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Cleaner Cars from Cradle to Grave

How Electric Cars Beat Gasoline Cars on Lifetime Global Warming Emissions

Union of Concerned Scientists

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Union of Concerned Scientists

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The Union of Concerned Scientists puts rigorous, independent science to work to solve our planet's most pressing problems. Joining with citizens across the country, we combine technical analysis and effective advocacy to create innovative, practical solutions for a healthy, safe, and sustainable future.

More information about UCS and the Clean Vehicles Program is available on the UCS website: *www.ucsusa.org*

This report is available online (in PDF format) at *www.ucsusa.org/EVlifecycle*.

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Electric vehicles (EVs) are a critical part of the American transportation future given their potential to dramatically cut global warming emissions—especially when charged by a clean electricity grid.

Together with other oil-saving approaches, such as more efficient vehicles and advanced biofuels, EVs can help cut projected U.S. oil use in half over the next 20 years. EVs will also be essential to achieving the deep emissions reductions by mid-century needed to avoid the worst impacts of climate change.

This report compares battery-electric vehicles (BEVs) with similar gasoline vehicles by examining their global warming emissions over their "life cycles"—from the raw materials to make the car through manufacturing, driving, and disposal or recycling. Toward that end, we performed up-to-date assessments of the carbon footprints of BEVs, taking into account the latest information about electricity generation and BEV models. The two BEVs we modeled, midsize and full-size, are not specific to any particular manufacturer but are based on the two most popular BEV models sold in the United States today: the Nissan LEAF and the Tesla Model S. Our analysis reflects the BEVs available to American consumers and comparable gasoline vehicles.

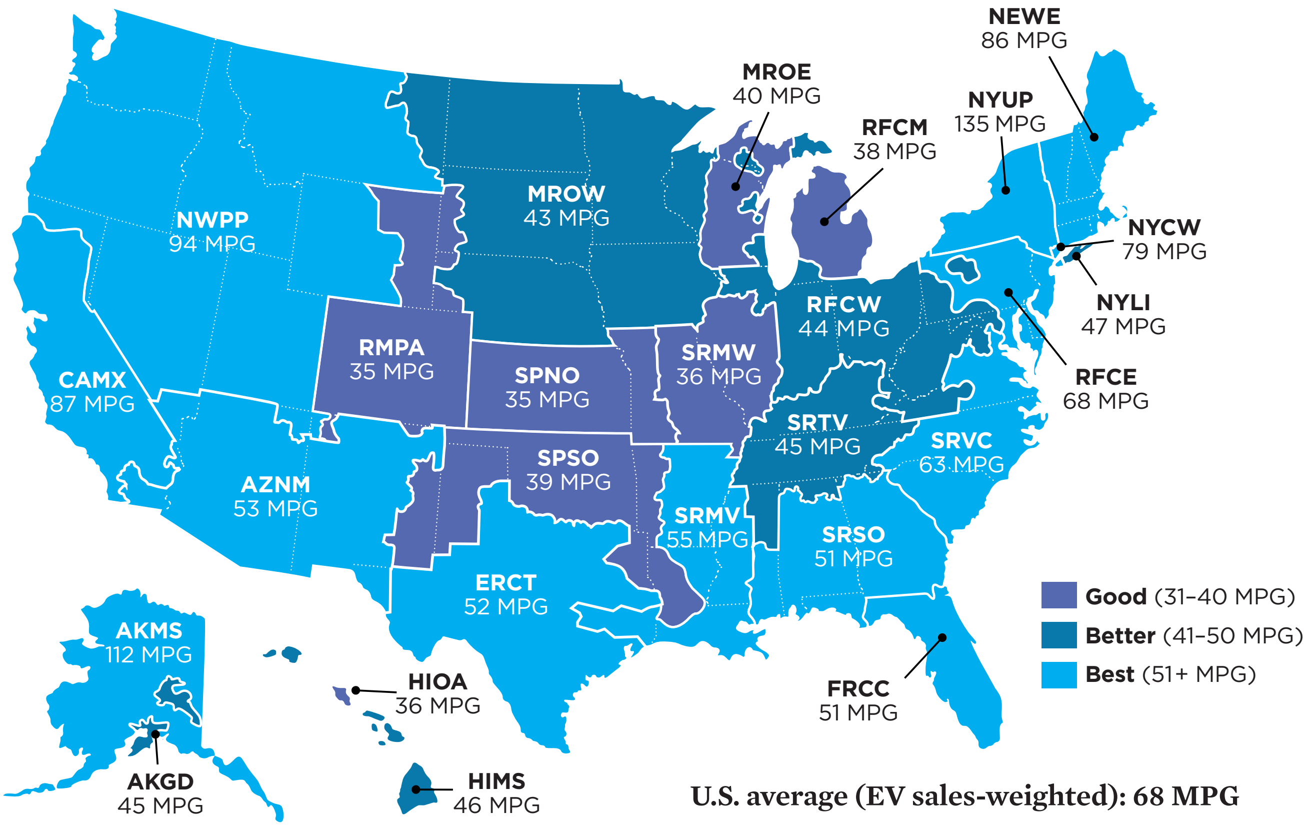
Our analysis revealed that:

- **From cradle to grave, BEVs are cleaner.** On average, BEVs representative of those sold today produce less than half the global warming emissions of comparable gasoline-powered vehicles, even when the higher emissions associated with BEV manufacturing are taken into consideration. Based on modeling of the two most popular BEVs available today and the regions where they are currently being sold, excess manufacturing emissions are offset within 6 to 16 months of average driving.
- **EVs are now driving cleaner than ever before.** Driving an average EV results in lower global warming emissions than driving a gasoline car that gets 50 miles per gallon (MPG) in regions covering two-thirds of the U.S. population, up from 45 percent in our 2012 report. Based on where EVs are being sold in the United States today, the average EV produces global warming emissions equal to a gasoline vehicle with a 68 MPG fuel economy rating.
- **EVs will become even cleaner as more electricity is generated by renewable sources of energy.** In a grid composed of 80 percent renewable electricity, manufacturing a BEV will result in an over 25 percent reduction in emissions from manufacturing and an 84 percent reduction in emissions from driving—for an overall reduction of more than 60 percent (compared with a BEV manufactured and driven today).

Global Warming Emissions from Driving Electric Vehicles

Although a BEV has no tailpipe emissions, the total global warming emissions from operating it are not insignificant; they depend on the sources of the electricity that charge the vehicle's batteries and on the efficiency of the vehicle. We estimated the global warming emissions from electricity consumption in the 26 "grid regions" of the United States (see Figure ES-1, p. 2)—representing the group of power plants that together serve as each region's primary source of

FIGURE ES-1. Electric Vehicle Global Warming Pollution Ratings and Gasoline Vehicle Emissions Equivalents by Electricity Grid Region



U.S. average (EV sales-weighted): 68 MPG

Note: The MPG (miles per gallon) value listed for each region is the combined city/highway fuel economy rating of a gasoline vehicle that would have global warming emissions equivalent to driving an EV. Regional global warming emissions ratings are based on 2012 power plant data in the EPA's eGRID 2015 database (the most recent version). Comparisons include gasoline and electricity fuel production emissions. The 68 MPG U.S. average is a sales-weighted average based on where EVs were sold in 2014.

SOURCE: EPA 2015C; IHS 2015.

electricity—and we rated each region based on how charging and using an EV there compares with driving a gasoline vehicle. We also estimated, based on recent sales data, the average efficiency of new EVs (battery-electric and plug-in electric vehicles combined) sold in the United States in 2015.

We found that: (1) driving the average electric vehicle in any region of the country produces lower global warming emissions than the average new gasoline car achieving 29 MPG; (2) our ratings in 20 out of 26 regions have improved since our 2012 report; and (3) about 66 percent of Americans—up from 45 percent just three years ago—live in regions where powering an EV on the regional electricity grid produces lower global warming emissions than a 50 MPG gasoline car.

Comparisons between electric vehicles and gasoline cars look even more attractive when one considers that many EVs are currently being sold and driven in areas where the electricity grid is cleaner than the U.S. mean. As a result, based on calculations that weighted where EVs were sold in 2014, driving an EV in the United States produced global warming emissions equal to a gasoline vehicle with 68 MPG during operation.

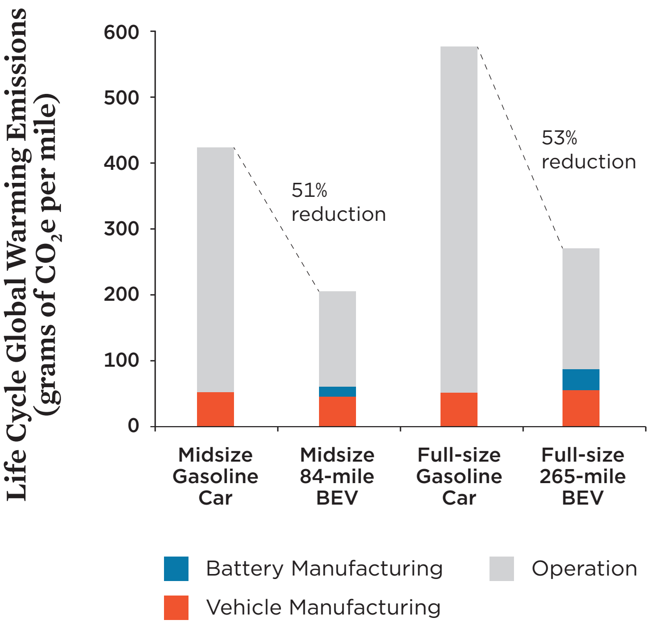
Emissions from operating electric vehicles are likely to keep falling, as national data from 2013 to 2015 show a declining percentage of electricity generated by coal power and an increase in renewable resources such as wind and solar. Additionally, the Clean Power Plan finalized by the U.S. Environmental Protection Agency (EPA) in 2015 offers opportunities for even greater progress, as states must collectively cut their 2005 power-sector carbon emissions 32 percent by 2030. Meanwhile, many EV owners are pairing electric vehicle purchases with home investments in solar energy. With increasing levels of renewable electricity coming onto the grid, with carbon standards for fossil-fuel power plants beginning to be implemented, and with continued improvements in vehicle technologies, the emissions-reduction benefits of EVs will continue to grow.

Global Warming Emissions from Manufacturing Battery-Electric Vehicles

Global warming emissions occur when manufacturing any vehicle, regardless of its power source, but BEV production results in higher emissions than the making of gasoline cars—mostly due to the materials and fabrication of the BEV lithium-ion battery. Under the average U.S. electricity grid mix, we found that producing a midsize, midrange (84 miles per charge) BEV typically adds a little over 1 ton of emissions to the total manufacturing emissions, resulting in 15 percent greater emissions than in manufacturing a similar gasoline vehicle. However, replacing gasoline use with electricity reduces overall emissions by 51 percent over the life of the car.

A full-size long-range (265 miles per charge) BEV, with its larger battery, adds about six tons of emissions, which increases manufacturing emissions by 68 percent over the gasoline version. But this electric vehicle results in 53 percent lower overall emissions compared with a similar gasoline vehicle (see Figure ES-2).

FIGURE ES-2. Life Cycle Global Warming Emissions from the Manufacturing and Operation of Gasoline and Battery-Electric Vehicles



Note: We assume that the midsize vehicles are driven 135,000 miles over their lifetimes and the full-size vehicles 179,000 miles. The difference in the two mileages derives from the dissimilar uses of 84-mile-range and 265-mile-range battery-electric cars, as described in Chapter 2. We further assume that a consumer buying a BEV would drive it the same total of miles as a corresponding gasoline vehicle. We use U.S. average electricity grid emissions to estimate manufacturing emissions, while the average electricity grid emissions intensity during vehicle operation are based on a sales-weighted average of where EVs are being sold today.

> ***The extra emissions associated with BEV manufacturing can be rapidly offset by reduced emissions from driving.***

In other words, the extra emissions associated with electric vehicle production are rapidly negated by reduced emissions from driving. Comparing an average midsize midrange BEV with an average midsize gasoline-powered car, it takes just 4,900 miles of driving to "pay back"—i.e., offset—the extra global warming emissions from producing the BEV. Similarly, it takes 19,000 miles with the full-size long-range BEV compared with a similar gasoline car. Based on typical usages of these vehicles, this amounts to about six months' driving for the midsize midrange BEV and 16 months for the full-size long-range BEV.

Meanwhile, the global warming emissions of manufacturing BEVs are falling as automakers gain experience and improve production efficiency. With a focus on clean manufacturing, emissions could fall even more. There are many ways in which the EV industry might reduce these manufacturing-related emissions, including:

- Advances in manufacturing efficiency and in the recycling or reuse of lithium-ion batteries;
- The use of alternative battery chemistries that require less energy-intensive materials; and
- The use of renewable energy to power manufacturers' and suppliers' facilities.

Recommendations

To accelerate the U.S. transition to a low-carbon future, we recommend the following:

- Under the EPA's Clean Power Plan, states should develop and implement strong compliance plans that prioritize renewable energy and energy efficiency in meeting their emissions-reduction targets.
- Policy makers at all levels of government should adopt new or strengthened policies and programs for increasing energy efficiency and the deployment of renewable energy. These options include renewable electricity standards, energy-efficiency resource standards, carbon-pricing mechanisms, tax incentives and other financial incentives,

and improvements in grid operation, transmission, and resource planning.

- Government and the private sector should support more research aimed at decreasing the global warming emissions associated with making electric vehicles' batteries, increasing the efficiency of their operation, and improving the processes for battery recycling or reuse. By supporting this emerging sector, we can help encourage manufacturers not only to reduce manufacturing emissions but also to lower the batteries' costs.
- To increase the benefits of electric vehicles—especially those in regions where global warming emissions from electricity generation are higher than the U.S. average—policies should support consumers who consider investing in cleaner sources of electricity, such as by installing rooftop solar photovoltaic systems or purchasing renewable energy credits.
- Electric vehicle makers and their suppliers should raise the percentage of renewable electricity they use to build these cars. The Union of Concerned Scientists estimates that, with a future 80 percent renewable electricity grid, manufacturing emissions alone could decrease by more than 25 percent compared with manufacturing BEVs today.

> ***To reach their full potential, EVs must account for a larger share of vehicle sales while the electricity grid shifts from coal to low-carbon renewable sources.***

Electric vehicles provide benefits both in carbon emissions and oil savings, with the greatest emissions benefits occurring in regions with the lowest-carbon electricity sources. To reach their full potential, EVs must account for a larger share of vehicle sales while the electricity grid shifts from coal to low-carbon renewable sources. Moving forward with both of these transitions constitutes a critical strategy for cutting projected oil use in half over the next 20 years and putting the United States on a trajectory toward net-zero climate emissions by mid-century.

[INTRODUCTION]

Electric vehicles (EVs) are becoming a critical part of the American transportation future because they can dramatically cut global warming emissions, especially when charged by a clean-electricity grid. Together with other oil-saving approaches—such as more efficient vehicles and advanced biofuels— EVs can help achieve the goal, advocated by the Union of Concerned Scientists (UCS) and others, that the United States cut projected oil use in half over the next 20 years. EVs will also be an essential part of any plan for proposed deep emissions reductions for avoiding the worst impacts of climate change (UCS 2012).

But EVs are not global warming emissions–free. They produce emissions, for example, during generation of the electricity required to charge the vehicles. The 2012 UCS report *State of Charge* examined the global warming emissions from operating an EV in different areas of the United States, and the authors found that in every region, driving the average EV produced lower global warming emissions than driving the average new gasoline car (Anair and Mahmassani 2012). Since *State of Charge* was published, those EV-related emissions have become even lower in many parts of the country. Electricity generation has been getting cleaner—coal-fired generation has declined while lower-carbon alternatives have increased—and electric vehicles are becoming more efficient. For example, the Nissan LEAF—the most popular battery-electric vehicle (BEV),[1] powered completely by electricity—now has greater efficiency than before, and other even more efficient BEV models, such as the BMW i3, have come to market.

