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The Carbon Footprint of Electric Vehicles in the United States

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Abstract

Battery electric vehicles (BEVs) do not themselves emit greenhouse gases but they may, like other electricity-powered devices, result in the emission of carbon dioxide due to the burning of fossil fuels to generate the electricity they use. Determining the amount of carbon dioxide that results from charging an electric vehicle requires consideration of the power sources for electricity generation whose use is increased because the vehicle is being charged. Calculations based on these marginal power sources show that in the western United States carbon dioxide emissions caused by operating most, but not all, of the ten popular BEVs examined are lower than those caused by any hybrid vehicle (HEV). However, the amount of carbon dioxide attributable to driving a BEV in the East is similar to or higher than the amount emitted when driving a high-efficiency hybrid vehicle (HEV).

Keywords

Electric Vehicles, Hybrid Vehicles, Carbon Dioxide, Marginal Emissions, Marginal Power Source, United States, Coal, Natural Gas, Climate Change

1. Introduction

Holland et al., (2022) determined the contributions of natural gas and coal as marginal power sources in the generation of electricity in the contiguous United States overall, in the West (Montana, Wyoming, Colorado, New Mexico and states west of these), in Texas (which has to be done separately since most of Texas is on its own power grid), and in the East (the remaining states). Marginal power sources are the ones that an electric utility increases usage of when an additional load is placed on the system. Therefore, they are the appropriate power sources to consider when evaluating the immediate emission of CO_2 resulting from the use of electricity for any purpose, including the charging of a battery electric vehicle (BEV), when the alternative is not to use electricity (Graff Zivin et al., 2014; Onat et al., 2015; Koch & Böhlke, 2021; Holland et al., 2022; Burton et al., 2023).

Holland et al. (2022) conclude, as shown in **Table 1**, that in 2019 coal was the marginal power source for electricity generation significantly more in the East (41.4%) than it was in the West (19.7%) or in Texas (20.0%), and so CO_2 emissions per kWh of electricity were also higher in the East. Surprisingly, they found that the use of coal as a marginal power source for electricity has increased in recent years as its overall usage to generate electricity has declined.

The miles per US gallon (MPG) equivalents with respect to CO_2 emissions for ten popular BEV models (Kelley Blue Book, 2022) were calculated by using the data provided by Holland et al. (2022) for marginal CO_2 emissions per kWh of electricity generated and information from the US Department of Energy (2023a) on the electricity usage (kWh/100 miles) of the BEV models.

2. Methods

Calculation of the MPG-equivalents with respect to CO_2 for the BEVs was based on the report of the US Environmental Protection Agency (2023) that combustion of 1 gallon of gasoline releases 8887 grams of CO_2.

According to the US Department of Energy (2023a), a Tesla Model 3 RWD BEV uses 25 kWh per 100 miles driven. As shown in **Table 1**, overall generation of electricity in the total U.S. results in the emission of 591 grams of CO_2 per kWh.

Before reaching an end user, such as a battery charger, electricity generated by a power plant will be reduced by transmission losses. The US Energy Information Agency (2023) says that transmission and distribution losses of electricity average about 5%. So, the MPG equivalent with respect to CO_2 emissions for the Tesla Model 3 in the total United States is calculated to be:

$$(8887\ \text{g } CO_2/\text{gal}) \times 0.95/[(0.25\ \text{kWh/mi}) \times (591\ \text{g } CO_2/\text{kWh})] = 57.1\ \text{mi/gal}.$$

Similar calculations were done to generate all the results shown in **Figure 1** and **Table 2** using the CO_2 emissions data (g CO_2/kWh) from Holland et al. (2022) and the energy efficiency (kWh/100 miles) of the popular models (Kelley Blue Book, 2022) of BEVs reported for 2023 by the US Department of Energy

Table 1. Marginal power sources for electricity generation and grams of CO_2 per kWh emitted from those sources.[a]

	Natural Gas	Coal	Grams CO_2 per kWh
Total US	50.7%	35.6%	591
East	47.3%	41.4%	638
West	56.8%	19.7%	450
Texas	67.1%	20.0%	492

a. Data from Holland et al., (2022) Supplementary Tables S2 and S9.

