Driving Cleaner

Electric Cars and Pickups Beat Gasoline on Lifetime Global Warming Emissions

Union of Concerned Scientists

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EXECUTIVE SUMMARY

To reduce both climate-changing emissions and exposure to air pollution, the United States must greatly reduce tailpipe emissions from cars and trucks. This makes the transition to electric vehicles (EVs) vital to meeting targets for both climate and public health. Using fully electric vehicles in place of conventional gasoline- and diesel-powered vehicles enables the complete elimination of tailpipe emissions.

While electric vehicles can eliminate tailpipe emissions, the *total* emissions from their use include emissions from two other sources: the electricity used to recharge EVs and the processes and materials used to manufacture them. Thus, the value of switching from gasoline and diesel cars and trucks to EVs will increase further as the electricity grid and manufacturing become cleaner.

Global Warming Emissions from Driving Electric Vehicles

To assess the total global warming emissions from charging electric vehicles, the Union of Concerned Scientists (UCS) addresses *all* contributions from electricity production. These include:

- Emissions that result from raw-material extraction, such as coal mining and natural gas drilling;
- Emissions from delivering these fuels to power plants;
- Emissions from burning those fuels in power plants to generate electricity;
- Electricity losses that occur during distribution from power plants to the point where the electric vehicle is plugged in; and
- The efficiency of the vehicle in recharging and using electricity.

Similarly, our assessment of the global warming emissions from comparable gasoline and diesel vehicles addresses emissions that result from:

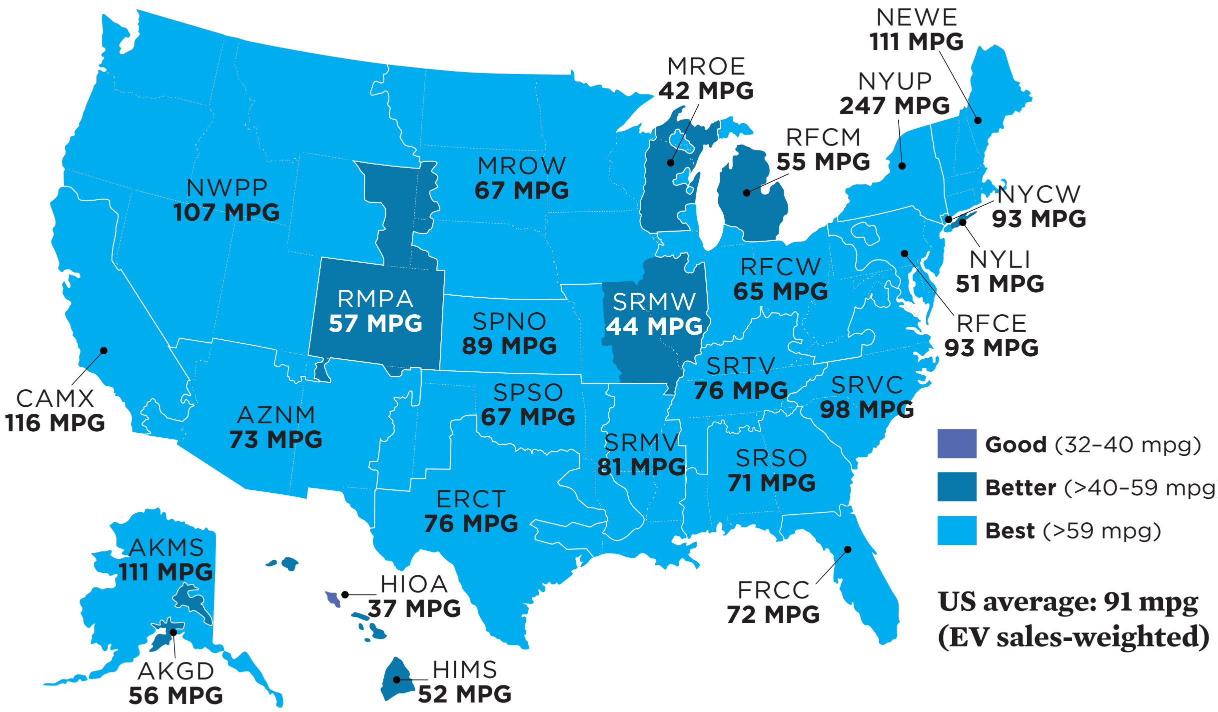
- Oil extraction at the well;
- Transporting crude oil to refineries;
- Refining oil into gasoline;
- Delivering fuel to gas stations; and
- Combusting fuel in the vehicle's engine.

Because of differences in electricity generation across the United States, the emissions produced from driving the average EV vary depending on where the vehicle is driven (Figure ES-1, p. 2). Considering the location of EV sales to date, the UCS assessment finds that:

- Everywhere in the United States, driving the *average* EV results in lower emissions than the *average* new gasoline vehicle.
- Over 90 percent of people in the United States live in regions where driving the *average* EV produces lower emissions than the *most efficient* gasoline vehicle on the market today (59 miles per gallon).
- Driving the average EV in the United States produces global warming emissions equivalent to those emitted by a gasoline car getting 91 miles per gallon.
- Driving the *most efficient* EV produces lower emissions than the *most efficient* gasoline car where 97 percent of the population lives—in other words, virtually everywhere in the United States.
- Everywhere in the United States, the emissions from driving an EV pickup truck are lower than those for the average new gasoline or diesel pickup truck.

While driving the average EV yields significant emissions savings, the more efficient the EV, the greater the benefits of switching from gasoline to electricity. For example, the emissions from driving a 2021 Tesla Model 3 Standard Range Plus in California equal those of a gasoline car getting 152 miles per gallon. The Tesla's global warming emissions are a fifth of those of the average new gasoline car and over 60 percent less than even the most efficient gasoline car on the market.

FIGURE ES-1. Driving Emissions: The Miles per Gallon Equivalent of the Average EV



The average EV is considerably cleaner to drive than the average new gasoline vehicle—and in some areas, much cleaner. For example, in upstate New York (NYUP), the emissions of the average EV compare with those of a gasoline-powered vehicle achieving 247 miles per gallon. Based on where EVs have been sold in the United States, driving on electricity produces emissions equal to those of a gasoline car getting 91 miles per gallon.

Note: Acronyms refer to electricity grid regions as defined by eGRID (EPA 2022a).

Global Warming Emissions from Manufacturing Electric Vehicles

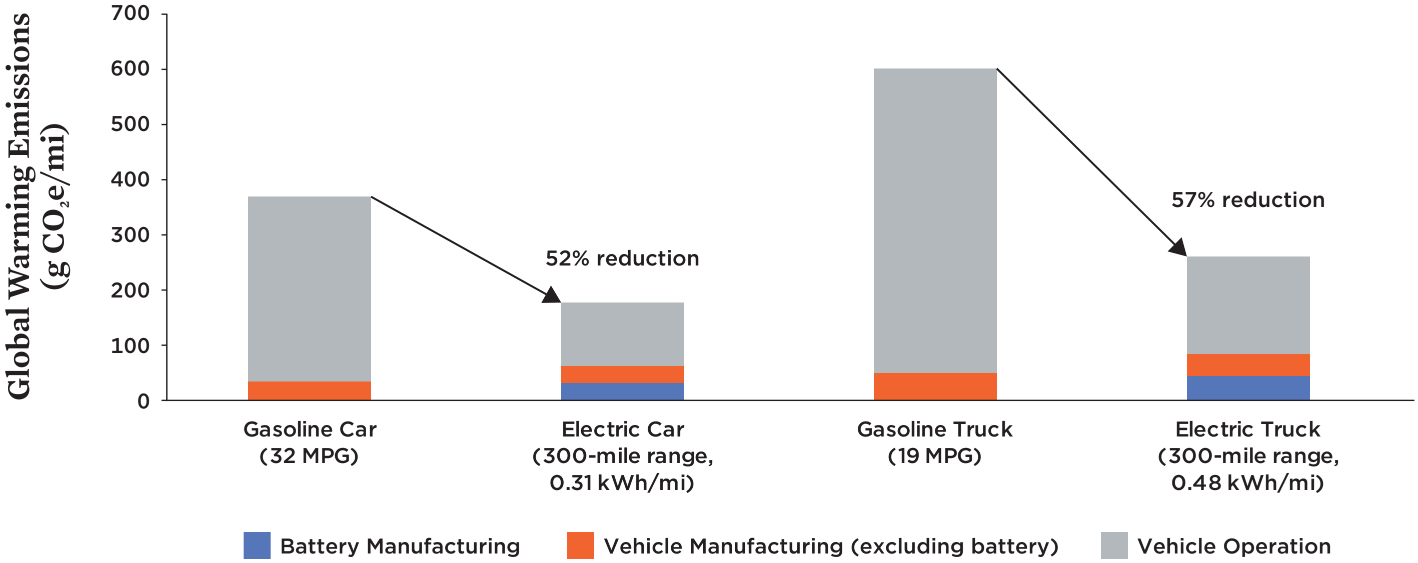
Manufacturing an EV results in more global warming emissions than manufacturing a comparable gasoline vehicle. This is chiefly due to the energy and materials required to produce an EV's battery. However, most of the global warming emissions over the lifespan of a vehicle occur during its use, so the reductions from driving an EV more than offset the higher manufacturing emissions. When comparing the average gasoline sedan (32 mpg) to the average-efficiency EV with a 300-mile-range battery, the EV reduces total lifetime emissions 52 percent. An EV pickup truck reduces lifetime emissions 57 percent compared with the average gasoline pickup (Figure ES-2).

Another way to understand how emissions savings from driving an EV offset additional manufacturing emissions is to consider the breakeven point: how far (or how long) an EV needs to drive for the savings to match the initial emissions "debt." This breakeven point varies depending on regional electricity emissions. Based on where the US population lives, the mean breakeven point for an electric car with a 300-mile range compared with the average new gasoline sedan is 21,300 miles of driving, or 22 months based on average annual driving. Breakeven occurs more quickly, after about 17,500 miles (17 months), when comparing an electric truck (300-mile range) with the average new gasoline pickup truck.

Both EV cars and trucks are much cleaner than their gasoline counterparts, but electric trucks are responsible for more global warming emissions than electric cars simply because

[Most of the global warming emissions over the lifespan of a vehicle occur during its use, so the reductions from driving an EV more than offset the higher emissions from manufacturing.]

FIGURE ES-2. Life Cycle Global Warming Emissions, EVs vs. Gasoline Cars and Trucks



Life cycle global warming emissions are significantly lower for EVs than for gasoline cars or trucks when considering manufacturing and usage, despite higher battery-manufacturing emissions for the EV.

Note: Emissions are measured in grams of carbon dioxide–equivalent per mile, averaged over the life of the vehicle.

trucks are larger and heavier. Choosing the most efficient EV that meets mobility needs will minimize overall pollution. If a sedan meets a driver's needs, that would be a better choice for the environment than a full-size SUV or a pickup.

