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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] 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

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 EV's indirect emissions is its lithium-ion battery.

## Life-Cycle Assessment of an EV Battery

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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 [illegible]

Figure 1. The range of cradle-to-gate carbon emissions reported of

## 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

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 $CO_2$

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 small-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, [illegible]

The potential for even greater reduction of an EV battery 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