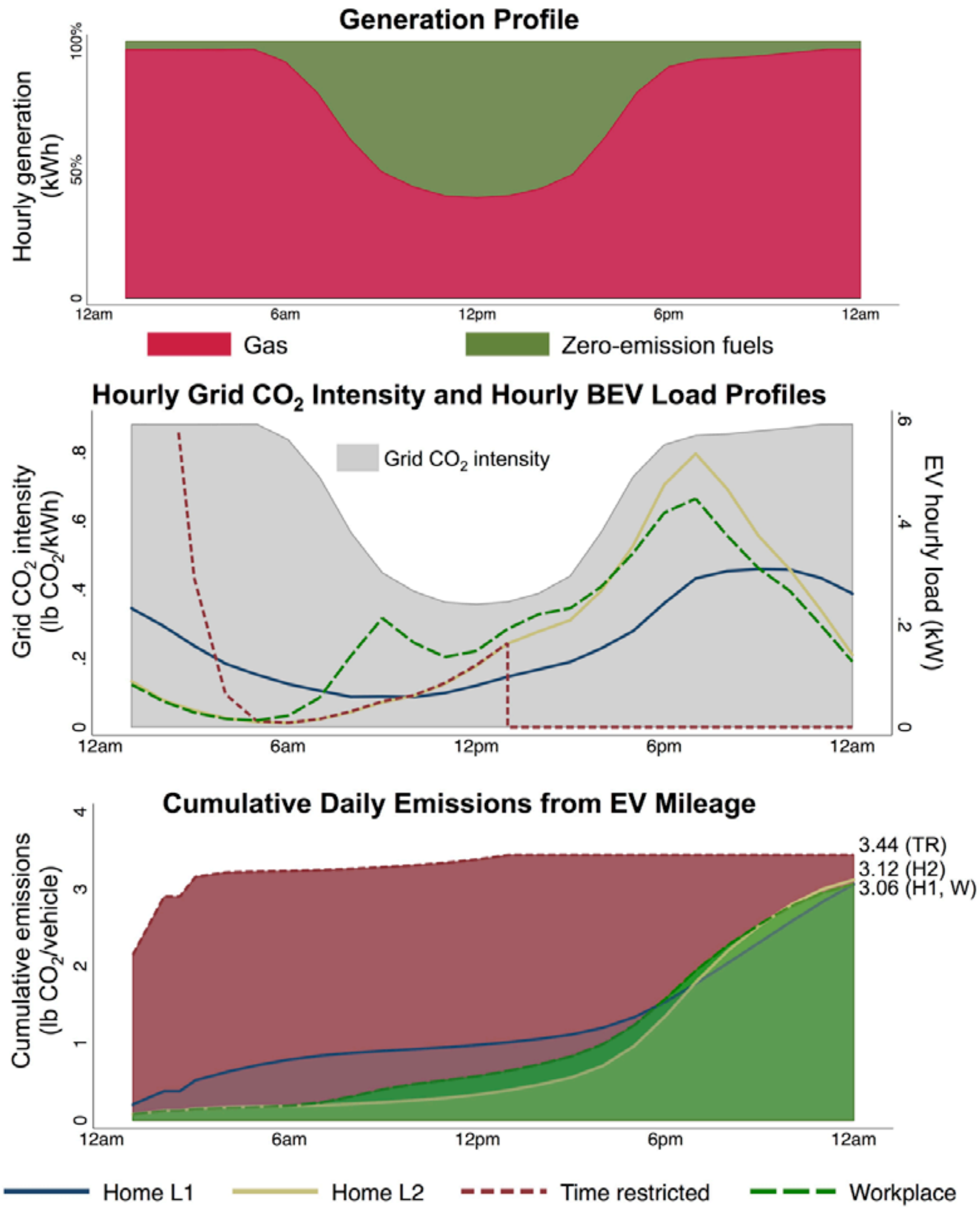

Figure 11. Analysis figure for medium carbon grid

Note: Figure based on BEV emissions.

The medium-high carbon grid (Figure 12), like the medium-low, has a fairly uniform carbon intensity throughout the day, making the load profile less significant in distinguishing between charging scenarios. Therefore, the total load, based on the total miles driven on electricity for each scenario, is responsible for the differences between emissions for the scenarios. Workplace charging has the highest grid emissions because of the higher number of miles that are driven on electricity.