The impacts of manufacturing EVs, including their batteries, extend beyond global warming emissions. Manufacturing processes and the sourcing of battery and other materials also affect water and air quality. Also, processes and sourcing can raise concerns over human rights and the ethical issues involved in mining and refining raw materials. This makes it essential to reduce the amount of raw materials needed to make EVs. In particular, reuse, remanufacturing, and recovery of materials from used batteries will help reduce these impacts.

Recommendations

To maximize emissions reductions and minimize negative manufacturing impacts, UCS recommends accelerating the transition to lower-emissions transportation through cleaner sources of electricity, improved vehicle manufacturing, and more efficient vehicles.

- Policymakers at all levels of government should adopt and strengthen policies and programs for increasing energy efficiency and deploying renewable energy. Reducing the emissions from generating electricity can reduce the emissions from driving and manufacturing EVs. Policy options include establishing renewable electricity standards, energy-efficiency resource standards, and incentives or mandates to improve grid operation, transmission, and resource planning.
- Governments and the private sector should invest more in research on both decreasing the global warming emissions associated with making EV batteries and improving the processes for recycling or reusing batteries.
- Policies should promote material circularity, in which materials reenter the supply chain when their use in the original product ends. Circularity includes encouraging materials recovery when a battery reaches the end of its life and using recovered materials in manufacturing. Offsetting the use of virgin materials can decrease the environmental and social impacts associated with mining.
- EV manufacturers should be responsible for sourcing materials ethically and sustainably throughout all steps in the supply chain. This means that their emissions and material sourcing must be transparent to the public and regulators.
- Public policies should ensure that manufacturers produce energy-efficient EVs. Policies also should encourage vehicle buyers to purchase the most efficient EVs that meet their mobility needs. The more efficient an EV, the smaller battery it needs to achieve a desired range capability, thereby reducing emissions from both driving and manufacturing.

- Policies, including funding, should support transportation options—including transit, shared mobility, and walking and biking infrastructure—that decrease the need for individual car ownership and limit the overall emissions from vehicle manufacturing and use.
- Vehicle incentives and infrastructure deployment should enable drivers across incomes and geographies to access EVs. To maximize the benefits of EVs, all drivers should be able to switch from gasoline and diesel vehicles.

Switching from conventional vehicles to electric vehicles reduces carbon emissions and smog-forming air pollution. To maximize these reductions, we must accelerate the adoption of EVs and transition to renewable electricity as quickly as possible. These dual transitions are a necessary part of putting the United States on a trajectory toward net-zero climate emissions by midcentury.

To maximize reductions in carbon emissions and smog-forming pollution, we must accelerate the adoption of EVs and transition to renewable electricity as quickly as possible.

[CHAPTER 1

Introduction

To reduce both climate-changing emissions[1] and exposure to air pollution, we must greatly reduce tailpipe emissions from cars and trucks. Using fully electric vehicles (also known as battery-electric vehicles, or BEVs) in place of conventional gasoline- and diesel-powered vehicles would completely eliminate tailpipe emissions from using cars and trucks. For this reason, the transition to BEVs is vital to meeting both public health and climate targets.

However, the total emissions from using an EV depend not only on tailpipe emissions but also on the source of the electricity used to recharge the vehicle and on the processes for manufacturing it. Thus, the value of switching from conventional gasoline and diesel cars and trucks to EVs will be even greater as the electricity grid and manufacturing become cleaner. This makes the transition to EVs even more central to any plan to achieve deep emissions reductions and avoid the worst impacts of climate change (Baek et al. 2021).

UCS first investigated the life cycle emissions of EVs a decade ago. Since then, the net benefit of driving an EV instead of a gasoline-powered vehicle has grown significantly. *State of Charge,* our 2012 examination, found that in every region driving the average new BEV produced lower global warming emissions than driving the average new gasoline car (Anair and Mahmassani 2012). However, at that time, only 46 percent of people lived where driving an electric vehicle had emissions lower than those of a 50 mpg gasoline car, the Toyota Prius hybrid, then the most fuel-efficient such car in the US market. In 2015, *Cleaner Cars from Cradle to Grave* updated the estimates: about two-thirds of the US population lived in areas where driving an electric car produced lower emissions than a 50 mpg gasoline car (Nealer, Reichmuth, and Anair 2015).

Since then, EV-related emissions have declined in many parts of the country, primarily because of changes to electricity generation. The nation's electricity generation has gotten cleaner: coal-fired generation has declined significantly, while electricity generation from wind and solar energy has increased. In the current UCS analysis, over 90 percent of the US population lives where driving the average all-electric car has emissions lower than the most efficient gasoline vehicle now on the market, the Hyundai Ioniq Blue, a hybrid rated at 59 miles per gallon.

However, we must also consider the global warming emissions from a vehicle's overall life cycle, taking into account production, operation, and end-of-life emissions. The manufacture of EV batteries is of particular concern, and emissions also can be associated with battery disposal, recycling, and remanufacturing.

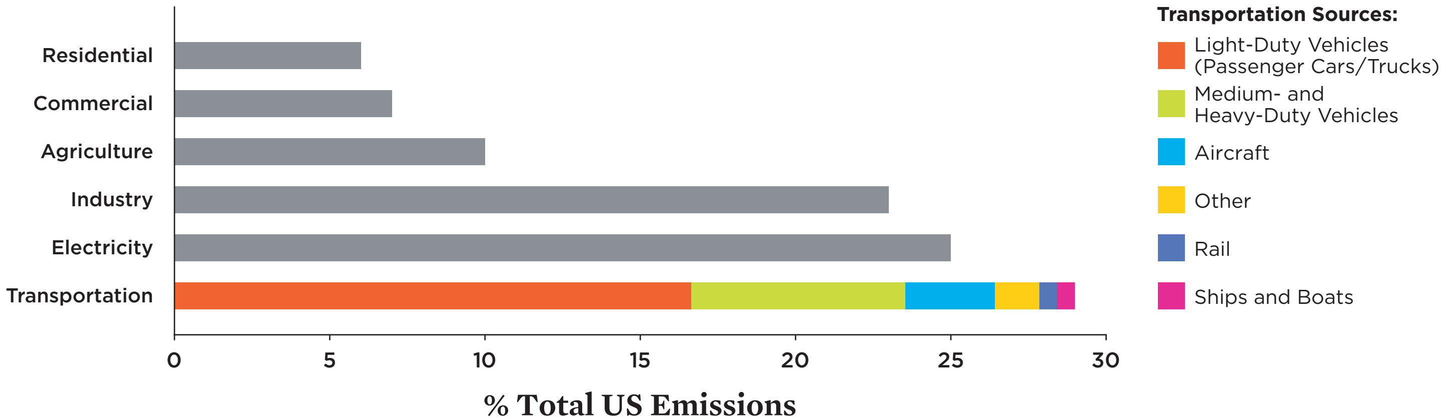
Like our 2015 report, this report compares battery-electric cars and trucks with gasoline cars and trucks by examining the global warming emissions from driving *and* manufacturing the vehicles and over their life cycles. Toward that end, *Driving Cleaner,* this up-to-date assessment of the carbon footprints of BEVs, takes into account the latest information about electricity generation and manufacturing processes.

Driving Cleaner addresses two key questions:

- **What are the global warming emissions from operating a fully electric vehicle on today's electricity grid?** Using the most recent electricity emissions data from the US Environmental Protection Agency (EPA), we estimated the miles-per-gallon rating a gasoline-powered vehicle would need in order to equal the emissions of a comparable EV charged on regional electricity grids.
- **What is the effect of manufacturing a BEV on its total global warming emissions?** Using Argonne National Laboratory's latest model of vehicle manufacturing emissions, we analyzed the global warming emissions of vehicle and battery manufacturing, focusing on long-range battery-electric cars and pickup trucks. We compared these with the emissions from manufacturing and using comparable gasoline vehicles.

In addition, *Driving Cleaner* looks briefly at the next stage: the environmental and global warming emissions consequences of what may be done with the EV battery after it has finished its useful life.

FIGURE 1. US Global Warming Emissions by Sector, 2019



Transportation is the largest source of human-caused global warming emissions in the United States. Passenger cars and trucks (light-duty vehicles) are responsible for over half of the global warming emissions within the transportation sector.

SOURCE: EPA 2021A.

It is important to note our focus on the benefits of vehicle electrification regarding global warming emissions from transportation. There are other potential benefits from the manufacture and use of electric vehicles in place of gasoline vehicles. For example, EVs have the potential to significantly reduce air pollution from passenger cars and trucks (CARB 2022), and they can reduce the need for oil extraction and refining. The sourcing of battery materials and EV manufacturing can affect water and air quality, as well as raise concerns over human rights and the ethical sourcing of materials.

Importance of Reducing Transportation Emissions

Transportation is the sector of the US economy producing the most global warming emissions, responsible for over one-quarter of total emissions arising from the activities of humans (Figure 1). Within transportation, light-duty vehicles (passenger cars, SUVs, and pickup trucks) are responsible for most climate-changing emissions. While it is important to reduce emissions from all sectors and sources as much and as quickly as possible, addressing the harmful emissions associated with passenger vehicles presents an immediate opportunity to reduce emissions significantly. Also, while some parts of the transportation sector, such as ocean-going vessels, may present a greater challenge as we seek to reduce air and climate pollution, electrification is a proven technology for curbing harmful emissions from cars and trucks.

Electrification Can Significantly Reduce Global Warming Emissions

Due to several factors, switching from gasoline- or diesel-powered engines to electric motors significantly reduces total global warming emissions:

- While gasoline and diesel fuels are derived mainly from a fossil fuel (crude oil), electricity can be generated from low- and zero-carbon resources like hydroelectricity, wind, and solar power.
- Electric-drive vehicles are more efficient than those powered by internal combustion engines.
- Electric vehicles lose no energy from idling, and there is no significant waste heat.
- The regenerative braking systems in EVs recapture the energy that conventional vehicles lose to friction when braking.

[CHAPTER 2

EV Savings Compared with a Gasoline Vehicle

In comparing the global warming emissions of BEVs with those of gasoline vehicles, UCS takes a "well-to-wheels" approach that accounts for the complete fuel cycle for both types of vehicle.

While BEVs have no tailpipe emissions, determining the net emissions benefit requires considering the total emissions from all steps in refueling both BEVs and conventional gasoline vehicles. To quantify this benefit, our well-to-wheels analysis considers not only tailpipe emissions but also the emissions from the steps required to produce gasoline and electricity, starting with primary energy sources like crude oil, coal, and natural gas.

To assess the global warming emissions from charging EVs, we include all contributions from electricity production:

- Emissions that result from raw-material extraction, such as coal mining and natural gas drilling;
- Emissions from delivering these fuels to power plants;
- Emissions from burning those fuels in power plants to generate electricity;
- Electricity losses that occur during distribution from power plants to the point where the electric vehicle is plugged in; and
- The efficiency of vehicles in recharging and using electricity.

