Vermont Legislative Research Service
http://www.uvm.edu/~vlrs/

The Carbon Footprint of Electric Vehicle Batteries

Fossil fuel consumption by on-road transport vehicles generates approximately twenty-four percent of the United States' annual carbon emissions, also known as greenhouse gases (GHGs).[1] Here in Vermont, emissions generated by on-road transport vehicles contribute approximately thirty-seven percent of the state's annual GHGs.[2] Interest in reducing these numbers through policy design and new technology has resulted in the promotion of electric vehicles (EVs) as the key to achieving zero-carbon transportation systems.[3]

The level of GHG emissions reduction an EV can deliver depends upon a variety of factors, including (but not limited to): the vehicle's size and weight; the type of drive train propelling it; the energy sources from which its power is derived; and the number of miles driven over its lifetime.[4] In this report, we will discuss the carbon footprint of an EV's most energy intensive component—one that factors heavily in overall GHG reduction potential—the lithium-ion battery pack.[5]

Currently, there are three main types of EVs available to consumers, each characterized by the degree to which electrical energy propels them:

1. A *hybrid electric vehicle* (HEV) is powered by conventional or alternative fuels, and uses electrical energy stored in a battery to increase fuel efficiency; the car charges its battery through "regenerative braking."[6]

---

[1] U.S. Environmental Protection Agency, "Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017" (Washington, DC: U.S. Environmental Protection Agency, February 12, 2019), 32-38, accessed March 27, 2019, https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.
[2] C. Smythe and J. Merrell, "Vermont Greenhouse Gas Emissions Inventory Update 1990 - 2015" (Montpelier, VT: Vermont Department of Environmental Conservation, 2018), accessed March 27, 2019, https://dec.vermont.gov/air-quality/climate-change.
[3] Paul Donohoo-Vallett, "Revolution Now: The Future Arrives for Five Clean Energy Technologies – 2016 Update" (U.S. Department of Energy, September 2016), accessed March 27, 2019, https://www.osti.gov/servlets/purl/1331045.
[4] Linda Ager-Wick Ellingsen, Bhawna Singh, and Anders Hammer Strømman, "The Size and Range Effect: Lifecycle Greenhouse Gas Emissions of Electric Vehicles," *Environmental Research Letters* 11, no. 5 (May 2016): 054010, accessed March 27, 2019, https://doi.org/10.1088/1748-9326/11/5/054010.
[5] Ellingsen, Singh, and Strømman, "The Size and Range Effect."
[6] U.S. Department of Energy Alternative Fuels Data Center, "Hybrid Electric Vehicles," last modified February 11, 2019, https://afdc.energy.gov/vehicles/electric_basics_hev.html.

2. A *plug-in hybrid electric vehicle* (PHEV) is powered by electrical energy, but also utilizes conventional or alternative fuels for extended range; the battery is charged by plugging it in to external sources and through regenerative braking.[7]
3. A *battery electric vehicle* (BEV) is powered entirely by electrical energy, requiring an external electrical source for charging; these vehicles burn no fuels and release no direct emissions.[8]

While an electric vehicle typically produces fewer direct emissions than comparably-sized conventional vehicles, the measure of its carbon footprint also incorporates indirect emissions.[9] These include GHGs from all the energy consumed throughout the production, usage, and disposal of a vehicle. A primary contributor to an EVs indirect emissions is its lithium-ion battery.

Life-Cycle Assessment of an EV Battery

Environmental impact studies on lithium-ion battery packs employ the life-cycle assessment (LCA) framework for estimating their carbon footprint.[10] An LCA ideally attempts to account for all GHGs generated throughout each distinct phase of a battery's life-cycle:

1. The "cradle-to-gate" (CTG) phase encompasses all production processes, beginning with the extraction of raw materials and ending with the installation of an assembled battery pack.[11]
2. The "well-to-wheels" (WTW) phase relates to the on-road usage of the battery.[12]
3. The "end-of-life" (EOL) phase involves the processes behind battery recycling and repurposing.[13]