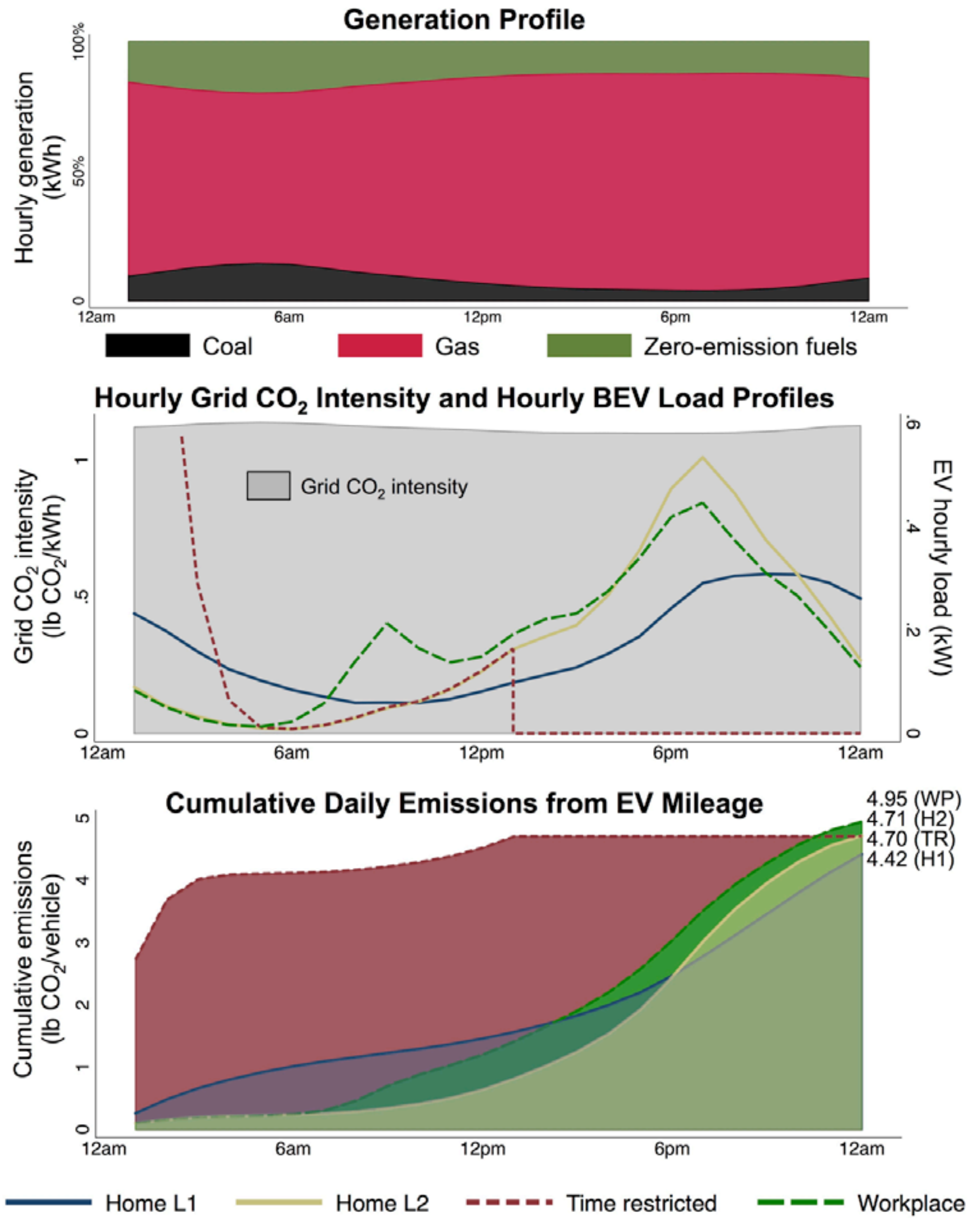

Figure 12. Analysis figure for medium-high carbon grid

Note: Figure based on BEV emissions.

On the high carbon grid (Figure 13), the Home L1 and L2 charging scenarios result in the lowest grid emissions. Workplace charging results in the most grid emissions, with the higher proportion of electric miles afforded by workplace charging not acting as an advantage, in this case.