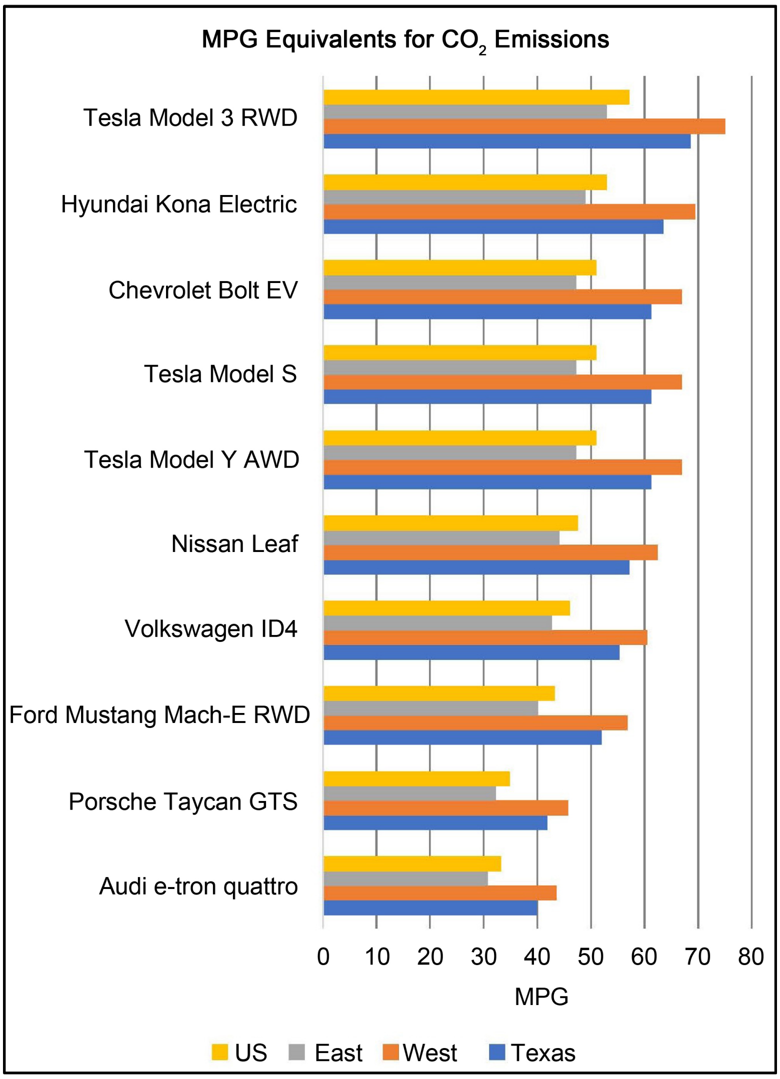

Figure 1. MPG equivalents for CO_2 emissions from BEVs. Operating the BEVs listed will result in emission of the amount of CO_2 produced by driving a gasoline-powered vehicle which gets the number of MPG shown.

(2023a):

25 kWh/100 miles, Tesla Model 3 RWD
27 kWh/100 miles, Hyundai Kona Electric
28 kWh/100 miles, Chevrolet Bolt EV
28 kWh/100 miles, Tesla Model S
28 kWh/100 miles, Tesla Model Y AWD
30 kWh/100 miles, Nissan Leaf
31 kWh/100 miles, Volkswagen ID.4
33 kWh/100 miles, Ford Mustang Mach-E RWD
41 kWh/100 miles, Porsche Taycan GTS
43 kWh/100 miles, Audi e-tron quattro

The results for each BEV model in the total U.S., the East, the West, and Texas based on the overall CO_2 emissions in 2019 from the electricity generated in each

Table 2. MPG (gasoline) equivalents for CO_2 emissions based on grams CO_2 per kWh of electricity data in Table 1. Operating the BEVs listed will result in emission of the amount of CO_2 produced by driving a gasoline-powered vehicle which gets the number of MPG shown in the table.

	MPG Equivalents for CO_2 Emissions			
	US	East	West	Texas
TeslaModel 3 RWD	57.1	52.9	75.0	68.6
HyundaiKona Electric	52.9	49.0	69.4	63.5
Chevrolet Bolt EV	51.0	47.2	66.9	61.3
Tesla Model S	51.0	47.2	66.9	61.3
Tesla Model Y AWD	51.0	47.2	66.9	61.3
Nissan Leaf	47.6	44.1	62.5	57.2
Volkswagen ID4	46.1	42.7	60.5	55.3
Ford Mustang Mach-E RWD	43.3	40.1	56.8	52.0
Porsche Taycan GTS	34.8	32.3	45.7	41.8
Audi e-tron quattro	33.2	30.8	43.6	39.9

area (Table 1) are shown in Figure 1 and Table 2.