Cradle-to-Gate Battery Emissions

During a lithium-ion battery's cradle-to-gate phase (CTG), two separate stages of production occur. The *materials production* stage, which includes the extraction, refinement, and eventual conversion of raw materials into manufactured parts, and the *battery assembly* stage, which involves steps to combine those component parts into a functional package.[14]

---

[7] U.S. Department of Energy Alternative Fuels Data Center, "Plug-In Hybrid Electric Vehicles," last modified February 11, 2019, accessed March 27, 2019, https://afdc.energy.gov/vehicles/electric_basics_phev.html.
[8] U.S. Department of Energy Alternative Fuels Data Center, "All-Electric Vehicles," last modified February 11, 2019, https://afdc.energy.gov/vehicles/electric_basics_ev.html.
[9] Ellingsen, Singh, and Strømman, "The Size and Range Effect."
[10] Amarakoon, Smith, and Segal, "Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-Ion Batteries for Electric Vehicles" (Washington, D.C.: U.S. Environmental Protection Agency, April 24, 2013, 15), accessed March 27, 2019, https://trid.trb.org/view/1300236.
[11] Helmers and Weiss, "Advances and Critical Aspects in the Life-Cycle Assessment of Battery Electric Cars," *Energy and Emission Control Technologies* 5 (February 1, 2017): 1–18, accessed March 27, 2019, https://doi.org/10.2147/EECT.S60408.
[12] Helmers and Weiss, "Advances and Critical Aspects in the Life-Cycle Assessment of Battery Electric Cars."
[13] Ramoni and Zhang, "End-of-Life (EOL) Issues and Options for Electric Vehicle Batteries," *Clean Technologies and Environmental Policy* 15, no. 6 (December 1, 2013): 881–91, accessed March 27, 2019, https://doi.org/10.1007/s10098-013-0588-4.
[14] J. B. Dunn et al., "The Significance of Li-Ion Batteries in Electric Vehicle Life-Cycle Energy and Emissions and Recycling's Role in Its Reduction," *Energy & Environmental Science* 8, no. 1 (December 18, 2014): 158–68, accessed March 27, 2019, https://doi.org/10.1039/C4EE03029J.

Notably, the proprietary nature of enterprise-funded research and development limits the availability of battery producers' data on their processes and energy consumption for these two stages.[15] Without the benefit of primary data, researchers rely on assumptions about the CTG phase when modelling a lithium-ion battery's overall emissions impact—its carbon footprint. As a result, LCA studies vary widely in scope and methodology, and collectively report a broad range of outcomes and interpretations.[16]

A primary driver of this variance comes from differing assumptions about the direct energy demands of the materials production and the battery assembly. Further differences stem from assumptions regarding cell chemistry and pack design. The range of estimates found in the literature, illustrated by Figure 1, indicates a high degree of uncertainty involved in assessing CTG emissions.[17]

Seeking to address the variance in the lifecycle assessments of CTG emissions, researchers affiliated with the Norwegian University of Science and Technology analyzed the underlying data from life-cycle assessment studies on lithium-ion batteries. After examining the key assumptions and differences, the group concluded that the primary source of emissions in the cradle-to-gate phase stems from materials production—specifically, cell manufacture.[18] Furthermore, they contend that the main source of GHG emissions over the life-cycle of a lithium-ion battery accumulates during the cradle-to-gate phase, contributing an average of 157kg CO_2e per kWh of battery capacity to its carbon footprint.[19]

On the top-ten list of today's highest selling electric vehicles,[20] plug-in hybrids utilize batteries which range from 8kWh to 17kWh, while batteries powering full electric vehicles range from 40kWh to 100kWh. Thus, the manufacture of PHEV-sized batteries produces 1.2 - 2.6 metric tons of GHG emissions on average; the manufacture of larger, BEV-sized batteries produces 6.3 - 11.8 metric tons of GHG emissions on average.