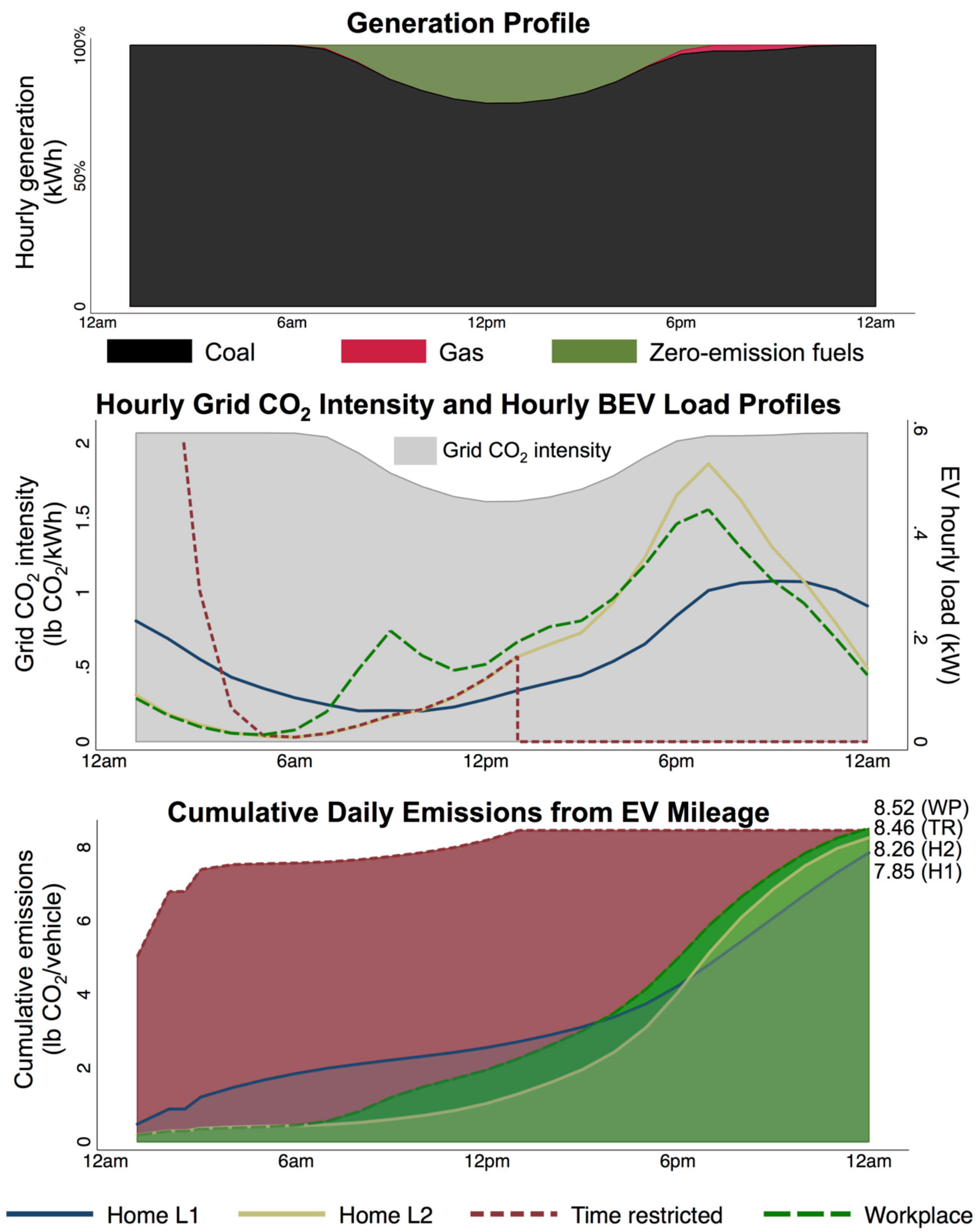

Figure 13. Analysis figure for high carbon grid region

Note: Figure based on BEV emissions.

Emissions Associated with Non-Electricity Miles

Figure 14 shows the emissions associated *only* with non-electric miles for the different charging scenarios. These are the emissions from driving the PHEV in gasoline mode and driving a conventional vehicle for trips unable to be made in a BEV. The results are similar for vehicles with different ranges, so we present only one set here.

Not surprisingly, the PHEV has more emissions from miles driven on gasoline because the PHEV drives more non-electric miles. For all scenarios, these emissions must be added to those associated with vehicle charging in order to gain a complete understanding of the total emissions for each vehicle type and charging scenario.

