Comparing Global Warming Impacts of Electric and Gas Powered Vehicles by Electrical Region

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About the 2 Degrees Institute

The 2 Degrees Institute's mission is to develop and support strategies that empower people to make the behavioural and lifestyle changes needed to keep our planet from warming by 2 degrees Celsius above pre-industrial levels. Find out more about the 2 Degrees Institute by visiting www.2degreesinstitute.org.

The Electric Pledge is a campaign of the 2 Degrees Institute to accelerate the adoption of zero emission transportation by encouraging people to take the pledge that their next vehicle purchase will be an electric one. Find out more at www.electricpledge.org.

This report can be downloaded online at:
http://www.2degreesinstitute.org/reports/comparing_ghg_emissions_of_bevs_and_icevs.pdf

The maps in this report can also be found at www.electricpledge.org.

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Introduction

At a time when anthropogenic greenhouse gas emissions are skyrocketing, battery electric vehicles (BEVs) represent an opportunity for us to transform our transportation sector from one that is powered by fossil fuels to one powered by clean energy. They will replace hundreds of millions of miniature, inefficient, fossil-fuel power plants that emit climate pollution: the internal combustion engine in vehicles. Instead, emissions will be concentrated in just a few centralized power plants that burn fossil fuels. This allows efforts for reducing greenhouse gas emissions and improving air quality to be focused at a small number of sources. All the BEVs in a region instantly get cleaner together as electricity power production gets cleaner. This cleaning of the electricity grid is already happening at a startling rate. Canada's electricity has become 33 per cent cleaner in the last decade; the US's by over 20 per cent (source: US Energy Information Administration 2017). Environment Canada projects that existing plans will lead to Canada's electricity being 50 percent cleaner than 2005 by 2020. At that point 85% of the utility electricity supply will be generated from non-emitting sources. The rapidly falling costs of renewable energy like wind and solar look set to continue or even accelerate this trend.

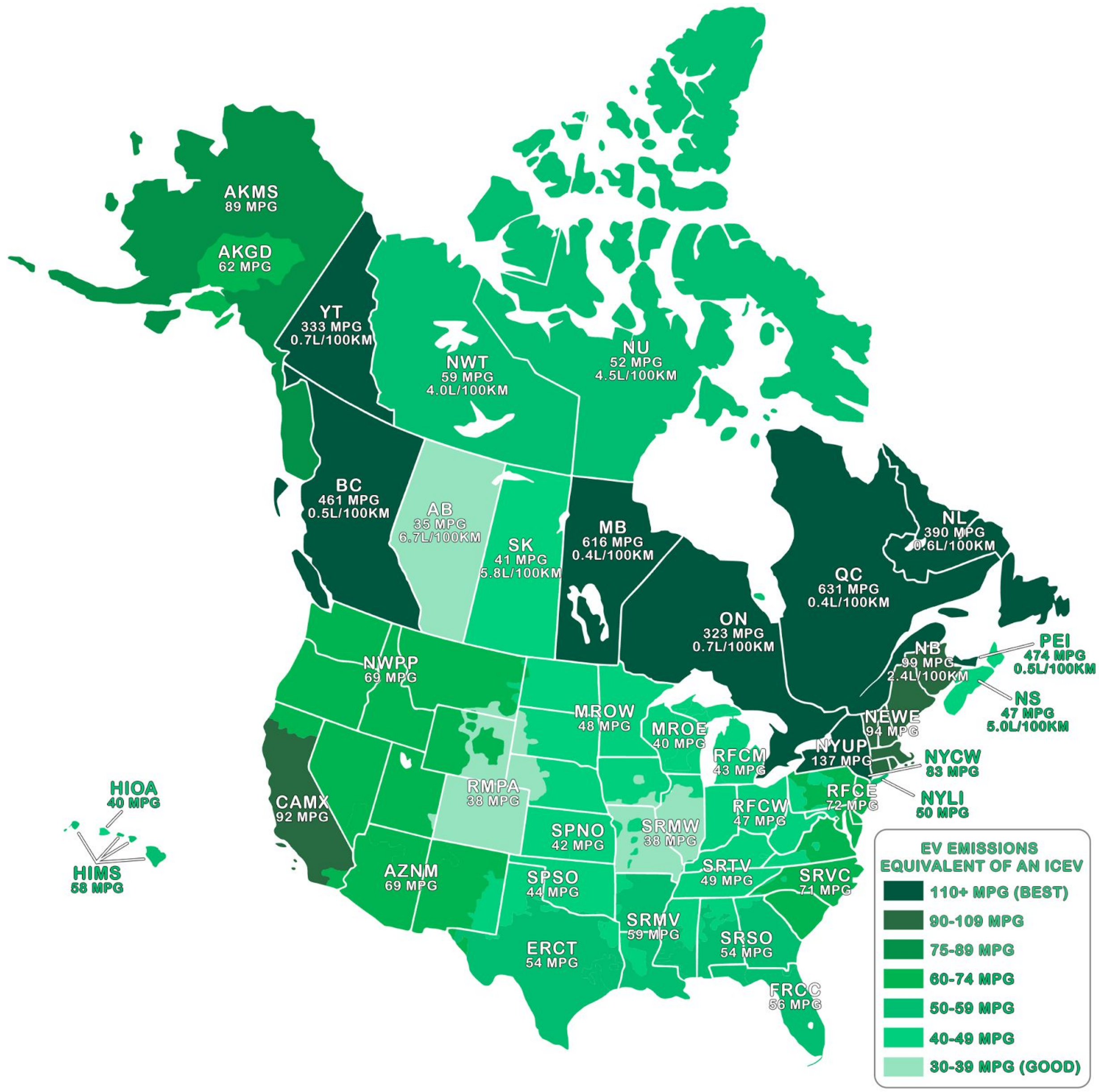
The purpose of these calculations are to compare the emissions that a battery electric car would create (factoring in vehicle embodiment, vehicle maintenance, electricity source emissions and upstream emissions) with a comparable internal combustion engine vehicle (ICEV). This comparison will then be shown visually on a map of North America. These comparisons would be calculated for each region (provinces and territories in Canada, electrical grid subregions in the USA).

The results of the comparison are expressed in the following methods:

1. MPG_{ghg}: What mileage a comparable ICE vehicle would need to achieve to equal the total greenhouse gas (GHG) emissions from a battery electric car over the same distance with the lifetime emission sources (mentioned above) factored in.
2. The lifecycle percent reduction in total GHG emissions (for both car and fuel) of a BEV over a comparable ICE vehicle.
3. The annual reduction in tons of GHG emissions (for both car and fuel) of a BEV over a comparable ICE vehicle.

4. How far a new average battery electric vehicle (BEV) would need to be driven before the extra global warming emissions from its manufacturing are offset by its lower emissions per mile or km.

MPG$_{ghg}$ Emissions of a BEV Compared to an ICEV by Electrical Region



This map displays the combined city/highway fuel economy rating of a gasoline vehicle that would have global warming emissions that equal a BEV. This value factors in emissions from vehicle embodiment + maintenance + upstream fuel emissions + fuel combustion of both vehicles. The fuel economy values are expressed in MPG (miles per gallon) or L/100km.

