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The Climate Change Mitigation Potential of Electric Vehicles as a Function of Renewable Energy

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Abstract: This project quantifies the carbon dioxide emissions produced by electric vehicles (EVs) as a function of renewable energy. These values are compared to the emissions for internal combustion engines (ICE) of varying efficiencies. Many studies quantify carbon dioxide emissions based on a static grid, but this fails to accurately measure the long-term potential of electric vehicles. This model disaggregates grid-based and non-grid-based emissions, which allows production-based emissions to accurately reflect the percentage of renewable energy that is entered into the model. Argonne National Laboratory's GREET Model and a variety of meta-analyses are used to determine the emissions per kWh and per gallon. The model also allows for the manipulation of a variety of variables other than the percentage of renewable energy, including: EV efficiency, miles per gallon, and battery-based emissions. The lifecycle EV carbon emissions for a vehicle powered by the 2016 US grid is 30.82 metric tons, while the emissions for an EV powered by 100 percent renewable energy is 6.3 metric tons. An average internal combustion engine vehicle (25.4 miles per gallon) is responsible for 68.38 metric tons of carbon dioxide over its lifetime, while an ICE vehicle with a utopian efficiency of 80 miles per gallon accounts for 25.5 metric tons of carbon dioxide.

Keywords: Electric Vehicles, Sustainable Transportation, Climate Change, Carbon Dioxide, Emissions

Introduction

The use of electric vehicles (EVs) has expanded significantly in the past decade: only 4,716 electric vehicles were sold in the United States between 2008 and 2010, while nearly 200,000 were sold in 2017 (Inside EVs 2018). The International Energy Agency (IEA) predicts that this growth will continue over the coming decades and lead to a worldwide fleet of 125 million electric vehicles on the road in the year 2030 (IEA 2017). This growth is especially significant, as the electric vehicle has been touted as a potential mitigator of anthropogenic climate change; although some have argued that electric vehicles running off the current grid are no cleaner than standard automobiles (Lomborg 2013). This opinion is an outlier within the body of research on electric vehicles (Nealer, Reichmuth, and Anair 2015), yet there is no argument over the fact that the current grid produces a nontrivial amount of carbon emissions per kWh. This situation can be remedied by combining electric vehicles and low carbon renewable energy. A nationwide fleet of electric vehicles would cause a significant increase in the demand for electricity, but this demand could be assuaged by a nationwide adoption of renewable energy programs (rooftop photovoltaics, grid-scale solar, wind power, hydropower).

The climate change mitigation potential of an electric vehicle is directly linked to the grid from which it draws its energy: a low carbon grid will lead to a low carbon vehicle. However, multiple studies, including a recent working paper by the National Bureau of Economic Research (NBER), analyzed the efficacy of electric vehicles based solely on our current grid (Holland et al. 2015). This is a severe research gap, as we cannot fully understand the potential for electric vehicles unless they are paired with a grid that unlocks their capability. An electric vehicle's potential for positive environmental impact is truly unleashed when the vehicle is tied to clean energy. There is no theoretical means for an internal combustion engine to run off of renewable energy; even a hybrid car with an efficiency of 100mpg is still burning gasoline and

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emitting carbon dioxide. Yet, a car that is running on solar, wind, or hydropower will have marginal emissions that approach zero (Moomaw et al. 2011). Furthermore, a reduction in grid-based emissions will also impact the production emissions for all automobiles, and thus, these reductions need to be accounted for in any assessment of the long-term efficacy of both electric vehicles and internal combustion engine vehicles.

Materials and Methods

This study aimed to create a model that would quantify the relationship between the percentage of renewable energy and the carbon dioxide emissions associated with both electric vehicles and internal combustion engine vehicles. This relationship is also impacted by temporal and geographic factors (the electric grid varies significantly based on location and the time of the day), but this study is focused specifically on the impact that renewable energy has on the climate mitigation potential of electric vehicles. The foundation of the model was based on the general composition of the 2016 United States electric grid (13.3 percent renewable energy) and is able to approximate an electric grid with a percentage of renewable energy between 13.3 percent and 100 percent. Any value of renewable energy could then be entered into the model and the model would output the corresponding carbon emissions. These hypothetic "grids" may not model any one specific region, but they do facilitate an analysis of the correlation between the percentage of renewable energy and the amount of carbon dioxide emissions. To accomplish this task, the model needed to include the following attributes: an accurate projection for renewable and nonrenewable power plant percentages (by electricity generation type), emissions per kWh and per gallon, and production-based emissions that float with the percentage of renewable energy (for electric vehicles and internal combustion engine vehicles).