[15] Han Hao et al., "GHG Emissions from the Production of Lithium-Ion Batteries for Electric Vehicles in China," *Sustainability* 9, no. 4 (April 2017): 504, accessed March 27, 2019, https://doi.org/10.3390/su9040504.
[16] Dale Hall and Nic Lutsey, "Effects of Battery Manufacturing on Electric Vehicle Life-Cycle Greenhouse Gas Emissions" (Washington, D.C.: International Council on Clean Transportation, February 21, 2018), accessed March 27, 2019, https://trid.trb.org/view/1502784.
[17] Linda Ager-Wick Ellingsen, Christine Roxanne Hung, and Anders Hammer Strømman, "Identifying Key Assumptions and Differences in Life Cycle Assessment Studies of Lithium-Ion Traction Batteries with Focus on Greenhouse Gas Emissions," *Transportation Research Part D: Transport and Environment* 55 (August 1, 2017): 82–90, accessed March 27, 2019, https://doi.org/10.1016/j.trd.2017.06.028.
[18] Ellingsen, Hung, and Strømman, "Identifying Key Assumptions and Differences in Life Cycle Assessment Studies of Lithium-Ion Traction Batteries with Focus on Greenhouse Gas Emissions."
[19] Ellingsen, Singh, and Strømman, "The Size and Range Effect."
[20] Inside EVs, "Monthly Plug-In EV Sales Scorecard" (InsideEVs.com, March 3, 2019), accessed March 19, 2019, https://insideevs.com/monthly-plug-in-sales-scorecard/.