To assess the global warming emissions from comparable gasoline vehicles, we address emissions that result from:

- Oil extraction at the well;
- Transporting crude oil to refineries;
- Refining oil into gasoline;
- Delivering fuel to gas stations; and
- Combusting fuel in the vehicle's engine.

See Appendix A for a discussion of the methodology.

Standardizing the Units of Comparison

The concept of miles per gallon (mpg), the number of miles a car travels on one gallon of gasoline, is familiar. The higher a vehicle's mpg (the higher its efficiency), the less fuel it burns and the lower its level of global warming emissions. To compare the emissions of an EV easily with those of a gasoline vehicle, we use an equivalency measure, calculating how many miles per gallon a gasoline-powered vehicle would need to achieve in order to match the global warming emissions of an EV.

The first step in this process is calculating the global warming emissions that result from generating the electricity needed to charge an EV. Then we convert this estimate into a gasoline miles-per-gallon equivalent—an MPG_{ghg}, where ghg stands for greenhouse gas (i.e., global warming) emissions. If an EV has an MPG_{ghg} value equal to the miles per gallon of a gasoline-powered vehicle, both vehicles would produce the same amount of global warming pollution for each mile traveled. If the MPG_{ghg} of an EV is twice that of a gasoline vehicle mpg, the emissions from driving the EV would be half those produced from driving the gasoline vehicle.

When estimating emissions from charging an EV in a particular region of the United States, we use *average emissions:* these are emissions averaged over the full mix of the region's electricity sources. An alternative approach would be to consider only *marginal emissions:* emissions from the power plants that operate to meet new electricity demand on the grid. Our analysis uses average generation because it can be calculated from historical generation data without making assumptions about such factors as charging behavior (e.g., time of day) or the response of electricity generation units to an increase in demand.

It is important to consider that these results are from utility-scale electricity generation. They do not reflect generation from rooftop solar or other types of residential generation. In addition, individual utilities and customers within a region may have access to electricity with emissions that differ from the regional average.

Appendix B discusses the issue of average and marginal emissions further.

Rating the Regions

To further help consumers evaluate the global warming benefits of driving an EV in different parts of the United States, we rate areas as Good, Better, or Best to characterize the emissions benefit of switching from gasoline to electricity (Table 1).

- **Good:** EVs are equal to or better than the *average* conventional gasoline sedan (32 to 40 MPG_{ghg}). That is, driving an average-efficiency EV in these regions results in global warming emissions equivalent to gasoline vehicles with a combined city/highway fuel economy rating of 32 to 40 mpg. This level is better than that of the average new gasoline sedan (32 mpg) on the market today (EPA 2021b).
- **Better:** These regions correspond to the *most efficient* gasoline-only (non-plug-in) hybrids (>40 to 59 MPG_{ghg}). The most efficient gasoline hybrid currently available in the United States is the Hyundai Ioniq Blue, rated at 59 mpg.
- **Best:** Driving a typical EV in these regions is equivalent to gasoline-powered vehicles with a combined city/highway fuel economy of more than 59 mpg. In these regions, driving the *average-efficiency* EV produces lower emissions than the *most efficient* gasoline-only hybrid car.

The Average EV: Cleaner Than the Average Gasoline Vehicle

Because of differences in electricity generation, the emissions produced while driving the average EV in the United States vary depending on where the driving takes place (Figure 2a, p. 9).[2] Everywhere in the country, driving the average EV results in lower emissions than the average new gasoline vehicle. Over 90 percent of the people in the country live in places where driving the average EV has a higher MPG_{ghg}, and thus produces lower emissions, than the most efficient gasoline vehicle (59 mpg).

In some parts of the country, driving the average new EV will produce a little as one-eighth to one-quarter of the emissions from the average new gasoline car. For example, the average EV driven in upstate New York has emissions equal to a (hypothetical) 247 mpg gasoline car. In California, a gasoline car would need to get 116 miles per gallon to have emissions levels as good as those of the average EV. Based on where EVs have been sold in the United States, driving on electricity on average produces emissions equal to a 91 mpg gasoline car.[3]

TABLE 1. EV Global Warming Emissions Scale

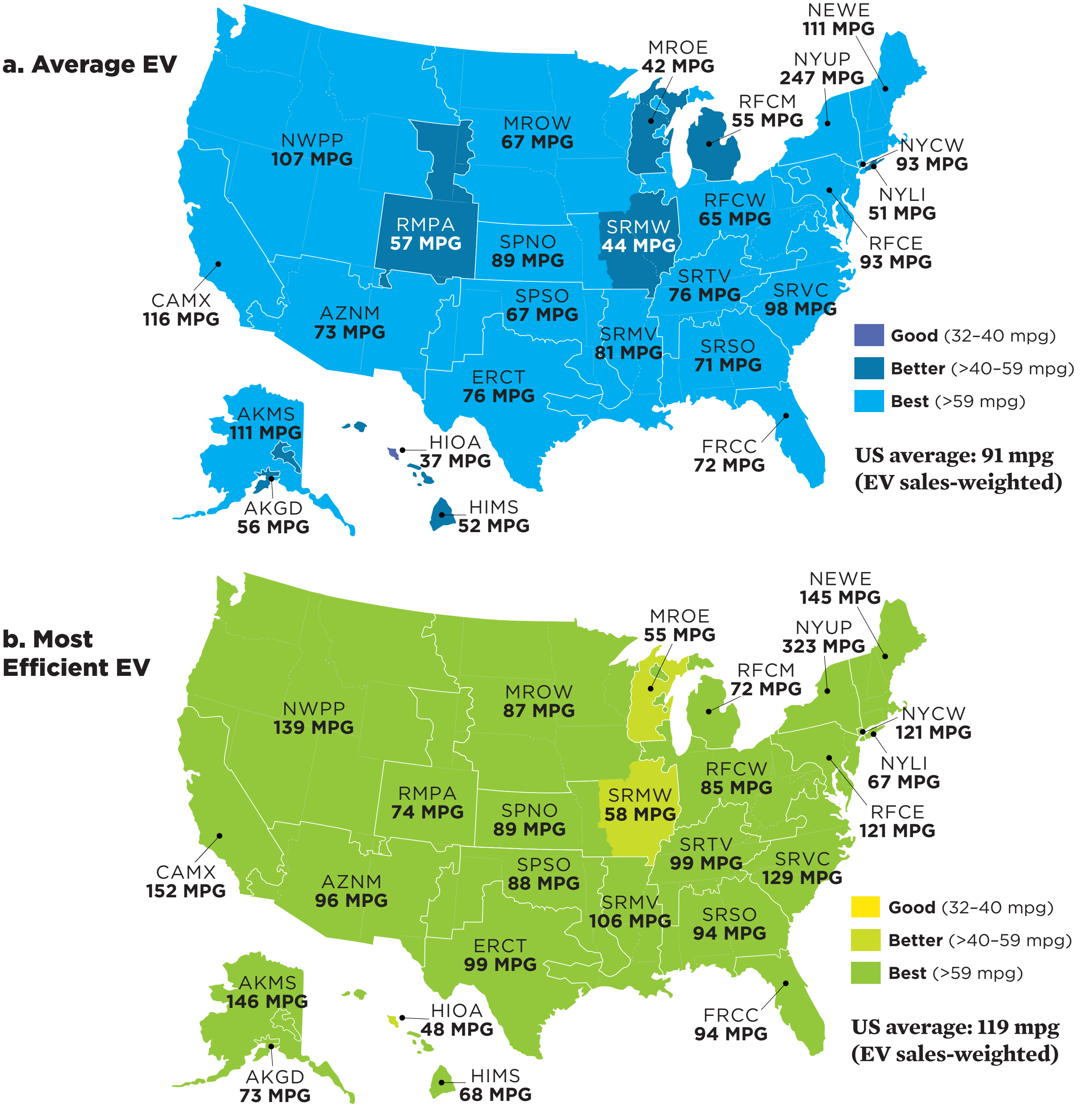
	EV Driving Global Warming Pollution Equivalent (MPG_{ghg})		The Meaning for Global Warming Emissions
	car	truck	
Good	32–40	19–26	EVs are comparable to an above-average-efficiency gasoline model.
Better	>40–59	>26–37	EVs are comparable to the most efficient gasoline hybrid models available.
Best	>59	>37	EVs outperform the most efficient gasoline hybrid model available.

To Maximize Emissions Reductions, Choose a More Efficient EV

Driving the average EV yields significant emissions reductions from switching fuels; using the most efficient EV maximizes those emissions reductions. Driving the most efficient EV means lower emissions than the most efficient gasoline car for virtually everyone in the United States, with 97 percent of the population living in these areas (Figure 2b, p. 9). For example, driving the 2021 Tesla Model 3 Standard Range Plus, which consumes 0.24 kilowatt-hour (kWh) of electricity per mile, in California has emissions equal to a 152 mpg gasoline car. In other words, that Tesla produces one-fifth of the global warming emissions of the average new gasoline car and over 60 percent less than even the most efficient gasoline car. In upstate New York, the emissions from driving an EV can be as low as one-tenth those of an average new gasoline car. Based on where EVs have been sold over the last six years, the most efficient EV would have global warming emissions equivalent to driving a 119 mpg gasoline car.

[***Based on where EVs have been sold in the United States, driving on electricity on average produces emissions equal to a gasoline car getting 91 miles per gallon.***]

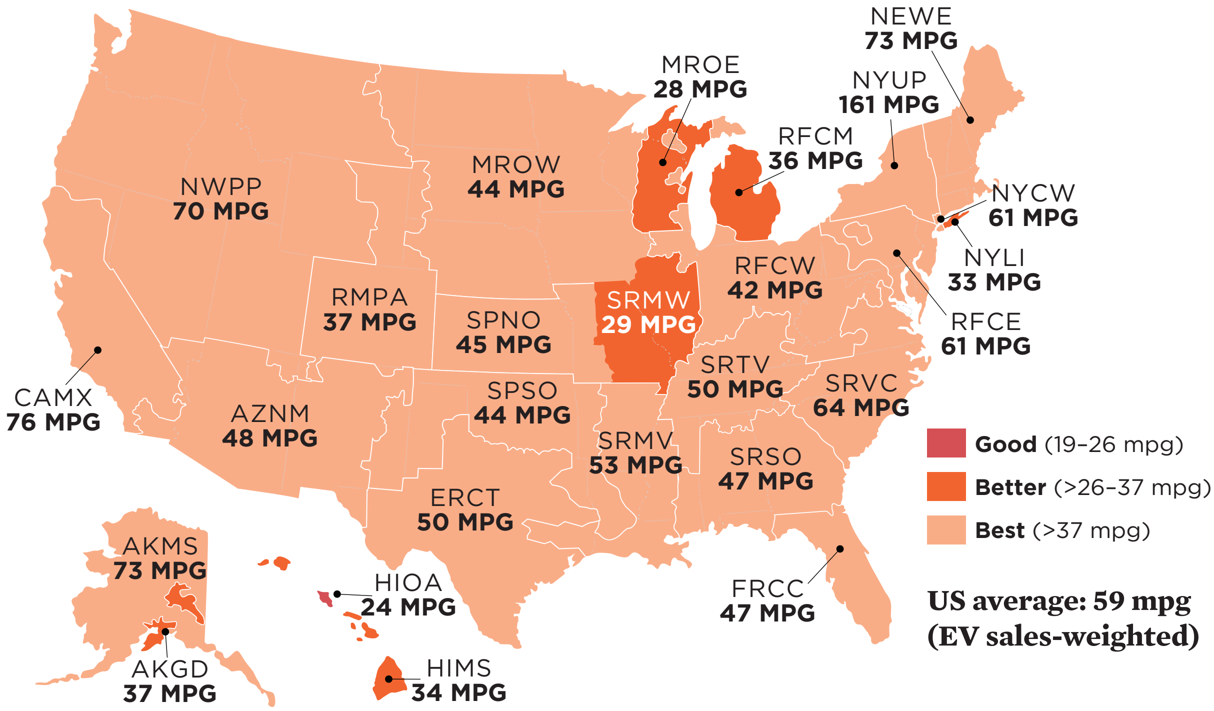
FIGURE 2. Comparing Emissions: Driving an EV as a Gasoline MPG Equivalent, 2020