However, global warming emissions from driving an EV are not the full story. We must be attentive to the "bottom line"—the vehicle's *overall* global warming emissions during its life cycle—which takes into account its operation, production, and disposal. The manufacture of EV batteries, for example, is of particular concern regarding global warming emissions.

This report compares battery-electric cars with similar gasoline cars by examining their global warming emissions, both from driving and manufacturing, over their lifetimes (see Figure 7, p. 21). Toward that end, we performed up-to-date assessments of the carbon footprints of BEVs, taking into account the latest information about electricity generation and BEV models.

We proceeded by addressing the following two key questions, whose successive answers gave rise to Chapters 1 and 2:

1) **What are the global warming emissions from operating an electric vehicle today?** We updated our previous *State of Charge* emissions analysis from 2012, using the latest available information on regional electricity grid emissions and current EV models. We thus derived new estimates of the miles-per-gallon rating a gasoline-powered vehicle would need in order to equal the emissions of a comparable EV charged on the regional electricity grid.

2) **How much does the manufacturing of BEVs affect their total global warming emissions benefits?** Broadening the scope from UCS's previous analysis, we examined the impact of BEV manufacturing on the vehicles' global warming emissions. We used the Argonne National Laboratory's vehicle manufacturing emissions model to analyze two composite vehicles representing midsize and full-size BEVs. These composites were similar, respectively, to the two best-selling BEVs in the United States: the Nissan LEAF (an 84-mile-range car) and the Tesla Model S (a 265-mile-range car).[2] We then compared our results with the global warming emissions from the manufacturing of like gasoline cars.

This report also discusses the global warming emissions consequences of what may be done with the BEV after it has finished its useful life. The disassembly of the vehicle, the recycling of its parts, and the disposal of its battery are briefly addressed in Chapter 2. Despite our conservative estimates of the global warming emissions from these end-of-life processes, they account for only a small fraction of the life cycle totals for BEVs—and for gasoline cars.

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[1] *In this report, EVs refer both to plug-in hybrid vehicles (such as the Chevrolet Volt) and battery-electric vehicles such as the Nissan LEAF, while BEVs refer specifically to battery-electric vehicles.*

[2] *The Tesla Model S has numerous configurations; for our analysis, we used a rear-wheel-drive model with a battery rated at 85 kilowatt-hours (kWh).*

[CHAPTER 1]

Global Warming Emissions from Driving Electric Vehicles

A vehicle's largest contribution of global warming emissions comes from its fuel consumption. In the case of gasoline vehicles, these emissions are the result of burning gasoline in the engine—and also of producing that fuel in the first place. With electric vehicles, which have little to no global warming emissions at the tailpipe during operation, these emissions are produced indirectly—from generating the electricity used to charge the vehicles' batteries and from producing the fuels to enable that electricity's generation.

In comparing electric and gasoline vehicles in 2012, our *State of Charge* report found that in every region of the United States, EVs produced lower global warming emissions than the average compact gasoline vehicle. However, because the sources of electricity varied across the country, some electric vehicles were cleaner in some regions than in others (Anair and Mahmassani 2012).

Over the three years since *State of Charge* was published, two major changes have occurred:

1) The efficiencies of EVs have improved, while the number of available models has widened. For example, the most popular BEV, the Nissan LEAF, and the most popular plug-in hybrid electric vehicle, the Chevrolet Volt, have undergone improvements to increase their efficiencies; and the most lightweight and efficient BEV so far, the BMW i3, has come to market.
2) The way we produce electricity across the country has been evolving. Coal use in power plants has declined, and lower-carbon sources of electricity have been used more often.

These changes have lowered the global warming emissions of operating an electric vehicle, making it, in more parts of the country, the most effective vehicle for reducing global warming emissions today.

In the next two sections of this chapter, we describe the methodologies for determining EV global warming emissions by region. In the three sections that follow, we deepen our discussion of the two kinds of major changes cited above. We then specify what individual EV owners might do to "beat the average," and in the final section we build on the chapter's overall content to provide a look into the future.

> ***The efficiencies of EVs have improved, the number of available models has widened, and lower-carbon electricity sources are now used more often.***

Methodology for Comparisons

In comparing EVs' global warming emissions with gasoline vehicles' emissions, we take a "well-to-wheels" approach that accounts for the full fuel cycle for both types of vehicles.

To assess the global warming emissions from charging electric vehicles, we address all contributions from electricity production. This includes: (1) emissions that result from extracting raw materials, such as coal mining or natural gas drilling, and from delivering these resources to the power plants; (2) emissions from burning the fuel in the power plant to generate electricity; (3) electricity losses that occur during distribution from the power plant to the point where the electric vehicle is plugged in; and (4) the efficiency of the vehicle in using electricity.

To assess the global warming emissions from a comparable gasoline vehicle, we address emissions that result from: (1) oil extraction at the well; (2) transporting the crude oil to a refinery; (3) refining the oil into gasoline; (4) delivering the fuel to the gas station; and (5) combusting the fuel in the engine of the vehicle.

STANDARDIZING THE UNITS OF COMPARISON: MPG$_{GHG}$

Most drivers are familiar with the concept of miles per gallon (MPG), the number of miles a car travels on a gallon of gasoline. The greater its MPG, the less fuel burned and the lower the car's global warming emissions. But how can such emissions be figured for electric vehicles, which don't use gasoline? One way is by determining how many miles per gallon a gasoline-powered vehicle would need to achieve in order to match the global warming emissions of driving an EV.

The first step in this process is to calculate the global warming emissions that result from generating the electricity needed to charge a vehicle. Then we convert this estimate into a gasoline miles-per-gallon equivalent—designated MPG$_{ghg}$, where ghg stands for greenhouse gas emissions. If an electric vehicle has an MPG$_{ghg}$ value equal to the MPG of a gasoline-powered vehicle, both vehicles will produce the same amount of global warming emissions for each mile traveled.

For example, if one were to charge a typical midsize BEV using electricity generated by coal-fired power plants, that BEV would have an MPG$_{ghg}$ of 29. In other words, the global warming emissions from driving it would be equivalent to the emissions from operating, and producing the fuel for, a gasoline vehicle with a 29 MPG fuel economy rating over the same distance (see Table 1).[3] Under this equivalency, the cleaner an electricity generation source, the higher the MPG$_{ghg}$. When charging a BEV from sources such as wind or solar, for example, the MPG equivalent is in the hundreds (or thousands) because these options produce no global warming emissions when generating electricity.

Finally, when estimating emissions from charging an electric vehicle, we use regional *average emissions* (averaged over the full mix of a region's electricity sources). An alternative approach is to consider only *marginal emissions*: emissions from the power plants that operate to meet new electricity demand on the grid. While the use of the marginal generation mix for electric vehicles is important for evaluating EV global warming emissions at a particular time, average generation provides more practical emissions information to consumers regarding a vehicle they might purchase and operate today. Note that no region gets electricity solely from one source, but rather from a mix of the electricity generation fuels listed in Table 1. Further discussion on this issue is provided in Appendix D.

TABLE 1. Well-to-Wheels BEV Miles-per-Gallon Equivalent (MPG$_{ghg}$) by Electricity Source

Electricity Source[1]	Gasoline Vehicle Emissions Equivalent (MPGghg)[2,3]	% Reduction from Average New 2014 Car[4]
Oil	29	0%
Coal	29	1%
Natural gas	58	51%
Geothermal	310	91%
Solar	350	92%
Nuclear	2,300	99%
Wind	2,500	99%
Hydro	5,100	99%

Notes:

(1) Represents electricity available at the wall outlet and includes emissions from power plant feedstocks (e.g., coal mining) and power plant combustion. Power plant construction emissions are also included; they are the only emissions associated with solar, wind, geothermal, and hydro sources.

(2) Gasoline vehicle emissions equivalents account for oil extraction and refining of crude oil, but not refinery construction.

(3) Average new car (excluding truck) fuel economy for model year 2014 is 28.7 MPG. Sources: EPA 2014; ANL 2014A.

(4) To calculate the MPG$_{ghg}$ estimate, we use the 2014 average sales-weighted efficiency of 0.33 kWh/mile, regarding both plug-in hybrid and battery-electric vehicles (see Table 3, p. 10).

Rating the Regions

To further help consumers evaluate the global warming benefits of electric vehicles in comparison with gasoline vehicles, we developed ratings in our *State of Charge* report—Good, Better, and Best—to characterize the country's different regions (see Table 2, p. 8).

GOOD

In regions rated Good, EVs are similar to the best conventional gasoline vehicles and some hybrids (31 to 40 MPG$_{ghg}$). That

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3 Note that MPG values in this report refer to combined city/highway operation estimates and that U.S. EPA window-label values should be used as the basis of comparison between specific vehicle models.

EVs are appealing not only to individual consumers but also to state and local governments. By generating lower global warming emissions, these vehicles (such as the plug-in hybrid truck above, tested by Massachusetts' public transit agency) are an important tool in city and state efforts to meet emissions-reduction targets.

is, driving a typical electric vehicle in these regions will result in global warming emissions equivalent to gasoline vehicles with a combined city/highway fuel economy rating of 31 to 40 MPG. This level is better than that of the average new gasoline car (29 MPG) on the market today (EPA 2014).

BETTER

EVs rated Better correspond to the most efficient hybrids (41 to 50 MPG_{ghg}). The most efficient gasoline hybrids, such as the Honda Insight and the Toyota Prius, are in this category, though the model year 2016 Toyota Prius is expected to exceed 50 MPG (Voelcker 2015).

BEST

Driving a typical EV in these regions is equivalent to gasoline-powered vehicles with a combined city/highway fuel economy of more than 50 MPG_{ghg}. While the most efficient gasoline hybrids are approaching this level of efficiency, electric vehicles can go well above—even exceeding 100 MPG_{ghg}. EVs are the best choice in these regions for reducing global warming emissions and cutting oil use.

Expanding EV Options and Improving Vehicle Efficiency

Since 2010, when the Chevrolet Volt (a plug-in hybrid [PHEV] powered by batteries and a conventional gasoline engine) and the Nissan LEAF (a BEV) came to market, automakers—spurred by government policy and consumer demand—have commercially introduced new and updated EV models. At this writing (in November 2015), consumers may choose from among 21 different kinds, offered mostly in California (see Figure 1).

Electric vehicles vary in how far they can go on a kilowatt-hour (kWh) of electricity. For example, the 2014 Nissan LEAF is estimated to consume 0.30 kWh of electricity per

TABLE 2. Global Warming Emissions Rating Scalen for Electric Vehicles

EV Regional Global Warming Emissions Rating	Good	Better	Best
EV Global Warming Emissions Equivalent (MPG_{ghg})[1]	31–40	41–50	51+
What Does It Mean Regarding EV Global Warming Emissions?	EVs have emissions comparable with the most efficient non-hybrid gasoline models available	EVs have emissions comparable with the most efficient 2015 gasoline hybrid models available	EVs outperform the most efficient 2015 gasoline hybrid models available today
Examples of Model Year 2015 Gasoline and Hybrid Vehicles[2]	Honda Fit (36 MPG) Ford Focus SFE (36 MPG) Chevrolet Cruze Eco (33 MPG)	Toyota Prius (50 MPG) Honda Accord Hybrid (47 MPG) Volkswagen Jetta Hybrid (42 MPG)	No gasoline or diesel comparisons in model year 2015

Notes:
(1) Assumes 10,881 grams of global warming pollution per gallon of gasoline and average EV efficiency of 0.333 kWh/mile.

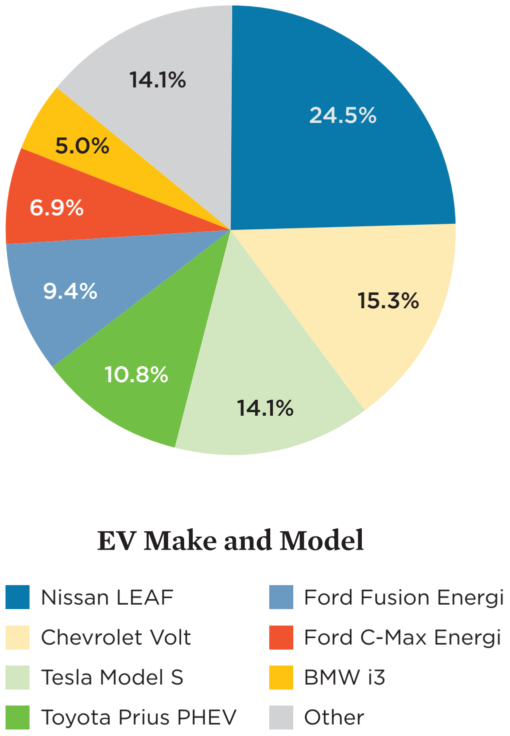
(2) Model year 2015 combined city/highway fuel economy window-label value. Data from the 2015 Fuel Economy Guide are available at EPA 2015a. All vehicles given as examples are classified by the EPA as midsize or smaller.

mile traveled, while the BMW i3 consumes 0.27 kWh/mile and the Tesla Model S consumes 0.38 kWh/mile (DOE 2015a).[4] Each vehicle's design and capabilities determine its energy efficiency, as is the case for gasoline vehicles. For example, the Tesla is a full-size BEV with substantial battery capacity, which allows to it go farther on a single charge. Such features also add to its weight, causing the Tesla to use more electricity than a smaller, lighter-weight, shorter-range electric vehicle in going the same distance. Even for vehicles of similar size (or footprint), changes in design can affect vehicle efficiency. The BMW i3, for example, is similar in size to the Nissan LEAF but has greater efficiency, due in part to a carbon-fiber body that helps reduce its overall weight.

Since our *State of Charge* analysis in 2012, efficiency has also improved in existing models such the Chevrolet Volt and Nissan LEAF. The 2014 LEAF, for example, represented a 12 percent improvement in efficiency compared with the 2011 LEAF, a result of vehicle upgrades that included better regenerative braking, improved aerodynamics, and a more efficient heater. The Chevrolet Volt also improved its electric-drive efficiency between model years 2011 and 2014, and the new redesigned 2016 model boasts even better performance. See Table 3 (p. 10) for a list of the top-selling EVs and their energy efficiencies.

Also since our 2012 report, the combination of recent model introductions and upgrades to existing models has affected the overall efficiency of the full electric vehicle fleet. Given the few models available at the time, the efficiency of the 2011 Nissan LEAF—0.34 kWh/mile—was chosen as representative of EV efficiency. However, there are now sufficient sales of EVs to use an average EV efficiency; based on sales data for the 2014 calendar year, that average efficiency is now 0.33 kWh/mile—a 3 percent improvement from the efficiency of the 2011 LEAF. The improvement in overall EV efficiency means that electric vehicles are on average going farther on a kilowatt-hour of electricity, resulting in lower emissions per mile.

FIGURE 1. Percent of Electric Vehicle Sales by Make and Model for Model Year 2014



Note: "Other" includes EVs produced by BMW, Cadillac, Chevrolet, Fiat, Ford, Honda, Kia, Mercedes, Mitsubishi, Porsche, Toyota, Smart, and Volkswagen.

SOURCE: INSIDEEVS 2015.

An Improving Electricity Grid

The sources of energy used to generate electricity in the United States have been changing, with a consequent reduction in "emissions intensity"—the average global warming emissions emitted from producing a given amount of electricity. Sustained lower natural gas prices have led to a declining share of coal-fired power (one of the highest-polluting sources of electricity) and a rising share of electricity generated from natural gas. The deployment of renewable energy sources, such as solar and wind, have also contributed to the electricity grid's improvements.