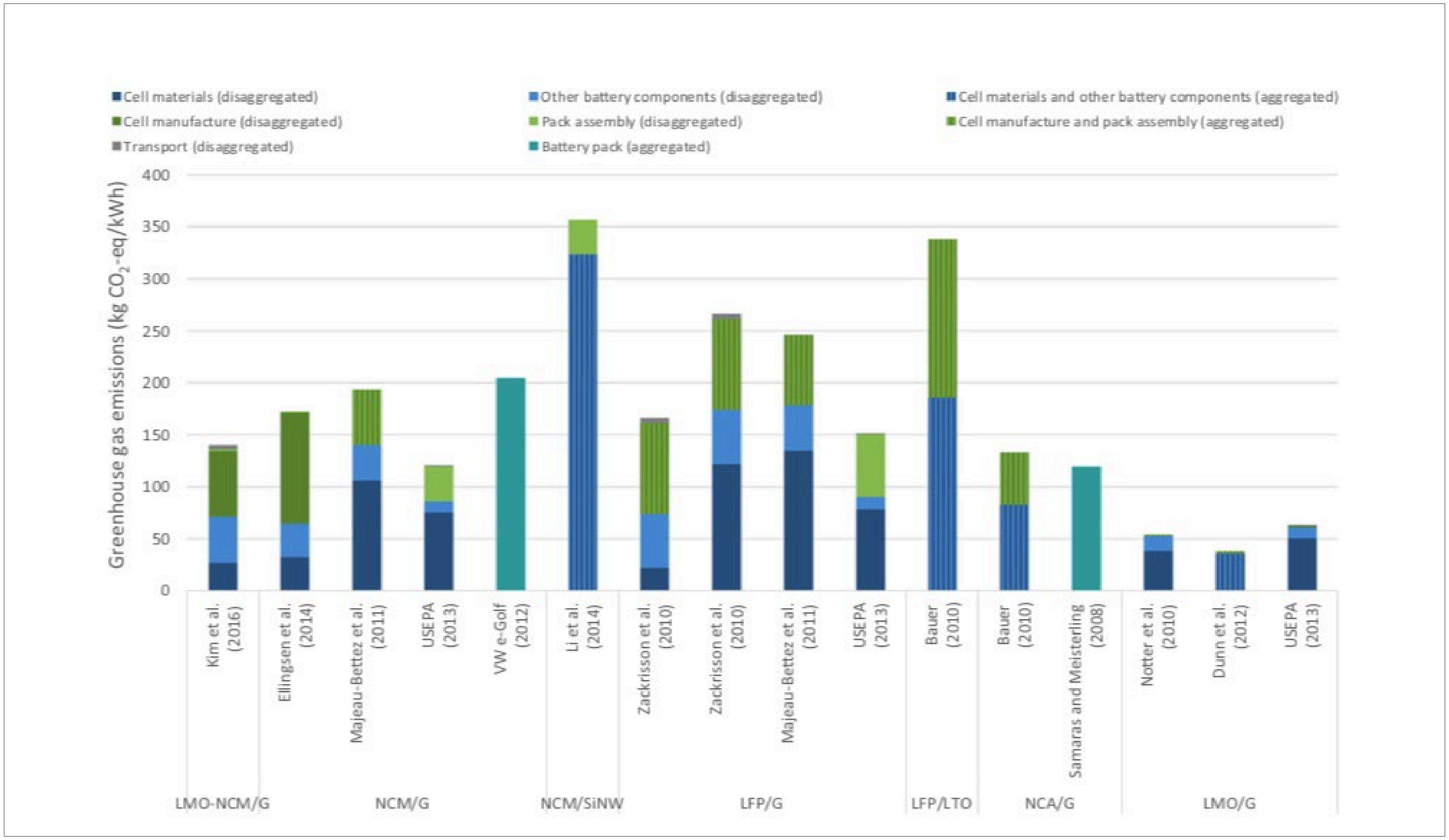

Figure 1. The range of "cradle-to-gate" carbon emissions reported by leading studies on lithium-ion batteries

Source: Linda Ager-Wick Ellingsen, Christine Roxanne Hung, and Anders Hammer Strømman, "Identifying Key Assumptions and Differences in Life Cycle Assessment Studies of Lithium-Ion Traction Batteries with Focus on Greenhouse Gas Emissions," Transportation Research Part D: Transport and Environment 55 (August 1, 2017): 82–90, accessed March 27, 2019, https://doi.org/10.1016/j.trd.2017.06.028.

Well-to-Wheels

The current use portion of an electric vehicle's overall lifecycle is highly variable in terms of emissions production. This makes measuring the carbon footprint of this phase quite difficult. Rather than being able to directly assess EV impact on a large scale, representative models must be produced. These models, such as the one created by the National Renewable Energies Lab (NREL), aggregate mitigating factors in order to provide average levels of carbon emission.[21] Such factors include the nature of the electric grid from which the EV is drawing its power, the time of day at which a vehicle is being charged, and the geographic/climatic region in which the vehicle is located.[22] The subsequent analysis described in this report will investigate each of these component elements in detail in order to clarify the direct emissions of EVs.

Impact of Grid Type Variations: The emissions impact of electric vehicle batteries vary greatly depending on the type of grid from which the vehicle is drawing its power. Electrical grids heavily reliant upon coal, for example, will result in greater emissions than renewable based grids, even though the actual energy consumption by the battery is the same.[23]

The National Renewable Energies Laboratory (NREL) provides data on emissions levels for representative high (coal based) and low (renewable based) carbon grids. Figures 2 and 3 display the results of NREL's emissions scenarios based on projected 2025 fuel efficiency. Each bar in the electric vehicle (BEV) and plug-in hybrid electric vehicle (PHEV) category represents a different charging scenario. H1 and H2 are both home charging models, with H1 representing a slow charge and H2 representing a fast charge. TR is a time restricted charging model. This model allows charging only between Midnight and 1pm. Finally, WP is a model permitting charging only at one's workplace.[24]

The results highlighted in this graph demonstrate clearly lower emissions for BEVs and PHEVs in comparison to conventional vehicles in low carbon grids. However, emissions become much more similar in high carbon grids, where BEV emissions approach the level of conventional vehicles and are significantly higher than PHEVs.[25]

[21] Joyce McLaren et al., "Emissions Associated with Electric Vehicle Charging: Impact of Electricity Generation Mix, Charging Infrastructure Availability, and Vehicle Type" (Golden, CO: National Renewable Energy Lab, April 11, 2016), accessed February 25, 2019, https://doi.org/10.2172/1247645.
[22] McLaren et al., "Emissions Associated with Electric Vehicle Charging."
[23] McLaren et al., "Emissions Associated with Electric Vehicle Charging."
[24] McLaren et al., "Emissions Associated with Electric Vehicle Charging."
[25] McLaren et al., "Emissions Associated with Electric Vehicle Charging."

