Methodology for Climate Friendly Cars Update 2017

Eric D. Larson, Nabeel Farooqui and Greta Shum
Climate Central

Introduction

This study is the third in Climate Central's periodic reports comparing lifecycle greenhouse gas (GHG) emissions for cars. This document provides a summary of the methodology and data sources used to compare a selection of new 2017 model year light-duty vehicles (cars and SUVs) available in the U.S. The methodology and data sources largely follow those of the earlier studies, but with a few revisions that reflect improved data sources, especially regarding estimates of the emissions associated with manufacturing of batteries for electric vehicles and hybrid electric vehicles.

In the present study, we estimated the lifecycle GHG emissions for 88 model-year 2017 cars, including 20 electric vehicles (EV), 17 plug-in hybrid electric vehicles (PHEV), 28 gasoline-fueled non-plug-in hybrid electric vehicles (HEV), 15 gasoline-fueled conventional internal combustion engine vehicles (GSLV), and 8 diesel-fueled conventional engine vehicles (DSLV).

EVs are cars with wheels driven by electric motors that are supplied with electricity from an on-board battery. The battery is recharged by plugging into an electrical outlet. PHEVs also operate using electricity from a battery, but battery recharging is done somewhat differently: a PHEV's battery is initially charged by plugging into an outlet (like an EV), but if the initial charge is used up during driving, the conventional gasoline engine that is part of every PHEV automatically starts and drives an electric generator supplying electricity to the battery as the battery continues to supply electricity to motors driving the wheels. An HEV operates using only gasoline. It includes a conventional gasoline engine and a battery that is typically smaller than on a PHEV. The gasoline engine powers the car and/or generates electricity to charge the battery, which provides an assist in powering the car. An important energy-efficiency feature of EVs, PHEVs, and HEVs is that they employ "regenerative braking": energy that would otherwise be dissipated as heat during braking is instead converted into electricity and used to partially recharge the on-board battery. GSLVs and DSLVs use traditional engine/power-train designs, with no regenerative braking capability.

The lifecycle GHG emissions estimated here include those associated with manufacturing the vehicles and driving them for 100,000 miles. Emissions associated with end-of-life disposal and/or recycling of vehicles are not included, but are generally less than 3% of lifecycle emissions in peer-reviewed studies, e.g., Hawkins (2013).[1] In the case of EVs and PHEVs, the emissions associated with generating the electricity used to charge the vehicles are included as part of the lifecycle emissions. This electricity is assumed to come from the grid.

Emissions that occur during driving

Our estimates of emissions that occur during driving are based on combined highway/city fuel economies for 2017 model-year vehicles as estimated by the U.S. Department of Energy and U.S. Environmental Protection Agency.[2] We have included all EVs, HEVs PHEVs, and DSLVs listed in DOE/EPA fuel economy guide.[a] We chose to include from the large number of GSLVs only the 17 most fuel efficient ones. For EVs, fuel economies are given in terms of kWh of electricity per mile (kWh/mi), and for HEVs, GSLVs, and DSLVs, fuel economies are given in miles per gallon. For PHEVs, fuel economies are given for two modes of operation: (1) while using the battery's initial charge to run the vehicle (kWh/mi) and (2) when gasoline is being burned after the initial battery charge is depleted (miles per gallon of gasoline). We have estimated the fraction of annual miles a PHEV drives on the battery alone (without engaging the gasoline engine) based on a study by the Idaho National Laboratory (INL) that examined the driving characteristics of over 9,000 model year 2014 PHEVs distributed across five different models.[3] Not surprisingly, we found that the estimated fraction of annual miles driven on battery alone correlated strongly with the vehicles' rated

[a] The DOE/EPA database includes multiple listings for the same basic make and model of a vehicle. We have chosen to include only the base model in most cases, e.g., the Buick LaCrosse, but not the Buick LaCrosse Sport. Where there is not an obvious "base" vehicle among those of the same make and model, we selected a model having fuel economy in the mid-range for that make and model. In the case of the Tesla EV, we have included models with the highest and lowest driving range for the Model X and the Model S, but have not considered the Enhanced Performance Model X nor the All-Wheel Drive Model S.

operating range on battery alone (Figure 1). We applied this correlation to estimate the fraction of annual miles driven on electricity for each PHEV.