Figure 2 (p. 11) shows how the primary sources of U.S. electricity generation have changed between 2009 (the year on which our previous estimates of EV global warming emissions were based) and 2012 (the most recent year for which data are available, at this writing, from the EPA's eGRID database[5]). Coal power remains the predominant source of electricity in the United States. However, the last several years

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[4] *The Nissan LEAF has a 24 kWh battery, the BMW i3 has a 22 kWh battery, and the Tesla Model S has a 85 kWh battery. Note the Tesla Model S is available in more battery sizes.*

[5] *The EPA periodically publishes the Emissions & Generation Resource Integrated Database (eGRID) of power plant electricity generation and emissions for 26 electricity grid regions around the country (EPA 2015C). These data are the basis for our regional emissions analysis of electric vehicles for 2009 and 2012 in Figure 3 (p. 12) and Figure 4 (p. 13).*

TABLE 3. Electric Vehicle Efficiency Ratings

2014 Models	Tesla Model S (265-mile range)	Tesla Model S (208-mile range)	Chevrolet Volt	Nissan LEAF (84-mile range)	Plug-in Prius	2014 Sales-Weighted Average of All EVs
EV Type	BEV	BEV	PHEV	BEV	PHEV	BEVs and PHEVs
Electric Efficiency (kWh/mile)	0.38	0.35	0.35	0.30	0.29	0.33

Notes: The plug-in Prius uses a small amount of gasoline when operating from battery power (charge depleting mode). The efficiency numbers here represent only the electricity consumed per mile.

SOURCE: DOE 2015A; IHS 2015.

have seen a substantial shift toward other sources of electricity, including natural gas and renewables. The share of coal in powering the nation's electricity grid dropped from 44 percent in 2009 to 37 percent in 2012. Natural gas increased by a similar amount, producing 30 percent of the nation's electricity in 2012, up from 23 percent in 2009. Non-hydro renewable electricity (biomass, wind, and large-scale solar), while still a small portion of the national grid mix, increased significantly, surpassing 5 percent of utility-level electricity generation.

These figures represent the average change across the 26 electricity grid regions of the United States. Changes in the grid mix of each region affect the emissions from electricity generation for that region, affecting in turn the estimates of global warming emissions from electric vehicles being operated in that region. These changes are discussed next.

Regional EV Emissions: Main Findings

Using the most recently available regional emissions data, we find that electric vehicles are not only getting cleaner but also becoming the best choice for more Americans aiming to help cut global warming emissions and slash oil consumption. Figure 3 (p. 12) shows, for each U.S. electricity grid region, the fuel economy rating that a gasoline vehicle would need in

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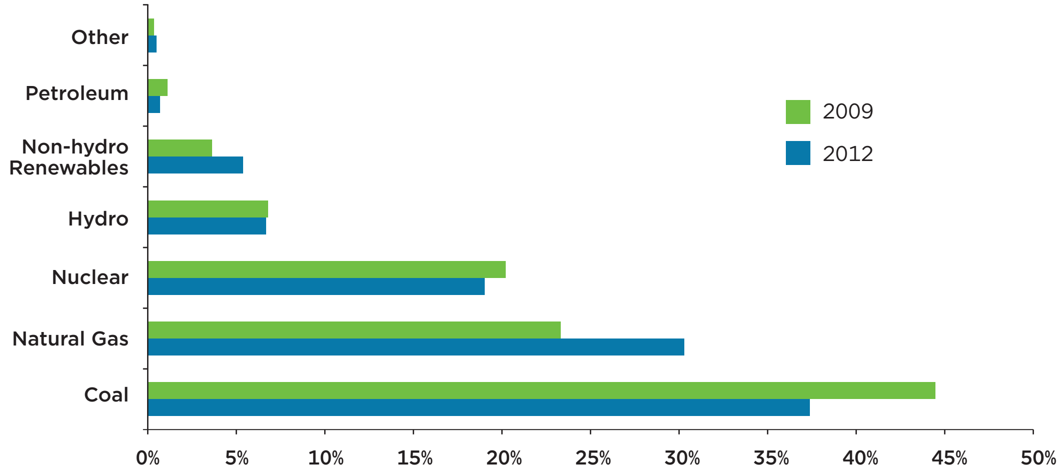
On average, battery-electric vehicles produce less than half the global warming emissions of comparable gasoline-powered vehicles; these emissions savings increase in regions of the country that get more of their electricity from renewable resources.

FIGURE 2. Percent U.S. Electricity Generation by Fuel Type for 2009 and 2012



Note: Non-hydro renewables include wind, solar, and geothermal electricity generation.

SOURCES: EPA 2015C; EPA 2012A.

order to achieve the same global warming emissions as the average EV. The numbers of Figure 3 are based on 2012 power plant emissions data. For comparison, Figure 4 (p. 13) shows the updated figures using power plant emissions from 2009.

Given these updated circumstances, our main findings are as follows:

As a result of a cleaner electricity grid and improved efficiency of electric vehicles, emissions from charging an electric vehicle on the grid have improved in 76 percent of the regions over the past three years. Twenty out of 26 regions saw reduced emissions from EVs because of regional changes in the mix of electricity sources. The biggest improvements occurred in the Pacific Northwest, where coal and natural gas generation dropped nearly 10 percent—with replacements largely by hydropower and wind—resulting in a greater than 20 percent decrease in the emissions intensity of electricity generation.

Driving an EV in any region of the country produces less global warming pollution than the average new gasoline car. Even on the dirtiest U.S. regional electricity grid, EVs produce the global warming emissions equivalent of a 35 MPG gasoline vehicle—a 21 percent improvement over the new gasoline car's average fuel economy of 29 MPG.[6] On the cleanest electricity grids, including those covering parts of California and New York, EVs emit lower global warming emissions than a gasoline vehicle rated at more than 85 MPG. This results in the cutting of global warming emissions by 70 percent or more, compared with the average new gasoline car in these areas.

> ***Emissions from charging an electric vehicle on the grid have improved in 76 percent of the regions over the past three years.***

Up from just 45 percent three years ago, about 66 percent of Americans now live in regions where powering an EV on the regional electricity grid produces lower global warming emissions than a 50 MPG gasoline car (Figure 5, p. 14). And down from 17 percent three years ago, only 12 percent of Americans now live in the lowest-rated regions, where powering an EV on the regional electricity grid produces global warming emissions similar to that of the best non-hybrid gasoline cars. Electricity grid improvements and improved EV efficiency mean several new regions of the country are now "Best" regions, including Florida and Texas. In these locales, EVs powered by the regional electricity grid do better than a 50 MPG gasoline vehicle on global warming emissions.

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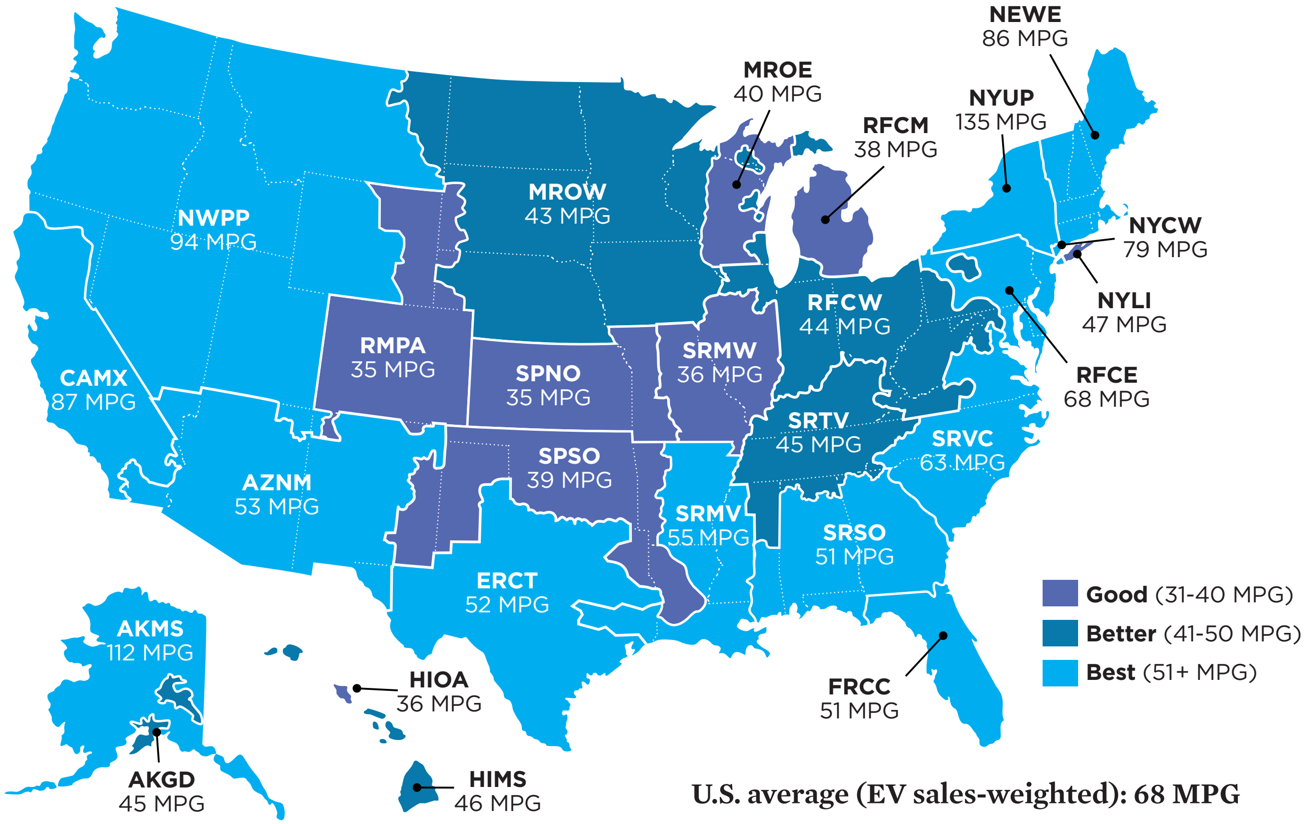
[6] *For the model year 2014, the EPA Trends report estimates average new car fuel economy, excluding trucks and SUVs, to be 28.7 MPG (EPA 2014).*

FIGURE 3. Electric Vehicle Global Warming Pollution Ratings and Gasoline Vehicle Emissions Equivalents by Electricity Grid Region for 2012



Note: The MPG (miles per gallon) value listed for each region is the combined city/highway fuel economy rating of a gasoline vehicle that would have global warming emissions equivalent to driving an EV. Regional global warming emissions ratings are based on 2012 power plant data in the EPA's eGRID 2015 database (the most recent version). Comparisons include gasoline and electricity fuel production emissions. The 68 MPG U.S. average is a sales-weighted average based on where EVs were sold in 2014.

SOURCE: EPA 2015C; IHS 2015.

Based on 2014 EV sales data, the average EV in the United States produces global warming emissions while driving similar to a 68 MPG gasoline vehicle, thereby cutting emissions 60 percent compared with the average new gasoline car. In 2014, approximately half of all EVs sold were in California, where plugging in produces emissions similar to that of an 87 MPG gasoline vehicle. Using data on new EV registrations across the country in 2014, we estimate that the sales-weighted average MPG$_{\text{ghg}}$ for EVs is 68 MPG, which means they produce less than half the emissions of the average new car while driving (IHS 2015).

Beating the Average with Cleaner Electricity

Our analysis of global warming emissions from charging an electric vehicle is based on the average mix of electricity sources in a given region. This provides an estimate of how EVs perform *on average* in each region. However, individual EV owners may be able to achieve lower-than-average emissions. Some utilities within the region may rely on cleaner sources of electricity than the regional average, many EV consumers may pair their EV purchase with rooftop solar, and green power programs may provide additional opportunities to heighten the global warming benefits of today's EVs.

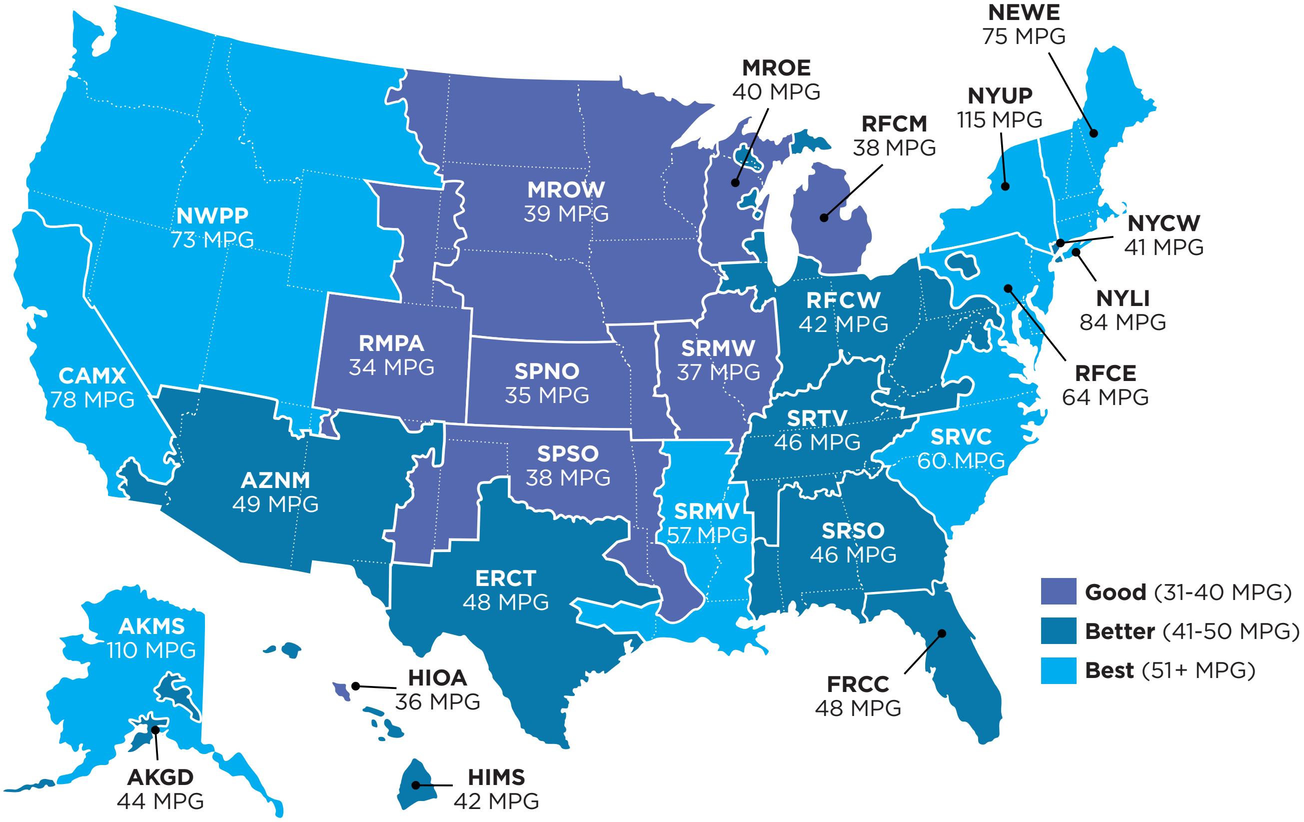
PAIRING EVS WITH ROOFTOP SOLAR

A 2013 survey of new EV owners in California, which represents more than 40 percent of the market for EVs, found that 32 percent of respondents had solar photovoltaic (PV) systems in their homes. An additional 16 percent indicated they planned to install a PV system in the future (CCSE 2013).

GREEN POWER PROGRAMS

Not everyone has the option of installing solar panels to

FIGURE 4. Electric Vehicle Global Warming Pollution Ratings and Gasoline Vehicle Emissions Equivalents by Electricity Grid Region for 2009



Note: The MPG value listed for each region is the combined city/highway fuel economy rating of a gasoline vehicle that would have global warming emissions equivalent to an EV. Regional global warming emissions ratings are based on 2009 power plant data in the EPA's eGRID 2012 database. Comparisons include gasoline and electricity fuel production emissions.