Power Plant Projections

It was necessary to create a model where a continuous input variable for renewable energy percentage (RE) could be entered into the model and it would output an accurate percentage breakdown for the corresponding grid.

The power plant projections were based on the 2015 National Renewable Energy Laboratory (NREL) Renewable Electricity Futures Study (Mai et al. 2012). The NREL study explores high-penetration renewable energy scenarios and how these scenarios could be implemented. Multiple nonlinear regressions were run on the NREL data (for each generation type) and the equation with the highest r^2 value was chosen for use in the model. All coefficients of determination were 0.97 or greater and the equations followed the NREL predictions with limited residuals. Each of the regression-based formulas were used to output the appropriate percentages for each electricity generation type, based on the input percentage of total renewable energy. The only exception was oil, as NREL does not give data for oil power plants. Consequently, the value for oil was fixed at 1/33 of coal power to reflect the oil-to-coal ratio that we see in 2016 (EIA 2016).

This model produces little deviation from the expected values, but in most cases the combined values for all renewable energy percentages were slightly different than the input renewable energy percentage. This problem was solved by indexing the output values (OutputRE) for each energy source (g) to the input percentage of renewable energy (RE).

$$IndexedRE\% = \frac{OutputRE_g}{\sum_g (OutputRE_g)} \times RE$$

Each percentage of renewable energy was divided by the regression-based total for renewable energy and then this value was multiplied by RE. This computation ensures that all output values will sum to the input value for renewable energy percentage (RE%). The same process was then followed for nonrenewable energy.

The NREL data also has one very significant flaw: NREL includes values for coal power that are substantially higher than the current percentage of coal power and are far higher than the EIA's predictions. While the EIA's model does not look at high penetration renewable energy scenarios, it does predict the energy distribution through 2040, and these values contrast starkly to NREL's coal power predictions (EIA 2016). NREL's percentage for coal is related to the fact that much of NREL's study was done prior to 2015, when coal production accounted for a far greater percentage of the overall grid (Mai et al. 2012).

The percentage of coal power has fallen significantly in recent years and the EIA predicts that this trend will continue (EIA 2016). Thus, it is unlikely that an increase in renewable energy will also coincide with a resurgence in the coal industry. The increase in coal power has a dramatic impact on the overall model for externalities associated with electric vehicles, and this results in a distortion of the central goal of this study: to determine the impact that renewable energy has on the environmental impact of electric vehicles. If this increase coincides with an increase in coal power, the potential benefit related to an increase in renewable energy will be confounded. This problem was fixed by using a Proportional Model to predict the percentages for nonrenewable energy. This was done to eliminate the confounding impact of disproportionally high coal power.

The relative percentage for each nonrenewable energy source was then multiplied by the overall value entered for nonrenewable energy (variable $IGrid_g$; g representing the index for all individual electricity generation types).

$$NonRenewablePercentage = (1 - RE\%) \times IGrid_g$$

The Power Plant Projection Model allows for the individual renewable energy generation methods to increase at the rate that NREL has deemed appropriate for each of the high penetration renewable energy scenarios. However, the benefits of renewable energy are not obscured by a dramatic increase relative to 2016 coal power output. The goal of this study is to isolate the variable for "renewable energy" and understand its impact on the environmental benefits of electric vehicles, ceteris paribus.

Power Plant Emissions

Power plant carbon emissions were evaluated from a life cycle assessment perspective. This is especially important for renewable energy, as the marginal emissions from photovoltaics, CSP, and hydropower approach zero. Argonne National Laboratory's life cycle assessment program "GREET 2015" was used to determine the emissions per kWh for coal, natural gas, oil, nuclear, and biomass power plants (Argonne National Laboratory 2015). GREET 2015 (Argonne National Laboratory 2015) does not include LCA emissions data for the other renewable energy power plants. Therefore, a meta-analysis from Klein and Whalley (2015) was used to collect emissions data for photovoltaic, concentrated solar power, geothermal, and hydroelectric power plants. Klein and Whalley's (2015) paper provides meta-analysis data for CO2 emissions for each type of renewable energy electricity generation and in each case the median/nominal value was recorded (Table 1).