For emissions associated with liquid fuel use, we include emissions due to combustion of the fuel and emissions associated with producing the fuel and delivering it to the vehicle. Emissions include CO_2 and non-CO_2 GHGs collectively expressed in terms of equivalent CO_2 (CO_{2eq}). To estimate the CO_{2eq} for non-CO_2 gases, we use the most recent estimates of 100-year Global Warming Potentials (GWPs) estimated by the IPCC.[4] Thus, one pound of methane (CH_4) emissions is 28 lbs CO_{2eq}, one pound of nitrous oxide (N_2O) emissions is 265 lbs of CO_{2eq}, and one pound of sulfur hexafluoride (SF_6) emissions is 23,500 lbs CO_{2eq}.[b] Emissions of CO_2, CH_4, N_2O, and SF_6 associated with extraction and refining of crude oil, plus transportation and combustion of gasoline and diesel are as estimated by analysts at the National Energy Technology Laboratory.[5] The resulting total lifecycle GHG emissions for gasoline and diesel fuel are 24.7 lb CO_{2eq}/gallon and 27.6 lb CO_{2eq}/gallon, respectively.

Thus, the emissions that occur during driving for HEVs, GSLVs, and DSLVs, are estimated using the following equation:

$$HEV, GSLV, DSLV\ driving\ \left(\frac{lbs\ CO_2e}{mile}\right) = \frac{24.7\ or\ 27.6\left(\frac{lbs\ CO_2e}{gallon}\right)}{Fuel\ economy\left(\frac{miles}{gallon}\right)} \qquad \text{Eqn. (1)}$$

For PHEVs, the contribution to total emissions from gasoline consumption is estimated taking into account the fraction of miles that the vehicle operates on battery alone each year:

$$PHEV\ gasoline\ driving\left(\frac{lbs\ CO_2e}{mile}\right) = \frac{24.7\left(\frac{lbs\ CO_2e}{gallon}\right)}{Fuel\ economy\ on\ gasoline\left(\frac{miles}{gallon}\right)} \cdot \left\{1 - Fraction_{electric}\left(\frac{miles_{elec.}}{miles_{total}}\right)\right\} \qquad \text{Eqn. (2)}$$

For EV emissions during driving and for the contribution of grid electricity to PHEV emissions during driving, we estimated grid emissions per kWh of electricity generated on a state-by-state basis, as follows. The Energy Information Administration (EIA) reports state level totals for electricity generation and CO_2 emissions associated

[b] These are estimated values excluding the impact of climate feedbacks. The latter are uncertain, but GWPs would likely be higher with climate feedbacks included.

with electricity generation by fuel type.[6] The most recent annual data that EIA has published is for 2015. These data were used to calculate grid-average emissions for electricity generation (lbs CO_2/MWh) at the state level. To these values we added estimates of the upstream emissions associated with extraction from the ground and delivery to power plants of coal and natural gas, the main fossil fuels used for power generation in the U.S. Upstream emissions of CO_2, CH_4, N_2O, and SF_6 are based on estimates given by Skone, *et al*.,[7] converted to CO_{2eq} using the GWP values mentioned above. The resulting upstream emission values are 144 lbs CO_{2eq}/MWh for coal and 174 lbs CO_{2eq}/MWh for natural gas.

Table 1 gives the resulting state-by-state average lifecycle emission for electricity generation.

To estimate the emissions during driving for an EV in a given state, the values in Table 1 were used in the following equation:

$$EV\ driving\left(\frac{lbs\ CO_2e}{mile}\right) = use\ rate\ \left(\frac{kWh}{mile}\right)\cdot State\ grid\ em\ \left(\frac{lbs\ CO_2e}{MWh}\right)\cdot 0.001\left(\frac{MWh}{kWh}\right) \qquad \text{Eqn. (3)}$$

To estimate the emissions for PHEVs when driving using grid electricity, the following equation is used:

$$PHEV\ electric\ driving\left(\frac{lbs\ CO_2e}{mile}\right) = use\ rate\ \left(\frac{kWh}{mile}\right)\cdot State\ grid\ em\ \left(\frac{lbs\ CO_2e}{MWh}\right)\cdot Fraction_{electric}\left(\frac{miles_{elec.}}{miles_{total}}\right)\cdot 0.001\left(\frac{MWh}{kWh}\right)$$

Eqn. (4)

For the PHEV, the total emissions per mile driven is the sum of PHEV electric driving emissions from Eqn. (4) and PHEV gasoline driving emissions from Eqn. (2).