SOURCE: EPA 2012A.

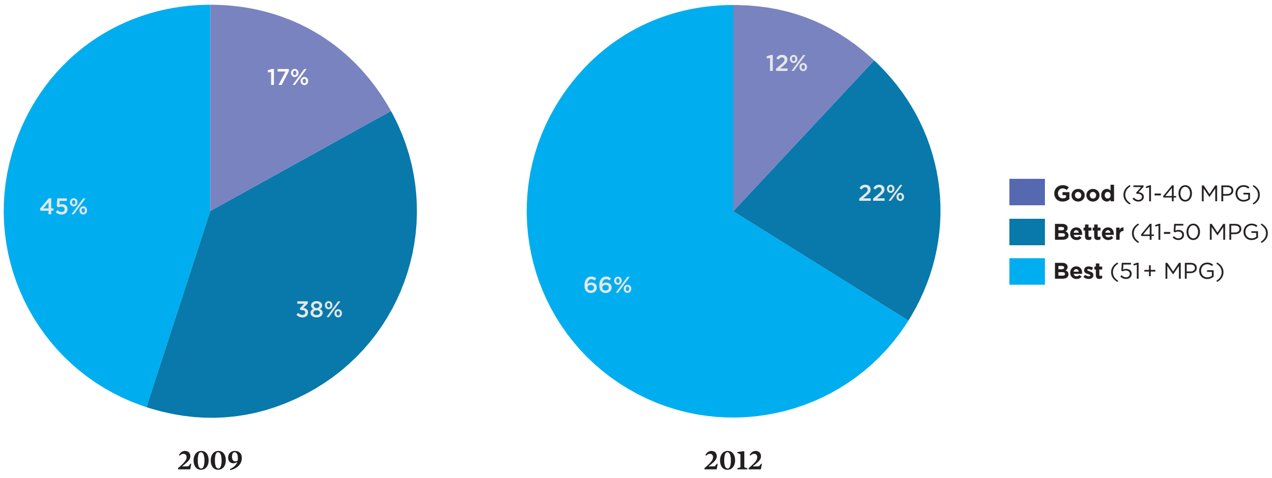
> ***By providing additional revenue for renewable energy projects, the purchase of RECs can help to increase the supply of renewable electricity.***

power their EV. But participating in a green power program offered by your utility, or independently purchasing renewable energy certificates, are two additional ways of supporting renewable energy.

According to the U.S. Department of Energy (DOE), nearly 850 utilities across the nation are offering some type of green pricing program (DOE 2015b; EPA 2015a). These initiatives allow consumers, by paying a small premium for renewable electricity, to support their utility's greater investment in renewables (Swezey and Bird 2001). The types of renewables and program details vary by utility (EPA 2015a). In some deregulated utility markets, consumers have the ability to choose their power provider. In those locales, choosing a provider that supplies electricity from renewable sources or that maintains a green pricing program may be distinct options. States offering this type of choice for at least some consumers include California, Connecticut, Illinois, Maine, Maryland, Massachusetts, New Jersey, New York, Pennsylvania, Rhode Island, Texas, and Virginia. The District of Columbia offers such a choice as well (DOE 2015b).

Purchasing renewable energy certificates (RECs), which are available nationwide, is another option. RECs are directly tied to electricity generated by renewable sources and are

FIGURE 5. Electric Vehicle Global Warming Emissions Ratings by Population



Note: Global warming emissions ratings are based on 2012 and 2009 power plant data in the EPA's eGRID 2015 and 2012 databases, respectively.

sold in a voluntary market (CRS 2015). By providing additional revenue for renewable energy projects, the purchase of RECs can help to increase the supply of renewable electricity (Heeter, Belyeu, and Kuskova-Burns 2014).

When reviewing options for buying green power, consumers should look for the Green-e certification label, which indicates that the products have been independently verified (see *www.green-e.org*).

ESTIMATES BY STATE OR INDIVIDUAL UTILITY

Finally, particular states or utilities within a region may have lower or higher emissions than the regional average, based on the types of power purchases they make. Utilities procure electricity from (1) power plants that they own, (2) direct contracts with owners of other power plants, (3) short-term purchases through the regional power grid, and (4) trades across regions. Emissions data at the individual utility level are not consistently or readily available across the country, which is in part why this report uses grid-level information for its primary estimates.

Similarly, individual states within a region may have cleaner or dirtier electricity than the regional average, based on the sources of energy used by the utilities in those states. In Washington, for example, carbon dioxide emissions associated with the power delivered to customers in the state are reported by utilities, which supply a great deal of renewable electricity (WA DOC 2015). Using data specific to Washington, an EV charged with electricity in that state averages more than 150 MPG_{ghg}, compared with the regional average of 94 MPG_{ghg} (UCS 2015).

States and utilities can help consumers determine how clean their electricity is by disclosing data on emissions and on electricity produced and consumed. Efforts have been made in this regard, and some utilities also report to their customers the specific mix of energy sources that generate their electricity (CEC 2015).[7] However, such disclosures are not consistent across all utilities, and they often do not contain an estimate of the actual emissions intensity of the delivered electricity.

Table A-1 (p. 34) provides the grid mix for each region. If a utility does provide a breakdown of its sources of electricity, consumers can compare that utility's mix with the regional mix. As a general rule of thumb, its percentage of coal indicates whether the utility is providing electricity that has higher or lower global warming emissions intensity than the regional average.

The Future of EV Emissions

While electric vehicles have begun to reduce global warming emissions today, if EVs are to deliver on their full potential—if they are to help us avoid the worst consequences of climate change—we must move systematically in the coming years to a clean-power grid. That is, a "decarbonizing" of the transportation and electricity sectors over the next several decades, in

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[7] *For example, California requires utilities to provide a Power Content Label specifying the mix of generation sources that are supplying their customers, but no emissions intensity values need to be reported. See* CEC 2015.

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As the United States develops more renewable energy resources, electric vehicles will become even cleaner.

> ***If EVs are to deliver on their full potential we must move systematically in the coming years to a clean-power grid.***

the United States as well as in other countries, is needed.

Standards to reduce global warming emissions from electricity generation are invaluable for moving the United States away from high-pollution sources such as coal. Several individual states—including California and the nine Northeast states participating in the Regional Greenhouse Gas Initiative—have adopted such standards and are successfully implementing them.

In August 2015, the EPA finalized the first-ever national standards for cutting power sector carbon emissions. Under the Clean Power Plan, states are collectively required to reduce power plant carbon emissions by 32 percent below 2005 levels by 2030. The plan provides for a number of options to cut carbon emissions, including investing in renewable energy, energy efficiency, natural gas, and nuclear power; and shifting from coal-fired power. States have until September 2016 to submit their final compliance plans, and emission reductions must begin in 2022 (EPA 2015b).

By 2050, much greater deployment of renewable energy sources could lower global warming emissions even further. UCS has modeled a scenario in which, by mid-century, 80 percent of U.S. electricity is produced from renewable sources (Cleetus et al. 2014; Mai et al. 2012). Under this scenario, electricity emissions intensity is reduced to below 100 grams of carbon dioxide–equivalent emissions (CO_2e) per kWh of electricity generated (g/kWh), resulting in global warming emissions from electric vehicles comparable with 300 MPG_{ghg} gasoline vehicles.

[CHAPTER 2]

Global Warming Emissions from Manufacturing Electric Vehicles

The use of different parts, materials, and processes to build components unique to electric vehicles means that global warming emissions from building a battery-electric vehicle differ from those of building comparable gasoline vehicles. The relative significance of those two sets of emissions differs as well. With gasoline cars, we have found that vehicle operation accounts for almost 90 percent of the lifetime global warming emissions, making the manufacturing emissions a smaller portion of the life cycle burden. By contrast, BEVs produce lower emissions during operation, with emissions from manufacturing being a more significant contributor to the total life cycle emissions.

To determine the impact of manufacturing emissions on the overall global warming emissions benefits of EVs, we modeled two common configurations of battery-electric vehicles available today: an 84-mile-range midsize BEV and a 265-mile-range full-size BEV.

How the Manufacturing of BEVs Differs From That of Gasoline Cars

Unlike gasoline vehicles, BEVs have no fuel tank or internal-combustion engine but instead have a battery pack, electric-drive motor, power-control electronics, and regenerative braking systems (see Figure 6). The greatest difference in the manufacture of BEVs compared with gasoline vehicles is in the type and size of batteries required. Gasoline vehicles only have a small lead-acid battery for starting the engine and powering accessories while the engine is off, whereas BEVs rely on much larger lithium-ion batteries to power the vehicle itself.

> [***The greatest difference in the manufacture of battery-electric vehicles compared with gasoline vehicles is in the type and size of batteries required.***]

The energy-storage capacity of a BEV battery, measured in kWh, varies in different electric vehicle models and is a key factor in determining how far a vehicle can travel on a single charge.[8] The larger the battery, the greater the vehicle range; but also the greater the weight added to the vehicle and the greater the emissions from manufacturing the battery. For example, the 24 kWh battery for the Nissan LEAF, which allows a driving range of 84 miles and weighs about 650 pounds (Nissan 2015). The much larger 85 kWh battery in the Tesla Model S weighs about 1,200 pounds and carries the vehicle 265 miles (Tesla Motors 2015).

In addition to a large battery pack, BEVs also have differing components, such as the power train, transmission, and traction motor. These components are not a large portion of the vehicle's materials and weight (less than 15 percent); and

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[8] *Additionally, various battery chemistries are used for the batteries in different BEVs.*

FIGURE 6. Drivetrain Components of Battery-Electric Vehicles

Power-control electronics. Directs electricity from the batteries to the motor when driving or from brakes to batteries during regenerative braking. Directs electricity from the outlet to the batteries during recharging.

Battery pack. The battery cells, assembled into a battery pack, are recharged by plugging into an outlet or vehicle charger. When driving, the batteries provide power to the electric motor to turn the wheels as well as power to run accessories such as heating and cooling systems.

Regenerative braking. Conventional cars rely entirely on friction brakes to slow down, dissipating the vehicle's kinetic energy as heat. Regenerative braking allows some of that energy to be captured, turned into electricity, and stored in the batteries.

Electric drive motor. Converts electrical energy into mechanical energy to propel the car. Can deliver efficiency of more than 90 percent during driving and offers quick acceleration.

There are a number of differences between the components of battery-electric vehicles and gasoline vehicles (the most significant are shown above). The efficiency and range of electric vehicles on the market today vary based on the size, composition, and configuration of these components.

they replace the functionality of the engine, which is a large part of the gasoline vehicle's weight (about 30 percent) (ANL 2014b).

Similarly, battery-electric and gasoline vehicles tend to have different ratios of the materials—such as copper, aluminum, and steel—used to make the components. Weight and material composition of the vehicle determine the majority of global warming emissions from manufacturing it. More material means more global warming emissions; and some materials—depending on the processes involved from resource extraction all the way up to ultimate disposal—generate more emissions than others. For more information about the weight and composition differences of gasoline and electric vehicles, see Appendix B.

Choice of Vehicles for Modeling Manufacturing Emissions

Even within the electric vehicle community, not all BEVs are created equal. While all BEVs do use similar components, their designs and capabilities vary. The top-selling BEV models in 2014, the Nissan LEAF and Tesla Model S, reflect this diversity. The LEAF is a midsize five-seat car that travels 84 miles when fully charged, and the Model S is a full-size five- to seven-seat car with a range of 265 miles (DOE 2015a).[9,10] These two electric vehicles provided the basis for our estimates of global warming emissions from BEV manufacturing—in which we took into account both a midsize midrange car and a full-size long-range car. But we note that the

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[9] *We retrieved the data on vehicle model specifications from the Department of Energy (2015a).*

[10] *The Model S is available with different battery sizes. We chose the 2015 Model S that is equipped with an 85 kWh battery pack (rated at a 265-mile range).*

underlying data used for modeling in this analysis were not specific to any manufacturer. Given the difficulty in obtaining specific information about a company's supply chain, energy use, and specific component manufacturing processes, we made assumptions applicable to the industry as a whole and included vehicle specific attributes when possible.

Similarly, for the midsize and full-size gasoline vehicles used for comparison, we examined the fuel economy of several available gasoline models, similar in size to the corresponding BEVs, to arrive at an average MPG rating for comparison.

MIDSIZE MIDRANGE BEV

The midsize BEV we modeled was similar to a Nissan LEAF, reflecting the range, efficiency, battery size, battery chemistry, and vehicle weight (see Table 4). The LEAF's 24 kWh battery pack and efficiency rating of 0.3 kWh per mile allows it to travel an EPA-rated 84 miles on a single charge (DOE 2015a).

Data collected over the last several years on the Nissan LEAF show that the car's drivers put on about 9,000 miles per year, less than the 12,000 miles per year seen with typical gasoline-powered cars (Carlson et al. 2014). Total BEV lifetime mileage data are not available, given the short time these vehicles have been on the road, but extrapolating from early data we projected full lifetime to be about 135,000 miles, compared with the 179,000-mile average lifetime of gasoline vehicles (FHWA 2009). For consistency, we made our comparisons under the assumption of a 135,000-mile, 15-year lifetime for both midsize electric and gasoline cars. We also assumed that this lifetime mileage requires only one battery, which is similar to most other peer-reviewed life cycle assessments (Hawkins et al. 2013).

TABLE 4. Midsize Battery-Electric and Gasoline Vehicle Characteristics

	Midsize BEV	Comparable Gasoline Vehicle
Similar to 2015 Vehicle Model	Nissan LEAF	Average
Energy Efficiency	0.3 kWh/mile	29 MPG
Vehicle Curb Weight (lbs)	3,300	3,000
Vehicle Footprint (ft^2)	45	44
Range on Full Charge (miles)	84	-
Battery Capacity (kWh)	24	-
Number of Lithium-ion Batteries over Lifetime	1	-

Note: Our results, based broadly on these specifications and the manufacturing process emissions typical of the auto industry, are not specific assessments of any manufacturers. The average gasoline vehicle comparable to the midsize BEV is a composite of five gasoline vehicles available today (see Appendix B).

SOURCES: DOE 2015A; NISSAN 2015.

TABLE 5. Full-size Battery-Electric and Gasoline Vehicle Characteristics

	Full-size BEV	Comparable Gasoline Vehicle
Similar to 2015 Vehicle Model	Tesla Model S	Average
Energy Efficiency	0.38 kWh/mile	21 MPG
Vehicle Curb Weight (lbs)	4,700	4,300
Vehicle Footprint (ft^2)	54	53
Range on Full Charge (miles)	265	-
Battery Capacity (kWh)	85	-
Number of Lithium-ion Batteries over Lifetime	1	-

Note: Our results, based broadly on these specifications and the manufacturing process emissions typical of the auto industry, are not specific assessments of any manufacturers. The average gasoline vehicle comparable to the full-size BEV was a composite of five gasoline vehicles available today (see Appendix B).

SOURCES: DOE 2015A; TESLA MOTORS 2015.

For a comparable gasoline vehicle, we modeled a midsize car with a fuel economy of 29 MPG and a vehicle weight of 3,000 lbs. These specifications were chosen based on the average fuel efficiency and vehicle weight of several models similar in size to the Nissan LEAF, including the Ford Focus, Mazda 3, and VW Golf.

FULL-SIZE LONG-RANGE BEV

The full-size BEV we modeled was similar to a Tesla Model S, reflecting the larger vehicle size in terms of battery capacity and vehicle range, weight, and structure (see Table 5). Several battery sizes are available with the Model S; we chose to model the largest, 85 kWh. The full-size gasoline vehicle we modeled for comparison resembled the full-size BEV in terms of size (or footprint), with an average fuel economy of 21 MPG and average weight of 4,300 lbs. These characteristics were based on the average of several similar gasoline vehicles, including the Audi A8, Hyundai Equus, and Porsche Panamera (see Appendix B).