Emissions of CO_2 from any BEV model in the West as compared to emissions in the East reflect the grams of CO_2 per kWh of electricity generated in each geographic area, as shown in Table 1:

$$\text{Emissions in West/Emissions in East} = 450/638 = 0.71.$$

Thus, operating a BEV in the West will result in 29% less CO_2 emissions than would the same vehicle in the East. Comparing Texas with the East shows a 23% reduction in emissions:

$$\text{Emissions in Texas/Emissions in East} = 492/638 = 0.77.$$

To compare emissions between the Tesla Model 3 RWD and the Toyota Prius in the West, gal/mi (GPM = 1/MPG) are compared, since CO_2 emissions will be proportional to GPM.

$$\text{Tesla GPM/Prius GPM} = 57/75.0 = 0.76.$$

Thus, operating a Tesla Model 3 in the West generates 24% less CO_2 than a Prius. A similar calculation for the Nisan Leaf shows that operating this BEV in the West results in 9% less CO_2 than a Prius:

$$\text{Nisan Leaf GPM/Prius GPM} = 57/62.5 = 0.91$$

These calculations and those presented in the Results and Discussion sections, below, consider only the emissions of greenhouse gases resulting from the operation of BEVs and HEVs. A more complete analysis would include the manufacture of the vehicles themselves and the production and distribution of natural gas, coal, and gasoline. These factors could add about 25% or more to the calculated CO_2 emissions from BEVs or HEVs, with the amounts depending on the assumptions made, especially the size of the battery in the BEV being considered. These considerations of complete vehicle life cycle analysis are discussed in the Addendum following the Discussion.

3. Results

The MPG (gasoline) equivalents for CO_2 emissions are shown in **Figure 1** and **Table 2** for different BEV models, based on the marginal CO_2 emissions per kWh generated in 2019 in the United States overall in the East, in the West, and in Texas.

For comparison, the MPG values for the most gasoline-efficient hybrid vehicles (HEVs) in 2023, as published by the US Department of Energy (2023b), are:

57 MPG, Toyota Prius
54 MPG, Hyundai Elantra Hybrid Blue
54 MPG, Toyota Prius AWD
53 MPG, Kia Niro FE
52 MPG, Toyota Prius XLE/LTD
52 MPG, Toyota Camry Hybrid LE
52 MPG, Hyundai Sonata Hybrid Blue
50 MPG, Toyota Corolla Hybrid
50 MPG, Hyundai Elantra Hybrid
49 MPG, Kia Niro
49 MPG, Toyota Prius AWD XLE/LTD

In the East, only one of the BEV models examined, the Tesla Model 3 RWD, has an MPG equivalent (52.9 MPG) higher than any of the eleven HEV models listed above. Thus, operating any of these HEVs has a carbon footprint equal to or smaller than nine of the ten BEVs. Four of the HEVs (Toyota Prius, Hyundai Elantra Hybrid Blue, Toyota Prius AWD, and Kia Niro FE) have smaller calculated carbon footprints than the Tesla Model 3 RWD.

In the West, most, but not all, of the BEVs have higher MPG-equivalent ratings, and thus smaller carbon footprints, than any HEV. As shown above in the Methods section, operating a Tesla Model 3 results in emission of 24% less CO_2 than a Toyota Prius, while for a Nissan Leaf it is 9% less than a Prius.

Two of the BEVs (the Porsche Tycan GTS and Audi e-tron quattro) have MPG equivalents in all three geographic regions of the United States less than the 49 MPG rating of the least efficient HEVs listed, and thus operating these two BEVs results in more CO_2 emissions than any of the eleven HEVs.