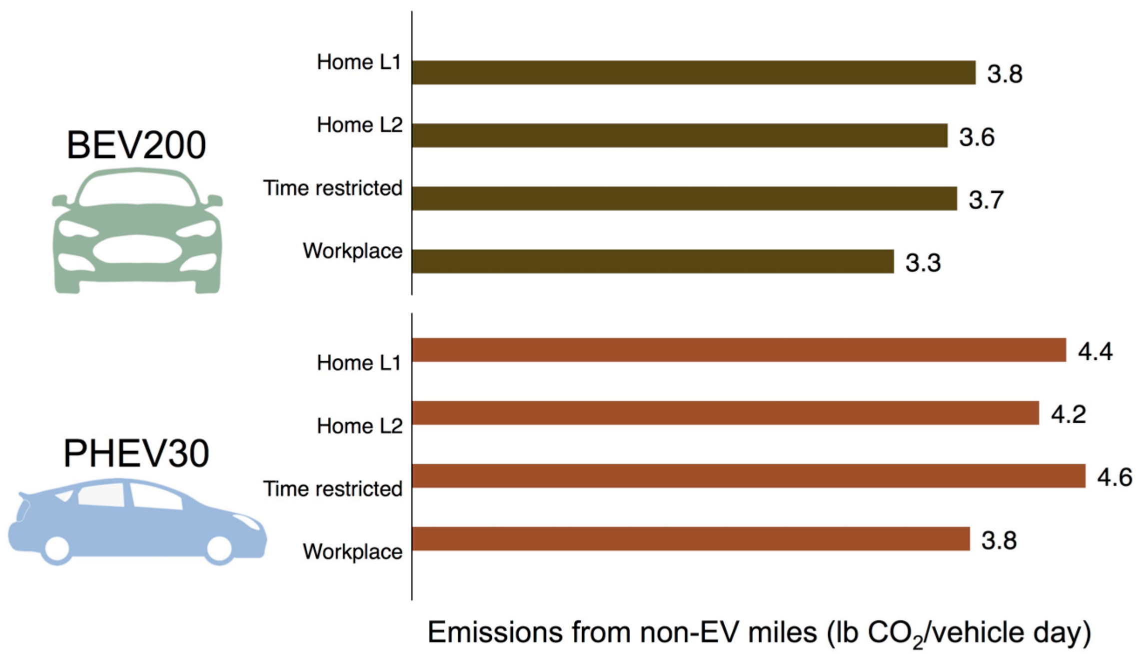

Figure 14. Emissions from non-electric miles for a BEV200 and a PHEV30

Total Emissions Results: Emissions from Electric + Non-Electric Miles

In this section, we show the total emissions associated with each charging scenario and vehicle. The total includes emissions from electric miles and non-electric miles. As this section demonstrates, once the emissions from the electric and non-electric miles are added together, lower emissions from electric miles in one scenario can be offset by higher emissions from non-electric miles, or vice-versa. This signals the importance of considering emissions from both electric and non-electric miles for each scenario.

Figure 15 shows the total emissions of a BEV200 for three electricity grids with low, medium, and high carbon intensities.[8] Figure 15 provides another visualization of the results for all grid intensities and all charging scenarios for all BEVs and PHEVs simulated.

[8] The results indicate that the relative emission levels for the different charging scenarios were similar for a PHEV.

Compared to other scenarios, the Workplace charging scenario results in relatively high emissions from electric miles on most grids. However, workplace charging results in relatively low emissions from non-electric miles. Low emissions from non-electric miles offset high emissions from electric miles such that workplace charging results in the least total emissions on all but high carbon grids.

These results suggest that emissions from non-electric miles may play a significant role in determining total emissions and provide further support for the potential importance of considering both electric and non-electric miles.

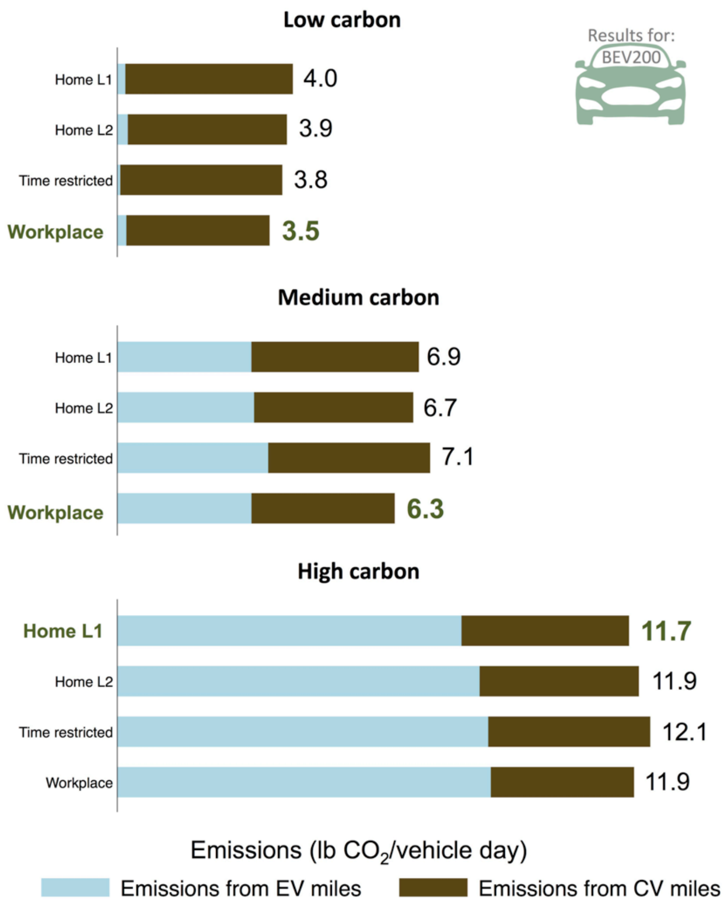

Figure 15. Total emissions for a BEV200 for all charging scenarios; three electricity grids