For each vehicle, the calculated emissions per mile of driving is multiplied by 100,000 to calculate total emissions during 100,000 miles of driving.

Vehicle Manufacturing Emissions

To calculate the emissions associated with vehicle manufacturing, we used the approach developed in Yawitz, *et al.* (2013),[8] but made a modification based on consideration of more recent peer-reviewed literature. A brief summary of the original approach to estimating manufacturing emissions is presented here – details are available in the original study. This is followed by a description of the modification made to the original approach.

Among the handful of peer-reviewed estimates of vehicle lifecycle emissions available at the time the original approach was developed,[9,10,11,12] the Hawkins, *et al*. estimates[9] were among the most detailed and well-documented, and these were selected as the basis for the original approach. Hawkins, *et al*. estimated the global warming impact of producing an EV modeled on the Nissan Leaf (with 24 kWh battery storage capacity) and a similarly-sized GSLV. Manufacturing emissions were estimated separately for the base vehicle, the battery, the electric motor, the gasoline engine, and the balance of powertrain components. In the original approach, emissions for these components were estimated for other cars by scaling the Hawkins, *et al*. estimates linearly. Emissions associated with the base vehicle were scaled by the ratio of the curb weight of the car of interest to that of Hawkins' vehicle. Emissions for the electric motor and gas engine were scaled by the ratio of reported horsepower capacity of these components, as were emissions for the balance of the powertrain. Emissions for battery manufacturing were scaled by the ratio of the rated kWh storage capacity of the battery.

The modification to the original approach was developed by reviewing many peer-reviewed studies published since the Yawitz, *et al*. work[13,14,15,16,17,18,19] and one non-peer reviewed study.[20] Collectively, these and the peer-reviewed studies reviewed in developing the original approach, formed the basis for the modification made to the original approach.

Table 2 compares estimates of lifecycle manufacturing emissions made using the original approach with estimates gleaned from the literature. Comparisons are made there for nine vehicles (5 EV, 2 PHEV, 1 HEV, 1 GSLV) plus two EV batteries, and the comparisons are displayed visually in Figure 2. A y-axis value of 1.0 in Figure 2 would mean that the emissions estimated using the original approach matches that estimated in the literature. Given the wide range of ratios plotted in Figure 2, it is difficult to draw any obvious correlation between the values estimated using the original approach and the literature estimates, so some additional analysis was undertaken.

Because battery manufacturing contributes significantly to total manufacturing emissions, especially for EVs, separate comparisons were made for the manufacturing emissions of the battery and of the vehicle excluding the battery. The latter are shown in Table 3 and plotted in Figure 3. Battery manufacturing emissions are shown in Table 4 and plotted in Figure 4. Because a result based on (Dunn, 2015)[13] in the left graph of Figure 4 looks to be an outlier, the right graph in Figure 4 is plotted without the two (Dunn, 2015) results.

By examination of Figure 3, we concluded that the original approach used by Yawitz, *et al*. (2013) to estimate manufacturing emissions for the vehicle without the battery gives results that are centrally within the range of results found in the literature. By examination of the right hand graph in Figure 4, it was concluded that the original approach used by Yawitz, *et al*. (2013) to estimate battery manufacturing emissions gives results that are higher than centrally-situated estimates in the literature. As a result, the following modified approach was adopted for estimating manufacturing emissions for complete vehicles: the original approach of Yawitz, *et al*. (2013) was used to estimate manufacturing emissions for the vehicle without the battery and to this was added battery manufacturing emissions estimated as 0.4 times the value estimated using the original approach of Yawitz, *et al*.