4. Discussion

Graff Zivin et al. (2014) reported that operating a BEV with efficiency between that of a Nissan Leaf and a Chevrolet Bolt generally resulted in lower CO_2 emissions than a Toyota Prius HEV in the West and in Texas. In their study, which was based on marginal emissions from electricity generation, the electricity network in the East was divided into six NERC (North American Reliability Corporation) regions. In most of these eastern regions, the BEV was responsible for approximately the same amount of, or more, CO_2 emissions as compared to the HEV Prius. In the MRO (Midwest Reliability Organization), representing the upper Midwest, the CO_2 emissions from charging a BEV generally exceeded not only those of a Prius HEV, but even those of a conventional gasoline-powered internal combustion vehicle (ICEV).

The results reported here confirm, update, and extend those of Graff Zivin et al. (2014). Based on more recent data on marginal CO_2 emissions as reported by Holland et al. (2022) and electricity consumption data on a variety of popular BEV models, the MPG equivalents of BEVs with respect to CO_2 emissions in the East are calculated to be roughly similar to or lower than the MPG ratings of the most fuel-efficient HEVs. Thus, in the eastern United States, the carbon footprints of BEVs are often not greatly different from, and in some cases are significantly greater than, those of the most gasoline-efficient HEVs sold today.

The CO_2 emissions caused by operating BEVs in the West are 29% lower than in the East, and in Texas they are 23% lower than in the East. This is primarily because coal is much less of a marginal power source for electricity generated in Texas and in the West, as shown in **Table 1**. Thus, in the West, most, but not all, of the BEVs analyzed have smaller carbon footprints than the most fuel-efficient HEVs.

The CO_2 emissions resulting from the use of BEVs are often calculated by averaging emissions caused by all the power sources used to generate electricity rather than focusing on the marginal emissions. Calculations using the marginal emissions yield the actual immediate emissions load. The averaging of emissions, which results in lower estimates of CO_2 released, is designed to take into account changing emissions in future years in which the vehicle will be used (Union of Concerned Scientists, 2015). But this averaging method would only be valid if the actual, marginal emissions were to decrease over time. Holland et al. (2022) found that marginal CO_2 emissions actually increased between 2010 and 2019 even as overall use of coal to generate electricity decreased. This implies not only that calculations using average emissions would have resulted in large underestimates of the carbon footprint of BEVs during this time, but that even using marginal emissions would have resulted in some underestimate. Thus, while no calculation method can accurately take into account the unpredictable future, the use of marginal emissions gives the most realistic results.

The results reported here reinforce the conclusion of Holland et al. (2022) that it is essential to eliminate the use of coal as a power source for electricity generation as quickly as possible. The findings also suggest that fuel-efficient HEVs could have substantially smaller carbon footprints than BEVs in parts of the world where coal is more likely to be the marginal power source for the production of electricity than it is in the western United States.

5. Addendum: Additions for Life Cycle Analysis of Emissions

The calculations presented above consider only the CO_2 emissions attributable to the actual operation of vehicles. Others have calculated CO_2 emissions resulting from the complete life cycles of vehicles, including the manufacture of the vehicles themselves and the production and distribution of natural gas, coal, and gasoline. For example, Onat et al. (2015) compared vehicle types and concluded that life cycle emissions of CO_2 were the lowest in every state of the United States for either HEVs or plug-in hybrid vehicles (PHEVs), and in no state for BEVs, when calculations were performed on what they term the "most realistic" basis, which is the marginal emissions from electricity generation. Burton et al. (2023), using marginal emissions from electricity generation in 2019 in the USA, concluded that there is no evidence that increasing usage of BEVs now will significantly reduce greenhouse gas emissions as compared to HEVs and that HEVs often emit less greenhouse gases than BEVs.

Miotti et al. (2016) evaluated many vehicles that were popular sellers in 2014 for their life cycle emissions in different parts of the United States. Using average emissions from electricity production in the West during the daytime of 477 g CO_2/kWh, they concluded that BEVs emissions were about 50% lower than ICEV emissions and about 25% lower than HEV emissions. However, using the 857 g CO_2/kWh average nighttime emissions in the upper Midwest area served by the Midwest Reliability Organization (MRO), they found that BEVs emitted only 25% less than ICEVs and that BEVs were no better than HEVs in terms of their CO_2 emissions.