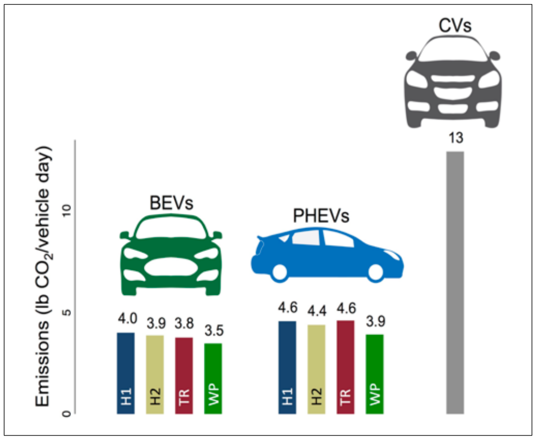

Figure 2: Comparing CO_2 emissions from EVs charged by low-carbon grid with those of conventional vehicles.

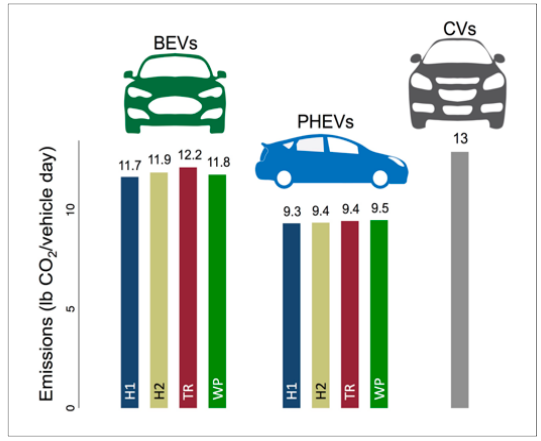

Figure 3: Comparing CO_2 emissions from EVs charged by high-carbon grid with those of conventional vehicles.

Figures 2 and 3. EV potential for CO_2-emissions reduction, relative to carbon-intensity of charge source

Source: Joyce McLaren et al., "Emissions Associated with Electric Vehicle Charging: Impact of Electricity Generation Mix, Charging Infrastructure Availability, and Vehicle Type" (Golden, CO: National Renewable Energy Lab, April 11, 2016), accessed February 25, 2019, https://doi.org/10.2172/1247645.

Hourly Variation: The carbon dependence of the electrical grid is not, however, the only factor affecting emissions levels. The time of day at which a vehicle is being charged further impacts the burden placed on the grid.[26] Power grid profiles often change throughout the day as additional generators are tapped to meet increased demands during peak use periods. Often, the generators that are most economical and responsive to short term demand are heavily reliant on carbon.[27] Typically, energy demand is lowest overnight, when buildings and businesses are closed, and lights are turned off. Conversely, late afternoon and early evening represent the height of demand, particularly during the summer when air conditioners are operating at high capacities.[28] Therefore, charging at peak hours is much more detrimental in terms of emission production than charging at the nadir of demand.

Battery Degradation: Finally, the rate of battery degradation affects emissions output. Research on battery degradation has found:

> In actual EV operation, battery degradation is gradually happening along time under specific driving conditions, and the battery degradation affects the EV electricity consumption and GHG emissions in three ways: decreasing driving range due to reduced capacity, decreasing

---

[26] Shanika Amarakoon, Jay Smith, and Brian Segal, "Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-Ion Batteries for Electric Vehicles" (Washington, D.C.: U.S. Environmental Protection Agency, April 24, 2013), accessed March 5, 2019, https://trid.trb.org/view/1300236.
[27] Amarakoon, Smith, and Segal, "Application of Life-Cycle Assessment to Nanoscale Technology."
[28] Amarakoon, Smith, and Segal, "Application of Life-Cycle Assessment to Nanoscale Technology."

charging/discharging efficiency due to increasing resistance, requiring battery replacement when the capacity is dropped to the battery degradation limit.[29]

Essentially, as a battery degrades, its efficiency decreases, placing a more significant load on the electrical grid. Battery degradation can be attributed to a variety of factors, most importantly, the environment and climate in which the battery operates, as well as the quality of consumer care. Extreme temperatures, notably extreme heat, are particularly devastating to the lifespan of these EV batteries. Consequently, battery life spans vary from state-to-state: under state-level average driving conditions in the U.S., battery life ranges from 5.2 years in Florida to 13.3 years in Alaska.[30]