Table 1: Power Plant Carbon Emissions

Electricity Generation Type	CO2 (g) per kWh
Wind	11.00
Photovoltaic	48.00
Concentrated Solar (CSP)	35.00
Hydropower	7.00
Geothermal	58.00
Biomass	30.78
Oil	942.04
Natural Gas	444.40
Coal	962.93
Nuclear	10.48

Source: Data from Cornell

Emissions per 150,000 Miles

The lifetime carbon dioxide emissions for an electric vehicle come into focus once the "lifetime mileage" and "efficiency" are taken into account. These variables facilitate the calculation of how many kWh would be needed over the lifetime of an electric vehicle. This number is a function of two values: efficiency and total miles. This study uses 150,000 miles, because it was the standard value used in NBER's 2015 white paper on the "environmental benefits of electric vehicles" (Holland et al. 2015). The efficiency value of 32 kWh per 100 miles is used, as it is the weighted value for all 2016 model year electric vehicles that were also sold in 2015 (U.S. Department of Energy 2016).

$$CarbonEmissionsEV = \sum_{g} \left(CarbonEmissons_g \times Percentage_g \times \frac{150000 \times Efficiency}{100} \right)$$

Note: "$CarbonEmissons_g$" is equal to the emissions of CO2 for power plant type "g"

Emissions for an Internal Combustion Engine (ICE) Vehicle

The gasoline emissions values are taken directly from the GREET 2015 software program, which breaks down emissions by well-to-pump (WTP) and well-to-wheels (WTW) emissions. The WTW emissions were recorded, which take into account both WTP emissions and emissions from operation (CarbonEmissions variable). The per gallon carbon emissions were then converted to lifetime emissions (Table 2). This was accomplished by determining the number of gallons that would be needed to power an ICE vehicle for 150,000 miles. This value is calculated by dividing 150,000 by the average miles per gallon.

Table 2: Emissions per Gallon of Gasoline

Pollutant	WTW per Gal (g)	WTW per Gal (tons)	Emissions per 150,000mi (tons)
CO2	10641.14	1.06E-02	62.84

Source: Data from Cornell

The University of Michigan (2018) tracks the "average sales-weighted fuel-economy rating of purchased new vehicles" based on data supplied by the EPA. This value has been steadily increasing and reached 25.3 miles per gallon in July 2016 (the most recent data at the time of model creation). This value (25.3) is used in Table 2, but the variable for miles per gallon can be manipulated to determine the relationship between miles per gallon and the marginal benefits of an electric vehicle.

$$CarbonEmissionsICE = CarbonEmissions \times \frac{150000}{MPG}$$

Nonoperating Carbon Emission

A nontrivial percentage of emissions for both electric vehicles and ICE vehicles occur outside the automobile's operating phase. These additional emissions can be attributed to the vehicle's components and the energy used during assembly, disposal, and recycling (ADR). This data is collected from GREET 2015, as the software breaks emissions down into multiple categories, including: components, ADR, and batteries.

The central objective of this research was to determine the impact that renewable energy penetration will have on the CO2 emissions associated with electric vehicles. Thus, it is important that nonoperating emissions do not remain static and rather are based upon any treatments made to the independent variable (renewable energy percentage or RE). It was necessary to break the nonoperating emissions down into grid-dependent and grid-independent factions (Table 3).

Table 3: Grid-based and Non-grid based Production Emissions for an Electric Vehicle

EV Components Emissions	2016 Grid WTP	No Carbon Grid WTP	WTP % from Grid
CO2	40.03g	26.65g	33%

Source: Data from Cornell

The decrease in production-related carbon emissions (PE) represents the percentage of emissions that could be attributed to the grid. This was calculated for the following categories (k): Components, ADR, and Batteries. These percentages (PCat%) facilitated a breakdown of the emissions into grid-dependent and grid-independent emissions. The production emissions for a specific category (Components, ADR, and Batteries) are computed by multiplying the grid-dependent emissions by an emissions factor derived from the input level of renewable energy ($\frac{Grid_{CO2}}{BaseGrid_{CO2}}$) and adding this value to the grid-independent emissions.

$$DynamicEmissions = \sum_{k} \left[\left((1 - PCat\%_k) \times PE_k \right) + (PE_k \times PCat\%_k) \times \frac{Grid_{CO2}}{BaseGrid_{CO2}} \right]$$

The emissions factor ($\frac{Grid_{CO2}}{BaseGrid_{CO2}}$) adjusts based on the emissions per kWh of CO2 at the input renewable energy percentage ($Grid_{CO2}$) compared to the emissions per kWh of CO2 from the baseline 2016 grid ($BaseGrid_{CO2}$). Thus, a 50 percent reduction in emissions per kWh of CO2 will result in a 50 percent reduction in grid-dependent emissions for said pollutant. The disaggregation of production emissions allows this model to produce a production-based CO2 value that responds to increases in renewable energy. These production-based emissions are then added to the operating emissions, producing the total lifecycle CO2 emissions for both electric vehicles and internal combustion engine vehicles.

