Updates to ACEEE's GreenerCars Rating System for Model Year 2020
American Council for an Energy-Efficient Economy
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This document details our updates for the analysis of model year (MY) 2020 cars and light trucks, reflected in the release of ACEEE's GreenerCars rankings available at GreenerCars.org for model year 2020. Aspects of the methodology not discussed in this memo will remain as described in the report *Rating the Environmental Impacts of Motor Vehicles: ACEEE's greenercars.org Methodology, 2016 Edition* (Vaidyanathan, Slowik & Junga 2016) or in subsequent annual methodology updates posted on GreenerCars.org.

Changes for the model year 2020 methodology are:

- Incorporate fuel cycle emission factors from GREET 1 2018
- Calculate battery electric vehicle embodied emissions dependent on the battery cathode material
- Revert to single lifetime VMT schedule for calculation of upstream emissions for battery electric vehicles

CHANGES FOR MY2020 GREENERCARS RATINGS

INCORPORATE FUEL CYCLE EMISSION FACTORS FROM GREET 1 2018

GreenerCars calculates a vehicle's upstream emissions from the production and transport of fossil fuels and hydrogen using emission factors from the Argonne National Lab (ANL) GREET 1 model. The GreenerCars methodology previously utilized emission factors obtained from GREET 1 2015.

To bring consistency with a MY2019 update for upstream electricity emissions, we have also updated fuel cycle emission factors to those in GREET 2018. Fuel cycle emission rates from GREET 1 2015 and GREET 1 2018 are compared in the following tables.

Table 1. GREET 2015 well-to-pump emission factors (Grams/mile)

	CO	NMHC	NOX	PM10	SOx	CH4	N2O	CO2
Gasoline	2.290	3.440	4.830	0.390	4.120	9.990	0.340	1662
Diesel	1.680	0.930	3.740	0.250	2.440	9.440	0.030	1593
Hydrogen	7.23	2.15	10.53	1.87	7.94	47.63	0.28	12904

Table 2. GREET 2018 well-to-pump emission factors (Grams/mile)

	CO	NMHC	NOX	PM10	SOx	CH4	N2O	CO2
Gasoline	1.936	3.344	4.095	0.394	2.456	13.165	0.315	1641
Diesel	1.766	1.040	3.783	0.263	1.932	14.722	0.032	1842
Hydrogen	6.305	1.991	8.707	0.492	5.709	41.968	0.276	12209

This accounts for the following relative change in emission rates.

Table 3. Percent change in emission rates, GREET 2015 vs. GREET 2018

	CO	NMHC	NOX	PM10	SOx	CH4	N2O	CO2
Gasoline	-15%	-3%	-15%	1%	-40%	32%	-7%	-1%
Diesel	5%	12%	1%	5%	-21%	56%	6%	16%
Hydrogen	-13%	-7%	-17%	-74%	-28%	-12%	-1%	-5%

The decrease in gasoline and diesel SOx emissions is the result of ANL's refined methodology to calculate refinery emissions. This update shows a sizeable decrease in the emission factor for pet coke stationary applications (ANL 2017), which we found to be the result of a more representative accounting of emissions from today's refining processes.

Similarly, for gasoline and diesel CH_4, ANL adopted a new methodology to calculate greenhouse gas emissions of petroleum fuels for the 2018 update. This reflects refined accounting of greenhouse gas emissions "from both fuel combustion and non-combustion activities associated with crude oil production and storage, transportation, refining operations, distribution of fuels and their end-use by vehicles" (Ou, L., H. Cai 2018). We find that the largest change in total CH_4 emissions is due to an increase in non-combustion (vented, fugitive, and flaring) emissions during crude oil processing in oil fields. ANL notes that its updated methodology reflects new EPA estimates of CH_4 and CO_2 emissions for petroleum systems.

Fuel cycle emissions for hydrogen saw a sharp decrease in emission rates for PM10 – the pollutant with the highest damage cost in the GreenerCars methodology. We find that the sharp decrease in PM emission rates occurred during the interim GREET 2017 update. The GREET well-to-pump methodology update cited above for SOx emissions also includes updates to the emissions factors for hydrogen production from steam methane reforming (SMR) plants.

GreenerCars calculates the environmental damage index, or EDX, for each vehicle on a cents-per-mile basis. This is the basis for calculating a vehicle's Green Score, with a lower EDX corresponding to a higher Green Score. To demonstrate the impact of adopting fuel cycle emission factors from GREET 2018, we show below the change in average EDX of prior model year (2019) vehicles for gasoline, diesel, and hydrogen cars and trucks, as well as for the average vehicle overall.