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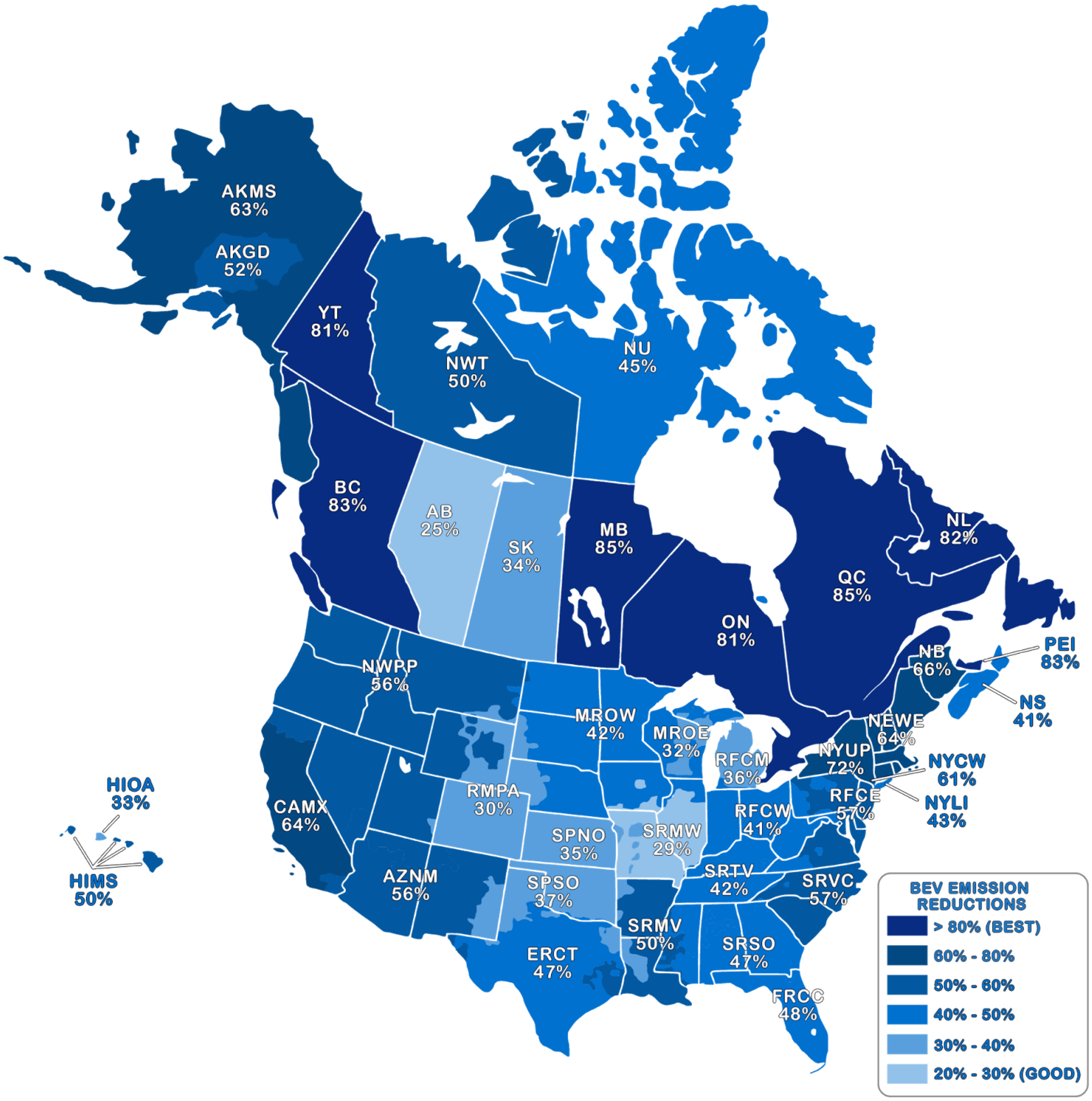
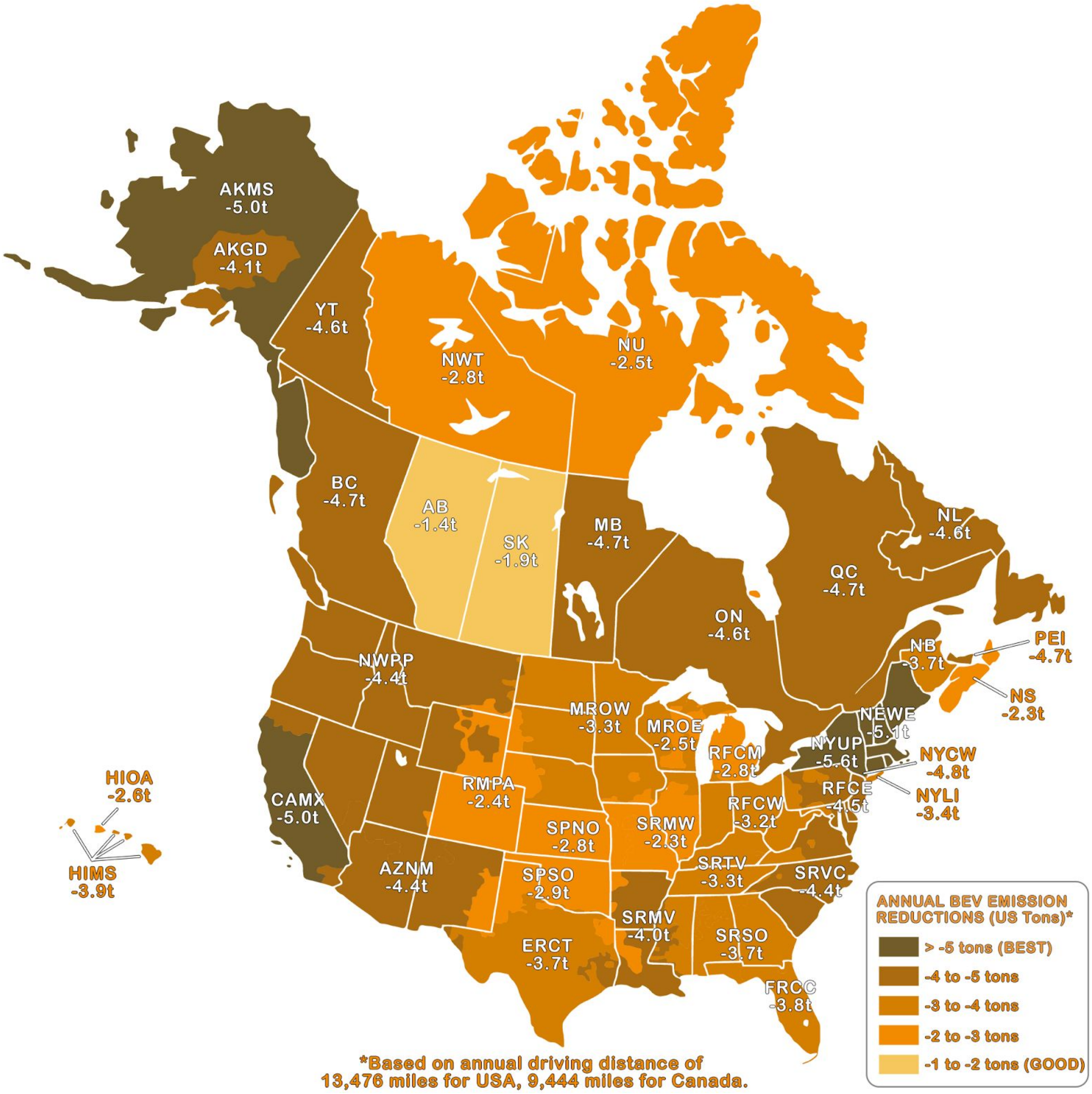
BEV Emissions Reductions Compared to an ICEV by Electrical Region