The average EV is considerably cleaner to drive than the average new gasoline vehicle—and in some areas, much cleaner. For example, in upstate New York (NYUP), the emissions of the average EV compare with those of a gasoline-powered vehicle achieving 247 miles per gallon. Driving the most efficient EVs results in even lower emissions. For example, driving the 2021 Tesla Model 3 Standard Range Plus in upstate New York is equivalent to driving a gasoline vehicle achieving 323 miles per gallon.

Note: Acronyms refer to electricity grid regions as defined by eGRID (EPA 2022a).

FIGURE 3. Comparing Emissions: Driving the Average EV Pickup Truck as a Gasoline MPG Equivalent, 2020



Driving an electric pickup truck produces lower emissions than the most efficient gasoline model in most of the United States. For example, recharging and driving the Rivian or Ford F-150 Lightning pickup in California has the emissions impact of a hypothetical 76 mpg gasoline truck. Overall, based on where EVs have been sold, EV pickups would have emissions equal to a 59 mpg gasoline truck.

Note: Acronyms refer to electricity grid regions as defined by eGRID (EPA 2022a).

Even Less-Efficient EVs Can Lower Transportation Emissions

While many early EV models were sedans or small hatchbacks, manufacturers now offer more options, including not only fully electric SUVs but also pickup trucks such as the Rivian R1T or Ford F-150 Lightning, both of which have an efficiency of 0.48 kWh/mi (DOE 2022a). Larger, heavier vehicles like SUVs and pickups are inherently less efficient than sedans and smaller hatchbacks, whether powered by gasoline or electricity. Even so, electrification of the larger vehicles can lower global warming emissions if they displace inefficient gasoline and diesel SUVs and pickup trucks, which produce more emissions than electric cars. Consumers should choose the most efficient vehicle that meets their needs, whether powered by gasoline or electricity.

Using today's electric grid, driving a fully electric pickup truck results in lower emissions than the most efficient hybrid pickup (37 mpg) for over 92 percent of the US population (Figure 3). In fact, the electric pickup produces lower emissions than the average new gasoline pickup (19 mpg) everywhere in the United States. On cleaner electric grids, even an inefficient electric pickup produces lower emissions than does a gasoline hybrid sedan. In California, recharging and driving the Rivian R1T or Ford F-150 Lightning pickup has the emissions impact of a hypothetical 76 mpg gasoline truck. Again, however, the goal is to lower emissions from personal transportation as quickly as possible; thus, buyers should choose the most efficient EV that meets their mobility needs.

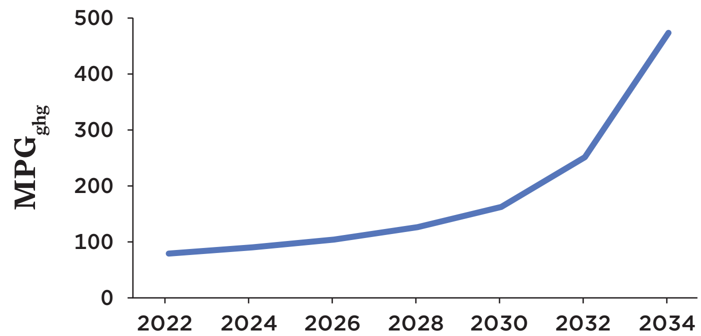
[Driving an electric pickup truck in the United States produces emissions equal to a gasoline car getting 59 miles per gallon.]

A Growing Advantage as Electricity Generation Becomes Cleaner

Most EVs charged using electricity generated in 2020 (the most recent available data) produce significantly lower emissions than even the most efficient gasoline vehicles. This advantage of EVs will continue to grow if emissions from electricity generation continue to fall. And if the United States aggressively decarbonizes such that renewables made up 95 percent of generation by 2035, emissions from driving EVs will drop to less than one-third of current levels by 2032 (Figure 4).

This is an important difference between EVs and gasoline vehicles. While the rate of global warming emissions from driving a gasoline vehicle will likely stay essentially constant, the emissions from driving an EV sold today will likely decline over time, effectively making it cleaner to use as the electricity grid gets cleaner.

FIGURE 4. Cleaner Electrical Generation Increases the Advantage of EVs



Nationally, the average EV's MPG_{ghg} rises from under 100 MPG_{ghg} today to the equivalent of a gasoline vehicle getting almost 500 miles to a gallon of fuel by 2035, assuming that the nation achieves 95 percent renewable power.

SOURCE: UCS CALCULATION BASED ON THE NREL CAMBIUM MODEL (COLE ET AL. 2021).

[CHAPTER 3

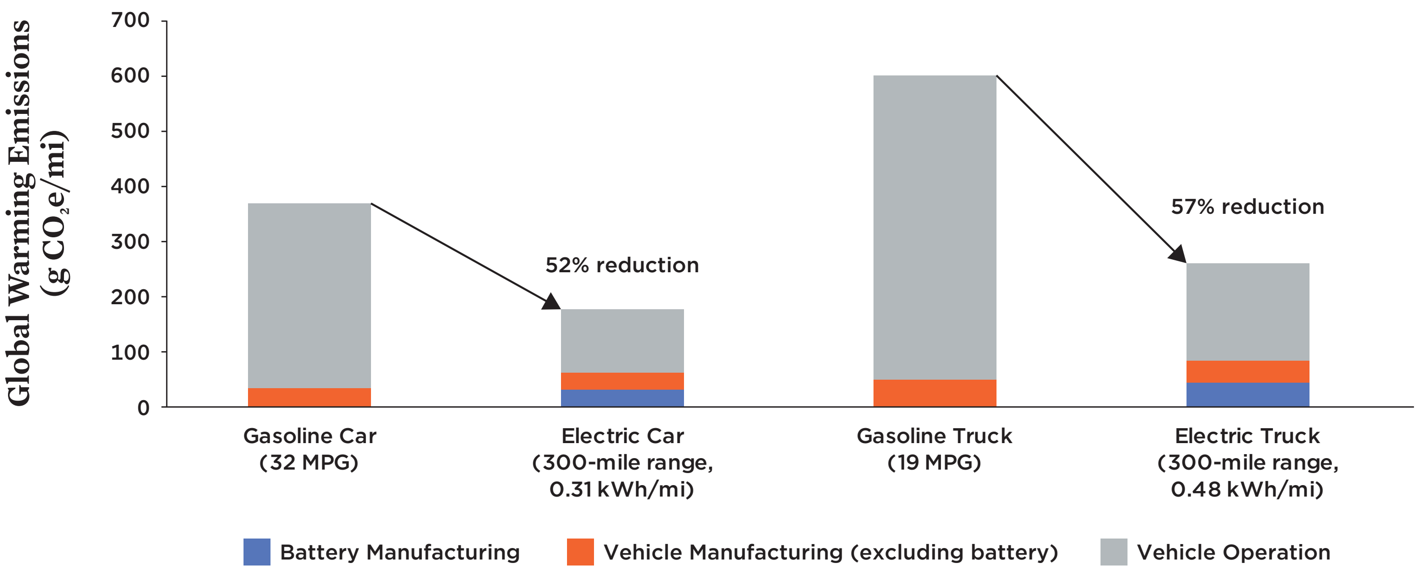
Global Warming Emissions from Vehicle Manufacturing

Just as the emissions associated with driving a battery-electric vehicle differ from those associated with driving a gasoline- or diesel-powered vehicle, so, too, do we find significant differences in the emissions due to their respective manufacturing processes. The greatest such differences come in connection with the type and size of batteries required. In gasoline vehicles, a small lead-acid battery starts the engine and powers accessories while the engine is off. In contrast, a battery-electric vehicle has no fuel tank or internal combustion engine; instead, it has a relatively large lithium-ion battery pack, an electric-drive motor, and power-control electronics. BEVs rely on the battery packs to move the vehicle and power all other systems (e.g., heating, air conditioning, electronics).

The lithium-ion battery packs in BEVs require significant amounts of material, with some packs weighing over 1,000 pounds. Extracting, processing, and transporting the raw materials all produce emissions. In addition, manufacturing the individual battery cells that comprise the battery packs requires significant energy, and that can lead to further global warming emissions.