Results and Discussion

The carbon dioxide emissions associated with an electric vehicle running on the 2016 grid (13.3 percent renewable energy) were 55 percent less than an internal combustion engine with an efficiency of 25.4 miles per gallon (Table 4). This advantage disappeared when the electric vehicle was compared to an internal combustion engine automobile operating at 80 miles per gallon. In this scenario, the internal combustion engine vehicle was actually responsible for 21 percent fewer carbon emissions than the electric vehicle (Table 4). There are currently no cars on the market with efficiencies close to 80 miles per gallon, but it is important to compare the electric vehicle to an idealized version of the internal combustion engine vehicle. A 100 percent renewable energy grid is also an idealized scenario, but a comparison between these "utopian examples" can inform policy that will guide us down the path to an ideal transportation model.

Table 4: Carbon Emissions Comparison Data for 2016 Grid (13.3% RE).

	25.4mpg	80mpg
ICE Total LCA CO2:	68.38	25.49
EV Total LCA CO2:	30.82	30.83
CO2 Difference:	37.56	-5.34
CO2 Percentage Difference:	55%	-21%

Source: Data from Cornell

An electric vehicle running off of 100 percent renewable energy produces far fewer greenhouse gas emissions than a vehicle based on the current grid: 6.30 tons of carbon dioxide compared to 30.82 tons of carbon dioxide. The move toward renewable energy has a dramatic impact on carbon emissions associated with an electric vehicle, as it reduces both the usage emissions and the production emissions. There is also an indirect link between the percentage of renewable energy and the carbon emission associated with an ICE vehicle, but the impact is nominal (Figure 1).

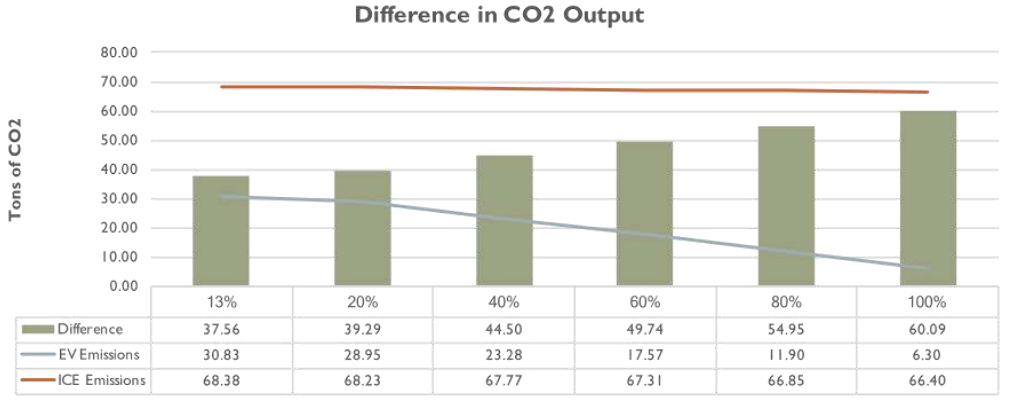

Figure 1: Difference in Carbon Dioxide Output by Renewable Energy (RE)%
Source: Data from Cornell

This is also substantially less than an internal combustion engine vehicle operating at 25.4 miles per gallon (68.38 tons of carbon dioxide) or a vehicle getting 80 miles per gallon (25.49 tons of carbon dioxide). The electric vehicle running on 100 percent renewable energy

impressively produces 73 percent fewer carbon dioxide emissions than an internal combustion engine automobile with an efficiency of 80 miles per gallon (Table 5).

Table 5: Carbon Emissions Comparison Data for 100% RE Grid

	25.4mpg	**80mpg**
ICE Total LCA CO2 (Tons):	66.40	23.51
EV Total LCA CO2 (Tons):	6.30	6.30
CO2 Difference:	60.10	17.21
CO2 Percentage Difference:	91%	73%

Source: Data from Cornell

While the 100 percent renewable energy scenario is purely academic, it is theoretically possible for a modern electric vehicle to be powered by rooftop photovoltaics (assuming the vehicle is charged during daylight hours). An electric vehicle powered from 100 percent photovoltaics will be responsible for 10.27 tons of carbon dioxide over its lifetime, which is 85 percent less than an internal combustion engine vehicle operating at 25.4 miles per gallon and 56 percent less than an internal combustion engine vehicle operating at 80 miles per gallon (Table 6).