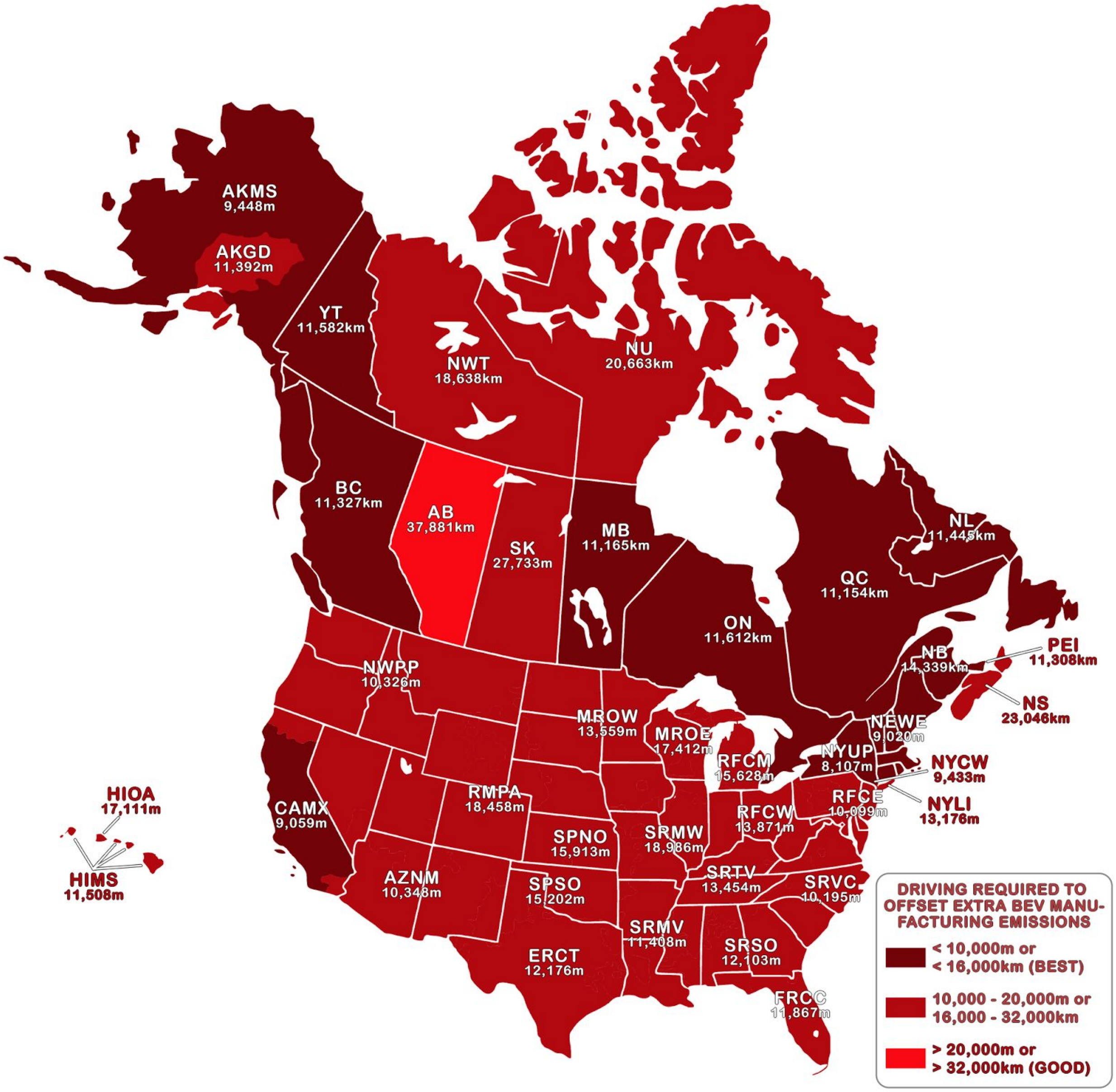
This map shows the life cycle (for both car and fuel) reduction in GHG emissions from replacing a gasoline vehicle with a comparable electric car. (Lifetime mileage: 157,000 miles or 252,667km, average ICEV fuel economy: 25mpg or 9.4L/100km, BEV fuel economy: 3.135 miles/kWh). *See Appendix A4*

Annual BEV Emissions Reductions Compared to an ICEV by Electrical Region



This map shows the annual reduction (for both car and fuel) in GHG emissions (US tons CO2e) from replacing a gasoline vehicle with a comparable electric car. (Annual mileage in USA: 13,476 miles or 21,687km, Canada: 9,444 miles or 15,199km, average ICEV fuel economy: 25mpg or 9.4L/100km, BEV fuel economy 3.135 miles/kWh).

Driving Required to Offset Extra BEV Embodied Emissions



This map displays how far you need to drive a new average battery electric vehicle (BEV) before the extra global warming emissions from its manufacturing are offset by its lower emissions per mile or km. From this point on, the net emissions of a BEV are lower than a comparable gasoline vehicle.

Background

The Union of Concerned Scientists (UOCS) was the first to compare BEV emissions with ICE vehicles in terms of MPG_{ghg} back in 2012 in their report "State of Charge". Since then they have been updating their values as new data become available. The 2 Degrees Institute's reasons for publishing a separate map are as follows:

1. To include Canada in the map.
2. To include the extra embodied emissions of manufacturing a BEV over a comparable ICE vehicle. (We believe this will counteract skeptics who would otherwise dismiss the values as not considering the larger impact of BEVs during the manufacturing process.)
3. To factor in reduced emissions in vehicle maintenance (parts and service) that are present with a BEV.
4. To factor in the average gasoline/ethanol blended fuel composition for both the USA (e10) and Canada (e5) markets.
5. To offer a variety of visual regional comparisons between BEVs and ICEVs.

Life Cycle Energy Emissions from the Grid (Upstream + Generation + Distribution)

We needed to determine the emissions generated in grams CO2e/kWh (at the end-user consumption level) of the energy grid in each applicable region. This value must factor in upstream emissions + generation + distribution.

Upstream Emissions

USA

Upstream emissions are determined by using upstream emission averages in grams CO2e/kWh for the extraction and transportation of each type of feedstock material (coal, diesel, natural gas, biomass, nuclear). These data are provided by GREET 2016 for fossil fuels, biomass and nuclear. These values factor in a 6.5% transmission line loss.

We remove transmission line loss from upstream emission calculations to avoid double counting it since we add them at the end. Hydro, solar, wind and geothermal have a value of 0 for upstream emissions since there is no extraction or transportation of feedstock material.

The percentage of each type of power source for a region's energy grid was obtained by eGrid2014v2 report. *See Figure 1A*

Canada

We used the same upstream emission values that GREET 2016 provided for the USA however retain the 6.5% transmission line loss. Although they are US based data, we feel that the emissions in extraction and transportation in the US should be similar for Canada. The total upstream emissions for each province/territory is determined by calculating what fraction of the grid in each region is powered by each type of fuel source. These numbers are obtained from the National Inventory Report for Canada. We then plug in the GREET 2016 emission values for each type of power plant.

Table 1. Example: Calculating Upstream Emissions in AZNM Sub-Region

Power Source	Upstream Values CO2e/kWh*	% of Grid	AZNM g CO2e/kWh
Coal	62.76	21.3%	12.5
Diesel	167.97	0%	0
Natural Gas	99.22	39.10%	36.3
Nuclear	9.09	23.60%	2
Biomass	45.9	0.4%	0.2
Total		**100%**	**51.0**

**GREET 2016. Transmission loss of 6.5% was included in original GREET values and has been removed.*

Generation

For Canada, generation + distribution, data come from the National Inventory Report that was submitted to the UN by the federal government (released on April 13, 2017). It already factors in transmission line energy loss (distribution) in their numbers. *See figure A1 for an example.*

For the US, energy grid data by region are made available by the EPA's eGrid2014v2 *Figure A2*. It includes a transmission loss percentage by region (*Figure A3*) in the report but does not add it into the emission values so we added it in.

Distribution (Transmission Line Loss)

USA

The eGrid2014v2 report calculates transmission line loss by region (*Figure A3*) so we factor these into the emission calculations for each region.

Canada

The National Inventory Report already factors in transmission line energy loss for power generation (power plant to consumer) in their power plant emission numbers.

Embodied BEV Emissions

To compare the extra emissions from the embodiment (manufacturing) of an electric vehicle over a comparable gasoline vehicle (*Figure A8,A9*), we compare a 2014 Nissan Leaf with the average of five comparable mid-size ICE vehicles and a 2014 Tesla model S85 with the average of five comparable full-size gas vehicles (David Reichmuth et al. Union of Concerned Scientists 'Cleaner Cars from Cradle to Grave' 2015). The following assumptions were made:

2014 Nissan Leaf

1. Battery lasting 135,000 miles (217,261 km)*
2. Embodied emissions in the production Nissan Leaf to be 1 ton higher than a comparable ICE car Vehicle.
3. Vehicle disposal/recycling is expected to be equal to a comparable ICE vehicle.*

2014 Tesla Model S 85 (rear wheel drive)

1. Battery lasting 179,000 miles (288,073 km)*

2. Embodied emissions in the production a Model S 85 to be 6 tons higher than a comparable ICE vehicle.*
3. Vehicle disposal/recycling is expected to be equal to a comparable ICE vehicle.*

*Source: David Reichmuth et al. Union of Concerned Scientists 'Cleaner Cars from Cradle to Grave' 2015

Calculations

To determine grams CO2e/mile for BEV embodied emissions, we divide the tons (total emissions) / total miles (battery lifespan). (i.e. for the Nissan Leaf 1 ton / 135,000 miles x 907185 (convert tons to grams) = 6.72 g CO2e/mile

Then we convert g/mile to g/kWh by multiplying g/mile by the average number of miles the Nissan Leaf travels per kWh (fuel efficiency obtained from the EPA):

6.72 g CO2e/mile x 3.33 miles/kwh (for Nissan Leaf) = 22.38 g CO2e/kWh

Then we do the same for the Model S (89g CO2e/kWh) and average the two = 55.89g CO2e/kWh