The operation of a vehicle is the major source of CO_2 emissions over the life cycle of the vehicle. To calculate the emissions over the full life cycle of a gasoline-powered vehicle, the production and distribution of gasoline have to be considered. Miotti et al. (2016) concluded that the upstream greenhouse gas contribution for gasoline was 1857 g CO_2-equivalents per gallon while combustion of gasoline resulted in 8607 g/gal, so the upstream contribution adds 22% to the emissions from operating the vehicle. Burton et al. (2023) add 24% to the emissions from gasoline-powered vehicles to account for upstream production and transportation of the gasoline.

One adjustment that has to be made to the operating emissions attributed to BEVs is the mining, processing, and transportation of the coal and natural gas used to generate the electricity they use. Bauer et al. (2015) reported that in different regions of the world greenhouse gas emissions for natural gas power plants other than those directly from the power plant range from 10% to 30% of the total, with the global average being about 20%. Dones et al. (2004) found that within the European countries belonging to the Union for the Coordination of Transmission of Electricity (UCTE), the average greenhouse gas emissions other than those from the power plant itself for electricity generated by natural gas averaged about 17% of the total. Upstream greenhouse gases within the UCTE varied from 8% to 12.5% of the total released when electricity was generated by hard coal. Based on these findings, Burton et al. (2023) add 10% to greenhouse gas emissions for the production and transportation of coal and 15% for natural gas used to generate electricity for BEVs. Applying the corrections used by Burton et al. (2023) to the coal and natural gas contributions to electricity generation in the West (**Table 1**) results in a 10.5% addition to the CO_2 emissions resulting from operating BEVs.

The major difference between the greenhouse gas generation caused by the manufacture of BEVs and HEVs arises from the large amount of energy required to make the batteries for BEVs. Emilsson and Dahllöf (2019) conclude that lithium-ion battery manufacture generates 61 kg CO_2 per kWh capacity of the battery if the electricity used in the production processes generates no CO_2 and 106 kg CO_2 per kWh capacity of the battery if the electricity used in the production processes generates 1 kg CO_2 per kWh. This does not include an additional 15 kg CO_2 per kWh of battery capacity emitted from recycling of the batteries. If the marginal emissions in the western United States of 450 g/kWh of electricity, as shown in **Table 1**, are adjusted to account for a 5% loss in transmission and distribution of electricity, then the marginal emissions are 474 g/kWh consumed. The calculated emissions from battery manufacture would be 82.3 kg CO_2 per kWh battery capacity.

As an example, the 2003 Nissan Leaf comes with either a 40 kWh battery or a 60 kWh option (Nissan, 2023). Using the 82.3 kg CO_2 per kWh battery capacity figure, 3293 kg CO_2 would be emitted in the manufacture of the 40 kWh Nissan Leaf battery in the West. If the battery lasts for 150,000 miles of driving, this would correspond to 22.0 g CO_2 per mile for battery manufacture. The Nissan Leaf is rated at 30 kWh/100 miles which, in the West, with emissions of 474 g/kWh when a 5% loss for transmission and distribution of electricity is factored in, corresponds to 142 g CO_2 per mile for operating the vehicle. So, battery production is estimated to add 22.0/142 = 15.4% to the CO_2 emissions attributable to the Nissan Leaf.

This, when added to a 10.5% correction for coal and natural gas production and transport would bring the total addition to operating emissions for BEVs to 25.9%. This does not include emissions resulting from disposal of batteries, as mentioned above, or the emissions from operating electric power plants which, according to Graff Zivin et al. (2014), consume 4.59% of the energy they generate. This 25.9% addition for BEVs can be compared to the 24% addition applied to gasoline-powered vehicles, including HEVs, for production and distribution of gasoline, as discussed above.

Calculations based on the 60 kWh Nissan Leaf battery option rather than the 40 kWh one would increase the CO_2 from BEV battery manufacture by half. If the BEV battery is made in the eastern United States or in any other place where coal is more likely to be the marginal power source for electricity production than it is in the western United States, then the carbon footprint of battery manufacture would be larger than what is calculated above.