Table 4. Average EDX (cents-per-mile) of existing methodology vs. GREET 2018 update

	Existing methodology	MY2020 update
Gasoline	1.593	1.550
Diesel	1.464	1.486
Hydrogen	0.909	0.830
All vehicles	1.567	1.526

CALCULATE ELECTRIC VEHICLE BATTERY EMBODIED EMISSIONS BASED ON THE BATTERY CATHODE MATERIAL

For purposes of estimating embodied emissions, GreenerCars has used ANL's default battery cathode material assumption in the GREET 2 model for rating EVs in recent years. The 2018 GREET update changed its default battery cathode material for lithium-ion batteries, from LMO to NMC111, and also included other battery cathode choices and their respective embodied emissions analysis (ANL 2018). The explanation for this change was that NMC111 better reflects evolving battery designs (Dai et al. 2018).

However, our research and the peer review of GreenerCars methodology indicated that due to the desire to minimize cobalt content today's battery electric vehicle batteries are trending towards more nickel-rich chemistries than NMC111, including NMC622 and NMC811. Many vehicles utilize NMC622 chemistry, while Tesla is using NCA, another nickel-rich cathode type (Benchmark 2018), as shown in Table 5. These chemistries provide higher energy density and can decrease battery prices given the high cost of cobalt.

Table 5. Battery cathode material for MY2019 BEV models

Cathode material	# MY2019 Vehicles	Example MY2019 vehicles
NMC111 (NMC333) (GREET default)	0	NA
NMC442	0	NA

NMC622	8	Hyundai Kona, Chevy Bolt, Kia Niro, BMW i3(s), Jaguar I-PACE, Nissan Leaf, Honda Clarity EV
NMC811	0	NA
NCA	10	Tesla
Lithium Polymer (LiPo)	2	Hyundai Ioniq, Kia Soul
Unknown	4	Fiat 500e, smart EQ fortwo (coupe & convertible), VW e-Golf

Source: Manufacturer or supplier literature

Nonetheless, given the difficulty of determining cathode material for each electric vehicle but the importance of properly representing today's vehicles, we adopted the NMC111 cathode for the 2019 GreenerCars methodology. This was because NMC111 was a better representation of today's cathode materials and energy density than the previous GREET default (LMO).

Assigning actual battery chemistry for each model would clearly be preferable, and the MY 2020 GreenerCars methodology moves in this direction. To see the impact of using actual battery chemistry on BEVs' EDX, we evaluated MY2019 vehicles with NMC622 and NCA batteries, applying the appropriate emission factors to reflect the cathode material. We find that EDX for MY2019 vehicles increased by 3.3%-7.8%, over the value obtained using NMC111, for those with NMC 622 batteries. For Tesla models with NCA chemistry, EDX increases by 12.6%-17.1%, with the corresponding Green Scores placing these models firmly below many gasoline hybrid vehicles. EDX and Green Score for MY2019 BEVs for our MY2019 methodology and for the MY2020 methodology are compared in table 6.

Table 6. Impact of 2020 methodology update on EDX and Green Score of MY2019 BEVs

	EDX (cents/mile)			Green Score	
NMC 622	**MY2019**	**MY2020**	**% Change**	**MY2019**	**MY2020**
BMW i3	0.743	0.783	5.4%	65	63
BMW i3s	0.772	0.813	5.2%	64	62
Chevrolet Bolt	0.859	0.925	7.6%	61	58
Honda Clarity EV	0.761	0.786	3.3%	64	63
Hyundai Kona	0.798	0.857	7.4%	63	61
Jaguar I-PACE	1.152	1.233	7.0%	52	49
Kia Niro	0.899	0.969	7.8%	59	57
Nissan Leaf	0.793	0.838	5.7%	63	61
Nissan Leaf S	0.823	0.868	5.5%	62	60
NCA	**MY2019**	**MY2020**	**% Change**	**MY2019**	**MY2020**
Model 3 Long Range	0.880	1.030	17.1%	60	55
Model 3 Long Range	0.952	1.103	15.8%	58	53
Model 3 Long Range Performance	0.952	1.103	15.8%	58	53
Model 3 Mid Range	0.903	1.053	16.6%	59	54
Model S 100D	1.058	1.220	15.3%	54	50
Model S 75D	1.049	1.211	15.4%	55	50
Model S P100D	1.069	1.231	15.1%	54	49

Model X 100D	1.106	1.247	12.7%	53	49
Model X 75D	1.046	1.186	13.5%	55	51
Model X P100D	1.115	1.255	12.6%	53	49

From our review of GREET documentation, we believe this change of embodied emissions reflects differences in emission rates related to mining materials used in Li-Ion batteries and the fact that certain battery types require a more energy-intensive mining and manufacturing process, as ANL notes. Batteries with a higher nickel content appear to require more energy to produce each kilogram of battery cathode produced.[1]

Unfortunately, battery cathode material type is not collected by EPA, nor is this information readily available from automakers or suppliers. We were able to determine cathode material for most, though not all, mass-market MY2020 BEVs by reviewing the literature. For the remaining vehicles, we used the battery's specific energy, which is reported by EPA, to make an assumption about cathode material. The reason for this approach is that specific energy of batteries in MY2019 BEVs fell into clusters based on cathode materials, as shown in Table 7.