Table 2: Calculating Embodied BEV Emissions

	2014 Nissan Leaf (24kWh)	2014 Tesla Model S (85kWh)
Battery Lifespan	135,000 miles 217,261 km	179,000 miles 288,073 km
Extra BEV Embodied Emissions	1 ton	6 ton
Extra BEV Emissions	6.72 grams/mile	30.41 grams/mile
Vehicle Efficiency	3.33 miles/kWh 5.36 km/kWh	2.89 miles/kWh 4.67 km/kWh
Extra BEV Emissions	22.38 grams/kWh	89.4 grams/kWh

Uncertainties

We believe the figures for embodied BEV emissions have poor data to back them up and we believe are conservative. These emissions are based on the US Average energy grid powering the manufacturing of the BEV. Factories in places with clean energy (i.e.: California) and manufacturing plants like Tesla's Gigafactory (which will soon be powered by solar) will bring down manufacturing emissions substantially. Since BEV batteries are relatively new, we have little data pointing to what their usable life cycle will actually be both as a vehicle battery and as a second life as energy storage for the grid. One report by a Tesla Motor Club in Germany shows the results of over 300 tesla owners' mileage and remaining charge capacity (See figure A6). It shows that Tesla batteries are on track to remain above 90% capacity after 200,000 miles (321,869 km) - indicating that a Tesla battery should still remain functional as a vehicle battery well after 200,000 miles (321,869 km) and possibly up to 500,000 miles (804,672 km).

GHG Emissions from Gasoline (Including Upstream Emissions)

To offer an accurate comparison of emissions generated from electric cars and ICE vehicles, we needed to calculate the upstream emissions and combustion emissions using the average type of fuel consumed in both Canada and the USA and their corresponding upstream emissions. In Canada, the average ethanol content in gasoline is 5% (e5) (Government of Canada Renewable Fuels Regulation) in the USA it is 10% (e10) (US Energy Information Administration). Upstream emissions include emissions associated with fuel production such as feedstock extraction, feedstock transport to a processing plant, and conversion of feedstock to motor fuel, as well as distribution of the motor fuel.

Calculations

The EPA's baseline fuel lifecycle emissions numbers (0.091g CO_2e/kJ) are based on a fuel type of 92.5% gasoline, 5.5% conventional biofuels, 1.1% advanced biofuels and <1% each of diesel, natural gas, propane, and electricity (source: EPA). The value is measured in g CO_2e/kJ. We felt that this was a close enough approximation to be relevant for calculating life cycle emissions for both types of fuel (e5 and e10) for each country.

The first step was to calculate how many kilojoules of energy is in 1 gallon of e5 and 1 gallon of e10 gasoline. For example, in Canada where e5 gasoline is the average:

(127,102kJ x 95% gasoline) + (80,496kJ x 5% ethanol) = 124,562kJ of energy in e5 Gasoline

124,562kJ x 0.091g CO2e/kJ = 11,335g CO2e/gallon of e5 Gasoline

Table 3: Calculating Total Emissions (combustion + upstream) of Gasoline

	United States (e10)	Canada (e5)
Energy from Gasoline	114,391 kJ	120,747
Energy from Ethanol	8,049 kJ	4,024 kJ
Total Energy	122,021 kJ/gallon	124,562 kJ/gallon
Total Emissions	11,104 g CO2e/gallon	11,335 g CO2e/gallon

Vehicle Maintenance Emissions

The maintenance and repair costs for electric vehicles (excluding tire replacements) will be around 78 percent below costs of a comparable internal combustion vehicle (M. Alexandar et al. Electric Power Research Institute 2013). Tire maintenance/replacement costs is $0.098/mile for an average car (AAA's 2015 driving costs). When adding tire costs/mile and all other maintenance costs we concluded that total savings on maintenance of a BEV is about 61%. We use a 1:1 ratio to calculate that emissions for vehicle parts and maintenance will also be roughly 61% less than a comparable ICE vehicle. (source: The Renewable and Appropriate Energy Laboratory at UC Berkeley)

Calculating Emissions for Auto Services and Parts.

We calculated the tons per mile of emissions for auto servicing and parts based on data provided by The Renewable and Appropriate Energy Laboratory at UC Berkeley. They factored that an average US household has 2 cars that total 22,700 miles (36,532 km) per year. They calculated annual CO2e emissions in auto services is 0.31 tons and 0.66 tons for auto parts, totalling 0.97 tons CO2e/year.

When dividing 0.97 tons CO2e by the total number of miles driven (22,700 miles) and converting to grams, we get 38.77g CO2e/mile. An electric car with 61% less emissions from maintenance will produce 15.15g CO2e/mile, a savings of 23.62g CO2e/mile in emissions over an ICE vehicle.

To factor these external emissions back into a gallon of gasoline, we multiply the grams of CO2e/mile by the average miles/gallon of an average mid-size (29 MPG) and full-size (21 MPG) car used in the UOCS study, giving us:

25 MPG x 23.62g CO2e/mile = 590.5g CO2e/gallon

Putting it all together, we calculate total GHG emissions per gallon of gasoline by adding the following: upstream emissions and combustion of 1 gallon of gasoline (e5 gasoline in Canada, e10 gasoline in USA). For example, in Canada (e5 gasoline): (.091 g CO2e/kJ x 124,562 kJ of energy/gallon) + extra maintenance emissions over a BEV (590.5g CO2e/gallon):

11,335g CO2e + 590g CO2e = 11,925g CO2e/gallon of gasoline consumed by an ICE vehicle in Canada.

Table 4: Calculating Service/Maintenance Emissions

	Electric Vehicle	Gasoline Vehicle
Tire Maintenance	\$0.01/mile	\$0.01/mile
Other Maintenance	\$0.00786/mile	\$0.0354/mile
Total Maintenance	\$0.01786/mile	\$0.0454/mile
Savings on Maintenance	60.93%	0%
Emissions on Service/Maintenance	15.15 g CO2e/mile	38.77 g CO2e/mile
Extra Emissions*	-	684.96g CO2e/gallon

*based on an average ICE vehicle with a fuel economy of 25mpg.

Comparing Emissions of BEVs and ICEVs

To best communicate the environmental impact of electric vehicles compared to gas powered ones, we chose to express the differences in a few ways: 1) MPG_{ghg}: fuel economy rating of a gasoline vehicle that would have greenhouse gas emissions that equal a BEV, 2) The savings as a percent (%) in GHG emissions by driving a BEV over an ICEV, 3) The annual savings in GHG emissions (in tons of CO2e) by driving a BEV and 4) how quickly it would take by driving a BEV to offset the extra emissions in manufacturing a BEV.

Calculating Life Cycle Emissions of a Battery Electric Vehicle as MPG_{ghg}

To calculate how battery electric vehicle emissions compared to an ICE vehicle, we did the following:

Step 1: Calculated how many kWh from each region's grid (includes BEV embodied emissions) would produce the same emissions as one gallon of gasoline consumed by an ICE vehicle (upstream emissions + combustion + extra maintenance emissions of an ICE vehicle).

Example calculation for Alberta, Canada with e5 gasoline:

11,925 g CO2e per gallon of gas / (58 g CO2e/kWh upstream + 950 g CO2e/kWh generation + 55.89 g CO2e/kWh extra BEV embodied emissions) = 11.21kWh

11.21 kWh of energy could be produced using Alberta's grid and consumed by a BEV to equal the emissions of 1 gallon of gasoline consumed by an average ICE vehicle.

Step 2: We used the average vehicle efficiency of a BEV 3.135 miles /kWh or 5.05 km/kWh (averaging a Nissan Leaf and Tesla Model S 85) to calculate what would be the equivalent MPG an ICEV would need to achieve to equal the emissions produced by an electric car in each region:

Example calculation for Alberta, Canada (*See figure A-6 for all regions*):

11.21kWh x 3.135 miles per kWh = 35 MPG

Calculating Life Cycle Emissions of a Battery Electric Vehicle as a % Reduction over a Gas Powered Vehicle

To calculate how much of a reduction in greenhouse gas emissions that a BEV provides over an ICEV, the following steps were performed:

Step 1: We need to add up the total emissions from the manufacturing (embodiment) and lifetime operation of both a BEV and comparable ICEV in both Canada and the USA. End of life ICEV disposal/recycling is considered equal to that of an EV (David Reichmuth et al. Union of Concerned Scientists 'Cleaner Cars from Cradle to Grave' 2015) and not included in these calculations.