That said, most of the life cycle global warming emissions for most of today's vehicles occur during their use. As a result, the emissions reductions from driving BEVs more than offset the increase in manufacturing emissions. Comparing the average gasoline sedan (32 mpg) with the average-efficiency BEV with a 300-mile-range battery, the BEV reduces total lifetime emissions by 52 percent (Figure 5). Even though manufacturing emissions

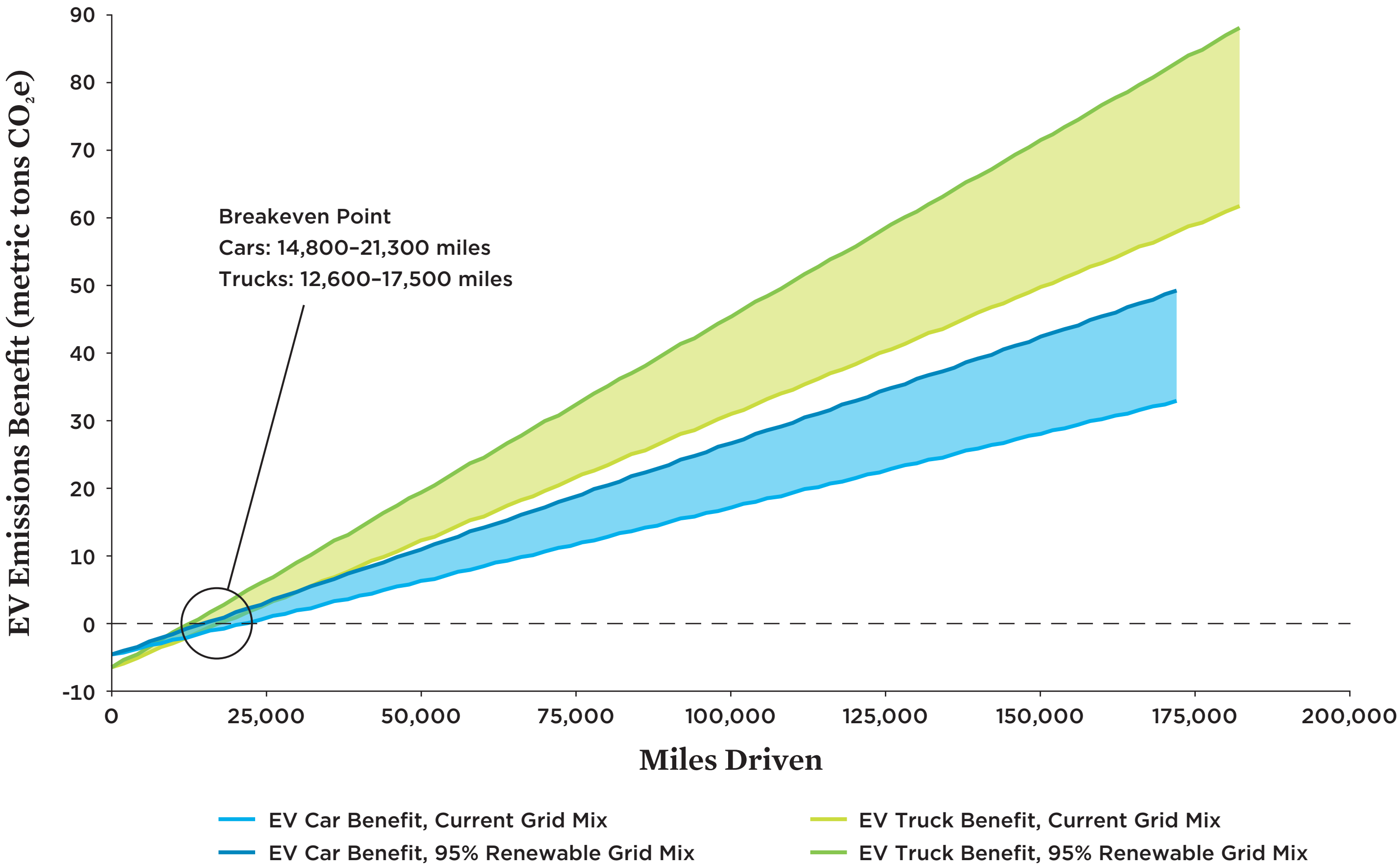
FIGURE 5. Life Cycle Global Warming Emissions: EVs vs. Gasoline Cars and Trucks



Life cycle global warming emissions are significantly lower for EVs than for gasoline cars or trucks when considering manufacturing and usage, despite higher battery-manufacturing emissions for the EV.

Note: Emissions are measured in grams of carbon dioxide–equivalent per mile, averaged over the life of the vehicle.

FIGURE 6. Breakeven Points for EV Car and Truck Emissions



The breakeven point for EV manufacturing emissions averages 17,500 miles (17 months) for 300-mile-range electric pickup trucks and 21,300 miles (22 months) for a 300-mile-range electric car, based on the current grid mix. This breakeven point assumes constant electricity emissions; actual breakeven points would be lower if electricity emissions fall over time.

average 64 grams per mile (g/mi) for the EV and 35 g/mi for a gasoline car, the savings advantage during use is far greater: the EV emits 117 g/mi versus 335 g/mi for the gasoline car. Similarly, lifetime emissions are 57 percent lower for an electric pickup truck than for the average gasoline pickup.

Another way to understand how emissions savings from driving an EV offset additional manufacturing emissions is to consider the breakeven point: how far or how long an EV needs to drive for the savings to match the initial emissions "debt." The breakeven point varies depending on regional electricity emissions. Based on where the US population lives, the mean breakeven point for an electric car with a 300-mile range compared with the average new gasoline sedan is 21,300 miles of driving or 22 months based on average annual driving (Figure 6). Breakeven occurs more quickly, after about 17,500 miles (17 months), when comparing an electric truck with a 300-mile range with the average new gasoline pickup truck.

> ***For both cars and pickups, the breakeven point comes early in an EV's lifetime, yielding a significant net emissions savings.***

For both cars and pickups, the breakeven point comes early in an EV's lifetime, yielding a significant net emissions savings. If we were to consider EVs recharging using 95 percent renewable power, the breakeven points would drop to 14,800 miles for cars and 12,600 miles for trucks.

TABLE 2. Switching to Renewable Electricity for Manufacturing: Another Opportunity to Reduce Life Cycle EV Emissions

	Battery	Vehicle (excluding battery)	Total	Percent Change vs. US Average
US Average Electric Mix	33.0 g/mi	28.5 g/mi	61.5 g/mi	0%
California (CAMX) Mix	29.5 g/mi	25.7 g/mi	55.2 g/mi	-10%
Upper Midwest (MRO) Mix	37.1 g/mi	31.7 g/mi	68.8 g/mi	+12%
Michigan–Ohio (RFC) Mix	33.0 g/mi	28.4 g/mi	61.4 g/mi	0%
100% Renewable Electricity	23.9 g/mi	21.1 g/mi	45.1 g/mi	-27%

Electric Grid Emissions and Manufacturing Emissions

The carbon intensity of electricity generation affects not only global warming emissions from driving but also those generated during the manufacture of the battery materials and the vehicle. Our baseline calculations for EV manufacturing use the average US electricity mix. However, we estimate that making an EV using electricity from the cleaner-than-average California regional grid would reduce total manufacturing emissions by 10 percent. And if the electricity for manufacturing comes solely from zero-carbon renewable energy sources, there is the potential to reduce manufacturing emissions by more than one-quarter (Table 2).[4]

TABLE 3. Emissions from Different Battery Chemistries, Relative to Those of NMC_{111}

NMC_{111}	100%
NMC_{532}	100%
NMC_{622}	95%
NMC_{811}	93%
NCA	109%
LFP	85%

The effects of different EV battery compositions on global warming emissions are relatively modest.

Notes: The number code associated with each NMC battery type refers to the proportion of nickel, manganese, and cobalt in the battery cathode. For example, NMC_{111} refers to a lithium-nickel-manganese-cobalt cathode with 1:1:1 ratio of nickel: manganese:cobalt while NMC_{532} has a ratio of 5:3:2 of nickel:manganese:cobalt. NCA is lithium-nickel-cobalt-aluminum; LFP is lithium iron phosphate.

Battery Chemistry: A Modest Effect on Global Warming Emissions

The raw materials for EV batteries vary depending on what cathode chemistry manufacturers choose as they strive to maximize performance, cost, and longevity. Most EV batteries today contain a lithium-nickel-manganese-cobalt (NMC), lithium-nickel-cobalt-aluminum (NCA), or lithium-iron phosphate (LFP) cathode.[5] While the choice of chemistry can lead to significantly different environmental impacts, the effects of different EV battery compositions on global warming emissions are relatively modest (Table 3). Even so, the choice of battery chemistry is important: factors like the amount of cobalt in the mix could affect the cost, environmental, and societal impacts of mining; supply constraints could differ as well (Ambrose and O'Dea 2021; Winjobi, Kelly, and Dai 2022).

[CHAPTER 4

Other Battery Considerations

Considerations Beyond Global Warming Emissions

Manufacturing and using any vehicle, whether powered by gasoline or electricity, have impacts beyond the global warming emissions (Tessum, Hill, and Marshall 2014; EEA 2018). For example, air and water pollution from fossil fuel extraction are tied to the production of gasoline, as is electricity from fossil sources that partially power EVs in the United States. Also, there are concerns over human rights, corruption, and environmental pollution from the sourcing of raw materials that are used for EV manufacturing, as well as in the extraction of the crude oil that ultimately powers gasoline vehicles.

We focus here on the benefits of EVs in terms of global warming emissions, but some actions, like recycling battery materials, also can reduce the amount of virgin materials needed for battery manufacture. Such actions could reduce environmental damage and lessen harm to the people and communities affected by raw materials extraction and refining. Strong protections for communities and the environment at the mining stage are also critical to lessening the impacts of EV battery manufacturing. As the transition to electric transportation accelerates, government and industry need to ensure a battery supply chain that is sustainable and ethical.

Remanufacture, Reuse, and Second Life for Used EV Batteries

EV battery packs are made up of hundreds or thousands of individual battery cells, along with sophisticated electrical and thermal management systems. It is possible to disassemble used EV battery packs to repair, refurbish, or salvage usable modules. Doing so could help reduce global warming emissions and other harms: recovered components and refurbished battery packs lessen the need to manufacture new ones.

Another route to reducing the demand for new EV batteries is to repurpose used EV battery packs; such approaches are often termed second-life applications. The range of an EV battery pack decreases both over time and with use. Because of tight constraints on the volume of an EV battery, this range reduction can make it necessary to replace the battery at some point in the vehicle's life, especially an EV with a lower initial range. However, other battery applications are less sensitive to the volume and weight of battery packs. For example, a stationary energy storage system might be able to use multiple EV battery packs with degraded capacity; the extra weight and volume of the battery packs are much less important in these applications than for an EV. A stationary battery installation with a few battery packs might power a building or an EV charging station; a megawatt-hour-scale energy storage system built with second-life batteries helps power the largest stadium in the Netherlands (Ambrose and O'Dea 2021; The Mobility House 2018).

Recycling Reduces Demand for Virgin Materials

After a battery is retired from use in an EV and reused and/or remanufactured, recycling can recover many of the materials that make up the battery pack. Recovered materials can reduce the need for virgin sourcing and reduce the emissions associated with refining and processing. Recycling can include pyrometallurgical and hydrometallurgical recycling processes, which reduces battery materials to elemental constituents, or direct cathode recycling, which recovers the full cathode. Pyrometallurgical recycling uses high-temperature smelting to recover "black mass," a mixture of the metals found in batteries; hydrometallurgical recycling uses a leaching process to separate metals (Zheng et al. 2018). Hydrometallurgical and direct recycling yield small global warming emissions benefits in the EV life cycle, varying by the type of battery recycled (Ciez and Whitacre 2019). For a cathode of NMC chemistries, a model developed by the Argonne National Laboratory estimates that use of recycled materials can reduce total battery manufacturing emissions by about 20 percent (ANL 2021).[6]

Widespread recycling is critical regardless of the potential global warming benefits. As the market for EVs grows, battery recycling has the potential to significantly reduce the need for virgin materials and associated impacts of mining battery materials. These impacts include air and water pollution, water consumption, public health impacts, community disruption, and human rights concerns. Extractive industries have earned a reputation for frequently violating human rights and degrading the environment. For example, cobalt mining in the Democratic Republic of Congo, a country with 70 percent of the world's existing cobalt production and more than 50 percent of cobalt reserves, has well-documented negative impacts on the environment, community health, and human rights (NMIS, n.d; Amnesty International 2016).