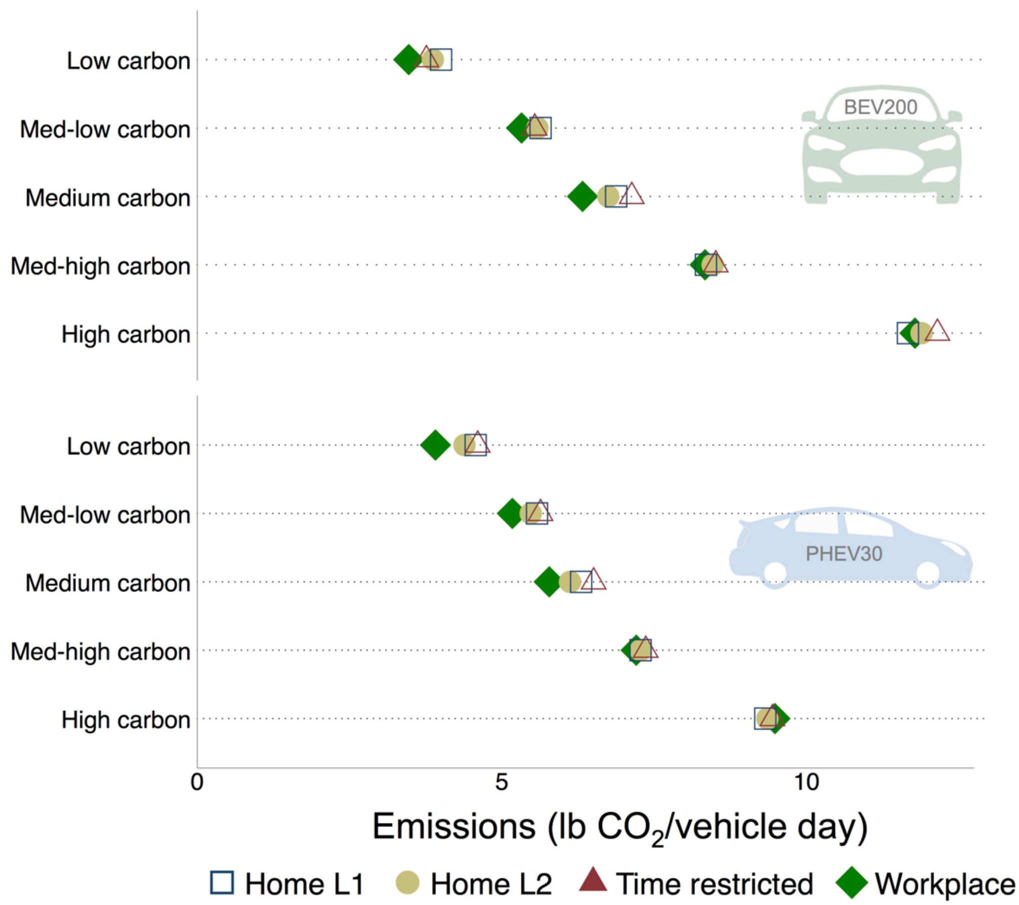

Figure 16. Total emissions per vehicle day by region, vehicle type, and scenario

Next, we compare the total emissions from BEVs and PHEVs to those generated when a CV (alone) is used to take the same set of trips. For a low carbon grid, BEVs and PHEVs each result in about one-third of the total emissions of a conventional vehicle (Figure 17). This result accounts for emissions from journeys that BEV owners must take in CVs. For a high carbon grid, BEVs and PHEVs result in slightly lower emissions than a CV (Figure 18).

Note that emissions savings are greater for PHEVs than BEVs when the grid CO_2 intensity is high. Although seemingly counterintuitive, this is easily explained by the relative efficiencies of the vehicles. BEVs result in more electric miles overall than the PHEVs, but the efficiency of the conventional vehicle that is used by BEV owners when they are unable to use their electric vehicle is only 40.8 m/gallon. This is compared to a PHEV efficiency of 66.8 mpg in gasoline mode. The carbon intensity of the BEV non-electric miles is 0.48 lb CO_2/mile, while the carbon intensity of the PHEV non-electric miles is 0.29 lb CO_2/mile.

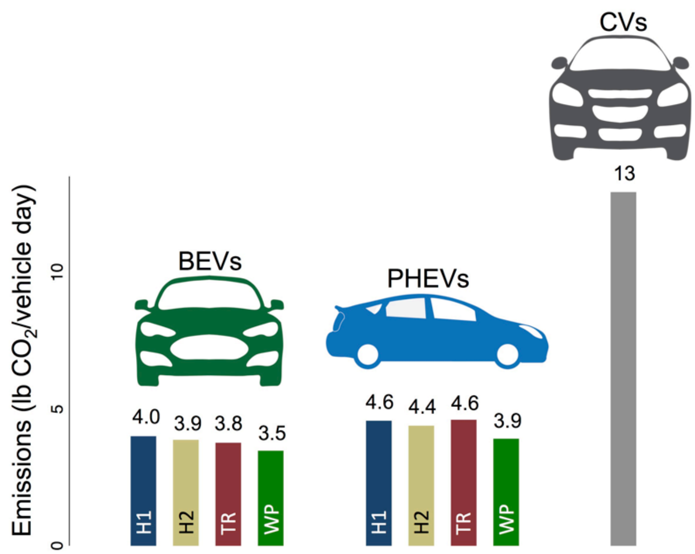

Figure 17. Comparison of total BEV and PHEV emissions with emissions from a conventional vehicle on a low carbon grid.