Example: ICEV Life Cycle Emissions in Alberta Canada:

manufacturing 7,257kg + maintenance 6,086kg + upstream and combustion of Fuel 71,185kg = 84,528kg CO2e

Example: BEV Life Cycle Emissions in Alberta Canada:

manufacturing 10,509kg + maintenance 2,378kg + upstream and consumption of energy from the grid 50,892kg = 63,779kg CO_2e

Step 2: We divided the difference in total emissions of the BEV and ICEV by the ICEV total emissions to get the % difference in Emissions.

Example: Percent reduction in Emissions of a BEV over a ICEV in Alberta, Canada:

(84,528kg ICEV - 63,779kg BEV) / 84,528kg ICEV x 100 = 24.5%

Calculating Annual Battery Electric Vehicle Emission Reductions over a Gas Powered Vehicle

To calculate annual savings in total greenhouse gas emissions (manufacturing + maintenance + fuel) that a BEV provides over an ICEV, the following steps were performed:

Step 1: We take the emissions from the manufacturing (embodiment) and lifetime operation of both a BEV and comparable ICEV in both Canada and the USA and divide it up annually. We used the average annual mileage of a vehicle in Canada of 9,444 miles (source: 2008 Canadian Vehicle Survey, Natural Resources Canada) and 13,476 miles for the USA (source: US Department of Transportation, 2016).

ICEV Annual Emissions (Manufacturing + Maintenance + Fuel) in the USA:

Manufacturing: 13,476 miles x 46.22 g CO_2e/mile	= 622,860g CO_2e/year
Maintenance: 13,476 miles x 38.77 g CO_2e/mile	= 522,464g CO_2e/year
Fuel: 13,476 miles / 25mpg x 11,104g CO_2e/gallon	= 5,985,500g CO_2e/year
Total	**= 7,131kg (7.86 US tons)**

BEV Annual Emissions (Manufacturing + Maintenance + Fuel) in the AZNM:

Manufacturing: 13,476 miles x 66.94 g CO_2e/mile	= 902,083g CO_2e/year
Maintenance: 13,476 miles x 15.15 g CO_2e/mile	= 204,161g CO_2e/year
Fuel: 13,476 miles / 3.135 m/kWh x 473g CO_2e/kWh	= 2,033,221g CO_2e/year
Total	**= 3,139kg (3.46 US tons)**

Step 2: We subtract the BEV emissions from the ICEV emissions value to get the annual BEV emission reductions over an ICEV:

BEV Annual Emissions Savings in the AZNM electricity region:

7.86 tons (ICEV Emissions) - 3.46 tons (BEV Emissions) = 4.4 tons CO2e savings

Calculating Driving Distance Required to Offset Extra BEV Manufacturing Emissions

To calculate the distance a BEV will need to travel to offset the extra embodied emissions generated in manufacturing, we divided the additional BEV embodied emissions by the savings in grams of CO2e emissions per mile achieved by the BEV for each electrical region:

$$\text{Distance} = \frac{\text{Additional BEV Embodied Emissions}}{(1/\text{ICEV MPG} \times \text{CO2e/gallon gas}) - (1/\text{BEV MPG}_{ghg} \times 11{,}694\text{g CO2e/gallon gas})}$$

Car Specific Data

Although the map offers a single average value for MPG_{ghg} equivalents for each region, we have performed separate calculations for specific values for a mid-size (Nissan Leaf) and full-size electric vehicle (Tesla Model S 85).

BEV embodied emissions are much higher for a vehicle like the Tesla Model S 85 compared to the Nissan Leaf (Model S 85 = 15 tons, Nissan Leaf = 8 tons) and vehicle efficiency is also different (Model S 85 = 2.94m/kWh, Nissan Leaf = 3.33m/kWh).

Vehicle maintenance emissions per gallon of gas for a midsize and full-size ICE vehicle also differ due to the efficiency difference of both sizes of vehicles. For example, a full-size ICEV (496g CO2e/gallon) will have lower maintenance emissions per gallon of gas consumed than a mid-size ICEV (685g CO2e/gallon) due to the full-size vehicle traveling less distance and therefore accumulating less wear and tear for each gallon of gas consumed.

These 3 factors (specific BEV embodied emissions, efficiency and maintenance) for the Nissan Leaf and Model S are calculated separately to show how a midsize BEV may make more sense than a comparable ICEV in regions where the energy grid is not very favorable for electric vehicle adoption.

For example, in Nova Scotia the average MPG_{ghg} for an electric car is 47 MPG_{ghg}, resulting in a few hybrid cars offering lower emissions than an EV. A Nissan Leaf however would get 53 MPG_{ghg} making it a more environmentally friendly option than any hybrid car available. *See Appendix A-6*

Table 5: Example of Calculating MPG_{ghg} for AZNM Sub-region

	Nissan Leaf	Tesla 85	Average
Gasoline emissions (10% ethanol)	11,104g CO2e/gallon	11,104g CO2e/gallon	11,104g CO2e/gallon
ICEV Extra Maintenance Emissions	685g CO2e/gallon	496g CO2e/gallon	590g CO2e/gallon
Total Gasoline Emissions	**11,789g CO2e/gallon**	**11,600g CO2e/gallon**	**11,694g CO2e/gallon**
Feedstock Upstream Emissions for Power Plant	51g CO2e/kWh	51g CO2e/kWh	51g CO2e/kWh
Power Plant Emissions	399g CO2e/kWh	399g CO2e/kWh	399g CO2e/kWh
Add. BEV Embodied Emissions	22.4g CO2e/kWh	89.4g CO2e/kWh	55.9g CO2e/kWh
Transmission Line Loss (5%)	23.6g CO2e/kWh	23.6g CO2e/kWh	23.6g CO2e/kWh
Total BEV Emissions	**496g CO2e/kWh**	**563g CO2e/kWh**	**529.5g CO2e/kWh**
Energy per Gallon of Gasoline Emissions	23.8 kWh/gallon	20.6 kWh/gallon	22.1 kWh/gallon
Fuel Economy	3.33 miles/kWh	2.94 miles/kWh	3.135 miles/kWh
EV Emissions Equivalent	**79 MPG_{ghg}**	**61 MPG_{ghg}**	**69 MPG_{ghg}**

The Greening of the Grid

In most regions in North America, the proportion of renewable energy powering the grid is increasing every year due to the shift of energy production from coal to natural gas, solar and wind generation. This will result in the MPG_{ghg} values becoming increasingly more favorable to electric car adoption.

As Solar PV prices continue to plummet, more and more people will choose to invest in Solar panels on their home. When using rooftop solar to charge their battery electric car, driving emissions will be reduced by 84-85% over a comparable gas vehicle. MPG_{ghg} values will be 650 MPG_{ghg} in the US and 663 MPG_{ghg} in Canada.

Recommendations

Electric Vehicles offer an emission reduction advantage over a comparable gasoline powered vehicle in every region in North America. This reduction advantage will only improve over time as regions work towards reducing their carbon emissions from electricity production. We recommend that everywhere in North America people should switch over to electric cars when shopping for a new vehicle - especially in areas where emission values are 50 MPG_{ghg} and higher.

What first? Buy Rooftop Solar or an Electric Car?

Switching to an electric car or installing rooftop solar will both contribute to reducing your carbon footprint. Depending on how much energy you consume at home or how much you drive, the return on investment on maximizing your carbon footprint reduction for installing solar or switching to electric will vary greatly.

Generally speaking, if you live in an area that already has a green electrical grid (ie: British Columbia or Upstate New York), switching to an electric car first would make the biggest reduction to your carbon footprint. The opposite would be the case in areas with a dirty grid that offers minor emission reductions from driving an electric car (ie: Alberta or Illinois). In that case, investing in rooftop solar would be the best first option.