Recycling battery materials can also help address concerns over the availability of critical materials such as cobalt, lithium, copper, nickel, and manganese. Under ideal conditions, between 20 and 60 percent of critical materials used in EV batteries could be derived from retired batteries by 2040 (Dunn et al. 2021; Xu et al. 2020). Various approaches are under development to capture the environmental, social, and energy-security benefits of increasing material circularity in the battery supply chain. In 2020, under California Assembly Bill 2832, the state tasked an advisory group with recommending policies that would lead as closely as possible to 100 percent recycling of EV batteries. The group's final report, released to legislators in March 2022, focuses on assigning a responsible party for EV recycling, enabling access to battery information, supporting the repurposing and recycling industry, and increasing the safety and efficiency of reverse logistics (Kendall, Slattery, and Dunn 2022). In one notable recommendation, the vast majority of the group's members support extended producer responsibility, a policy that would assign EV manufacturers with the responsibility of ensuring the batteries are recycled when their lives end.

Both China and Japan have developed regulations regarding recycling used EV batteries. For example, China makes manufacturers responsible for battery recycling and specifies battery labeling to facilitate recycling. Japan makes new vehicle manufacturers responsible for battery disposal or recycling (Bird et al. 2022).

The European Union, which is also further along than the United States in developing end-of-life policy for EV batteries, has required extended producer responsibility for all battery types since the 2006 Battery Directive. The policy is not specific to EV batteries, but an updated version is in development to address social, environmental, and technical challenges throughout the EV supply chain and life cycle. A 2021 European Commission report proposes a policy focused on creating responsible, transparent, and lower-impact supply chains, with an emphasis on creating a circular economy. Proposed policies cover such topics as manufacturing and recycling emission standards, battery collection rates, recycling material recovery rates, manufacturing recycled content standards, and labeling requirements (European Commission 2020).

[CHAPTER 5

Policy Recommendations: Maximizing Emissions Reductions

Replacing gasoline vehicles with electric vehicles reduces carbon emissions and air pollution. To maximize those and other benefits, we must accelerate not only the adoption of EVs but also the transition to renewable sources of electricity. Moving forward with this dual transition constitutes a critical strategy for putting the United States on a trajectory toward net-zero climate emissions by midcentury.

Toward those goals, UCS makes the following recommendations.

- **Accelerate the transition to cleaner sources of electricity.** Reducing emissions from electricity generation can reduce the emissions from manufacturing and driving EVs. Policymakers at all levels should adopt and strengthen policies and programs for increasing energy efficiency and deploying renewable energy. Policy options include establishing renewable electricity standards, energy-efficiency resource standards, and incentives or mandates to improve grid operation, transmission, and resource planning. Future EVs with "smart charging," which can respond to time-of-day and demand-related signals from electric utilities, can also play a role in enabling greater deployment of variable renewable energy from solar and wind.
- **Fund R&D aimed at lowering manufacturing emissions and increasing battery recycling and reuse.** Governments and the private sector should invest more in research aimed at decreasing the global warming emissions and other negative effects associated with making EV batteries, including research into the use of alternative materials and improving the processes for battery recycling and second-life use. "Recycling and second-life use" is an emerging sector of the economy; supporting it can encourage manufacturers to reduce emissions, and it also can reduce the need to extract raw materials. It is important to note research in these areas is ongoing, with funding at the federal and state levels. The 2021 Infrastructure Investment and Jobs Act (IIJA) includes funds for research, development, and demonstration to further battery recycling and second-life use (DOE 2022b; CRS 2022).
- **Enact policies that drive material circularity.** In addition to funding the development of improved battery recycling processes, public policies should ensure that batteries are recycled when they reach the end of their lives and that battery manufacturers use recovered materials. Increasing the recovery of critical materials has the potential to offset the use of virgin materials and reduce the environmental and social impacts associated with mining. Provisions in the IIJA support battery circularity, but more can be done. Policies like extended producer responsibility and labeling and collection requirements can help accelerate a circular economy.
- **Increase supply chain transparency, accountability, and sustainability.** EV manufacturers must be responsible for ethical and sustainable material sourcing throughout the supply chain and, to enable enforcement of this, they must

[***Public policies should ensure that batteries are recycled when they reach the end of their lives and that battery manufacturers use recovered materials.***]

ensure that their emissions and material sourcing are transparent to the public and regulators. Voluntary industry standards—the Initiative for Responsible Mining Assurance, for example—are a positive step, but only some manufacturers currently participate.[7] Standardized, verifiable reporting of material and manufacturing processes, such as the Global Battery Alliance's Battery Passport program, could help governments and nongovernmental organizations monitor and verify that battery production is environmentally sustainable and sourced using ethical practices (GBA 2020).

- **Minimize materials demand by increasing vehicle efficiency.** Vehicle efficiency standards should be developed to ensure that manufacturers produce high-efficiency EVs. Policies also should encourage vehicle buyers to purchase the most efficient EVs that meet their mobility needs. Higher-efficiency EVs reduce per-mile emissions. Also, they make it possible for lower-capacity batteries to provide the needed range, reducing manufacturing emissions.
- **Decrease the need for individual car ownership.** Policies and funding should support a variety of transportation options—including transit, shared mobility options, and walking and biking infrastructure. This would further reduce materials demand and limit the overall emissions from vehicle manufacturing and use.
- **Promote equity in the transition to EVs.** Vehicle incentives and infrastructure deployment should enable drivers across incomes and geographies to access EVs. For us to reap the maximum benefits of EVs, all drivers must be able to switch from gasoline and diesel vehicles.

APPENDIX A: METHODOLOGY

Emissions Estimates for the Use Phase

The global warming emissions this study attributes to the use phase of operating an electric vehicle today result from producing the electricity needed to charge the vehicle. We factor in emissions created by power plants when generating the electricity, as well as emissions that result from obtaining and transporting the fuel used in these plants.

Power Plant Emissions

For the emissions values related to electricity generation, this analysis uses the Emissions & Generation Resource Integrated Database (eGRID) of the US Environmental Protection Agency (EPA). This is a comprehensive source of emissions data for every power plant in the United States. We used eGRID2020, the most up-to-date eGRID version available. It contains plant emissions and generation estimates for calendar year 2020 for the nation and for subregions, and it includes the mix of generation sources for each region. (EPA 2022a).

The subregions are groups of power plants organized by the EPA based on Power Control Areas and North American Reliability regions (EPA 2022b). These groupings, reflecting which plants serve which households, reasonably approximate the grid mix of electricity used by those households. The global warming emissions rates for electricity generation for each of the 26 regions analyzed in the report come from the eGRID2020 Subregion datasheet (EPA 2022a).

The level of disaggregation of the eGRID subregions, which takes into account regional variations in grid mix, allows for more precise calculations of plants' emissions intensities than does a national average. For this reason, we chose eGRID over other data sources that had the same detail in plant information but fewer subregions. The actual grid mix of a household's electricity is specific to the utilities serving each household, but specific grid-mix data are not readily available for most utilities and therefore are not used in the study.

The eGRID methodology treats subregions as closed systems, calculating the emissions intensity of generation for each subregion based on the emissions intensities of the plants it contains. This methodology ignores imports and exports of electricity between subregions, lessening the accuracy of regional emissions estimates. The eGRID's designers recommend the 26 subregions as the level of disaggregation best suited for estimating emissions related to electricity use; this achieves the best balance between the precision gained by disaggregation and the accuracy lost by omitting imports and exports (EPA 2022b).

Transmission Loss Factors

The eGRID emissions rates do not account for transmission and distribution losses between power plants and households. To calculate emissions per unit of energy used (rather than energy produced), we increased the emissions rates using grid-loss factors found in data files (EPA 2022a).

There are five grid-loss factors that vary by regions called interconnect power grids; each state has a grid-loss factor based on the interconnect power grid to which it belongs. Although eGRID subregions are based on utility service territories that do not coincide with state boundaries, we assigned each subregion one of these factors based on those of the states. This avoids having multiple emissions rates for a single subregion serving two or more states with different grid-loss factors. For subregions that encompass parts of multiple states with different grid-loss factors, we used the most prevalent factor, based on the state with the largest geographic area in the subregion.

Upstream Emissions Factors

The eGRID subregion emissions rates include only emissions produced at the plant generating the electricity; the rates exclude upstream emissions resulting from the mining and transport of the power plant feedstock. Therefore, we calculated a feedstock emissions rate for each subregion; this rate depends on which fuel types the corresponding power plants use. Each fuel type has a unique upstream emissions rate, which we obtained from GREET—the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model. This is a publicly available life cycle emissions model developed by Argonne National Laboratory (ANL 2021). Our analysis used the AR5 Global Warming Potential values with 100-year time horizon. The percentage of generation from each fuel type in a subregion came from the eGRID2020 Subregion datasheet. For each subregion, we multiplied fuel-type emissions rates by the share of generation each represents in that subregion; the sum of these products was a subregion's feedstock emissions rate.

In GREET, most fuel types correspond directly to a fuel type in eGRID, with a few exceptions. A very small share of generation in eGRID subregions corresponds to a fuel type labeled "generic fossil." For this fuel type, we chose the GREET emissions rate for natural gas as a conservative guess, given that its upstream emissions value is higher than those of coal or oil (the other two fossil fuels with known feedstock emissions rates in GREET). An even smaller share of generation in eGRID subregions comes from unknown sources; for this category of fuel type, the feedstock emissions rate is the generation-weighted average of the upstream emissions rates for the other fuel types.

GREET builds a uniform grid-loss factor into the feedstock emissions rates. However, to keep the loss factors consistent with those applied to power plant emissions, we backed GREET's grid-loss factor out of the feedstock emissions rates. We then applied eGRID's power plant grid-loss factors to each subregion's feedstock emissions rate.

We computed the totals of global warming emissions related to electricity generation for each eGRID subregion by summing the grid-loss-adjusted power plant emissions rates for each subregion with the corresponding grid-loss-adjusted feedstock emissions rate.

Emissions Rate Assumptions and Results by Subregion

To translate electricity-related emissions intensity into driving-related emissions intensity (measured as a gasoline miles-per-gallon equivalent, or MPG_{ghg}), we multiplied the EPA emissions intensity values (expressed in grams of carbon dioxide–equivalent emissions per kilowatt-hour, or gCO_2e/kWh) from Table A-1 (see p. 21) by the EV average efficiency values (kWh/mile), resulting in a gCO_2e/mile estimate. EV average efficiency was calculated using the sales-weighted average electric-drive efficiency (including charging losses) of the 10 battery EVs and 10 plug-in hybrid EVs (PHEVs) with the highest US sales over the past six years (DOE 2022a; EV Hub 2022). PHEV efficiencies were weighted by utility factor. The overall average efficiency for all EVs was 0.314 kWh/mi.