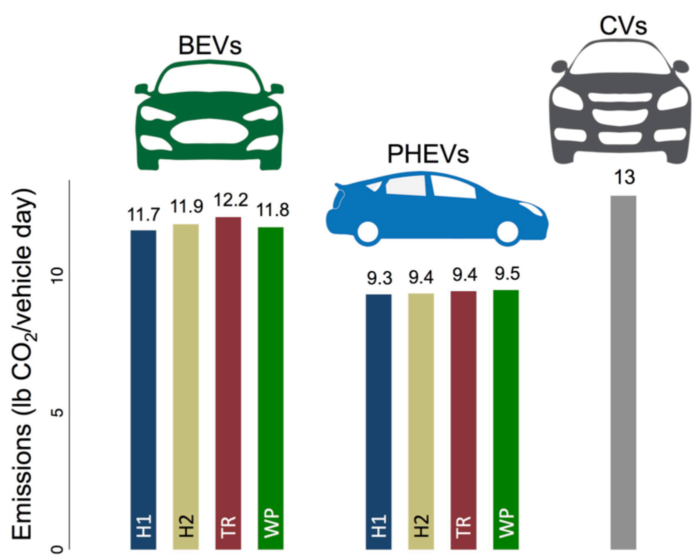

Figure 18. Comparison of total BEV and PHEV emissions with emissions from a conventional vehicle on a high carbon grid

Sensitivity Analysis

Next, we examine the sensitivity of the results to electricity grids with higher and lower carbon intensities by replacing a percentage of the generation fuel mixes with either more or less natural gas or coal. This allows for exploration of the impact of higher or lower levels of renewable energy deployment (or an increased use of nuclear power) than assumed for the main analysis. Table 2 shows the adjustments made to the original electricity grid profiles for the sensitivity analysis.

Table 2. Sensitivity Adjustments to Electricity Grid Fuel Mixes

Grid Scenario	High Renewables Sensitivity Adjustment	Low Renewables Sensitivity Adjustment
Low Carbon	N/A	+20% gas
Med-Low Carbon	-20% gas	+20% gas
Medium Carbon	-20% gas	+20% gas
Medium-High Carbon	-10% coal; -10% gas	+6% coal; +6%gas
High Carbon	-10% coal; -10% gas	N/A

The sensitivity analysis supports two findings, which hold for both BEVs and PHEVs. First, it further supports the initial conclusion that workplace charging generally results in the lowest emissions, with the exception of grids with very high carbon intensities.

Second, the sensitivity analysis suggests that the Workplace charging scenario is the most sensitive to changes in renewable/zero-emission fuel penetration. There is an average difference of a 30% in emissions for the Workplace charging scenario between the high renewables and low renewables cases. This is compared to average difference of 27%–29% for the other three charging scenarios.

Figure 19 presents the results of the sensitivity analysis for the Workplace and Home L1 charging scenarios, which are the most elucidating.

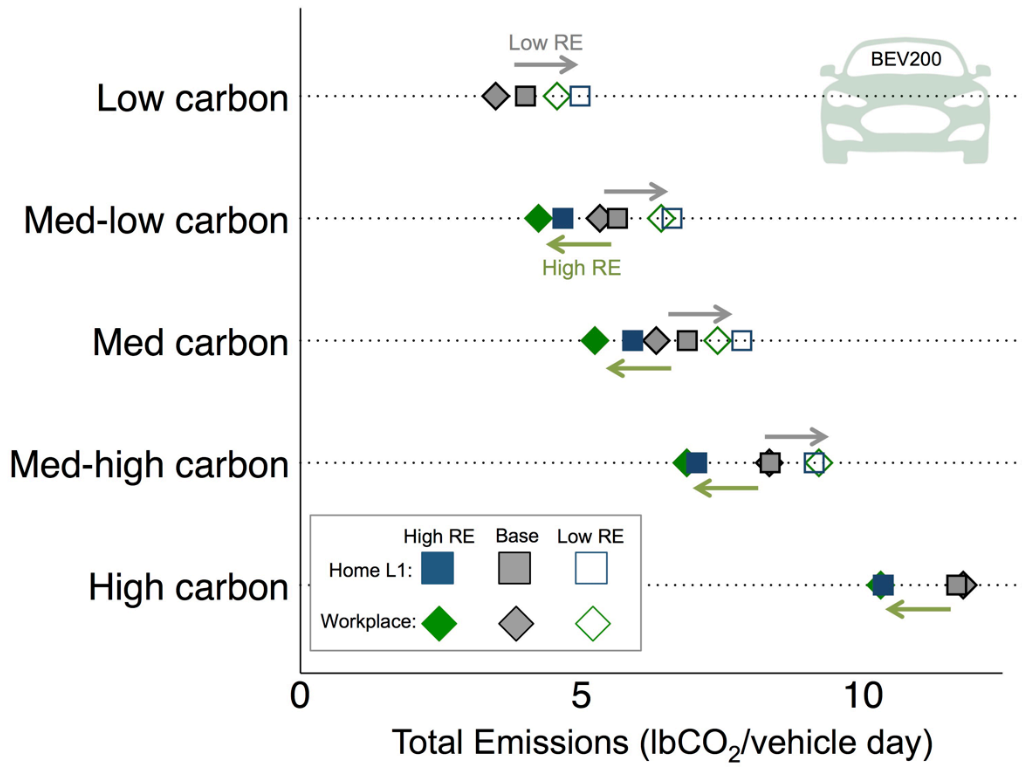

Figure 19. Sensitivity of BEV emissions to higher and lower carbon intensities; Home L1 and Workplace charging scenarios

Next we examine the sensitivity of the emissions from the Workplace and Home L1 charging scenarios to individual electricity generation fuel types. Figure 20 shows the rise in emissions for these two charging scenarios as the electricity grid mix changes from zero-emission to 100% natural gas (on the left) or 100% coal (on the right).