A1: Electricity Generation Resource Mix

United States

Electrical Sub-region	Coal	Natural Gas	Other Fossil Fuels (oil, diesel, etc.)	Nuclear	Hydro	Biomass	Renewables (geothermal, wind, solar, tidal etc.)
AKGD	11.7%	66.1%	7.0%	0.0%	11.5%	1.2%	2.6%
AKMS	0.0%	10.3%	8.7%	0.0%	78.3%	0.5%	2.2%
AZNM	21.3%	39.1%	0.0%	23.6%	6.4%	0.4%	9.2%
CAMX	0.4%	62.5%	1.1%	9.0%	8.4%	3.4%	15.2%
ERCT	33.2%	45.3%	0.6%	10.6%	0.1%	0.3%	9.9%
FRCC	21.7%	61.4%	2.1%	12.7%	0.1%	1.9%	0.1%
HIMS	1.6%	0.0%	68.2%	0.0%	3.3%	3.6%	23.2%
HIOA	19.9%	0.0%	74.1%	0.0%	0.0%	3.1%	2.8%
MROE	71.3%	10.5%	1.6%	0.0%	5.0%	4.7%	6.9%
MROW	58.4%	3.2%	0.5%	13.0%	5.7%	1.3%	18.0%
NEWE	4.5%	43.2%	3.7%	33.3%	6.4%	6.8%	2.1%
NWPP	36.2%	11.9%	0.5%	2.8%	39.7%	1.1%	7.7%
NYCW	0.0%	55.2%	2.5%	41.9%	0.0%	0.5%	0.0%
NYLI	0.0%	84.0%	11.2%	0.0%	0.0%	4.2%	0.6%
NYUP	5.5%	25.9%	0.9%	30.6%	30.4%	2.1%	4.7%
RFCE	23.3%	30.7%	1.4%	40.5%	1.2%	1.3%	1.5%
RFCM	59.6%	14.6%	2.9%	16.1%	0.0%	2.3%	4.4%
RFCW	60.0%	9.3%	1.3%	25.7%	0.6%	0.6%	2.4%
RMPA	68.3%	16.0%	0.1%	0.0%	2.9%	0.2%	12.6%
SPNO	66.2%	6.5%	0.2%	12.1%	0.0%	0.1%	14.9%
SPSO	48.4%	34.5%	2.4%	0.0%	2.2%	1.6%	10.9%
SRMV	25.8%	49.0%	2.9%	19.2%	1.4%	1.7%	0.0%
SRMW	82.4%	1.2%	0.4%	12.2%	0.8%	0.1%	2.9%
SRSO	36.2%	36.5%	0.2%	21.5%	2.6%	3.0%	0.0%
SRTV	52.4%	14.8%	0.7%	23.0%	7.9%	1.1%	0.0%
SRVC	31.7%	20.8%	1.0%	42.2%	1.3%	2.9%	0.2%

Source: US EPA eGrid2014v2 report

Canada

Province / Territory	Coal	Natural Gas	Other Fossil Fuels (oil, diesel, etc.)	Nuclear	Hydro	Renewables (geothermal, wind, solar, tidal etc.)
Alberta	67.0%	19.6%	0.0%	0.0%	2.8%	9.6%
British Columbia	0.0%	1.3%	1.5%	0.0%	90.8%	7.3%
Saskatchewan	52.4%	25.1%	0.1%	0.0%	14.8%	7.8%
Manitoba	0.2%	0.1%	0.0%	0.0%	96.9%	2.9%
Ontario	0.0%	11.0%	0.5%	59.4%	22.8%	5.6%
Quebec	0.0%	0.0%	0.5%	0.0%	98.3%	1.1%
PEI	0.0%	0.0%	1.4%	0.0%	98.6%	0.0%
Nova Scotia	56.8%	11.6%	15.0%	0.0%	9.0%	7.3%
Newfoundland	0.0%	0.0%	3.8%	0.0%	95.6%	0.7%
New Brunswick	12.4%	11.8%	11.6%	31.7%	19.5%	0.6%
Nunavut	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%
Yukon	0.0%	0.0%	6.0%	0.0%	94.2%	0.1%
NW Territories	0.0%	3.4%	45.5%	0.0%	51.1%	0.0%

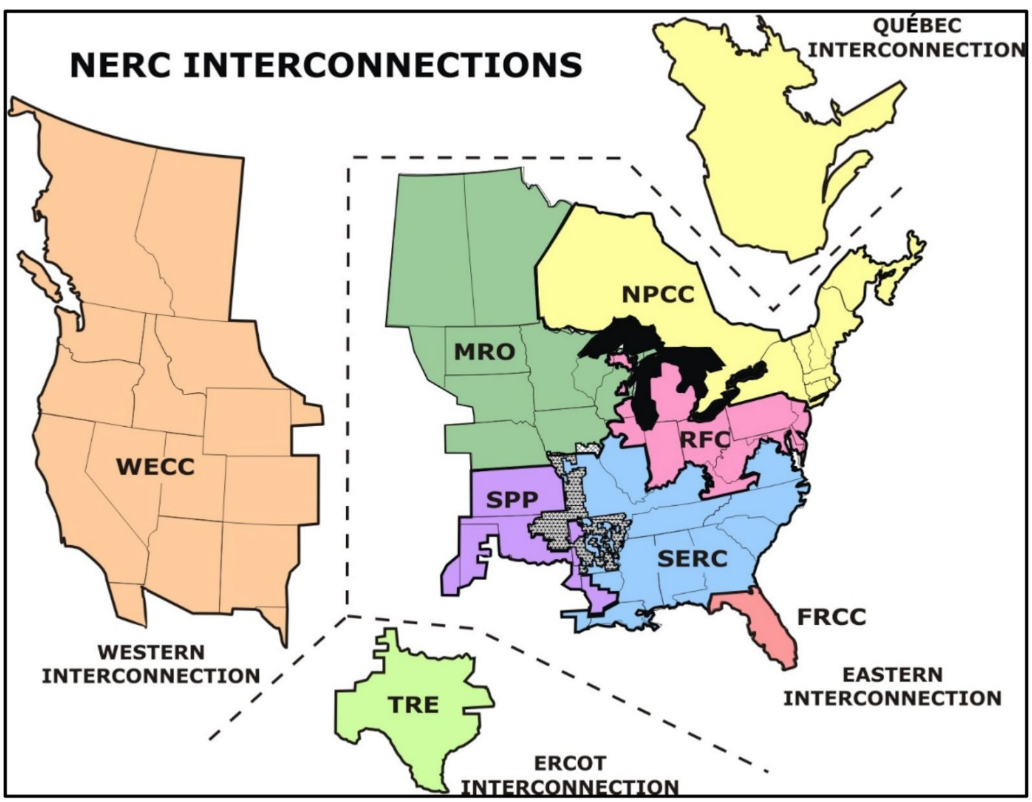
Source: Government of Canada National Inventory Report April 2017

A2: US Subregion Output Emission Rates - Greenhouse Gases (eGrid2014v2)