Table 6: Carbon Emissions Comparison Data for the 100% PV-powered EV

	25.4 MPG	80 MPG
ICE Total LCA CO2:	68.38	23.51
EV Total LCA CO2:	10.27	10.27
CO2 Difference:	58.11	13.24
CO2 Percentage Difference:	85%	56%

Note: This scenario is based off of photovoltaic panels operating in the year 2016, and thus, the production emissions are from the 13.3% RE grid. This causes the carbon dioxide emissions to be higher than the 100% RE scenario.

Source: Data from Cornell

Battery Scenarios

Battery-related emissions account for a nontrivial percentage of electric vehicles production emissions. These emissions vary from study to study, and thus, it was important to run the model using battery emissions from a study that found battery-related emissions to be significantly higher than those output by GREET. The Kim et al. (2016) data is based on emissions per kWh of battery capacity, which facilitates an analysis of carbon dioxide emissions based on battery pack size (Figure 2).

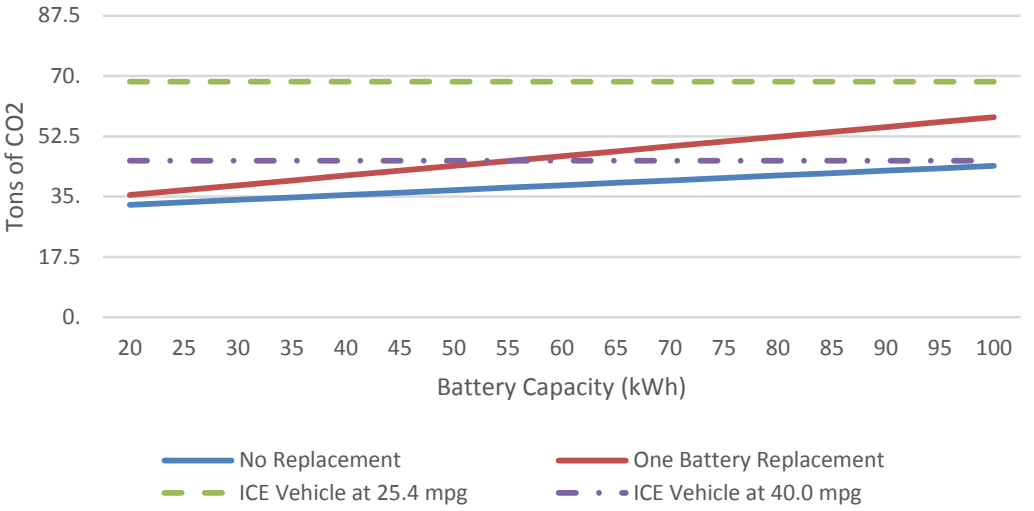

Figure 2: Carbon Dioxide Emissions per kWh of Battery Capacity (13.3% RE).
Source: Data from Cornell

Based on the 2016 grid (13.3% RE) and data from Kim et al. (2016), the carbon emissions for an EV (blue line) would remain less than ICE vehicles with efficiencies of 25.4 miles per gallon (orange dashed line) and 40 miles per gallon (grey dashed line). This changes if the battery needs to be replaced (orange line): the EV would be responsible for fewer carbon emissions than an ICE vehicle with an efficiency of 25.4 mpg, but the carbon emissions for an EV with a battery larger than 55 kWh would exceed those of an ICE with an efficiency of 40 miles per gallon (Figure 3).