National and Vermont State Emission Averages: The U.S. Department of Energy and National Renewable Energies Lab estimate that nationally, the average fully electric vehicle emits about 2-2.3 metric tons of CO_2 annually; conversely, the average conventional vehicle emits approximately 5.2-5.9 metric tons of CO_2.[31]

Due to Vermont's low carbon electric grid, which is primarily based on renewables rather than coal, the statewide annual emissions of fully electric vehicle batteries are negligible in terms of the actual use phase of a vehicle's lifecycle.[32] However, complete reliance on renewables is rare among states. The average composition of the US electric grid reflects heavy usage of fossil fuels, and a high degree of emissions variability exists nationwide.[33] In states that derive electricity primarily from fossil fuels, the carbon footprint of electric vehicles is roughly comparable to that of conventional vehicles when accounting for both production and usage emissions.[34] In Vermont, as well as other regions that derive power from renewable sources, conventional vehicles produce a far greater carbon footprint than fully electric vehicles.

End-of-Life

The National Renewable Energy Laboratory estimates a ten-year service life for an EV battery, after which its value can be further exploited through repurposing and recycling.[35] The practice of reusing

[29] Fan Yang et al., "Predictive Modeling of Battery Degradation and Greenhouse Gas Emissions from U.S. State-Level Electric Vehicle Operation," *Nature Communications* 9, no. 1 (June 21, 2018): 2429, accessed March 18, 2019, https://doi.org/10.1038/s41467-018-04826-0.
[30] Yang et al., "Predictive modeling of battery degradation of greenhouse gas emissions from U.S. state-level electric vehicle operation."
[31] U.S. Department of Energy Alternative Fuels Data Center, "Emissions from Hybrid and Plug-In Electric Vehicles," (U.S. DOE, February 11, 2019), accessed March 18, 2019, https://afdc.energy.gov/vehicles/electric_emissions.html.
[32] U.S. Energy Information Administration, "Vermont-State Energy Profile Analysis," (U.S. EIA, July 19, 2018), accessed March 18, 2019, https://www.eia.gov/state/analysis.php?sid=VT.
[33] U.S. Energy Information Administration, "Vermont - State Energy Profile Overview" (U.S. EIA, July 19, 2018), accessed March 27, 2019, https://www.eia.gov/state/?sid=VT#tabs-4.
[34] McLaren et al., "Emissions Associated with Electric Vehicle Charging."
[35] J. Neubauer et al., "Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries" (Golden, CO: National Renewable Energy Lab, February 1, 2015), accessed March 18, 2019, https://doi.org/10.2172/1171780.

partially depleted battery packs and later salvaging their materials offers potential reductions in the greenhouse gas emissions from future battery manufacturing.[36]

Repurposing: A lithium-ion battery is only viable in an electric vehicle when it operates between 80-100% of its capacity, so extending its service life through repurposing is important for realizing its full emissions-reduction potential.[37] Repurposing involves testing and remanufacturing an EV battery for energy storage in an application less demanding than vehicle use–a "second life".[38] Applications can include storing energy from renewables such as solar or creating a backup storage for homes and businesses in the event of a power-outage. However, testing to measure the safety and quality of used batteries is complex, and logistical and economic obstacles have inhibited the development of a second life market.[39]

Recycling: Recycling is the most common end-of-life treatment for used EV batteries today,[40] but less than five percent of those discarded in the United States are recaptured by the few facilities that exist. [41] Most of the materials used in EV batteries have low market value, and salvage efforts become profitable only if a significant amount of cobalt and nickel can be extracted.[42] There are three general categories of technologies employed to recover these metals: pyrometallurgical, hydrometallurgical, and mechanical processes.[43] Recyclers typically incorporate two or more techniques, and each carries an energy cost that contributes to a battery's carbon footprint.[44]

Pyrometallurgy uses high heat to break down the materials in the battery, and requires the most energy to perform. [45] Hydrometallurgy involves the combination of various chemical applications for separation, requiring somewhat less energy consumption. Alternately, a mainly mechanical technique called "direct recycling" separates battery materials at much lower temperatures and significantly less energy intensity. [46] The Argonne National Laboratory estimates that an EV battery's cradle-to-gate emissions