<u>"Leaf Rating" (LR)</u>

For each car in this analysis, Climate Central assigned a "Leaf Rating" (LR) that indicates where its lifecycle emissions (for 100,000 miles driven) ranks within the range of emissions for the full set of vehicles we analyzed. For each electric vehicle and plug-in hybrid vehicle, the lifecycle emissions will be different in different states because of different average greenhouse gas emissions per kWh of electricity generated, so the LR for these types of cars can vary from one state to another. Gas-powered hybrids, conventional gas-powered cars, and diesel vehicles each have the same LR regardless of the state in which they are evaluated. The lower the emissions for a car, the higher it's LR value.

We assigned a LR of 5 to the 5% of car/state combinations having the lowest lifecycle emissions. The next lowest 30% of combinations are assigned LR4; the next lowest 30% beyond LR4 are assigned LR3; the next lowest 30% beyond LR3 are assigned LR2; and the final 5% of car/state combinations are assigned a LR of 1.

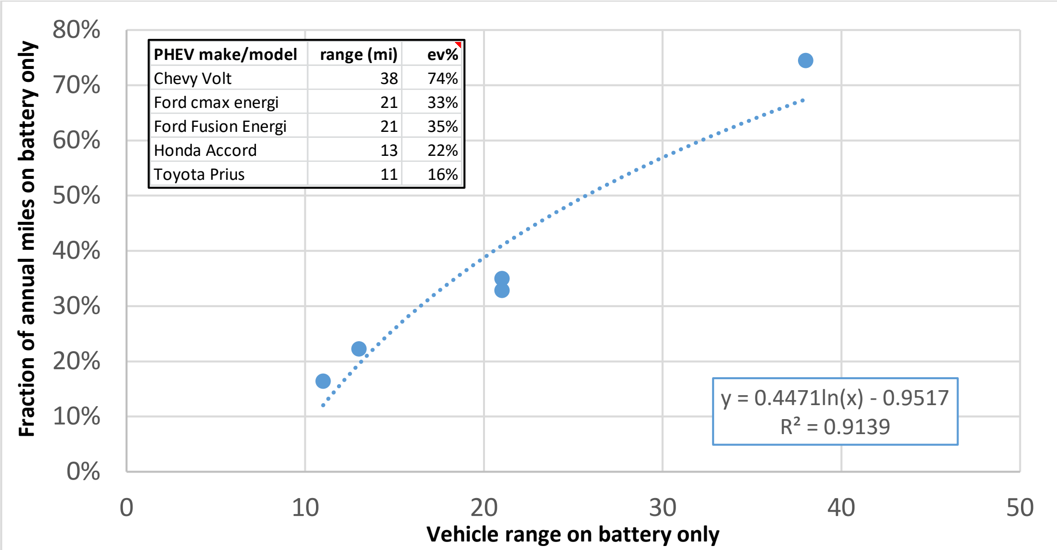


Figure 1. Relationship between estimated annual miles driven by PHEVs on battery power versus vehicle range on initial full battery charge for model-year 2014 vehicles, based on data from Carlson (2015).[3]

Table 1. Estimated 2014 state-average lifecycle GHG emissions for electricity generation (lbs CO_{2e}/MWh).

AK	1,391	LA	1,278	OH	1,639
AL	1,035	MA	1,046	OK	1,331
AR	1,237	MD	1,187	OR	397
AZ	1,076	ME	600	PA	1,026
CA	725	MI	1,408	RI	1,078
CO	1,700	MN	1,258	SC	745
CT	615	MO	1,915	SD	481
DE	1,315	MS	992	TN	1,193
FL	1,179	MT	1,447	TX	1,324
GA	1,124	NC	1,019	UT	1,913
HI	1,315	ND	1,965	VA	1,009
IA	1,179	NE	1,489	VT	12
ID	1,124	NH	462	WA	261
IL	1,622	NJ	664	WI	1,617
IN	1,447	NM	1,815	WV	2,160
KS	305	NV	972	WY	2,267
KY	1,023	NY	594	**USA**	**1,203**

Table 2. For nine vehicles and for two batteries for EVs, total estimated vehicle manufacturing emissions are shown in the left-most column of numbers as estimated using the original model of Yawitz, *et al*. (2013).[8] The 10 right-most columns show the ratio of estimated total manufacturing emissions for the same vehicles (or batteries) estimated in the literature divided by the estimate in the left-most column of numbers.