Table 7. Specific energy of BEV batteries by cathode material for MY 2019 EPA vehicle dataset

Specific energy (Wh/kg)	NMC622	LiPo	NCA	Unknown
# models	8	2	10	4
Median	141.2	104.0	150.0	
Average	143.0	104.0	156.0	
Min	132.0	103.7	150.0	
Max	153.0	104.3	170.0	

Hence, for those vehicles for which we were unable to verify battery cathode from the literature, we used the battery energy density in the EPA data and "rounded down" to the next-most emissions-intensive cathode choice. We recognize that this approach is far from perfect and in particular that energy density varies substantially for batteries of given cathode material, so this remains an area for further methodology improvements going forward.

We believe adopting this approach based on cathode material rather than a single default chemistry reflects a more realistic but appropriately generic estimate of emissions from battery manufacturing. This is similar to our general approach for calculating embodied emissions which in effect assumes all vehicles of a certain type are produced in the same factory. Data does not

[1] In a memo from 2018, ANL states "The electricity requirement per kg of cathode materials produced also increases with the number of calcination stages required, and Ni-rich materials are the most energy-intensive to produce. If operating at capacity, a production line consumes 6~8 kWh of electricity for each kg of cathode powder produced." ANL also states: "Piecing the information together, we estimate that producing 1 kg of LCO via calcination consumes 6 kWh of electricity, 1kg of Ni-rich cathode material (i.e., NCA and NMC811) consumes 8 kWh, and 1 kg of NMC of other stoichiometric ratios consumes 7 kWh" (Dai et al. 2018).

currently exist to support a more detailed calculation of embodied emissions for parts, batteries, or vehicles manufactured at a specific location.

Ongoing research combined with the growing popularity of BEVs is likely to result in refinements to the accounting of emissions related to battery manufacturing. In the interim, we have adopted this change in methodology in an effort to remain consistent with the calculation of vehicle embodied emissions based on major differentiating factors.

This is a critical area of the GreenerCars methodology and will be revisited as new research is developed.

Revert to single lifetime VMT schedule assumption for calculation of embodied emissions for battery electric vehicles

Assumptions regarding lifetime VMT are used in only two aspects of the GreenerCars methodology: embodied emissions and lifetime plug-in electric vehicle charging emissions. This is necessary to determine a per-mile emissions damage cost.

For MY2019, we adopted a methodology update to the annual vehicle miles traveled schedule used exclusively for calculating lifetime emissions associated with charging plug-in electric vehicles. This updated included two parts: first, the adoption of more recent data on annual vehicle miles traveled and survival rates for cars and light trucks, and second, calculating separate lifetime charging emission factors for cars and trucks to reflect different VMT schedules.

For MY2020, we considered adopting separate lifetime VMT assumptions for cars and trucks for purposes of calculating embodied emissions. This would bring consistency across these two areas of methodology and reflect differences in vehicle durability between cars and light trucks.

However, given recent increases in vehicle durability across all vehicle types, along with nuances in how certain vehicles are used and classified, we decided against such an approach. It would have been especially problematic for the crossover segment, in which a vehicle of a given nameplate may fall into either the car or light truck category, depending on the drivetrain, with no apparent implication for durability or driver behavior.

In view of these considerations, the MY 2020 GreenerCars methodology uses a single VMT schedule (the updated car schedule) to evaluate upstream emissions of plug-in vehicles over their lifetimes provided in table 8.

Table 8. Fraction of vehicle survival miles for cars by age

Vehicle age (years)	Vehicle survival miles for cars
0	7.9%
1	7.7%
2	7.5%
3	7.3%
4	7.1%
5	6.8%
6	6.6%
7	6.2%

8	5.9%
9	5.5%
10	5.2%
11	4.8%
12	4.4%
13	3.8%
14	3.1%
15	2.5%
16	2.0%
17	1.5%
18	1.1%
19	0.8%
20	0.6%
21	0.5%
22	0.3%
23	0.2%
24	0.2%
25	0.1%
26	0.1%
27	0.1%
28	0.0%
29	0.0%
30	0.0%

Source: Transportation Energy Data Book, Edition 36.2

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