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Technicians test the performance of EV battery packs during vehicle manufacturing and assembly. Batteries increase EVs' manufacturing-related emissions compared with gasoline vehicles, but the excess manufacturing emissions are offset in 6 to 16 months of average driving.

ADDITIONAL ASSUMPTIONS

Battery life. For this analysis we expected the midsize and full-size BEV to need only one lithium-ion battery pack over its lifetime. As most BEVs on the road today were sold less than five years ago, there is little experience with actual long-term battery durability. However, many manufacturers offer warranties of 100,000 miles or more, indicating an expectation that the batteries will have acceptable performance for at least that distance. Early data on battery replacements are consistent with this assumption (DeMorro 2015), though we note that factors such as regional temperature and weather conditions may affect the longevity of the battery.

Regardless of climate, over time the effectiveness and range of the battery decreases during use. Such reductions would result in a loss of range in original battery capacity, but the battery could still meet the needs of most EV drivers (Saxena et al. 2015). We expect this reduction to be more important for a vehicle with shorter original range (under 100 miles) and less significant for a vehicle with longer range (greater than 200 miles). Whether BEVs typically get battery replacements, or find drivers who have suitable range requirements, or boast larger batteries (installed by manufacturers to maintain the car's residual value) will become clear over the next few years as the BEV market grows and matures.

Vehicle recycling. In this study we took into consideration the recycling rates of various materials and the energy and global warming emissions associated with recycling and disposing of vehicles at the end of their lives. Our assessment included recycling of vehicle components at levels that are typical today, but it did not include any recycling of the lithium-ion battery (due to limited data). As the scale of BEV use expands, the economic pressure to find second uses or recycling options for batteries will expand as well. To the extent this occurs, the emissions attributed to lithium-ion batteries in our analysis could decrease. For the other vehicle components, we used the recycling rates of similar materials—such as iron and aluminum—that the Argonne National Laboratory has collected from industry and that has been optimized in gasoline vehicles over time (Burnham 2012). Without recycling of the vehicle materials (excluding the batteries), the BEV's and gasoline car's global warming emissions from manufacturing each increase by about 15 to 20 percent. See Appendix C for these recycling rates and other related information.

Vehicle disposal. Vehicle disposal refers to vehicle components that are sent to a landfill. The literature suggests that the global warming emissions from disposing either of gasoline vehicles and BEVs are small, and similar for both vehicle types—except for the BEV battery (Nealer and Hendrickson 2015; Hawkins, Gausen, and Strømman 2012). We calculated

BOX 1.

Disposal Considerations

Our sensitivity analysis of battery disposal options shows that possible differences in end-of-life scenarios do not alter the conclusions of our life cycle assessment (see Appendix C). When gasoline cars reach the end of their service lives, they are disassembled for parts and materials that are either reused or recycled. Only a small remnant of the vehicle is sent to a landfill (American Recycler 2009). Assuming that most parts of BEVs are recycled similarly to gasoline cars, the only major difference will involve the BEVs' lithium-ion batteries. There are three possibilities for these batteries: reuse, recycle, or landfill.

Reuse. The lithium-ion battery at the end of the vehicle application is assumed to have 75 percent of its original capacity to store energy. The battery could then be used in other applications—for example, storage for intermittent renewable energy sources such as solar and wind. Such a second life for BEV batteries on the grid, after they are no longer being used by the car, could offset fossil fuel–related global warming emissions by displacing coal- or natural gas–based electricity generation.

Recycle. Parts or materials of the BEV lithium-ion battery can be recycled for use in new batteries—a service currently performed by two major companies: Umicore of Belgium and Retriev Technologies of the United States and Canada (Retriev Technologies 2015; Umicore 2015). The ability to recycle the battery materials or parts depends significantly on the design of the battery and the economics of recycling the materials. Recycling requires energy and produces global warming emissions, but recycling can reduce emissions compared with using new materials (see Appendix C) (Hendrickson et al. 2015; Dunn et al. 2012).

Landfill. The battery can go directly to a landfill, where it is neither reused nor recycled. This scenario is the least expected by experts; they cite concerns about localized pollution beyond global warming emissions), resource scarcity, and the market for batteries even in second use (Dunn et al. 2014). In other words, if the value of the lithium-ion battery is high enough, there will be an incentive to reuse or recycle it. Also, if federal, state, or local governments regulated the recycling of lithium-ion batteries, as they do for other materials such as tires and lead-acid batteries, demand might be more stable and predictable.

Resource scarcity. Production of most lithium-ion BEV batteries requires not only lithium but also cobalt, nickel, and other metals, most of which are mined outside the United States (NMA 2015). Early in the development of BEVs, there were concerns that the demand for lithium for battery production would be greater than its global supply. However, more recent studies have quantified that supply and concluded there is enough lithium for large increases in BEV manufacturing (Gruber et al. 2011). Cobalt and nickel are today's biggest economic drivers for recycling because the market prices of these metals are relatively high; recycling them not only reduces cost but decreases the amounts of virgin materials extracted and lowers the risk of resource scarcity (Dunn et al. 2014).

Disposal toxicity. Beyond global warming emissions, cars—electric and gasoline vehicles alike—produce air pollutants (such as nitrogen oxides, sulfur oxides, and particulate matter) and contribute to other environmental impacts (for example, water pollution such as eutrophication and acidification) that can be toxic to humans and other species. With BEVs, these degradations can occur throughout the car's life cycle—directly during its manufacture and disposal (in particular, disposal of the battery) and indirectly through electricity generation to charge the vehicle during its service life. In the United States, virtually all of the associated production, disposal, and generation processes are subject to air and water quality regulations. Quantifying these impacts is outside the scope of this report, which focuses on global warming emissions.

that the disposal process accounts for less than 5 percent of the global warming emissions attributable to production of the vehicles. Nevertheless, the data available for BEV end-of-life procedures are limited because the majority of BEVs are still on the road—i.e., they have not yet been retired. In the absence of pertinent data, we made conservative assumptions by allocating no emissions savings to the reuse or recycling of the lithium-ion battery and by applying industry averages to other recycled materials. (See Box 1 and Appendix C.)

Estimating Emissions from Vehicle Manufacturing

Having identified the many materials and components, across numerous supply chains, that are assembled to produce the final vehicle, we summed the global warming emissions attributable to each item. Specifically, as noted earlier, we did this for two types of BEVs—a midsize midrange battery-electric car and a full-size long-range battery-electric car—along with their comparable gasoline models, using a life cycle model developed by Argonne National Laboratory (ANL 2014a; ANL 2014b). Most of the components, made largely of steel, aluminum, and plastic, of the battery-electric and gasoline cars were similar; the vehicle body and chassis made up about 60 percent of the total vehicle weight for both gasoline and electric vehicles (Burnham 2012).

The largest manufacturing difference between gasoline and electric cars, of course, is the production of the lithium-ion battery. Emissions from producing the battery come from extracting raw materials such as lithium, cobalt, copper, and iron ores, processing these materials into finished metals, and then fabricating them into the parts of the battery. Finally, when the battery is assembled and installed in the car, there are global warming emissions from the assembly.

Excluded from the life cycle assessments are the global warming emissions from building the infrastructure (such as factories and industrial equipment) required to do all of the processing and assembling, and the emissions from transportation of raw materials for manufacturing. We not only expect these emissions to be small on a per-vehicle basis but also that they are likely to be about the same in gasoline and electric cars.

The gasoline and battery-electric cars we modeled were “representations” of what is available on the market today. They were representations—similar, say, to the Nissan LEAF or the Tesla Model S, but not those actual vehicles—because instead of using data unique to specific models or manufacturers to estimate the global warming emissions of producing cars, we used industry averages and data from the published literature (Burnham 2012). Given that our analyses involved representative cars and not particular models—due to the lack of specificity in the data, we cannot model the actual cars—we have not captured areas in which individual automakers are better or worse than the average, and the results are not detailed assessments of these companies’ manufacturing processes.

For more detail on the methodology used in this report and on the representative components of the vehicles modeled, see Appendix B.

Manufacturing Emissions of Today’s BEVs: Main Findings

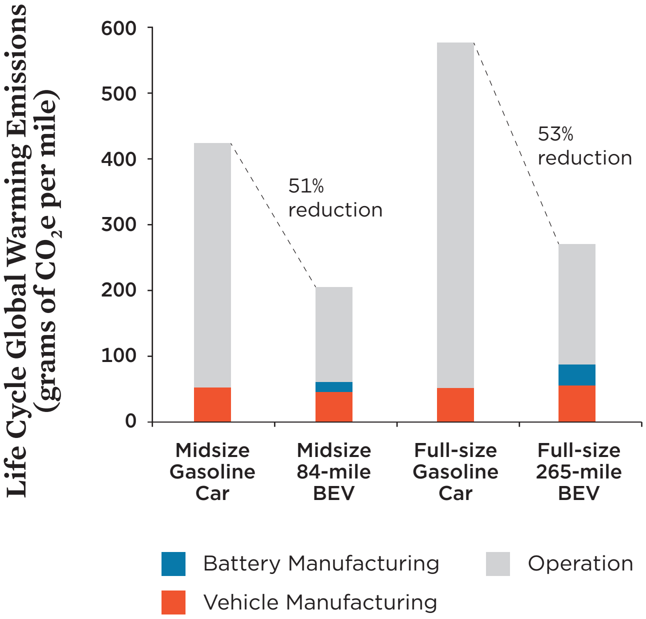
The lifetime global warming emissions from vehicle manufacture and operation, both for the midsize midrange BEV and the full-size long-range BEV, are shown in Figure 7, along with the totals for their comparable gasoline vehicles.

Our main findings are as follows:

On average, battery-electric vehicles have much lower global warming emissions than comparable gasoline vehicles, despite higher emissions from vehicle manufacturing. For a midsize 84-mile-range BEV, manufacturing emissions are approximately 15 percent, or 1 ton of CO_2e higher than those of a comparable conventional gasoline vehicle. However, total global warming emissions of the midsize BEV, when powered by the electricity grid mix representative of where BEVs are sold today, are 51 percent lower than the comparable midsize gasoline car, thereby saving 29 tons of CO_2e. The global warming emissions from manufacturing a midsize BEV are about 30 percent of its lifetime global warming emissions; the remaining 70 percent come from driving it.

For a full-size 265-mile-range BEV, manufacturing emissions are approximately 68 percent, or 6 tons of CO_2e higher than a comparable conventional gasoline vehicle. Total global warming emissions of the full-size BEV, when powered by the electricity grid mix representative of where BEVs are sold today, are 53 percent lower than the comparable full-size gasoline car, thereby saving 54 tons of CO_2e. The global warming emissions from manufacturing a full-size BEV are

FIGURE 7. Life Cycle Global Warming Emissions from the Manufacturing and Operation of Gasoline and Battery-Electric Vehicles



Notes: We assume that the midsize vehicles are driven 135,000 miles over their lifetimes and the full-size vehicles 179,000 miles. The difference in the two mileages derives from the dissimilar uses of 84-mile-range and 265-mile-range battery-electric cars, as described in Chapter 2. We further assume that a consumer buying a BEV would drive it the same total of miles as a corresponding gasoline vehicle. We use U.S. average electricity grid emissions to estimate manufacturing emissions, while the average electricity grid emissions intensity during vehicle operation are based on a sales-weighted average of where EVs are being sold today.

about 33 percent of its lifetime global warming emissions; the remaining 67 percent come from driving it.

Battery manufacturing accounts for the most significant difference between the manufacturing emissions of BEVs and gasoline vehicles, but it represents only a small percentage of the cars' respective total emissions. For a midsize 84-mile-range BEV, the battery-manufacturing global warming emissions account for 24 percent of the total manufacturing emissions of the midsize BEV, but less than 8 percent of the lifetime emissions.

For a full-size 265-mile-range BEV, the battery-manufacturing global warming emissions are larger than those of the midsize BEV because of the increased battery size and its longer range. The battery-manufacturing emissions for this vehicle represent 36 percent of its total manufacturing emissions, but still less than 12 percent of the lifetime emissions.

The higher manufacturing emissions of a BEV are quickly offset by emissions savings from driving the vehicle, but how long it takes to realize this benefit depends on where the owner plugs in. The regions that use the most fossil fuel energy to generate electricity, especially coal, have longer "break-even mileages"—the number of miles it takes a BEV to offset the global warming emissions of producing the lithium-ion battery.

For a midsize 84-mile-range BEV, on average, the extra manufacturing emissions are offset within 4,900 miles, or in less than six months, based on the sales-weighted electricity emissions of where EVs are sold today (assuming an 84-mile-range BEV travels 75 percent of the typical first-year mileage of a new gasoline car). When driving a BEV charged from the cleanest regional grids in the United States, these extra manufacturing emissions are offset even quicker, within the first 3,700 miles of driving. On the dirtiest grid they are offset within 13,000 miles, slightly more than a year for the typical vehicle owner (though this time can be reduced if the BEV driver finds a cleaner source of power).

For a full-size 265-mile-range BEV, on average, the extra manufacturing emissions are offset within 19,000 miles, or in about 16 months of driving, based on the sales-weighted electricity emissions of where EVs are sold today (assuming a 265-mile-range BEV travels the same first-year mileage as the typical new gasoline car). When driving a BEV recharged from the cleanest regional grids in the United States, these extra manufacturing emissions are offset within the first 15,000 miles of driving, or in just under one year for the average driver. On the dirtiest grid they are offset within 39,000 miles, or in less than three years for the typical vehicle owner.

Overall, offset occurs as fast as six months or at most within three years, which means that everywhere in the

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With the exception of EVs' lithium-ion battery, most of the materials and components used in EV and gasoline vehicle manufacturing are similar. The additional emissions associated with EV battery manufacturing are more than offset by the emissions generated from driving a gasoline vehicle.

> ***Across the country, BEVs will produce net emissions savings well before the end of the vehicle life.***

United States BEVs will produce net emissions savings well before the end of the vehicle life.

Future Potential for Reducing BEV Emissions from Manufacturing

The global warming emissions from manufacturing BEVs can be reduced (1) through the use of renewable energy to power the production facilities, (2) through advances in lithium-ion battery fabrication and recycling, and (3) through the application of alternative materials and designs. Also, the BEV market is still relatively small; the economies of scale realized by manufacturing greater numbers of cars for a much larger market will possibly reduce per-vehicle costs and improve efficiencies (Dunn et al. 2014).

Global warming emissions from producing a vehicle can vary by as much as 30 percent, depending on the source of electricity. If a vehicle is manufactured using regional electricity with relatively high global warming emissions, as is presently the case in the U.S. Midwest and in China, this will result in higher manufacturing emissions than in areas, such as California, that have significantly reduced their global warming emissions from electricity generation by using renewable electricity sources. In the future, there will be more possibilities to reduce emissions as we add more renewable sources of electricity to the U.S. grid (see Box 2). By producing a BEV using 80 percent renewable energy, the global warming emissions from manufacturing can be reduced by about 30 percent compared with the average U.S. electricity grid emissions today.

Advances in batteries may reduce global warming emissions of battery manufacturing. Because the automotive battery industry is growing and BEV battery chemistry is still being researched, we examined a range of lithium-ion battery chemistries (see Appendix B). Our sensitivity analysis on battery chemistry shows that global warming emissions from battery production could range from a 45 percent increase to a 43 percent decrease, depending on the vehicle battery chemistries we modeled. Data for these new technologies are often only available at the laboratory scale, so the emissions as a function of battery chemistry could diminish due to economies of scale. Also, we expect the emissions per battery to decrease as industry scales up the production of BEV batteries.