eGRID subregion acronym	eGRID subregion name	Total output emission rates				Fossil fuel output emission rate	Non-baseload output emission rates			
		CO_2 (lb/MWh)	CH_4 (lb/GWh)	N_2O (lb/GWh)	CO_2e (lb/MWh)	CO_2 (lb/MWh)	CO_2 (lb/MWh)	CH_4 (lb/GWh)	N_2O (lb/GWh)	CO_2e (lb/MWh)
AKGD	ASCC Alaska Grid	926.5	46.6	7.2	929.7	1,093.0	1,051.6	47.9	7.8	1,055.1
AKMS	ASCC Miscellaneous	680.5	36.1	6.0	683.1	3,416.4	3,766.0	176.5	30.5	3,779.1
AZNM	WECC Southwest	875.6	66.4	9.3	879.9	1,466.1	1,257.1	67.7	9.2	1,261.4
CAMX	WECC California	568.6	33.1	4.0	570.5	866.6	913.9	35.5	4.2	915.8
ERCT	ERCOT All	1,142.8	81.8	11.6	1,148.0	1,455.3	1,389.4	85.6	11.9	1,394.9
FRCC	FRCC All	1,075.2	87.8	12.1	1,080.8	1,259.1	1,209.0	82.1	11.3	1,214.2
HIMS	HICC Miscellaneous	940.8	95.3	15.2	947.5	1,515.0	1,329.2	142.9	22.6	1,339.2
HIOA	HICC Oahu	1,479.4	159.4	24.5	1,490.4	1,523.9	1,470.1	140.0	22.4	1,480.0
MROE	MRO East	1,663.8	191.2	28.2	1,676.5	2,007.2	1,808.7	200.9	29.4	1,822.0
MROW	MRO West	1,365.1	161.4	23.3	1,375.6	2,196.3	2,032.7	238.4	34.3	2,048.2
NEWE	NPCC New England	570.9	96.0	12.8	576.8	1,011.3	1,066.0	107.9	14.7	1,072.6
NWPP	WECC Northwest	907.0	97.8	14.2	913.4	1,866.1	1,562.3	154.0	22.1	1,572.4
NYCW	NPCC NYC/Westchester	665.5	24.4	3.0	666.9	1,206.4	1,312.8	25.9	3.0	1,314.2
NYLI	NPCC Long Island	1,196.2	132.4	17.2	1,204.3	1,143.0	1,345.4	43.8	5.7	1,348.1
NYUP	NPCC Upstate NY	365.7	30.7	4.1	367.6	1,111.7	1,194.7	90.5	12.4	1,200.4
RFCE	RFC East	829.4	73.9	11.2	834.5	1,480.3	1,472.6	119.7	17.3	1,480.5
RFCM	RFC Michigan	1,531.5	170.1	24.5	1,542.6	1,974.9	1,863.6	194.0	27.9	1,876.3
RFCW	RFC West	1,380.9	150.2	22.0	1,390.9	1,966.4	1,949.8	202.6	29.9	1,963.3
RMPA	WECC Rockies	1,737.7	178.2	25.8	1,749.4	2,061.0	1,803.3	164.2	23.5	1,814.0
SPNO	SPP North	1,575.0	173.8	25.2	1,586.5	2,161.4	2,065.9	218.3	31.6	2,080.3
SPSO	SPP South	1,475.9	135.4	19.7	1,484.8	1,723.2	1,597.0	127.7	18.3	1,605.4
SRMV	SERC Mississippi Valley	1,022.0	78.6	11.2	1,027.1	1,338.3	1,250.3	85.5	12.1	1,255.9
SRMW	SERC Midwest	1,772.0	208.8	30.4	1,785.8	2,110.5	2,120.3	246.4	35.8	2,136.6
SRSO	SERC South	1,143.8	103.7	15.3	1,150.7	1,560.0	1,527.9	136.5	20.1	1,537.0
SRTV	SERC Tennessee Valley	1,336.3	138.6	20.2	1,345.4	1,964.7	1,923.4	185.3	26.9	1,935.6
SRVC	SERC Virginia/Carolina	856.6	95.7	13.8	862.8	1,605.3	1,427.5	141.8	20.3	1,436.7
U.S.		**1,122.9**	**110.9**	**16.0**	**1,130.2**	**1,665.0**	**1,543.7**	**269.6**	**38.7**	**1,552.5**

A3: US Grid Gross Loss (%) (eGrid2014v2)

Region*	Grid Gross Loss (%)
Alaska	5.63%
Eastern	4.97%
Hawaii	5.18%
Texas (ERCOT)	5.12%
Western	4.79%
U.S.	**4.95%**
*One of three interconnect power grids plus AK, HI, and U.S.	



A4: Comparing Life Cycle Emissions of a BEV and ICEV

ICEV life cycle emissions CO2e (manufacturing 7,257kg + maintenance 6,086kg + upstream and combustion of Fuel [71,185kg e5 gas for Canada] or [69,733kg e10 gas for USA]) = 83,076kg CO2e Canada and 84,528kg CO2e USA. End of life ICEV disposal/recycling is considered equal to that of an EV (David Reichmuth et al. Union of Concerned Scientists 'Cleaner Cars from Cradle to Grave' 2015) and not included in these calculations.

US Electricity Subregions

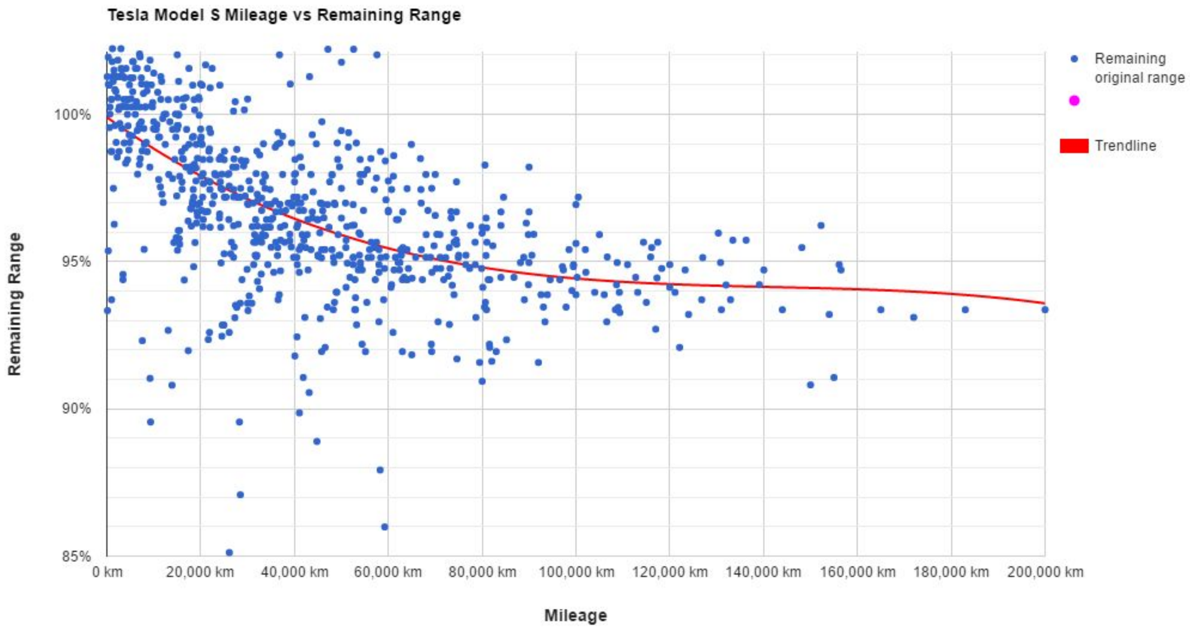
	BEV (kg CO2e)				ICEV (kg CO2e)	Emissions Difference
Region	Manufacturing	Maintenance	Driving	Total	Total	Savings
AKGD	10,509	2,378	26,859	39,746	83,076	52.2%
AKMS	10,509	2,378	17,854	30,741	83,076	63.0%
AZNM	10,509	2,378	23,896	36,783	83,076	55.7%
CAMX	10,509	2,378	17,039	29,926	83,076	64.0%
ERCT	10,509	2,378	31,128	44,015	83,076	47.0%
FRCC	10,509	2,378	30,061	42,948	83,076	48.3%
HIMS	10,509	2,378	28,754	41,641	83,076	49.9%
HIOA	10,509	2,378	42,937	55,824	83,076	32.8%
MROE	10,509	2,378	43,440	56,327	83,076	32.2%
MROW	10,509	2,378	35,305	48,192	83,076	42.0%
NEWE	10,509	2,378	16,803	29,690	83,076	64.3%
NWPP	10,509	2,378	23,793	36,680	83,076	55.8%
NYCW	10,509	2,378	19,226	32,113	83,076	61.3%
NYLI	10,509	2,378	34,235	47,122	83,076	43.3%
NYUP	10,509	2,378	10,582	23,469	83,076	71.8%
RFCE	10,509	2,378	22,707	35,594	83,076	57.2%
RFCM	10,509	2,378	40,172	53,059	83,076	36.1%
RFCW	10,509	2,378	36,132	49,019	83,076	41.0%
RMPA	10,509	2,378	45,063	57,950	83,076	30.2%
SPNO	10,509	2,378	40,743	53,630	83,076	35.4%
SPSO	10,509	2,378	39,278	52,165	83,076	37.2%
SRMV	10,509	2,378	28,375	41,261	83,076	50.3%