---

[36] Rebecca E. Ciez and J. F. Whitacre, "Examining Different Recycling Processes for Lithium-Ion Batteries," *Nature Sustainability* 2, no. 2 (February 2019): 148, accessed April 8, 2019, https://doi.org/10.1038/s41893-019-0222-5.
[37] Mia Romare and Lisbeth Dahllöf, "The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries" (Stockholm, Sweden: IVL Swedish Environmental Research Institute, May 2017), accessed March 27, 2019, https://www.ivl.se/sidor/publikationer/publikation.html?id=5407.
[38] Silvia Bobba et al., "Life Cycle Assessment of Repurposed Electric Vehicle Batteries: An Adapted Method Based on Modelling Energy Flows," *Journal of Energy Storage* 19 (October 1, 2018): 213–25, accessed April 7, 2019, https://doi.org/10.1016/j.est.2018.07.008.
[39] Romare and Dahllöf, "The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries."
[40] Silvia Bobba et al., "Life Cycle Assessment of Repurposed Electric Vehicle Batteries."
[41] U.S. Department of Energy, "Energy Department Announces Battery Recycling Prize and Battery Recycling R&D Center" (U.S. DOE, January 17, 2019), accessed April 7, 2019, https://www.energy.gov/articles/energy-department-announces-battery-recycling-prize-and-battery-recycling-rd-center.
[42] Linda Gaines, "The Future of Automotive Lithium-Ion Battery Recycling: Charting a Sustainable Course," *Sustainable Materials and Technologies*, no. 1 (2014): 2–7, accessed March 9, 2019, https://doi.org/10.1016/j.susmat.2014.10.001.
[43] Ahmad Mayyas, Darlene Steward, and Margaret Mann, "The Case for Recycling: Overview and Challenges in the Material Supply Chain for Automotive Li-Ion Batteries," *Sustainable Materials and Technologies* 19, no. C (April 1, 2019): e00087, accessed April 7, 2019, https://doi.org/10.1016/j.susmat.2018.e00087.
[44] Ellingsen, Hung, and Strømman, "Identifying Key Assumptions and Differences in Life Cycle Assessment Studies of Lithium-Ion Traction Batteries with Focus on Greenhouse Gas Emissions."
[45] L. Gaines and J. Sullivan, "How Green Is Battery Recycling?" (Argonne National Laboratory, February 2018), https://www.anl.gov/es/reference/how-green-is-battery-recycling.
[46] Mayyas, Steward, and Mann, "The Case for Recycling."

could be reduced by up to thirty percent when the manufacturer utilizes salvaged metals rather than virgin materials.[47]

Conclusion

Determining the carbon footprint of an electric vehicle battery involves assessing the three distinct phases of its lifecycle: cradle-to-gate, well-to-wheels, and end-of-life. The factors that influence the amount of greenhouse gasses released during each phase are highly variable, which complicates efforts to calculate net emissions.

A review of the current literature highlights the differing methodologies employed by life-cycle assessments of the cradle-to-gate phase and the diverse range of conclusions they produce; however, an aggregate approach points to cell manufacture as the primary driver of emissions for a lithium-ion battery.[48] On average, the production of smaller-sized batteries suitable for plug-in hybrids typically generates between 1.2 metric tons and 2.6 metric tons of greenhouse gas (GHG) emissions. For comparison, 2.6 metric tons of GHGs equates to driving approximately 6,357 miles in a conventional passenger vehicle, or burning approximately 293 gallons of gasoline.[49] The manufacture of lithium-ion batteries that are large enough for full-electric vehicles to be driven extended distances produces 6.3 - 11.8 metric tons of GHG emissions on average. These emissions accrued during the cradle-to-gate phase are the dominant inflator of a battery's carbon footprint, imposing a "legacy debt" that can only be offset through optimal conditions during use and end-of-life processing.[50]

The carbon intensity of the well-to-wheels phase of an electric vehicle battery varies greatly depending on the grid type from which the battery draws its power. As the National Renewables Energy Laboratory reports, the carbon intensity of the grid is more significant in terms of total emissions than the specific charging scenario (scenarios as portrayed in figures 2 and 3). In general, battery electric vehicles yield lower emissions than plug in hybrid electric vehicles in only the low carbon grid, although BEVs still produce fewer emissions than conventional vehicles in all grid types.