		Literature estimate / Original CC model estimate									
	Total manufacturing emissions, Original CC model estimate ($lbsCO_{2eq}$)[a]	UCS, 2015[b]	Dunn, 2015[c]	Ellingsen, 2013[d]	Onat, 2015[e]	Nordelof, 2016[f]	Notter, 2010[g]	Ma, 2012[h]	Samaras, 2008[i]	Majeau-Bettez, 2011[j]	Kim, 2016[k]
Nissan Leaf (24 kWh) EV	23975	0.46			0.80	0.38					
Tesla Model S EV	65793	0.37									
Toyota Prius PHEV	15109		1.63		1.07						
Ford Focus EV	20767		1.53								
26.6 kWh battery (Li-Ion)	11359			1.24							
26.6 kWh battery (NiMH)	20924									0.55	
Toyota Prius HEV	13785				1.20				0.74		
Chevy Volt PHEV	22692				0.81						
VW E-golf EV	26958						0.74				
Mini E EV	25985							0.69			
Toyota Corolla GSLV	11756				1.18						
Ford Focus EV battery (24 kWh)	10251										0.72

(a) Most of the estimates in this table are based on papers where 100-year GWP values were used for non-CO_2 greenhouse gases. Four of the studies[12, 13,18,20] did not specify the GWP time horizon. We have assumed those studies used 100-year GWP values. See Yawitz, *et al*. (2013)[8] for detailed discussion of methodology used to calculate manufacturing emissions. The emissions estimated here assume the characteristics of 2016 model-year vehicles, with the following exceptions: Toyota did not produce a 2016 model-year PHEV, so the Prius PHEV analyzed by Yawitz et al. (2013)[8] was used for this estimate. The Toyota Prius HEV estimate assumes a 16.5 kWh NiMH battery rather than the 18.4 kWh NiMH battery found in the 2016 model-year Prius because Onat (2015) analyzed emissions for a 2014 model year Prius, which came with a 16.5 kWh battery.

(b) From Chapter 2 of UCS (2015).[20]

(c) Figure 5b in Dunn (2015)[13] gives manufacturing emissions estimates per vehicle mile. Dunn indicated (personal communication, July 14, 2016) that this estimate assumed 160,000 lifetime vehicle miles traveled.

(d) Ellingson (2013),[14] estimated the emissions for a 26.6 kWh lithium-ion battery pack. The value used here is the "asymptotic value" (ASV) given in Table 2 of that paper.

(e) Onat (2015),[19] presents disaggregated estimates of lifecycle emissions for 5 different vehicles (see Table S17 in the online supplementary information). Manufacturing emissions are assumed here to be total lifecycle emissions minus driving emissions in that table. The Toyota Prius results here are based on the grams/km emission values for "PHEV18" in Onat's table S17.

(f) Based on Figure 4 of Nodelof (2016)[18] and Section K.2 of the online supplemental information published with Nordelof (2014).[17]

(g) Based on Table S19 of the online supplementary information published with Notter (2010).[11]

(h) Based on Figure 3 of Ma (2012).[16]

(i) From Figure 1 of Samaras (2008).[21]

(j) Kim, *et al.* (2016)[15] cites (in Table 1) the manufacturing emissions per kWh of battery capacity estimated by Majeau-Bettez (2011) for a NiMH battery.[12] We have multiplied that estimate by 26.6 kWh to arrive at the value 0.55 in this table.

(k) Kim, *et al.* (2016)[15] estimate emissions of 140 kg CO_{2eq}/kWh for the 24 kWh Li-Ion vehicle battery pack found on the Ford Focus EV.