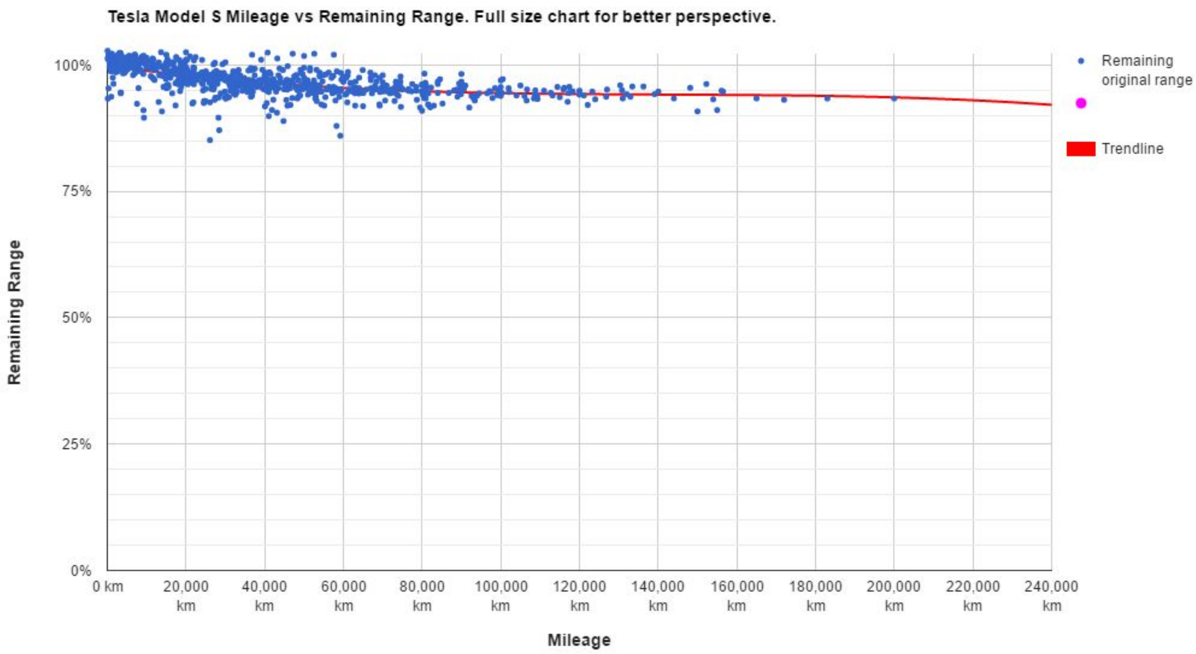
SRMW	10,509	2,378	45,814	58,701	83,076	29.3%
SRSO	10,509	2,378	30,880	43,767	83,076	47.3%
SRTV	10,509	2,378	35,019	47,906	83,076	42.3%
SRVC	10,509	2,378	23,175	36,062	83,076	56.6%
100% Rooftop Solar	10,509	2,378	0	12,887	83,076	84.5%

Canadian Provinces and Territories

	BEV (kg CO2e)				ICEV (kg CO2e)	Emissions Difference
Region	Manufacturing	Maintenance	Driving	Total	Total	Savings
Alberta	10,509	2,378	50,892	63,779	84,528	24.5%
British Columbia	10,509	2,378	1,242	14,128	84,528	83.3%
Saskatchewan	10,509	2,378	43,143	56,030	84,528	33.7%
Manitoba	10,509	2,378	214	13,101	84,528	84.5%
Ontario	10,509	2,378	2,980	15,867	84,528	81.2%
Quebec	10,509	2,378	144	13,031	84,528	84.6%
PEI	10,509	2,378	1,124	14,011	84,528	83.4%
Nova Scotia	10,509	2,378	37,259	50,146	84,528	40.7%
Newfoundland	10,509	2,378	1,972	14,859	84,528	82.4%
New Brunswick	10,509	2,378	16,122	29,009	84,528	65.7%
Nunavut	10,509	2,378	33,189	46,075	84,528	45.5%
Yukon	10,509	2,378	2,803	15,690	84,528	81.4%
NW Territories	10,509	2,378	29,021	41,908	84,528	50.4%
100% Rooftop Solar	10,509	2,378	0	12,887	84,528	84.8%

A5: Mileage vs Remaining Range for Tesla EV Batteries





Source: Tesla Motors Club (Dutch-Belgium Tesla Forum)

A6: MPG_{ghg} and $L/100km_{ghg}$ by Region for Mid-Size, Full-Size and Average BEVs

US Electricity Subregions

	Mid-Size BEV (Nissan Leaf)		Full-Size BEV (Tesla Model S 85)		Average BEV*	
Region	MPG	L/100km	MPG	L/100km	MPG	L/100km
AKGD	71	3.3	55	4.3	62	3.8
AKMS	104	2.2	77	3.1	89	2.6
AZNM	79	3.0	61	3.9	69	3.4
CAMX	109	2.2	80	2.9	92	2.5
ERCT	61	3.8	48	4.9	54	4.3
FRCC	64	3.7	50	4.7	56	4.2
HIMS	66	3.5	52	4.5	58	4.0
HIOA	45	5.2	36	6.5	40	5.9
MROE	44	5.3	36	6.5	40	5.9
MROW	54	4.3	43	5.4	48	4.9
NEWE	111	2.1	81	2.9	94	2.5
NWPP	80	3.0	61	3.9	69	3.4
NYCW	97	2.4	73	3.2	83	2.8
NYLI	56	4.2	44	5.3	50	4.7
NYUP	169	1.4	114	2.1	137	1.7
RFCE	83	2.8	63	3.7	72	3.3
RFCM	48	4.9	39	6.1	43	5.5
RFCW	53	4.4	42	5.5	47	5.0
RMPA	43	5.5	35	6.8	38	6.1
SPNO	47	5.0	38	6.2	42	5.6
SPSO	49	4.8	39	6.0	44	5.4
SRMV	67	3.5	52	4.5	59	4.0
SRMW	42	5.6	34	6.9	38	6.2
SRSO	62	3.8	49	4.8	54	4.3
SRTV	55	4.3	44	5.4	49	4.8
SRVC	82	2.9	62	3.8	71	3.3
100% Rooftop Solar	1,754	0.1	381	0.6	650	0.4

Canadian Provinces and Territories

	Mid-Size BEV (Nissan Leaf)		Full-Size BEV (Tesla Model S 85)		Average BEV*	
Region	MPG	L/100km	MPG	L/100km	MPG	L/100km
Alberta	39	6.0	32	7.4	35	6.7
British Columbia	852	0.3	305	0.8	461	0.5
Saskatchewan	46	5.1	37	6.4	41	5.8
Manitoba	1,504	0.2	371	0.6	616	0.4
Ontario	492	0.5	234	1.0	323	0.7
Quebec	1,587	0.1	377	0.6	631	0.4
PEI	897	0.3	312	0.8	474	0.5
Nova Scotia	53	4.5	42	5.6	47	5.0
Newfoundland	652	0.4	271	0.9	390	0.6
New Brunswick	117	2.0	85	2.8	99	2.4
Nunavut	59	4.0	47	5.0	52	4.5
Yukon	514	0.5	240	1.0	333	0.7
NW Territories	67	3.5	52	4.5	59	4.0
100% Rooftop Solar	1,789	0.1	389	0.6	663	0.4

A7: Midsize Gasoline Vehicles Comparable to a Nissan Leaf

Make	Model	Engine	Fuel Economy (mpg)		Curb Weight	Footprint
			MPG	L/100km	(lbs)	(sq.ft)
Mazda	3- or 5- Door i	2.0L I4	33	7.1	2,900	45
Ford	Focus (Hatchback)	2.0L I4	30	7.8	3,000	43
Mitsubishi	Lancer Sportback	2.0L I4	29	8.1	3,100	43
Volkswagen	Golf	1.8L Turbo I4	29	8.1	3,000	43
Kia	Forte5	1.6L Turbo and 2.0L I4	26	9	3,000	45
Average Fuel Economy			29	8.1	3,000	44
Nissan	Leaf	80kW/280Nm	0.3 kWh/mile		3,300	45

Sources: DOE 2015A, Nissan 2015

A8: Full-size Gasoline Vehicles Comparable to a Tesla Model S 85

Make	Model	Engine	Fuel Economy (mpg)		Curb Weight	Footprint
			MPG	L/100km	(lbs)	(sq.ft)
Hyundai	Equus	5L V8	18	13.1	4,600	53
Chrysler	300 RWD	3.6L V6	23	10.2	4,000	53
Mercedes	S 550 RWD	4.7L V8	20	11.8	4,600	55
Porsche	Panamera	3.6L V6	22	10.7	3,900	52
Audi	A8	3L V6	22	10.7	4,400	53
Average Fuel Economy			21	11.2	4,300	53
Tesla	Model S 85	283kW/441Nm	0.38 kWh/mile		4,700	54

Sources: DOE 2015A, Tesla Motors 2015