Grid types, charging scenarios, and levels of battery degradation result in an emission load specific to local and individual trends. Yet, even with the current variability in the US electrical grid, electric vehicles are still cleaner and produce, on a national average, less than half of the emissions of conventional vehicles.[51]

---

[47] Argonne National Laboratory, "Closing the Loop on Battery Recycling" (Argonne National Laboratory, January 25, 2018), accessed April 7, 2019, https://www.anl.gov/article/closing-the-loop-on-battery-recycling-0.
[48] Ellingsen, Hung, and Strømman, "Identifying Key Assumptions and Differences in Life Cycle Assessment Studies of Lithium-Ion Traction Batteries with Focus on Greenhouse Gas Emissions."
[49] U.S. Environmental Protection Agency, Office of Air and Radiation, "Greenhouse Gas Equivalencies Calculator" (U.S. EPA, August 28, 2015), accessed March 27, 2019, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.
[50] Ellingsen, Singh, and Strømman, "The Size and Range Effect."
[51] U.S. Department of Energy Alternative Fuels Data Center, "Emissions from Hybrid and Plug-In Electric Vehicles," (U.S. DOE, February 11, 2019), accessed March 18, 2019, https://afdc.energy.gov/vehicles/electric_emissions.html.

The potential for even greater reduction of an EV battery's carbon footprint emerges with the development of optimized networks for end-of-life processing.[52] Several industrial techniques for reclaiming materials of value are employed, typically in tandem. Each method's energy intensity, efficiency, and production of waste varies due to the wide array of chemistries and designs used in lithium-ion battery production.[53] The marginal profitability of salvaging materials currently keeps the percentage of batteries captured for recycling low.[54] The looming challenge of diverting millions of EV batteries from the waste stream as they reach end-of-life in the next decade has prompted increased government response.[55] While there are no federal regulations on the handling of spent EV batteries yet in place, subsidies and research programs for developing environmentally sound, economically viable end-of-life treatments are on the rise.[56]

Overall, despite the vastly higher emissions associated with the manufacture of EV batteries, the carbon footprint of electric vehicles is substantially smaller than that of similarly sized conventional vehicles. This advantage in net emissions is related to the lower energy costs incurred throughout the use phase, which offset the legacy emissions debt from the cradle-to-gate phase. As is stands today, electric vehicles present a cleaner alternative to conventional vehicles.

This report was completed on April 12, 2019, by Hunter Heberg, Olivia Matthews, and Timothy Nyhus under the supervision of VLRS Research Assistant Eric Tucker and VLRS Director, Professor Anthony "Jack" Gierzynski in response to a request from Representative Charen Fegard.

Contact: Professor Anthony "Jack" Gierzynski, 534 Old Mill, The University of Vermont, Burlington, VT 05405, phone 802-656-7973, email agierzyn@uvm.edu.

52 Argonne National Laboratory, "Closing the Loop on Battery Recycling."
53 Xiaohong Zheng et al., "A Mini-Review on Metal Recycling from Spent Lithium Ion Batteries," *Engineering* 4, no. 3 (June 1, 2018): 361–70, https://doi.org/10.1016/j.eng.2018.05.018.
54 Mayyas, Steward, and Mann, "The Case for Recycling."
55 U.S. Department of Energy, "Energy Department Announces Battery Recycling Prize and Battery Recycling R&D Center" (energy.gov, January 17, 2019), https://www.energy.gov/articles/energy-department-announces-battery-recycling-prize-and-battery-recycling-rd-center.
56 Argonne National Laboratory, "DOE Launches Its First Lithium-Ion Battery Recycling R&D Center: ReCell" (ANL.gov, February 15, 2019), https://www.anl.gov/article/doe-launches-its-first-lithiumion-battery-recycling-rd-center-recell.