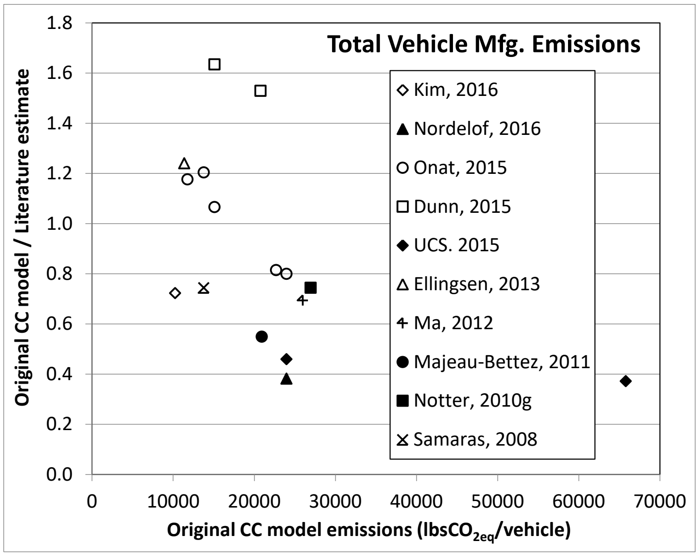


Figure 2. Comparison of total manufacturing emissions. Data in Table 2 are plotted here. The average y-axis value is 0.88, with a standard deviation of 0.37.

Table 3. Comparison of vehicle manufacturing emissions excluding the battery for a subset of vehicles shown in Table 2. The left-most column of estimates were made using the original model of Yawitz, *et al*. (2013).[8] The four right-hand columns show the ratio of a literature estimate divided by the estimate using the original model of Yawitz, *et al*. Literature estimates for vehicle manufacturing that exclude the battery were available for only seven of the nine vehicles shown in Table 2.

		Lit. estimate / Original CC model			
	Vehicle manufacturing emissions excluding battery, Original CC model estimate ($lbsCO_{2eq}$)	UCS, 2015	Dunn, 2015	Onat, 2015	Notter, 2010
Nissan Leaf (24 kWh) EV	13727	0.48		1.26	
Tesla Model S EV	20129	0.53			
Toyota Prius PHEV	13230		0.80	1.17	
Ford Focus EV	10945		1.29		
Toyota Prius HEV	12762			1.27	
Chevy Volt PHEV	14776			1.12	
VW E-golf EV	13957				1.15

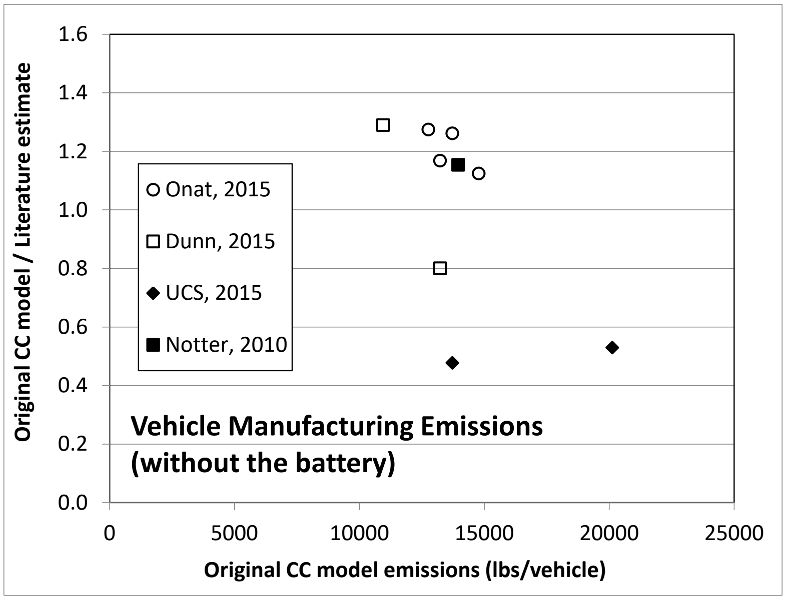
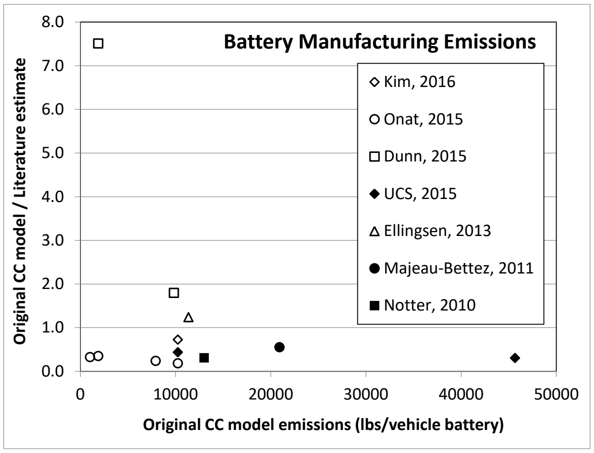


Figure 3. Comparison of emissions for vehicle without battery. Data in Table 3 are plotted here. The average y-axis value plotted is 1.01, with a standard deviation of 0.30.