Making batteries with recycling options can reduce global warming emissions of batteries. Many companies recycle lithium-ion batteries for small electronics, but the batteries needed for vehicles are much larger. There are currently two major companies that are capable of recycling lithium-ion batteries at vehicle sizes. Being able to recycle batteries may prove to be an advantage in the long term. For our estimates, we attribute all the global warming emissions of battery manufacturing to the first use of the battery, but reusing or recycling it could reduce the battery emissions over the vehicle's lifetime. See Box 1 for more information.

BOX 2.

Manufacturers Are Making Greener Choices

Automakers are already showing interest in using renewable energy to produce BEVs and their parts. A few examples:

BMW. The i3 BEV uses carbon fiber–reinforced plastics made at a supplier's facility in Moses Lake, Washington, that is powered exclusively by hydro-based electricity generated nearby (SGL 2015). Although the process to make carbon fiber–reinforced plastics can result in higher manufacturing global warming emissions than from making steel, at least a portion of these emissions are offset by producing the material with renewable energy; further, emissions are reduced during vehicle operations as a result of a lighter and more energy-efficient vehicle.

Nissan. The LEAF vehicle and its batteries are assembled in Smyrna, Tennessee, where the electricity grid produces lower global warming emissions than in other international regions where batteries are often made (Nissan 2015).

Tesla. The company plans to build a large-scale battery-manufacturing facility in Nevada, with wind and solar electricity generation located nearby. Tesla is already using the California grid, one of the cleanest grid regions in the United States, to power its Model S production and assembly facility in Fremont (Tesla Motors 2014).

Because bigger batteries add to vehicles' production costs and total vehicle weight, manufacturers have a great incentive to use lighter materials and designs.

The use of alternative materials and redesign for weight reduction and vehicle efficiency can reduce BEV manufacturing's share of global warming emissions. Because bigger batteries add to vehicles' production costs and total vehicle weight, manufacturers have a great incentive to use lighter materials and designs. Lighter vehicles will also be more efficient in their fuel use, with consequent decreases in emissions while driving. Strategies to reduce vehicle weight can involve replacing heavier materials (such as steel) with lighter materials (aluminum or carbon fiber–reinforced plastics). Changes in vehicle design—e.g., using welds instead of bolts—can also result in weight reductions.

[**CHAPTER 3**]

How Federal Policies Could Increase the Benefits of Electric Vehicles

> ***Renewable electricity will be the primary mechanism for reducing global warming emissions from electric vehicles.***

The research described in this report shows that even with the greater global warming emissions from manufacturing (largely because of lithium-ion battery manufacturing), a battery-electric vehicle still results in significantly lower global warming emissions over its lifetime than its gasoline counterpart. Other studies on this topic have come to similar conclusions (Nealer and Hendrickson 2015; Hawkins, Gausen, and Strømman 2012).

Thus given the potentially major role of BEVs—if they are widely deployed—in reducing global warming emissions from the transportation sector, we recommend the adoption of innovative policies in the following areas: (1) increased renewable electricity generation; (2) advanced battery technology; and (3) facilitation of electric vehicle accessibility.

Limit Power Plant Emissions and Expand Renewable Electricity Generation

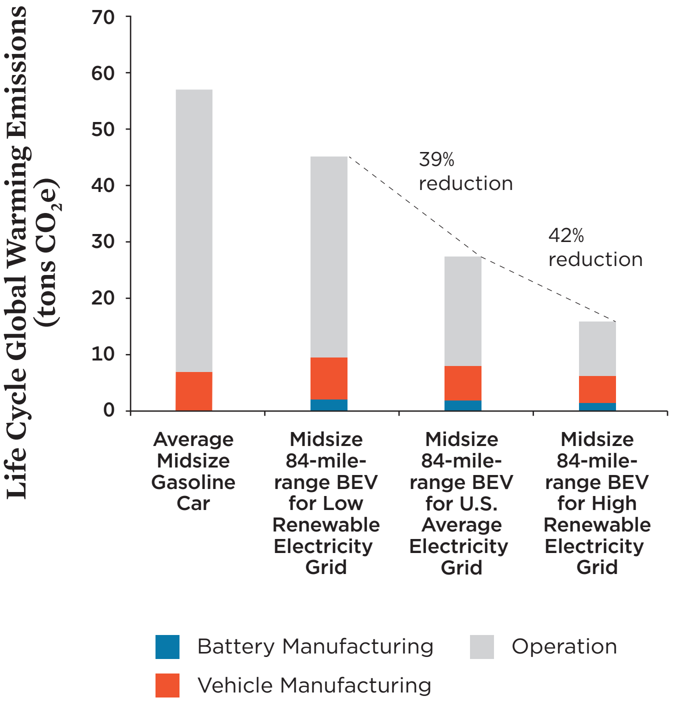
How electricity is generated greatly affects the global warming emissions of electric vehicles, both in their manufacture and operation. As such, renewable electricity will be the main mechanism for reducing global warming emissions from EVs. Consider one achievable future: if the nation's grid relied on renewable energy for 80 percent of its power supply by 2050, the emissions from BEVs (including manufacturing emissions) would be 60 percent lower than those under the average U.S. mix today. That level is roughly equivalent to a gasoline car that achieves more than 300 MPG_{ghg}. Even with today's grid mixes, as represented by the range of Figure 8 (p. 26), we can see about a 39 percent reduction if the EV is manufactured and operated in a region similar to the national average, and another over 20 percent reduction from the national average in a high renewable grid region.

The EPA recently finalized its Clean Power Plan, which aims to reduce global warming emissions from power plants by 32 percent below 2005 levels by 2030 (EPA 2015b). This is the first-ever national policy designed to lower the carbon emissions from electricity generation. To ensure its success, states should now develop and implement strong compliance plans that prioritize the use of renewable energy and energy efficiency to meet their emissions-reduction targets.

Although the Clean Power Plan is an important step forward in limiting carbon pollution from the electricity sector, it is not sufficient to meet long-term U.S. climate goals. Our nation's response to climate change should also include a federal policy that puts a price on polluters' carbon emissions and sets mandates that by 2050 we reduce power-sector emissions by at least 90 percent below 1990 levels and reduce economy-wide emissions by at least 80 percent.

Congress should enact a federal Renewable Electricity Standard (RES), and encourage the strengthening of state

FIGURE 8. Life Cycle Global Warming Emissions for a Midsize BEV for Three Different Electricity Grid Mixes



Note: The low renewable and high renewable electricity grid mixes are based on the electricity regions with the most and least fossil fuel electricity generation, respectively. These regions are RMPA and NYUP in the eGRID 2015 data with regional electricity grid mixes equivalent to 890 gCO2e/kWh and 240 gCO2e/kWh at the consumer's wall outlet. See Appendix A for more details.

RESs, as effective ways of decreasing the global warming emissions from electricity generation and consequently from EVs. Over the past 15 years, state-level RESs have proven to be one of the most successful and cost-effective means for driving renewable energy development in the United States (Heeter et al. 2014; UCS 2013a). Currently, 29 states and the District of Columbia have adopted some kind of RES. Figure 9 shows the stringency and type (mandatory or voluntary) of each state RES. California recently expanded the nation's largest market for renewable energy by increasing its RES to 50 percent by 2030. Earlier in 2015, Hawaii increased its RES to require 100 percent renewables by 2045. Other state governments should follow suit.

For its part, Congress should enact a national RES of at least 30 percent by 2030. A recent UCS analysis found such a policy would level the playing field across all states, stimulate nearly $300 billion in new capital investments, and cut U.S. power-sector global warming emissions 11 percent by 2030 (Bailie, Clemmer, and Deyette 2015).

In addition to establishing renewable electricity standards, policy makers at all levels of government should encourage greater deployment of renewable energy through carbon-pricing mechanisms, tax incentives and other financial incentives, and improvements in grid operation, transmission, and resource planning.

Consumers and organizations should invest directly in renewable energy technologies. Homeowners, businesses, and diverse institutions can also accelerate the transition to greater renewable energy use through on-site generation, green power purchasing, and REC purchases. Net metering allows consumers who generate their own electricity from renewable technologies—such as a rooftop solar panel or a small wind turbine—to feed excess power back into the electricity system and thereby spin their meter backward. Forty-four states and the District of Columbia now have net metering requirements, with only four states that do not have such policies, and two states that have net metering policies that are not uniform across the state (DSIRE 2015).

In some deregulated utility markets, consumers have the ability to select their power provider. In those locales, choosing a provider that supplies electricity from renewable sources or that maintains a green pricing program may be distinct options. States offering this type of choice for at least some consumers include California, Connecticut, Illinois, Maine, Maryland, Massachusetts, New Jersey, New York, Pennsylvania, Rhode Island, Texas, and Virginia. The District of Columbia offers such a choice as well.[11]

Purchasing RECs, which are available nationwide, is another option. RECs are directly tied to electricity generated by renewable sources and are sold in a voluntary market.[12] By providing additional revenue for renewable energy projects, the purchase of RECs can help to increase the supply of renewable electricity (Mai et al. 2012).

Directly Invest in Battery Technology

Policies that support additional battery research and development should be pursued in order to increase EV batteries' efficiency, lower their costs, and reduce the global warming emissions attributable to them from their manufacture and at their end of their service lives.

Congress should continue to fund federal battery research programs in order to reduce battery costs and

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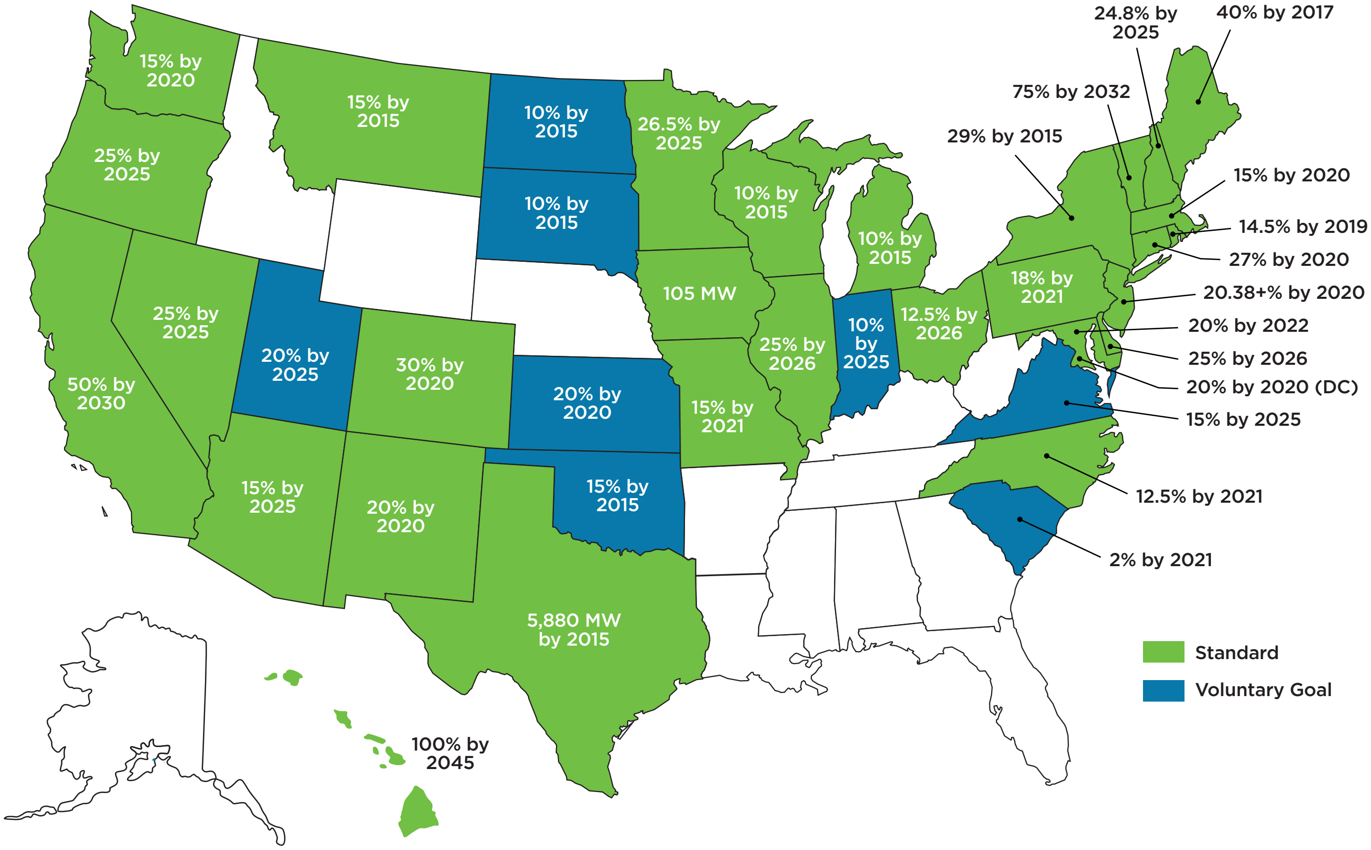
[11] *See* apps3.eere.energy.gov/greenpower/markets/marketing.shtml *for additional information*

[12] *See CRS 2015 for additional information.*

FIGURE 9. State Renewable Electricity Standards (Including the District of Columbia)



SOURCE: DSIRE 2015.

increase EV affordability. Government investment in battery technology has already played a significant role in reducing battery costs. In 2007, lithium-ion batteries cost about $1,000 per kWh, but by 2014 they were at $300 per kWh (Nykvist and Nilsson 2015).

Several federal programs played important roles to make this achievement a reality, mostly run by the DOE. Research funded by the DOE's Advanced Research Projects Agency-Energy (ARPA-E) and Joint Center for Energy Storage Research helped to modify batteries for EV use (JCESR 2015). ARPA-E and the DOE's Vehicle Technologies Office are presently funding research into novel battery chemistries, which have the potential to greatly extend batteries' range and durability, and funding technology-transfer processes to expedite such improved batteries' commercial availability. (DOE 2014; DOE 2009).

Congress should fund programs that facilitate battery recycling or reuse. Although today's market for recycling large lithium-ion batteries is limited, given that most of the first-generation EVs have not reached the end of their service lives, it is important to ensure there will be a ready market for used batteries when their time comes.

This can be done, in part, by designing batteries to be easily recycled, thus requiring little extra energy and resulting in modest levels of additional global warming emissions. Currently there are only two companies, Retriev Technologies and Umicore, that can recycle lithium-ion batteries from EVs, and they have entered partnerships with EV manufacturers to achieve that end. But the recycling—and reuse—of used lithium-ion batteries are in their infancies; they would benefit from more research and development, including public-private collaborations and pilot projects, to help them become more efficient and broader in scale.

Facilitate Electric Vehicle Accessibility

A 2013 survey conducted by UCS and the Consumers Union found that 42 percent of American households, representing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Solar-powered charging stations—such as those in (from top to bottom) Austin, Texas; Portland, Oregon; and Atlanta, Georgia—are popping up around the country, offering EV drivers the opportunity to recharge with renewable electricity.

nearly 42 million American homes with a vehicle, could benefit today from using an electric vehicle (UCS 2013b). To help EVs grow into this large potential market, their upfront costs must be reduced.

Congress should protect the existing $7,500 federal EV tax credit and reinstate the infrastructure tax incentive. Offsetting EV purchase prices through incentives such as the $7,500 federal tax credit and additional state tax credits have helped stimulate the markets for EVs across the country. In California, for example, more than 3 percent of new vehicle registrations were plug-in hybrid and battery-electric vehicles in 2014 (CNCDA 2015). Governor Jerry Brown has also set a goal of 1.5 million zero-emissions vehicles,[13] on the state's roads by 2025 (Office of Governor Edmund G. Brown Jr. 2012). California was an early adopter of state-level incentives for EVs, and this policy influenced others—Connecticut, Maryland, Massachusetts, New York, Oregon, Rhode Island, and Vermont—to follow suit. These eight states' governors have signed an agreement establishing action plans in each state that would put a total of 3.3 million zero-emissions vehicles into service by 2025 (CARB 2013).