The Workplace charging scenario results in lower emissions than Home L1 until a 92% natural gas penetration, or 55% coal penetration, is reached. This suggests that the electricity generation profile can vary substantially before the emissions associated with the Workplace charging scenario are higher than for the other scenarios.

This result also suggests that regions with grids that have higher carbon intensities (e.g., more coal dependence) may not realize significant emissions reductions by switching from home charging to workplace charging. This is because the emissions reduction benefits of workplace charging diminish as the CO_2 intensity of the grid increases. These regions may experience greater emissions reductions associated with electric vehicles by focusing on reducing the carbon intensity of the electricity grid.

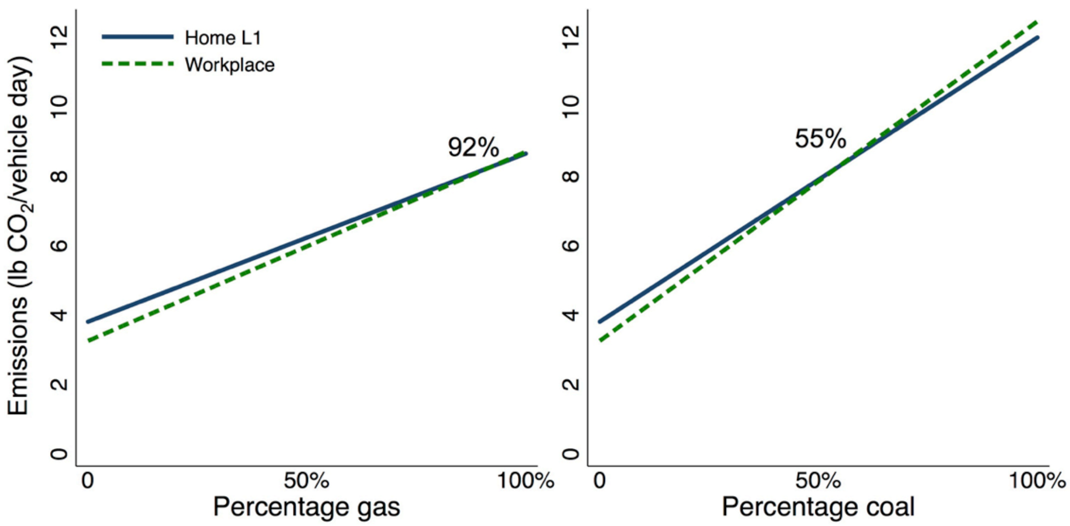

Figure 20. Comparison of Home L1 and workplace emissions in different fossil fuel scenarios

Note: Based on BEV200

Figure 21 plots the percentage difference in emissions between the Workplace scenario and Home L1 scenario as a function of grid carbon intensity. Figure 21 demonstrates that the potential emissions reduction from encouraging workplace charging is a function of the carbon intensity of the grid. Overall, emissions reductions are greatest for low carbon grids and diminish as carbon intensity increases. Emissions reductions are greatest in regions with grids that have more zero-carbon fuel sources, decline as grids rely more on natural gas, and approach zero as grids use more coal. On coal-heavy grids, Workplace charging emissions exceed Home L1 emissions.

Based on the assumptions used in this analysis, the wide-spread use of workplace charging could be expected to reduce emissions on grids with an average carbon intensity of less than 1.5 lb CO_2/kWh.