Table 4. Comparison of battery manufacturing emissions for a subset of vehicles shown in Table 2. The left-most column of numbers are estimates using the original model of Yawitz, *et al*. (2013).[8] The seven right-hand columns show the ratio of literature estimates divided by the estimate using the original model of Yawitz, *et al*. Literature estimates for battery manufacturing were not available for two of the vehicles shown in Table 2 (Toyota Corolla GSLV and Mini E EV).

		Literature estimate / Original CC model estimate						
	Battery manufacturing emissions, Original CC model estimate ($lbsCO_{2eq}$)	UCS, 2015	Dunn, 2015	Ellingsen, 2013	Onat, 2015	Notter, 2010	Majeau-Bettez, 2011	Kim, 2016
Nissan Leaf (24 kWh) EV	10249	0.44			0.18			
Tesla Model S EV	45664	0.30						
Toyota Prius PHEV	1879		7.51		0.35			
Ford Focus EV	9822		1.80					
26.6 kWh battery (Li-Ion)	11359			1.24				
26.6 kWh battery (NiMH)	20924						0.55	
Toyota Prius HEV	1023				0.32			
Chevy Volt PHEV	7915				0.24			
VW E-golf EV	13001					0.31		
Ford Focus EV battery (24 kWh)	10251							0.72



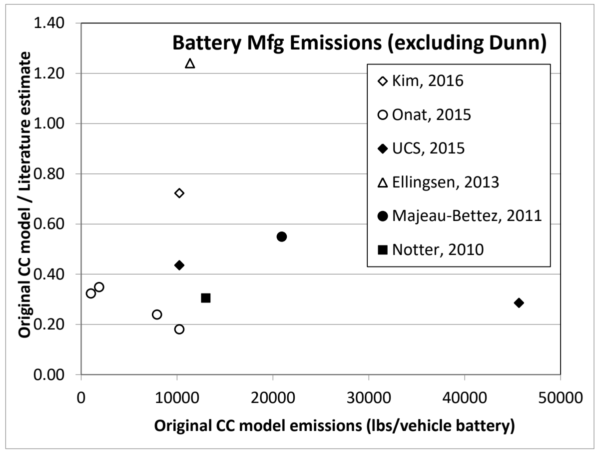


Figure 4. Comparison of manufacturing emissions estimates for vehicle batteries. All values from Table 4 are plotted in the left graph, where the average y-axis value is 1.16, with a standard deviation of 1.97. The right graph excludes the estimates of Dunn, *et al*. (2015).[13] The average y-axis value there is 0.46, with a standard deviation of 0.30.

References

[1] Hawkins, T.R., B. Singh, G. Majeau-Bettez, A.H. Strømman (2013b), "Corrigendum to: Hawkins, T. R., B. Singh, G. Majeau-Bettez, and A. H. Strømman. Comparative environmental life cycle assessment of conventional and electric vehicles." *J. Ind Ecology,* 17(1): 158–160, 2013.

[2] U.S. Department of Energy and U.S. Environmental Protection Agency, "Model Year 2017 Fuel Economy Guide."

[3] Carlson, B. (Idaho National Laboratory), "Electric Vehicle Mile Traveled (eVMT): On-road Results and Analysis," INL/MIS-15-34807, presentation at 2015 DOE Vehicle Technologies Program Annual Merit Review, 9 June 2015.

[4] Intergovernmental Panel on Climate Change, 2013, *Climate Change 2013: The Physical Science Basis*, contribution of Working Group I to the 5th Assessment Report of the IPCC [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)], Cambridge University Press, Cambridge, UK and New York, NY, US. See Table 8.A.1.