So, in the end, additions to estimated CO_2 emissions from BEVs for the manufacture of vehicles and for the production and distribution of coal and natural gas will vary significantly depending on the size of the BEV's battery and assumptions made in the calculations. These additions for emissions attributable to BEVs, as calculated above, are similar to the additions needed for CO_2 emissions from HEVs for the production and transportation of gasoline. However, there are so many uncertainties in the numbers that underlie these calculations that it's difficult to come to any firm general conclusion about this.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

Bauer, C., Treyer, K., Heck, T., & Hirschberg, S. (2015). *Greenhouse Gas Emissions from Energy Systems, Comparison, and Overview. Reference Module in Earth Systems and Environmental Sciences*. Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.09276-9

Burton, T., Powers, S., Burns, C., Conway, G., Leach, F., & Senecal, K. (2023). A Data-Driven Greenhouse Gas Emission Rate Analysis for Vehicle Comparisons. *SAE International Journal of Electrified Vehicles, 12,* 91-127. https://doi.org/10.4271/14-12-01-0006

Dones, R., Heck, T., & Hirschberg, S. (2004). Greenhouse Gas Emissions from Energy Systems: Comparison and Overview. In C. J. Cleveland (Ed.), *Encyclopedia of Energy* (Vol. 3, pp. 77-95). Elsevier. https://doi.org/10.1016/B0-12-176480-X/00397-1

Emilsson, E., & Dahllöf, L. (2019). *Lithium-Ion Vehicle Battery Production.* IVL Swedish Environmental Research Institute. https://www.ivl.se/download/18.694ca0617a1de98f473464/1628416191286/FULLTEXT01.pdf

Graff Zivin, J. S., Kotchen, M. J., & Mansur, E. T. (2014). Spatial and Temporal Heterogeneity of Marginal Emissions: Implications for Electric Cars and Other Electricity-Shifting Policies. *Journal of Economic Behavior and Organization, 107,* 248-268. https://doi.org/10.1016/j.jebo.2014.03.010

Holland, S. P., Kotchen, M. J., Mansur, E. T., & Yates, A. J. (2022). Why Marginal CO_2 Emissions Are Not Decreasing for US Electricity: Estimates and Implications for Climate Policy. *Proceedings of the National Academy of Sciences of the United States of America, 119,* e2116632119. https://doi.org/10.1073/pnas.2116632119

Kelley Blue Book (2022). *10 Most Popular Electric Cars.* https://www.kbb.com/best-cars/most-popular-electric-cars

Koch, T., & Böhlke, T. (2021). The Averaging Bias—A Standard Miscalculation, Which Extensively Underestimates Real CO_2 Emissions. *ZAMM Journal of Applied Mathematics and Mechanics, 101,* e202100205. https://doi.org/10.1002/zamm.202100205

Miotti, M., Supran, G. J., Kim, E. J., & Trancik, J. E. (2016). Personal Vehicles Evaluated against Climate Change Mitigation Targets. *Environmental Science and Technology, 50,* 10795-10804. https://doi.org/10.1021/acs.est.6b00177

Nissan (2023). *Refreshed 2023 Nissan LEAF, Electrifying LEAF*. https://www.nissanusa.com/vehicles/electric-cars/leaf.html

Onat, N., Kuckukvar, M., &Tatari, O. (2015). Conventional, Hybrid, Plug-In Hybrid or Electric Vehicles? State-Based Comparative Carbon and Energy Footprint Analysis in the United States. *Applied Energy, 150,* 36-49. https://doi.org/10.1016/j.apenergy.2015.04.001

Union of Concerned Scientists (2015). Average vs. Marginal Electricity Global Warming Emissions. In R. Nealer, D. Reichmuth, & D. Anair (Eds.), *Cleaner Cars from Cradle to Grave* (pp. 42-43). Union of Concerned Scientists. https://www.ucsusa.org/sites/default/files/attach/2015/11/Cleaner-Cars-from-Cradle-to-Grave-full-report.pdf

US Department of Energy (2023a). *Electric Vehicles*. https://www.fueleconomy.gov/feg/findacar.shtml

US Department of Energy (2023b). *2023 Hybrid Vehicles*. https://www.fueleconomy.gov/feg/PowerSearch.do?action=noform&year=2023&vtype=Hybrid&srchtyp=yearAfv&pageno=1&sortBy=Comb&tabView=0&rowLimit=10

US Energy Information Agency (2023). *How Much Electricity Is Lost in Electricity Transmission and Distribution in the United States*? https://www.eia.gov/tools/faqs/faq.php?id=105&t=3

US Environmental Protection Agency (2023). *Greenhouse Gases Equivalencies Calculator—Calculations and References*. Gallons of Gasoline Consumed. https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references