We used the GREET carbon intensity for a weighted average of California and national gasoline on a lower heating value basis (10.629 kg CO_2e/gal), which includes emissions for petroleum extraction, gasoline refining and production, transportation of finished product, and combustion (ANL 2021). This intensity was divided by the gCO_2e/mile estimate to estimate the MPG_{ghg} for each region. This figure is an EV equivalent to the miles per gallon of a gasoline-powered vehicle: vehicles with the same MPG_{ghg} will produce the same amount of global warming pollution for each mile traveled, regardless of the type of fuel.

Emissions Estimates for the Manufacturing Phase

To model vehicle manufacturing, we used the 2021 versions both of GREET 1 (a fuel-cycle model) and GREET 2 (a vehicle-cycle model). In the absence of specific details about the material composition of the gasoline and battery-electric models, we used model default values for cars and trucks. The EV car was modeled as having a 300-mile range with a 95 kWh battery capacity. EV pickups were modeled using a 300-mile-range battery of 135 kWh capacity. We used the GREET default vehicle lifetime: 173,151 miles for cars and 183,363 miles for pickup trucks.

Temperature Effects on Efficiency and Emissions

Temperature affects the efficiency of both gasoline and electric vehicles, with reduced efficiency—and hence increased emissions—at both hot and cold temperatures. Effects generally appear at temperatures above 75°F and below 60°F (Wu et al. 2019). However, we did not adjust the data for temperature effects because of uncertainty in the magnitude of that effect, especially for newer EVs.

For EVs, the most significant decrease in efficiency occurs at low temperatures. This decrease stems from several sources. First, while a gasoline vehicle can use waste heat from the engine to warm the cabin, an EV must use energy from the battery to power heating systems. Second, warming the battery in many EVs improves battery longevity and performance. On the other hand, lower temperatures reduce the performance of lithium-ion batteries, with higher internal resistance. In addition, the ability of EVs to recoup energy during braking can be limited at lower temperatures (Steinstraeter, Heinrich, and Lienkamp 2021).

However, quantification of such efficiency changes is hampered by the lack of data on the performance of new models of gasoline and electric vehicles at high and low ambient temperatures. Further complicating the analysis is the emerging use of heat pump systems in newer EV models. Heat pumps can be more efficient than the resistance heating systems commonly found in the first generation of modern EVs and can lead to a smaller reduction in EV efficiency in cold weather (Phillips 2022). Existing quantitative analyses of EV cold-weather performance, such as by Wu et al. (2019), necessarily rely on data from early EV models; they may not reflect the performance of EVs now available for purchase in the United States.

Because of the uncertainty in the magnitude of the temperature effect on efficiency, especially for newer EVs, the data presented in the body of this report are not adjusted for temperature effects. Based on the methods and data from Woody et al. (2022), we estimate the US average MPG_{ghg} value for an average efficiency EV would be 77 MPG_{ghg}. However, this may underestimate the emissions benefits from newer EVs with heat pumps or other cold-weather optimizations.

TABLE A-1. eGRID Subregion Electricity Emissions Rates and EV Use-Phase Emissions

eGRID Subregion Acronym	eGRID Subregion Name	2020 Subregion Average Emissions Rate (gCO_2e/kWh)	Use Phase Emissions, Average EV (gCO_2e/mi)	Use Phase Emissions, Most Efficient EV (gCO_2e/mi)
AKGD	ASCC Alaska Grid	605	190	145
AKMS	ASCC Miscellaneous	303	95	73
ERCT	ERCOT All	447	141	107
FRCC	FRCC All	472	148	113
HIMS	HICC Miscellaneous	652	205	156
HIOA	HICC Oahu	914	287	219
MROE	MRO East	799	251	192
MROW	MRO West	507	159	122
NYLI	NPCC Long Island	661	208	159
NEWE	NPCC New England	305	96	73
NYCW	NPCC NYC/Westchester	366	115	88
NYUP	NPCC Upstate NY	137	43	33
RFCE	RFC East	365	115	88
RFCM	RFC Michigan	615	193	148
RFCW	RFC West	523	164	125
SRMW	SERC Midwest	767	241	184
SRMV	SERC Mississippi Valley	418	131	100
SRSO	SERC South	473	149	114
SRTV	SERC Tennessee Valley	445	140	107
SRVC	SERC Virginia/Carolina	344	108	83
SPNO	SPP North	495	156	119
SPSO	SPP South	502	158	120
CAMX	WECC California	291	91	70
NWPP	WECC Northwest	318	100	76
RMPA	WECC Rockies	598	188	144
AZNM	WECC Southwest	461	145	111

The average EV has an efficiency of 0.314 kWh/mi; the most efficient EV has an efficiency of 0.24 kWh/mi.

APPENDIX B: AVERAGE AND MARGINAL ELECTRICITY EMISSIONS CONSIDERATIONS

Electricity is produced using a mix of generation units that vary in size, fuel, and efficiency. The mix varies over both long and short time scales: the demand for electricity, its availability, and the fuel costs are always changing. Emissions attributable to electricity use link directly to this generation mix, and they vary by region, time of year, and time of day. Because of the complexity of the electricity grid and how it operates, as well as the inability to track specific electricity generation to a specific end use, multiple methods have been developed to estimate the emissions from electricity use. This analysis used an average emissions approach, averaging the emissions from electricity production over all the electricity generating units in an entire electricity grid region for a year.

Average Emissions Estimation

We based the data used to calculate regional global warming emissions intensities on actual power plant emissions for 2020.

To estimate EV emissions from plugging into the electricity grid, we calculated the average intensity of global warming emissions (i.e., emissions emitted for each net kilowatt-hour of electricity delivered) by region. This method of averaging emissions intensity treats all electricity produced and consumed in the region equally. That is, no matter how much electricity you use or when you use it, this method assumes your electricity to be just as clean (or dirty) as anyone else's in the same region. In essence, it assumes that any additional electricity needed to power an EV would come from the same mix of sources that generate electricity to meet all other current demands.

The averaging approach makes it possible to capture changes in the underlying generation mix when estimating future years' emissions. However, it does not reflect short-term changes in the electricity grid that may result from adding a new electricity load to the grid. Nor does the average emissions approach account for the import and export of electricity across regions.

Marginal Emissions Estimation

An alternative approach involves "marginal" emissions intensity. This is estimated by identifying which power plants, or types of power plant, are likely to be deployed or to increase output when new demand is added to the electricity grid above and beyond existing demand. In this type of analysis, the electricity consumed by an additional load, such as a newly purchased EV or even an extra television set, would be assigned a different emissions intensity from electricity used by existing electric loads (e.g., a light fixture in a home). A variety of analyses have used various marginal emissions approaches to evaluate the potential impacts of increasing amounts of EV charging on future emissions of the electricity grid (EPRI and NRDC 2015; Tamayao et al. 2015; Graff Zivin, Kotchen, and Mansur 2014). These marginal emissions analyses can be broken into two categories: short term and long term.

Short-Term Marginal Emissions Analysis

The short-term method looks at how the electricity grid responds instantaneously to a new load, such as when an EV is plugged in. This approach specifically ties the emissions from plugging in the EV to how the grid would respond to the new load, all other factors being fixed. Increases in electricity demand are met through increasing generation output at a power plant operating at less than full output—typically, a natural gas or coal power plant. These types are considered the marginal generation sources. In contrast, sources such as nuclear, hydro, wind, and solar are rarely "on the margin" because of their limited ability to vary output. These electricity sources provide nonmarginal generation.

This short-term marginal emissions approach can provide a more precise snapshot of how the grid responds to a new load during a short amount of time, and it quantifies the net emissions change during that period. Carrying out the same type of analysis in future years could produce very similar results, regardless of changes to nonmarginal load generation. For example, if over some time period 25 percent of electricity generation in a region moved to renewable sources, fossil fuel power plants might still be the only electricity sources on the margin responding to instantaneous increases in demand for electricity. Using this type of marginal emissions analysis, an EV powered on a grid with no renewables and one with 25 percent renewables might have the same emissions profile.

Eventually, new electricity demand will lead to changes in the sources of electricity production. Over time, a large number of EVs will create significant demand that must be met through greater energy efficiency, increased utilization of existing sources, new electricity generation, or, very likely, a combination of all three.

Long-Term Marginal Emissions Analysis

A short-term marginal analysis considers only increased utilization of existing generating resources, although researchers have looked into a more consequential approach with new capacity as a consideration (Weis, Jaramillo, and Michalek 2014). The long-term marginal emissions approach, also known as a consequential life cycle approach, evaluates how the electricity grid responds over a longer period. This approach estimates what would happen to the grid without adding new electricity load, then contrasts that outcome with what would happen under the new load. For example, an analysis could estimate electricity demand between 2015 and 2030 assuming no EVs, then estimate demand with several million EVs added (EPRI and NRDC 2015).

This type of modeling approach makes it possible to evaluate long-term changes in the electricity grid, including power plant retirements, new electricity generation, and changes in EV demand. Importantly, it also makes it possible to evaluate policies to reduce emissions from both the transportation and electricity sectors, as well as to estimate the cumulative impact on emissions from both sectors.

While a long-term marginal emissions approach does not tell us what the emissions are from EVs today, it is an important tool for assessing the impacts of transportation and energy policies designed to reduce emissions—of deploying more EVs while also deploying cleaner electricity sources. However, this approach is outside the scope of our analysis because it requires modeling the transportation and energy sectors as well as the specific changes to the electricity grid that might occur under various future scenarios.

Why We Used Average Emissions Estimation

The goal of this analysis was to identify the typical global warming emissions of the mix of electricity sources used to charge EVs on today's power grid, as well as to evaluate how that mix changes over time and compares with past and possible future electricity grids. Therefore, we used the average emissions intensity of the electricity, essentially treating all electricity on the grid at a given time as a shared resource available to all electricity consumers. While this approach does not capture the very short-term marginal emissions impact on the grid from plugging in a new EV, it does reflect changes occurring in nonmarginal load generation around the country.

The average emissions approach also allows for comparing future and past emissions analyses, and it captures the impact of ongoing changes to the electricity grid as a whole resulting from regulatory policy and other factors. In other words, as consumers buy EVs today, the approach can take into account the trajectory of the grid and the global warming emissions over the life of the vehicles.

ENDNOTES

1. This report investigates the global warming potential for emissions from gasoline- and electricity-powered vehicles. Global warming leads to climate change (a broader set of impacts), so we refer to the emissions as both "global warming" and "climate changing."
2. Average EV efficiency is based on a sales-weighted average of EPA combined highway and city efficiency values for the 10 battery-electric and 10 plug-in hybrid electric models with the highest US sales over the last six years. Plug-in hybrid EV efficiencies are also weighted by utility factor.
3. Based on EV sales from 2016 through 2021.
4. This analysis does not model the potential emissions reductions from decarbonization of material production.
5. The cathode is the positive electrode of the battery. For the battery to charge and discharge, lithium ions pass between the cathode and anode (negative electrode). Between the electrodes are electrolyte and a separator used to prevent a short circuit.
6. The model is GREET—the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model. GREET is a publicly available life cycle emissions model.
7. For information on the Initiative for Responsible Mining Assurance, see https://responsiblemining.net.