[5] Skone, T. and Gerdes, K., *Development of Baseline Data and Analysis of Life Cycle Greenhouse Gas Emissions of Petroleum-Based Fuels*, DOE/NETL-2009/1346, National Energy Technology Laboratory, 26 November 2008. See Table L-1.

[6] Energy Information Administration, Electricity: Detailed State Data, Final annual data for 2015, accessed February 2017.

[7] Skone, T., Littlefield, J., Marriott, J., Cooney, G., Jamieson, M., Hakian, J., and Schivley, G., *Life Cycle Analysis of Natural Gas Extraction and Power Generation*, DOE/NETL-2014/1646, National Energy Technology Laboratory, 29 May 2014. See Table D-4 (average mix coal/fleet baseload and average mix NG/fleet baseload).

[8] Yawitz, D., Kenward, A., and Larson, E.D., A Roadmap to Climate Friendly Cars: 2013, Climate Central, Inc. Princeton, NJ, September 2013.

[9] Hawkins, T.R., B. Singh, G. Majeau-Bettez, A.H. Strømman, "Corrigendum to: Hawkins, T. R., B. Singh, G. Majeau-Bettez, and A. H. Strømman. Comparative environmental life cycle assessment of conventional and electric vehicles." *J. Ind Ecology,* 17(1): 158–160, 2013.

[10] Dunn, J.B., L. Gaines, J. Sullivan, M.Q. Wang, "Impact of Recycling on Cradle-to-Gate Energy Consumption and Greenhouse Gas Emissions of Automotive Lithium Ion Batteries," *Environ. Sci. Technol*., 46 (22): 12704, 2012.

[11] Notter, D.A., M. Gauch, R. Widmer, P. Wäger, A. Stamp, R. Zah, and H-J. Althaus, "Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles." *Environ. Sci. Technol.*, 44, 6550–6556, 2010.

[12] Majeau-Bettez, G., T.R. Hawkins, and A.H. Strømman, "Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles." *Environ. Sci. Technol*., 45, 4548–4554, 2011.

[13] Dunn, J.B., L. Gaines, J.C. Kelly, C. James, and K.G. Gallagher, "The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction." *Energy Environ. Sci.*, 8, 158-168, 2015.

[14] Ellingsen, L.A-W., G. Majeau-Bettez, B. Singh, A.K. Srivastava, L.O. Valøen, and A.H. Strømman, "Life Cycle Assessment of a Lithium- Ion Battery Vehicle Pack," *J. Industrial Ecology*, 18(1): 113-124, 2013.

[15] Kim, H.C., T.J. Wallington, R. Arsenault, C. Bae, S. Ahn, and J. Lee, "Cradle-to-Gate Emissions from a Commercial Electric Vehicle Li-Ion Battery: A Comparative Analysis." *Environ. Sci. Technol.*, Just Accepted Manuscript, 2016.

[16] Ma, H., F. Balthasar, N. Tait, X Riera-Palou, and A. Harrison, “A new comparison between the life cycle greenhouse gas emissions of battery electric vehicles and internal combustion vehicles.” *Energy Policy,* 44 160–173, 2012.

[17] Nordelof, A., M. Messagie, A-M. Tillman, M.L. Söderman, and J. Van Mierlo, “Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment?” *Int J Life Cycle Assess,* 19:1866–1890, 2014.

[18] Nordelof, A., M. Messagie, A-M. Tillman, M.L. Söderman, and J. Van Mierlo, “Erratum to: Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment?” *Int J Life Cycle Assess*, 21:134–135, 2016.

[19] Onat, N.C., M. Kucukvar, and O. Tatri, “Conventional, hybrid, plug-in hybrid or electric vehicles? State-based comparative carbon and energy footprint analysis in the United States.” *Applied Energy,* 150 36-19, 2015.

[20] Nealer, R., D. Reichmuth, and D. Anair, “Cleaner Cars from Cradle to Grave: *How Electric Cars Beat Gasoline Cars on Lifetime Global Warming Emissions*.” Union of Concerned Scientists, 2015.

[21] Samaras, C. and K. Meisterling, “Life Cycle Assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles: Implications for Policy.” *Environ. Sci. Technol. 42,* 3170–3176, 2008.