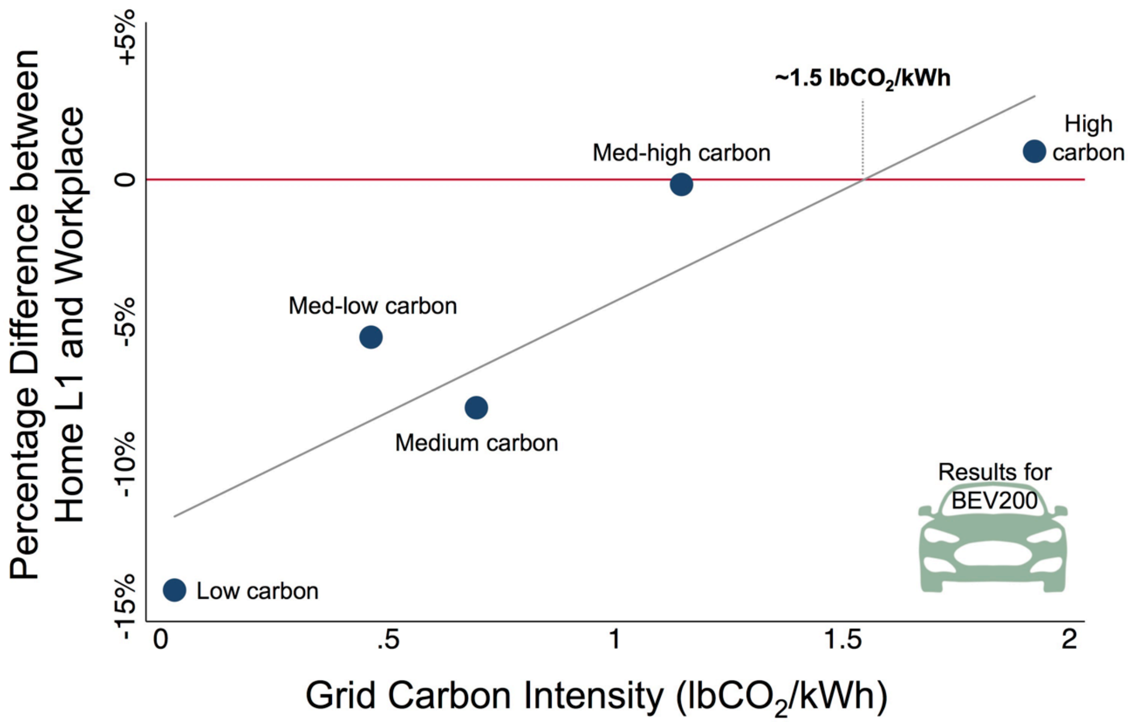

Figure 21. Percentage difference in emissions between Home L1 and workplace charging scenarios as a function of grid CO_2 intensity

Conclusions

This study analyzes the emissions associated with electric vehicles, with consideration to the vehicle type, the carbon intensity of the grid, and the charging infrastructures and patterns employed. It uses a novel methodology that allows us to consider not only the emissions resulting from charging the PEVs, but also the emissions associated with the miles driven on gasoline. The emissions are calculated for a defined set of trips taken by multiple vehicle types, using anticipated 2025 vehicle efficiencies.

Our analysis suggests the following conclusions:

- The carbon intensity of the electricity grid has a greater impact on the total emissions associated with electric vehicles than does the charging scenario. However, differences in emissions between charging scenarios are detectable, with advantages of each differing somewhat according to the carbon intensity of the grid.
- Notably, PHEVs yield lower total emissions than BEVs in four of the five grid types. The low-carbon grid is the only case in which BEVs have lower total emissions. This is due to our inclusion of non-electric miles in the calculation of total emissions. PHEVs have a higher mile-per-gallon efficiency and their non-electric miles have a lower carbon intensity than BEV non-electric miles (which are driven in a conventional vehicle).
- Workplace charging results in the greatest percentage of electric miles for both BEVs and PHEVs and consistently results in lower total emissions across all charging scenarios, with exceptions only for high carbon grids.[9]
- The emissions benefits of workplace charging increase as the carbon intensity of the grid is reduced. Sensitivity analysis indicates that the Workplace charging scenario continues to result in the least emissions, even when the carbon intensity of the grid varies substantially. However, the larger number of electric miles afforded by workplace charging can result in higher total emissions than other charging scenarios on high carbon grids.
- Of the charging scenarios studied, time-restricted charging results in the lowest number of electric miles and the highest level of emissions for most grids and vehicle types.
- Looking across all of the vehicle types, charging scenarios and grids studied, a BEV using time-restricted charging on a high carbon grid results in the highest level of emissions.
- A BEV using workplace charging on a low carbon grid provides the greatest emissions reductions as compared to driving a conventional vehicle.

[9] Our results support the conclusion of Parks et al. (2007) and Denholm et al. (2013) that the availability of daytime charging increases the percentage of miles that PHEVs drive on electricity, resulting in greater petroleum displacement.

Resulting policy and technology considerations include:

- Changes in carbon intensity of the grid impact the emissions associated with workplace charging. This supports the notion that encouraging increased renewable energy in combination with increased workplace charging can have a significant impact on emission reductions associated with electric vehicle deployment.
- Based on the assumptions used in this analysis, the wide-spread use of workplace charging could be expected to reduce emissions associated with electric vehicles on grids with an average carbon intensity of less than 1.5 lb CO_2/kWh.
- Regions with carbon-intense electrical grids will realize little (or even negative) benefit by switching from home charging to workplace charging. Policies to reduce grid carbon intensity may provide greater value than policies to promote workplace charging.
- Restricting charging to off-peak hours results in higher total emissions associated with PEVs. This is, in part, a consequence of the reduced number of trips that PEV drivers can comfortably make when charging is restricted to off-peak hours. This result suggests that existing policies and utility rate structures that encourage off-peak charging may lead to higher emissions associated with PEVs than policies that support daytime charging. Altering the times that charging restrictions or special PEV charging rates are in place to increase flexibility may reduce the negative impacts of time-restricted charging on emissions. More analysis of the impacts of time-restricted charging on specific electric grids could help to both reduce the grid impacts associated with increased levels of PEV charging as well as maximize emissions reductions.

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