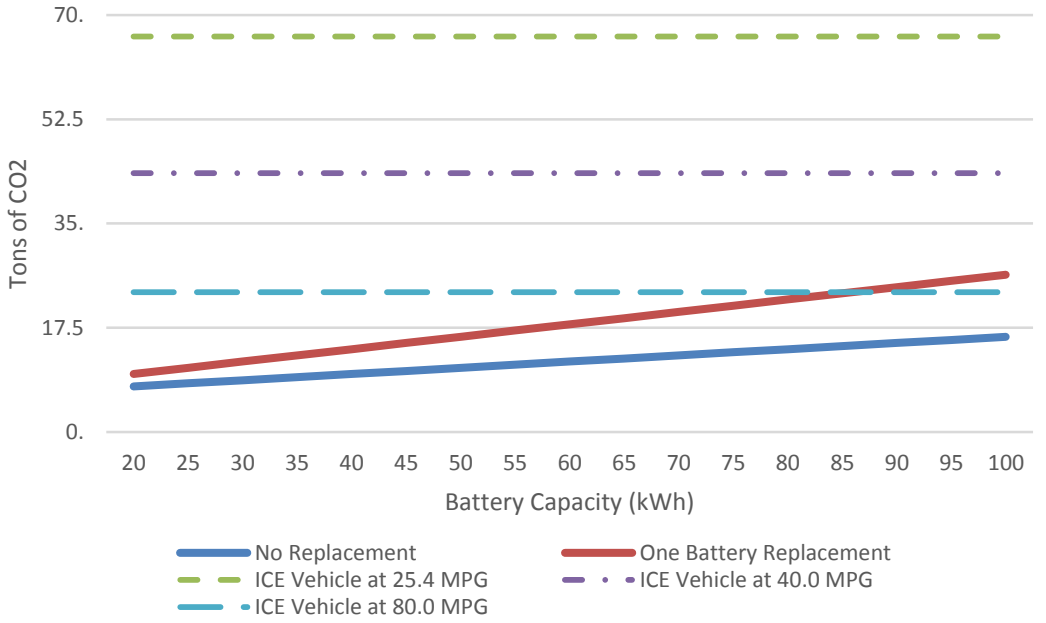

Figure 3: Carbon dioxide emissions per kWh or battery capacity (100% RE).
Source: Data from Cornell

Once again, the percentage of renewable energy plays a key role in the pollution assigned to an electric vehicle. Based on a 100 percent renewable energy scenario, the carbon dioxide emissions for an EV with a battery ranging from 20–100 kWh are significantly lower than the carbon emission from an ICE vehicle with an efficiency of 25.4 miles per gallon (grey dashed line in Figure 3) or 40 miles per gallon (orange dashed line). An EV needs to contain a battery pack of at least 85 kWh, and it needs to be replaced at least once, for it to produce more carbon emissions than an ICE with an efficiency of 80 miles per gallon. This clearly demonstrates the extreme efficiency of an EV paired with 100 percent renewable energy and highlights the symbiotic ways in which these technologies can be used to mitigate climate change.

Table 7: Battery Carbon Emissions

RE%	GREET CO2 (tons)	Kim et al. CO2 (tons)
13%	0.983	4.512
20%	0.963	4.422
50%	0.874	4.012
80%	0.785	3.603
100%	0.727	3.334

Note: This table compares battery-related carbon emissions from two datasets: GREET 2015 and Kim et al.
Source: Data from Cornell

The output variable of carbon emissions is impacted by the data sets that are entered into the model and the input variables that are manipulated (miles per gallon, percentage of renewable energy, EV efficiency). This results in a range of possible outcomes, but in all scenarios there is one constant that remains true: increased RE% leads to lower battery-based emissions. This relationship is displayed in Table 7, as the RE% has a profound impact on the carbon emissions associated with both battery scenarios. This model allows the grid-based emissions from battery production to float with the percentage of renewable energy. An increase in RE% leads to a decrease in battery-related carbon emissions, but the model does not reduce non-grid emissions. Non-grid emissions will most likely decrease as well; however, this was outside the scope of this study. It is thus noted that the impact that RE% has on production emissions is likely far greater than what is reported in Table 7.

Batteries and their environmental impact will likely remain the most controversial aspect of electric vehicles. The results of this study plainly demonstrate that the vast majority of RE% and MPG scenarios will result in lower carbon emissions for the EV. Only a combination of a data set that assigns higher emissions to battery packs (such as Kim et al. 2016), large battery packs, multiple battery replacements, and high ICE efficiency will lead to a scenario where an ICE is responsible for fewer carbon emissions.

Conclusion

A move from internal combustion engine vehicles to electric vehicles would lead to a nontrivial reduction in transportation-related CO2 emissions. This reduction in emissions would be amplified by a move toward a low-carbon grid. There are temporal and spatial characteristics that vary throughout the United States and these characteristics deserve additional research. But, the results of this study clearly indicate that there is a positive relationship between the percentage of renewable energy and the effectiveness of electric vehicles for reducing transportation-related carbon dioxide emissions.

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