Ensuring that the federal tax credit remains in place will help decrease the current cost differences between EVs and comparable gasoline-powered vehicles, but such policy support will not be needed indefinitely. As EV technology improves, more models become available, and they are produced at greater scales, costs will come down—while EV drivers continue to save money in fuel costs. For example, we expect that over the vehicle's lifetime an EV driver will save nearly $13,000 on fuel not purchased (Anair and Mahmassani 2012).

Similarly, reinstating the tax incentive to provide funding for infrastructure such as charging stations and to reduce the costs of installing infrastructure both at home and at workplaces could help overcome the barriers to easily accessible charging discussed below.

Congress should support unifying guidance on charging installations. At present there are three ways to charge EVs: AC Level 1 and Level 2 chargers; and DC fast chargers. Each type of charger replenishes the lithium-ion battery at different rates. Typically, the Level 1 charger adds two to five miles of range per hour, the Level 2 charger adds 10 to 20 miles of range per hour, and the DC fast charger adds 50 to 70 miles of range in 20 minutes (DOE 2015c). There also are various types of connectors and plugs for EVs. The DC charging connectors are not uniform across all vehicle manufacturers. Tesla has its own connector and charging infrastructure, which

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[13] Zero-emissions vehicles include plug-in hybrid electric vehicles, along with battery-electric cars and fuel cell cars.

can only be used by Tesla owners. Nissan, Kia, and Mitsubishi vehicles use a different type of connector, and BMW and Chevrolet utilize yet another connector.[14] This situation can make understanding charging difficult for potential EV drivers.

To date, state-by-state installation guidance has been provided by the Society of Automotive Engineers and the DOE, but streamlined and easier-to-understand guidance would encourage more widespread installation. Similarly, building codes across the United States vary, and some are unclear on how EV chargers can be installed. Policy makers could clarify these standards, and establish a federal standard, to allow for more EV charging stations.

Congress should fund programs and partnerships for more charging stations. The DOE is currently running a workplace-charging challenge, which encourages employers, through industry pledges, to provide charging access to their staffs. This is especially important for consumers, such as residents of multiunit dwellings, who may lack such access at home (DOE 2015d). The DOE also offers valuable information for these residents on overcoming such obstacles at home, and it provides case studies on how the dwellers of apartment or condominium buildings in various cities succeeded (DOE 2015d). Congressionally funded programs should give priority to projects that install charging stations in locations with proximity to many potential consumers and where the proposed location is appropriate for the type of charging proposed.

Congress should support and adopt uniform EV charging signage. As noted above, the many ways to charge an EV can be confusing to consumers. Similarly, the chargers that are available may be difficult for new drivers to find. Developing uniform signage that is clearly displayed would help new EV drivers know where to charge and also raise awareness of the accessibility of chargers for potential EV buyers. The DOE and Federal Highway Administration have developed such signage through the Manual on Uniform Traffic Control Devices, which defines standards that apply to all types of traffic signs, but the proposed EV signs have not yet been finalized (DOE 2015e). Efforts to do so, and to implement these EV standards, should proceed, with increased use of the signs along interstates and other major roadways.

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Clear, uniform signage is critical to helping EV drivers know where to charge, as well as raising awareness of the accessibility of chargers for potential EV buyers.

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[14] *There are three types of connectors in the United States: SAE J1772, CHAdeMO, and Tesla (DOE 2015c).*

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Operation Emissions Modeling

The global warming emissions we attribute to operating an electric vehicle (EV) today are those that result from the production of electricity needed to charge the vehicle. We factor in emissions created by power plants when generating the electricity, and also emissions that result from obtaining and transporting the fuel used in these plants.

Power Plant Emissions

The electricity generation-related emissions values used in our analysis come from the U.S. Environmental Protection Agency's (EPA's) Emissions & Generation Resource Integrated Database (eGRID), which is a comprehensive source of emissions data for every power plant in the United States that provides its generation data to the government. We used to the most up-to-date version of eGRID available—eGRID 2015v1.0—which contains plant emissions and generation data from the year 2012 and subregion organization from the year 2012 (EPA 2015c). The mixes of generation sources for each region are shown in Table A-1.

The subregions are groups of plants organized by the EPA, based on Power Control Areas and North American Reliability regions (EPA 2015d). These groupings reflect which power plants serve which households, and they 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 eGRID2015 (EPA 2015c).

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

eGRID's methodology treats the subregions as closed systems, calculating the emissions intensity of generation for each one based on the emissions intensities of the plants it contains. This methodology ignores imports and exports of electricity between subregions, which harms the accuracy of the regional emissions estimates. Therefore, the 26 subregions are recommended by eGRID's designers as the level of disaggregation best suited for estimating electricity use–related emissions, as they achieve the best balance between the precision gained by disaggregation and the accuracy lost by omitting imports and exports (EPA 2009).

Transmission Loss Factors

The eGRID emissions rates do not account for transmission and distribution losses between the power plant and the household. To calculate emissions per unit of energy used (rather than energy produced), we followed eGRID's recommendation (EPA 2015d) to increase the emissions rates using grid loss factors found in the data files in EPA 2015c, shown here in Table A-2 (p. 36). There are five grid loss factors that vary by regions called interconnect power grids, and each eGRID subregion is given a grid loss factor based on the interconnect power grid to which it belongs (EPA 2015c).

Upstream Emissions Factors

The eGRID subregion emissions rates include only those emissions produced at the plant generating the electricity, and they exclude upstream emissions resulting from the mining and transport of the power plant feedstock (EPA 2015d). 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 a publicly available life cycle emissions model called GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation), developed by the Argonne National Laboratory (ANL 2014a; ANL 2014b).[15] The percentage of generation from each fuel type in a subregion was then obtained from eGRID2015 (EPA 2015c).

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[15] GREET1 2014 was used. Feedstock emissions factors come from Table 9: Fuel-cycle energy use and emissions of electric generation: Btu or grams per mmBtu of electricity available at user sites (wall outlets), in the Electricity tab.

TABLE A-1. Mix of Generation Sources for Each Grid Region

Grid Region Acronym	Grid Region Name	% Coal	% Natural Gas	% Other Fossil	% Nuclear	% Biomass	% Hydro	% Wind, Solar, Geothermal
AKGD	ASCC Alaska Grid	13	65	12	0	0	10	0
AKMS	ASCC Miscellaneous	0	8	27	0	0	64	1
ERCT	ERCOT All	31	49	1	11	0	0	8
FRCC	FRCC All	19	68	1	8	2	0	0
HIMS	HICC Miscellaneous	1	0	64	0	4	4	20
HIOA	HICC Oahu	20	0	75	0	2	0	1
MROE	MRO East	64	8	1	16	4	3	4
MROW	MRO West	61	5	0	11	1	6	15
NYLI	NPCC Long Island	0	89	3	0	4	0	0
NEWE	NPCC New England	3	52	0	30	6	6	1
NYCW	NPCC NYC/ Westchester	0	62	0	37	0	0	0
NYUP	NPCC Upstate NY	6	30	0	29	2	29	4
RFCE	RFC East	24	31	0	41	1	1	1
RFCM	RFC Michigan	59	25	0	12	2	0	2
RFCW	RFC West	59	11	1	26	1	1	2
SRMW	SERC Midwest	75	7	0	15	0	0	2
SRMV	SERC Mississippi Valley	21	54	1	21	2	1	0
SRSO	SERC South	34	42	0	19	3	2	0
SRTV	SERC Tennessee Valley	54	16	1	22	1	7	0
SRVC	SERC Virginia/ Carolina	35	20	0	41	2	1	0
SPNO	SPP North	71	10	0	12	0	0	7
SPSO	SPP South	48	39	1	0	1	2	8
CAMX	WECC California	5	59	1	9	3	13	10
NWPP	WECC Northwest	25	11	0	3	1	52	8
RMPA	WECC Rockies	70	17	0	0	0	3	10
AZNM	WECC Southwest	37	34	0	18	0	6	4

For each subregion, the fuel-type emissions rates are multiplied by the share of generation they represent in that subregion; the sum of these products is the subregion's feedstock emissions rate. Most fuel types in GREET correspond directly to a fuel type in eGRID, but there were a few exceptions. A very small share of generation in eGRID subregions corresponds to a fuel type labeled "generic fossil"; for this fuel type, the emissions rate from GREET for natural gas was chosen as a conservative guess, given that its upstream emissions value is higher than those of coal and 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 has already built a uniform grid loss factor into these feedstock emissions rates. But to keep the loss factors consistent with those applied to power plant emissions, we back GREET's grid loss factor out of the feedstock emissions rates. We then apply eGRID's power plant grid loss factors to each subregion's feedstock emissions rate.

The totals of electricity generation-related global warming emissions for each eGRID subregion were computed 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

The regional grid mix and estimated emissions intensity for all eGRID subregions, with adjustments for upstream emissions and grid losses, are shown in Tables A-1 and A-2.

Conversion of g/kWh to MPG_{ghg}

To translate electricity-related emissions intensity into driving-related emissions intensity (measured as gasoline miles-per-gallon equivalent, or MPG_{ghg}), we multiplied the EPA emissions intensity values (gCO_2e/kWh) from Table A-2 and the EV average efficiency values (kWh/mile) from Table 2, resulting in a $gCO_2e/mile$ estimate. Then we used the GREET carbon intensity of gasoline (ANL 2014a) and divided by the $gCO_2e/mile$ estimate to get the estimated MPG_{ghg} for each region. This figure is an electric vehicle equivalent to the MPG 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 fuel type.

TABLE A-2. Emissions Intensity from Electricity Generation by Region in 2012

eGrid Subregion Acronym	Direct Emissions at Power Plants (gCO_2e/kWh)	Transmission Loss Multiplier	Emissions from Power Plants After Transmission Loss (gCO_2e/kWh)	Upstream Emissions After Transmission Loss (gCO_2e/kWh)	Emissions Intensity from Electricity Generation (gCO_2e/kWh)
AKGD	577	1.09	631	88	719
AKMS	219	1.09	240	51	291
ERCT	520	1.08	560	67	627
FRCC	512	1.10	564	80	644
HIMS	547	1.08	592	115	708
HIOA	719	1.08	779	140	919
MROE	694	1.10	764	56	821
MROW	650	1.10	716	48	764
NYLI	547	1.10	602	92	694
NEWE	291	1.10	321	59	380
NYCW	317	1.10	349	63	411
NYUP	186	1.10	205	37	242
RFCE	391	1.10	431	52	483
RFCM	715	1.10	788	66	854
RFCW	629	1.10	692	55	747
SRMW	780	1.10	859	60	918
SRMV	479	1.10	528	70	597
SRSO	524	1.10	576	66	642
SRTV	610	1.10	671	55	726
SRVC	425	1.10	468	49	518
SPNO	785	1.10	864	59	923
SPSO	701	1.10	772	71	843
CAMX	296	1.06	314	59	373
NWPP	304	1.06	322	27	349
RMPA	831	1.06	882	61	942
AZNM	525	1.06	557	57	614

Note: Upstream emissions are those associated with the extraction and transportation of feedstocks for electricity generation. Emissions intensity is based on 2012 generation data. Sales-weighted average based on where EVs are sold today (480 gCO2e/kWh) is used to calculate the average operation emissions for EVs (IHS 2015).

Manufacturing Emissions Modeling

This appendix details the calculation of global warming emissions from vehicle manufacturing. We describe the selection of comparable gasoline vehicles, modifications to existing manufacturing modeling, battery manufacturing sensitivities, the impact of the electricity source on manufacturing emissions, and the battery lifetime and replacement impacts.

Gasoline Vehicle Selection

In addition to estimating the global warming emissions from battery-electric vehicles (BEVs), we chose comparable gasoline vehicles and then determined their manufacturing-related global warming emissions. We examined a range of gasoline vehicles that are similar to the representative BEVs we modeled—an 84-mile-range midsize BEV and a 265-mile-range full-size BEV.

Table B-1 shows the five midsize cars we chose because of their similarity in vehicle footprint to a Nissan LEAF, the midsize BEV whose representative we modeled—note that the Nissan LEAF has a footprint of 45 square feet. We used data for the most popular version of each vehicle make and model (WardsAuto 2015).

We used the average curb weight of 3,000 pounds and average fuel economy of 29 MPG to calculate the manufacturing- and operation-related global warming emissions of a gasoline vehicle comparable with the smaller 84-mile-range BEV.

We applied the same methods as above to find five gasoline vehicles comparable in footprint with a Tesla Model S, the car on which the 265-mile-range full-size BEV is based—note that the Tesla Model S footprint is 54 square feet (see Table B-2).

We used the average curb weight of 4,300 pounds and average fuel economy of 21 MPG to model the manufacturing- and operation-related global warming emissions of a gasoline vehicle comparable with a 265-mile-range BEV.

Methods for Modeling Manufacturing Emissions

For all of our vehicle manufacturing modeling efforts, we used the 2014 versions both of GREET 1 (a fuel cycle model) and GREET 2 (a vehicle cycle model) (ANL 2014a; ANL 2014b). In the absence of specific details about the gasoline model and BEV model material composition, we used the

TABLE B-1. Midsize Gasoline Vehicles Comparable with the Nissan LEAF

Make	Model	Engine	Fuel Economy (MPG)	Curb Weight (lb.)	Footprint (sq. ft.)
Mazda	3- or 5- Door i	2.0L I4	33	2,900	45
Ford	Focus (Hatchback)	2.0L I4	30	3,000	43
Mitsubishi	Lancer Sportback	2.0L I4	29	3,100	43
Volkswagen	Golf	1.8L Turbo I4	29	3,000	43
Kia	Forte5	1.6L Turbo and 2.0L I4	26	3,000	45
Average (harmonic for fuel economy)			**29**	**3,000**	**44**

Note: The Kia Forte5 numbers shown are sales-weighted averages of vehicles offered with two types of engines.

SOURCE: DOE 2015A.

TABLE B-2. Full-size Gasoline Vehicles Comparable with the Tesla Model S

Make	Model	Engine	Fuel Economy (MPG)	Curb Weight (lb.)	Footprint (sq. ft.)
Hyundai	Equus	5L V8	18	4,600	53
Chrysler	300 RWD	3.6L V6	23	4,000	53
Mercedes	S 550 RWD	4.7L V8	20	4,600	55
Porsche	Panamera	3.6L V6	22	3,900	52
Audi	A8	3L V6	22	4,400	53
Average (harmonic for fuel economy)			**21**	**4,300**	**53**

SOURCE: DOE 2015A; WARDSAUTO 2015.

model default values related to the supply chain global warming emissions of each material. Using the GREET framework, the percentage of each material in the vehicles was scaled by total vehicle weight.

Specifications of Modifications in GREET

The material composition of the vehicles is an important component of modeling vehicle manufacturing because the material's life cycle global warming emissions vary by material type. For example, manufacturing wrought aluminum produces, by weight, more than twice the global warming emissions of steel. To complicate this relationship for different parts of the vehicle, the replacement ratio varies. Because we had limited data on the actual composition of the vehicle models, we used the best available data in the GREET model.

We modeled the midsize and full-size gasoline car as an average gasoline car; the midsize 84-mile-range BEV as an average battery-electric vehicle; and the full-size 265-mile-range BEV as a lightweight battery-electric vehicle. Moreover, we modeled the full-size 265-mile-range BEV with more aluminum and no carbon fiber–reinforced plastics to more accurately represent what we know industry is providing today (Tesla Motors 2015). However, for the majority of the materials we used the GREET default values because further information on the specific models was not available. Table B-3 shows the composition by percentage of the vehicle weight (without the battery or fluids), as defined by GREET; note, however, that the values in Table B-3 are different from the GREET model defaults for the full-size BEV.

The modifications made for the battery specifications are detailed in Table B-4.