REFERENCES

Ambrose, Hanjiro, and Jimmy O'Dea. 2021. *Electric Vehicle Batteries: Addressing Questions about Critical Materials and Recycling*. Cambridge, MA: Union of Concerned Scientists. https://www.ucsusa.org/resources/ev-battery-recycling

Amnesty International. 2016. *"This Is What We Die For": Human Rights Abuses in the Democratic Republic of the Congo Power the Global Trade in Cobalt*. London, England. https://www.amnesty.org/en/documents/afr62/3183/2016/en

Anair, Don, and Amine Mahmassani. 2012. *State of Charge: Electric Vehicles' Global Warming Emissions and Fuel-Cost Savings across the United States*. Cambridge, MA: Union of Concerned Scientists. https://www.ucsusa.org/resources/state-charge

ANL (Argonne National Laboratory). 2021. "The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model," released October 11. https://greet.es.anl.gov/index.php

Baek, Y., T. Boettner, R. Cleetus, S. Clemmer, C. Esquivia-Zapata, C. Farley, B. Isaac, et al. 2021. *A Transformative Climate Action Framework: Putting People at the Center of Our Nation's Clean Energy Transition*. Cambridge, MA: Union of Concerned Scientists. https://www.ucsusa.org/clean-energy-transformation

Bird, Robert, Zachary J. Baum, Xiang Yu, and Jia Ma. 2022. "The Regulatory Environment for Lithium-Ion Battery Recycling." *ACS Energy Letters 7* (2): 736–740. DOI: 10.1021/acsenergylett.1c02724

CARB (California Air Resources Board). 2022. *Public Hearing to Consider the Proposed Advanced Clean Cars II Regulations. Staff Report: Initial Statement of Reasons*. Sacramento CA. https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/accii/isor.pdf

Ciez, Rebecca E., and J. F. Whitacre. 2019. "Examining Different Recycling Processes for Lithium-Ion Batteries." *Nature Sustainability* 2: 148–56. https://doi.org/10.1038/s41893-019-0222-5

Cole, Wesley, J. Vincent Carag, Maxwell Brown, Patrick Brown, Stuart Cohen, Kelly Eurek, Will Frazier, et al. 2021. *2021 Standard Scenarios Report: A U.S. Electricity Sector Outlook*. NREL/TP-6A40-80641. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy22osti/80641.pdf

CRS (Congressional Research Service). 2022. *Energy and Minerals Provisions in the Infrastructure Investment and Jobs Act (P.L. 117-58)*. Washington, DC. https://crsreports.congress.gov/product/pdf/R/R47034

DOE (Department of Energy). 2022a. "Fueleconomy.gov: The Official U.S. Government Source for Fuel Economy Information." www.fueleconomy.gov

———. 2022b. "Biden Administration Announces $3.16 Billion from Bipartisan Infrastructure Law to Boost Domestic Battery Manufacturing and Supply Chains." Press release, May 2. https://www.energy.gov/articles/biden-administration-announces-316-billion-bipartisan-infrastructure-law-boost-domestic

Dunn, Jessica, Margaret Slattery, Alissa Kendall, Hanjiro Ambrose, and Shuhan Shen. 2021. "Circularity of Lithium-Ion Battery Materials in Electric Vehicles." *Environmental Science & Technology 55* (8): 5189–5198. https://pubs.acs.org/doi/10.1021/acs.est.0c07030

EEA (European Environment Agency). 2018. *Electric Vehicles from Life Cycle and Circular Economy Perspectives*. Copenhagen, Denmark. https://www.eea.europa.eu/publications/electric-vehicles-from-life-cycle

EPA (Environmental Protection Agency). 2021a. "Fast Facts: U.S. Transportation Sector Greenhouse Gas Emissions 1990–2019." https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1013NR3.pdf

———. 2021b. *The 2021 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology Since 1975*. Washington, DC. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1013L1O.pdf

———. 2022a. "The Emissions & Generation Resource Integrated Database (eGRID) (eGRID2020)." https://www.epa.gov/egrid/download-data

———. 2022b. "The Emissions & Generation Resource Integrated Database eGRID Technical Guide with Year 2020 Data." https://www.epa.gov/egrid/download-data

EPRI and NRDC (Electric Power Institute and Natural Resources Defense Council). 2015. *Environmental Assessment of Full Electric Transportation Portfolio*. Palo Alto, CA. https://www.epri.com/research/products/3002006881

European Commission. 2020. *Proposal for a Regulation of the European Parliament and of the Council Concerning Batteries and Waste Batteries, Repealing Directive 2006/66/EC and Amending Regulation (EU) No 2019/1020*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020PC0798

EV Hub. 2022. "New State Registrations." https://www.atlasevhub.com/materials/evgridx/ (paywall restricted)

GBA (Global Battery Alliance). 2020. *The Global Battery Alliance Battery Passport: Giving an Identity to the EV's Most Important Component*. Briefing Paper. https://www.globalbattery.org/media/publications/wef-gba-battery-passport-overview-2021.pdf

Graff Zivin, Joshua S., Matthew J. Kotchen, and Erin T. Mansur. 2014. "Spatial and Temporal Heterogeneity of Marginal Emissions: Implications for Electric Cars and Other Electricity-Shifting Policies." *Journal of Economic Behavior & Organization* 107: 248–268. https://www.sciencedirect.com/science/article/pii/S0167268114000808

Kendall, Alissa, Margaret Slattery, and Jessica Dunn. 2022. *Lithium-ion Car Battery Recycling Advisory Group Final Report*. Prepared on behalf of the AB 2832 Advisory Group for the California Environmental Protection Agency. Sacramento, CA. https://calepa.ca.gov/wp-content/uploads/sites/6/2022/05/2022_AB-2832_Lithium-Ion-Car-Battery-Recycling-Advisory-Goup-Final-Report.pdf

The Mobility House. 2018. "The 3 Megawatt Energy Storage System in Johan Cruijff ArenA Is Now Live." Press release, June 29. https://www.mobilityhouse.com/int_en/magazine/press-releases/johan-cruijff-arena-3mw-energy-storage-system-launch.html

NMIS (National Mineral Information Center). n.d. "Cobalt Statistics and Information." Accessed June 8, 2022. https://www.usgs.gov/centers/nmic/cobalt-statistics-and-information

Nealer, Rachael, David Reichmuth, and Don Anair. 2015. *Cleaner Cars from Cradle to Grave: How Electric Cars Beat Gasoline Cars on Lifetime Global Warming Emissions*. Cambridge, MA: Union of Concerned Scientists. https://www.ucsusa.org/resources/cleaner-cars-cradle-grave

Phillips, Sam. 2022. "Revealed: How Winter Weather Affects Real-World Range." Move Electric.com, March 17. https://www.moveelectric.com/e-cars/revealed-how-winter-weather-affects-real-world-range

Steinstraeter, Matthias, Tobias Heinrich, and Markus Lienkamp. 2021. "Effect of Low Temperature on Electric Vehicle Range." *World Electric Vehicle Journal* 12: 115. https://doi.org/10.3390/wevj12030115

Tamayao, Mili-Ann, Jeremy J. Michalek, Chris Hendrickson, and Inês M. L. Azevedo. 2015. "Regional Variability and Uncertainty of Electric Vehicle Life Cycle CO_2 Emissions Across the United States." *Environmental Science & Technology* 49 (14): 8844–8855. http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00815

Tessum, Christopher W., Jason D. Hill, and Julian D. Marshall. 2014. "Life Cycle Air Quality Impacts of Conventional and Alternative Light-Duty Transportation in the United States." *Proceedings of the National Academy of Sciences* 111 (52): 18490–18495. https://doi.org/10.1073/pnas.1406853111

Weis, Allison, Paulina Jaramillo, and Jeremy Michalek. 2014. "Estimating the Potential of Controlled Plug-In Hybrid Electric Vehicle Charging to Reduce Operational and Capacity Expansion Costs for Electric Power Systems with High Wind Penetration." *Applied Energy* 115: 190–204. https://www.sciencedirect.com/science/article/pii/S0306261913008374

Winjobi, Olumide, Jarod C. Kelly, and Qiang Dai. 2022. "Life-Cycle Analysis, by Global Region, of Automotive Lithium-Ion Nickel Manganese Cobalt Batteries of Varying Nickel Content." *Sustainable Materials and Technologies* 32: e00415. https://www.sciencedirect.com/science/article/pii/S221499372200029X

Woody, Maxwell, Parth Vaishnav, Gregory A. Keoleian, Robert De Kleine, Hyung Chul Kim, James E. Anderson, and Timothy J. Wallington. 2022. "The Role of Pickup Truck Electrification in the Decarbonization of Light-Duty Vehicles." *Environmental Research Letters* 17 (3): 034031. https://iopscience.iop.org/article/10.1088/1748-9326/ac5142

Wu, Di, Fendi Guo, Frank R. Field, Robert D. De Kleine, Hyung C. Kim, Timothy J. Wallington, and Randolph E. Kirchain. 2019. "Regional Heterogeneity in the Emissions Benefits of Electrified and Lightweighted Light-Duty Vehicles." *Environmental Science & Technology* 53 (18): 10560–70. https://doi.org/10.1021/acs.est.9b00648

Xu, Chengjian, Qiang Dai, Linda Gaines, Mingming Hu, Arnold Tukker, and Bernhard Steubing. 2020. "Future Material Demand for Automotive Lithium-Based Batteries." *Communications Materials* 1: 99. https://doi.org/10.1038/s43246-020-00095-x

Zheng, Xiaohong, Zewen Zhu, Xiao Lin, Yi Zhang, Yi He, Hongbin Cao, and Zhi Sun, 2018. "A Mini-Review on Metal Recycling from Spent Lithium Ion Batteries." *Engineering* 4 (3): 361–370. https://doi.org/10.1016/j.eng.2018.05.018

Driving Cleaner

Electric Cars and Pickups Beat Gasoline on Lifetime Global Warming Emissions

[Passenger cars and trucks are one of the largest sources of global warming emissions in the United States. Electric vehicles (EVs) have the potential to dramatically reduce these emissions, especially when charged by low-carbon renewable electricity. New UCS analysis finds that over its lifetime—from manufacturing to operation to disposal—the average new battery electric vehicle produces more than 50 percent less global warming pollution than a comparable gasoline or diesel vehicle. Based on the most recently available data on power plant emissions and EV sales, driving the average EV in the United States produces global warming emissions equal to a gasoline vehicle that gets 91 miles per gallon. To speed climate benefits and to encourage more drivers to choose electric vehicles, the report recommends policy changes and investments to bring even more renewable energy onto the grid, develop robust battery recycling programs to help reduce manufacturing impacts, and make EVs more accessible and affordable.]

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