TABLE B-3. Composition of Vehicles by Material Type

Material	Gasoline Vehicle	Midsize BEV	Full-size BEV
Steel	62%	66%	21%
Cast Iron	11%	2%	3%
Wrought Aluminum	2%	1%	26%
Cast Aluminum	5%	5%	17%
Copper/Brass	2%	5%	6%
Glass	3%	3%	4%
Average Plastic	11%	12%	15%
Rubber	2%	2%	3%
Glass Fiber–reinforced Plastic	0%	0%	3%
Other	2%	3%	3%

Note: Excludes batteries and fluids.

Comparing our results with other battery literature (Dunn et al. 2014; EPA 2013; Dunn et al. 2012; Notter et al. 2010), the emissions (kilograms of CO_2 per kilogram of battery weight) depend on the battery chemistry. These estimates are on the lower end of the spectrum for battery-production global warming emissions because they derive from process-level analyses. The alternative approach—top-down methods, which refer to how the battery production

TABLE B-4. Lithium-ion Battery Specifications for Midsize and Full-size BEVs

	Midsize BEV Battery	Full-size BEV Battery
Chemistry	Lithium nickel manganese cobalt oxide	Lithium cobalt oxide via hydrothermal process
Specific Energy (Wh/kg)	81.5	156
Weight (kg)	290	540
Size (kWh)	24	85

energy is assessed—results in higher estimates because the scope of the assessment is larger (Hawkins et al. 2013; Majeau-Bettez, Hawkins, and Strømman 2011; Zackrisson, Avellan, and Orlenius 2010). These values are dependent on battery chemistry.

We conducted a sensitivity analysis, based on battery chemistry, around the default GREET values for a 28 kWh battery. If the battery chemistry were changed, the global warming emissions for the midsize battery could decrease by 18 percent or increase by 45 percent, and the full-size battery global warming emissions could decrease by up to 43 percent, when using alternative battery chemistries for the same 28 kWh output (see Table B-5). The differences are due to the supply chain manufacturing differences of the cathode chemistries. Assembly of the batteries remains the same across the battery chemistries.

Electricity Mix for Battery and Vehicle Manufacturing

We investigated the impact that electricity-related global warming emissions could have on vehicles' manufacturing alone—i.e., the electricity used to power manufacturing equipment—in light of the fact that different sources of electricity result in higher or lower global warming emissions. The electricity mixes with more fossil fuels cause higher global warming emissions for vehicle manufacturing. We investigated the impacts of a future electricity grid with 80 percent renewable energy sources, and we concluded that vehicle manufacturing-related global warming emissions could be reduced by up to 45 percent, as opposed to a grid with 90 percent coal power, as is the case today in China. These impacts are similar for gasoline and BEV. Compared with today's average U.S. grid mix, manufacturing emissions could be reduced by just over 30 percent if the United States generated 80 percent of its electricity from renewable sources.

Vehicle and Battery Lifetime

The most common way to compare the life cycle impact of one vehicle with that of another is to measure emissions per distance driven over their lifetimes. BEVs tend to create more

TABLE B-5. Global Warming Emissions Changes Based on Battery Chemistry for 28 kWh Battery

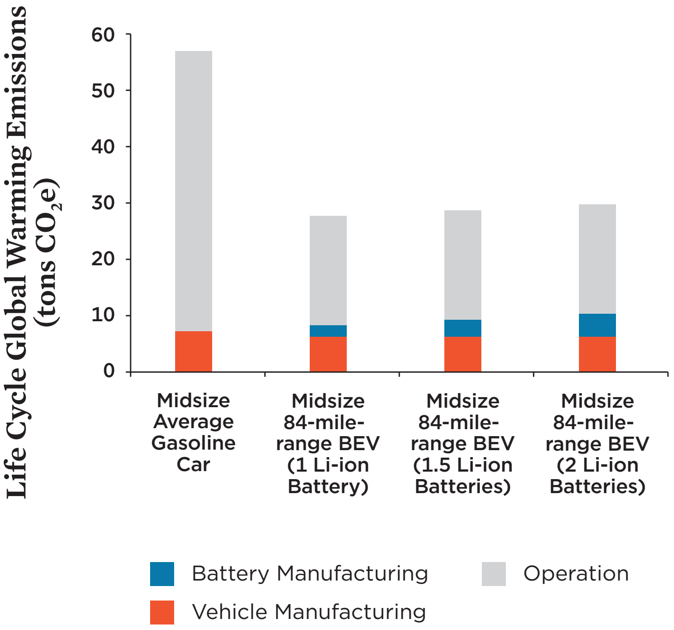
	Global Warming Emissions Change from Modeled BEV Battery Chemistries (%)	
Battery Chemistry	Midsize BEV Battery	Full-size BEV Battery
Lithium Manganese Oxide (LMO)	-18%	-43%
Lithium Nickel Manganese Cobalt Oxide (NMC)	--	-31%
Lithium Iron Phosphate (LFP) via Hydrothermal Process	-7%	-36%
Lithium Iron Phosphate (LFP) via Solid State Process	-14%	-41%
Lithium Cobalt Oxide (LCO) via Hydrothermal Process	45%	--
Lithium Cobalt Oxide (LCO) via Solid State Process	9%	-25%
Advanced Lithium NMC (LMR-NMC) with Graphite	-13%	-40%
Advanced Lithium NMC (LMR-NMC) with Silicon	5%	-28%

TABLE B-6. First 15 Years of Vehicle Lifetime in Mileage

	Annual Mileage		
Vehicle Age	**Gasoline Car**	**84-mile-range BEV**	**265-mile-range BEV**
1	14,700	11,000	14,700
2	14,300	10,700	14,300
3	14,000	10,500	14,000
4	13,600	10,200	13,600
5	13,300	10,000	13,300
6	13,000	9,800	13,000
7	12,800	9,600	12,800
8	11,400	8,500	11,400
9	11,100	8,300	11,100
10	10,800	8,100	10,800
11	10,500	7,900	10,500
12	10,300	7,700	10,300
13	10,000	7,500	10,000
14	9,800	7,400	9,800
15	9,600	7,200	9,600
Total Miles	**179,200**	**134,400**	**179,200**

SOURCE: EPA 2012B.

FIGURE B-1. Life Cycle Global Warming Emissions from the Manufacturing and Operation of Gasoline and Battery-Electric Vehicles with More Than One Battery Replacement



Note: This figure assumes battery production scales linearly and only battery manufacturing emissions are increased, not total vehicle manufacturing emissions. We only show the results for the midsize 84-mile BEV, because the results are similar for the full-size 265-mile BEV.

global warming emissions when they are manufactured than gasoline vehicles because of the former's battery production. However, gasoline vehicles give off more global warming emissions per mile while being driven. This creates a tradeoff: greater upfront emissions from the manufacturing of BEVs versus higher emissions from the use of gasoline vehicles because of their engines' combustion.

For this study we assumed a lifetime of 179,000 miles, both for gasoline and long-range battery-electric vehicles, based on the National Household Travel Survey (FHWA 2009) data for the first 15 years of a vehicle's lifetime. However, we posited an exception for the 84-mile-range BEV and comparable gasoline car—that total mileage would be 135,000—75 percent of the mileage of the 265-mile-range BEV. This difference is due to "range limitations" of a car with a more modest-sized battery: its driver would likely be unwilling to drive long distances very often, given the frequent need for stopping to "fill up" (Plotz 2015; Carlson et al. 2014). Table B-6 shows the annual distances assumed to driven during each year of the modeled vehicles' lifetimes.

We explored the possibility that the midsize 84-mile-range BEV might not reach the full 135,000 miles on one lithium-ion battery, due to required or voluntary battery replacement. We analyzed the impacts of one, two, and 1.5 battery replacements, with the latter representing a mix of some BEVs needing only one and others needing two battery replacements. Figure B-1 shows the results of this analysis for the midsize vehicle. An important finding is that despite higher global warming emissions for more battery replacements, the total emissions are still lower than those of a comparable gasoline vehicle. The total life cycle global warming emissions increase by 6 percent and 11 percent for 1.5 and 2 batteries, respectively, compared with only one battery for the lifetime of the vehicle.

Disposal, Recycling, and Reuse

We assume that BEVs will be disposed of, with the exception of their lithium-ion batteries, in similar ways as their gasoline counterparts. This section describes some of the details of the recycling possibilities, related assumptions in the manufacturing modeling, and second use of the vehicle battery after it is retired.

Recycling of Vehicle Materials

Table C-1 shows the recycling assumptions for each material in GREET, the Argonne National Laboratory's vehicle manufacturing emissions model. When these assumptions are changed to use all virgin materials, the global warming emissions from the vehicles' manufacture increase by about 15 to 20 percent. Note that "recycling rates" refer to what is used in the manufacturing of the vehicle, not to what is recycled at the end of the vehicles' lifetime; although a large percentage of the vehicle is recycled, not all the materials reenter the automotive industry.

TABLE C-1. Recycling Rates of Metals for All Vehicles Modeled

	Virgin Material	Recycled Material
Steel	74%	26%
Wrought Aluminum	89%	11%
Cast Aluminum	15%	85%
Lead	27%	73%
Nickel	56%	44%
Magnesium	67%	33%

Note: These recycling rates are developed by GREET, and left unmodified for the vehicle modeling presented in this report.

SOURCE: ANL 2014A; ANL 2014B.

Lithium-ion Battery Recycling

There are only two companies that currently have the capability to recycle the large lithium ion batteries required for BEVs—Retriev Technologies and Umicore (Retriev Technologies 2015; Umicore 2015)—and there are three different approaches to the recycling: hydrometallurgy, pyrometallurgy, and direct physical recycling. It is expected that recycling can reduce battery manufacturing–related energy consumption by 10 to 17 percent, depending on the manufacturing process and battery type (Hendrickson et al. 2015; EPA 2013). Our results do not incorporate this energy savings because there are sparse data on how industry is currently recycling batteries or intends to do so in the future, but there is potential for recycling to reduce emissions and increase resource utilization.

Lithium-ion Battery Reuse

Various pilot projects are under way to reuse lithium-ion batteries for other purposes after the vehicle is retired. From a life cycle perspective, this would effectively spread the impacts of the battery over a longer battery lifetime. But without more information on the nature of the battery second use, and on how long it is used, we are unable to estimate the emissions savings this would have on the life cycle of the battery. Therefore for this report we assume that all global warming emissions are attributed to the first use of the battery—in the vehicle.

[APPENDIX D]

Average vs. Marginal Electricity Global Warming Emissions

Electricity is produced using a mix of generation units that vary in size, fuel, and efficiency. This mix of generation varies over both long and short time scales, as demand for electricity, availability, and fuel costs are always changing. Emissions attributable to electricity use are linked directly to this generation mix; the emissions from electricity 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. For this analysis, an average emissions approach is used, in which the emissions from electricity production are averaged over all of the electricity generating units in an entire electricity grid region for a year. The rationale for this choice is described below, as along with a discussion of alternative approaches.

Average Emissions Estimation

To estimate electric-vehicle emissions from plugging into the electricity grid, the average global warming emissions intensity (i.e., emissions emitted for each net kilowatt-hour of electricity delivered) is calculated by region. This method of averaging emissions intensity treats all of the electricity produced and consumed in the region equally. That is, no matter how much electricity you use or when you use it, your electricity is assumed to be just as clean (or dirty) as anyone else's in the same region. In essence, this approach 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 import and export of electricity across regions are not accounted for in the average emissions approach.) Using the averaging approach allows changes in the underlying generation mix to be captured when estimating future years' emissions. However, as described below, it does not reflect the short-term changes in the electricity grid that may result from a new electricity load being added to the grid.

The data used in this report to calculate regional global warming emissions intensities were based on actual power plant emissions for the year 2012. In eGRID, the U.S. Environmental Protection Agency (EPA) assembled global warming and other emissions data from thousands of power plants operating across the country. The eGRID subregion emissions rates include only those emissions produced at the plant generating the electricity, and they exclude transmission and upstream emissions resulting from the mining and transport of the power plant feedstock (EPA 2015d). To account for the transmission emissions, we increased the emissions rates using grid loss factors found in eGRID2015 (EPA 2015c) for the transmission losses. To account for the upstream emissions, we used a feedstock emissions rate obtained from *GREET1_2014* (ANL 2014a).

Marginal Emissions Estimation

An alternative approach involves "marginal" emissions intensity, which is estimated by identifying which power plants, or types of power plants, are likely to be deployed or increase their output when new electricity demand is added to the electricity grid above and beyond the demand that already exists. 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 your 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; Elgowainy et al. 2010; Hadley and Tsvetkova 2008). These marginal emissions analyses can be broken into two different categories: short-term and long-term.

The short-term approach looks at how the electricity grid responds instantaneously to a new load, such as when an EV is plugged in. In this approach, the emissions from plugging in the EV are tied specifically 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 that is 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 they have limited ability to vary output. These electricity sources provide non-marginal 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 non-marginal 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 may still be the only electricity sources on the margin responding to instantaneous increases in demand for electricity. So an EV powered on a grid with no renewables and one with 25 percent renewables might still have the same emissions profile using this type of marginal emissions analysis. In addition, new electricity demand will eventually lead to changes in the source of electricity production. Over time a large number of EVs will create significant demand that will need to be met through either greater energy efficiency, increased utilization of existing sources, new electricity generation, or very likely a combination of all three. A short-term marginal analysis only considers increased utilization of existing generating resources, though researchers have been looking into a more consequential approach with new capacity as a consideration (Weis, Jaramillo, and Michalek 2014).

The long-term marginal emissions approach, or a consequential life cycle approach, evaluates how the electricity grid responds over a longer time period. This approach can estimate what would happen to the grid without new electricity load being added and then contrast this outcome with what would happen under a the new load. For example, an analysis could estimate electricity demand between 2015 and 2030 assuming no EVs and then what demand would look like with several million EVs added (EPRI and NRDC 2015). This type of modeling approach allows long-term changes in the electricity grid to be evaluated, including power plant retirements, new electricity generation, and changes in EV demand. Importantly, it also allows for the evaluation of policies to reduce emissions from both the transportation and electricity sectors, as well as for estimates of the cumulative impact on emissions from both sectors. For example, one could use this approach to examine the impact of the increased EV deployment triggered by implementation of the EPA's Clean Power Plan.

While a long-term marginal emissions approach doesn't 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. But because this approach requires modeling both of the transportation and energy sectors, and of the specific changes to the electricity grid that might occur under various future scenarios, it was outside the scope of this report's analysis.

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. This approach does not capture the very short-term marginal emissions impact on the grid from plugging in a new EV, but it does reflect changes that are occurring in non-marginal load generation around the country. The average emissions approach also allows for comparison with future and past emissions analyses and 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 trajectory of the grid and the global warming emissions over the life of the vehicles should be taken into account.

Cleaner Cars from Cradle to Grave

How Electric Cars Beat Gasoline Cars on Lifetime Global Warming Emissions

> ***On average, driving an electric vehicle produces lower global warming emissions than the most fuel-efficient gasoline car on the market today.***

Electric vehicles (EVs) are a critical part of the American transportation future given their potential to dramatically cut oil use and global warming emissions—especially when charged by a clean-electricity grid. Based on our calculations that weighted where EVs were sold in 2014, along with updated power plant emissions data, driving an EV in the United States produced global warming emissions similar to a gasoline vehicle that gets 68 miles per gallon, on average. And over its lifetime—from manufacturing to operation to disposal—a battery-electric vehicle (BEV) cuts emissions just over 50 percent relative to a comparable gasoline car.

To reach their full potential, EVs must account for a larger share of vehicle sales while the electricity grid shifts from coal to low-carbon renewable sources. This report presents the comprehensive results of comparing the global warming emissions of BEVs with their gasoline counterparts in the United States today, accompanied by recommendations on how to increase their environmental benefits over the next 30 years.

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