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SUMMARY

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Increased deployment of battery electric vehicles (BEVs) and other alternative-fueled vehicles in the United States could have a variety of effects on energy security, the economy, and the environment. In an effort to address certain environmental concerns, including climate change, some Members of Congress and some stakeholder interest groups have expressed interest in the promotion of these technologies—specifically BEV technologies. This interest may include an analysis of the environmental effects of BEVs from a systems perspective, commonly referred to as "life cycle assessment" (LCA).

Practitioners of LCAs strive to be comprehensive in their analyses, and the environmental effects modeled by many rely on a set of boundaries referred to as "cradle-to-grave." Cradle-to-grave assessments in the transportation sector model the environmental effects associated with the "complete" life cycle of a vehicle and its fuel. This consists of the vehicle's raw material acquisition and processing, production, use, and end-of-life options, and the fuel's acquisition, processing, transmission, and use. LCA practitioners focus on a variety of potential environmental effects, including global warming potential, air pollution potential, human health and ecosystem effects, and resource consumption.

Literature analyzing the life cycle environmental effects of BEV technology—both in isolation and in comparison to internal combustion engine vehicle (ICEV) technology—is extensive and growing. However, as the literature grows, so does the range of results. The divergence is due to the differing system parameters of each study, including the selected goals, scopes, models, scales, time horizons, and datasets. While each study may be internally consistent based upon the assumptions within it, analysis across studies is difficult. Because of these complexities and divergences, CRS sees significant challenges to quantifying a life cycle assessment of BEV and ICEV technologies that incorporates all of the findings in the published literature. A review of the literature, however, can speak broadly to some of the trends in the life cycle environmental effects as well as the relative importance of certain modeling selections.

Broadly speaking, a review of the literature shows that in most cases BEVs have lower life cycle greenhouse gas (GHG) emissions than ICEVs. In general, GHG emissions associated with the raw materials acquisition and processing and the vehicle production stages of BEVs are higher than for ICEVs, but this is typically more than offset by lower vehicle in-use stage emissions, depending on the electricity generation source used to charge the vehicle batteries. The importance of the electricity generation source used to charge the vehicle batteries is not to be understated: one study found that the carbon intensity of the electricity generation mix could explain 70% of the variability in life cycle results.

In addition to lower GHG emissions, many studies found BEVs offer greater local air quality benefits than ICEVs, due to the absence of vehicle exhaust emissions. However, both BEVs and ICEVs are responsible for air pollutant emissions during the upstream production stages, including emissions during both vehicle and fuel production. Further, BEVs may be responsible for greater human toxicity and ecosystems effects than their ICEV equivalents, due to (1) the mining and processing of metals to produce batteries, and (2) the potential mining and combustion of coal to produce electricity. These results are global effects, based on the system boundaries and input assumptions of the respective studies.

In addition to a review of the literature, CRS focused on the results of one study in order to present an internally consistent example of an LCA. This specific study finds that the life cycle of selected lithium-ion BEVs emits, on average, an estimated 33% less GHGs, 61% less volatile organic compounds, 93% less carbon monoxide, 28% less nitrogen oxides, and 32% less black carbon than the life cycle of ICEVs in the United States. However, the life cycle of the selected lithium-ion BEVs emits, on average, an estimated 15% more fine particulate matter and 273% more sulfur oxides, largely due to battery production and the electricity generation source used to charge the vehicle batteries. Further, the life cycle of the selected lithium-ion BEVs consumes, on average, an estimated 29% less total energy resources and 37% less fossil fuel resources, but 56% more water resources. These results are global effects, based on the system boundaries and input assumptions of the study.

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Introduction

Increased deployment of battery electric vehicles (BEVs)[1] and other alternative-fueled vehicles in the United States could have a variety of effects on energy security, the economy, and the environment.[2] In an effort to address certain environmental concerns, including climate change, some Members of Congress and some stakeholder interest groups have expressed interest in the promotion of these technologies—specifically BEV technologies. Much of this interest has focused on the electrification of passenger vehicles. This focus reflects the fact that, historically, passenger vehicles have dominated emissions (of both greenhouse gases and other air pollutants) in the transportation sector and that passenger vehicles have shorter development and in-use times than other modes of transportation (e.g., aircraft, trains, and ships), and thus can be more readily and systematically addressed.

Motor vehicle electrification has emerged in the past decade as a potentially viable alternative to the internal combustion engine.[3] In 2018, more than 361,000 plug-in electric passenger vehicles (including plug-in hybrid electric vehicles [PHEVs] and BEVs) were sold in the United States, as well as more than 341,000 hybrid electric vehicles (HEV).[4] Nearly all automakers offer plug-in electric vehicles for sale: 42 different models were sold in 2018, with Tesla and Toyota recording the largest numbers. Sales of PHEVs and BEVs in 2018 rose by over 80% from the previous year, bringing total U.S. sales of plug-in vehicles since 2010 to just over 1 million.[5] The plug-in hybrid and battery electric share of the U.S. passenger vehicle market in 2018 was 2.1%.[6]

This report discusses and synthesizes analyses of the environmental effects of BEVs as compared to the internal combustion engine vehicle (ICEV)[7] and is part of a suite of CRS products on electric vehicles and related technology (see text box below). This report employs research done by federal agencies,[8] other (non-U.S.) government agencies, and academics concerning the short-

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[1] Some sources use the term all electric vehicles (AEVs). For consistency, this report uses BEV throughout.

[2] U.S. Department of Energy, "Chapter 1: Energy Challenges," *Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities*, September 2015, pp. 16-17, https://www.energy.gov/quadrennial-technology-review-2015.

[3] For more information on the electric vehicle market, see CRS Report R45747, *Vehicle Electrification: Federal and State Issues Affecting Deployment*, by Bill Canis, Corrie E. Clark, and Molly F. Sherlock, and CRS Report R46231, *Electric Vehicles: A Primer on Technology and Selected Policy Issues*, by Melissa N. Diaz.

[4] Hybrid electric vehicles (HEVs) have both internal combustion engines and electric motors that store energy in batteries. Plug-in electric vehicles include two types: (1) plug-in hybrid electric vehicles (PHEVs) use an electric motor and an internal combustion engine for power, and they use electricity from an external source to recharge the batteries; and (2) battery electric vehicles (BEVs) use only batteries to power the motor and use electricity from an external source for recharging.

[5] U.S. Department of Energy, "One Million Plug-In Vehicles Have Been Sold in the United States," November 26, 2018, at https://www.energy.gov/eere/vehicles/articles/fotw-1057-november-26-2018-one-million-plug-vehicles-have-been-sold-united.

[6] CRS calculations based on Oak Ridge National Laboratory data; Oak Ridge National Laboratory, *Transportation Energy Data Book*, Tables 3.11 and 6.2, at https://tedb.ornl.gov/wp-content/uploads/2019/03/TEDB_37-2.pdf#page=178.

[7] While the report discusses certain data and findings pertaining to HEV technology (a hybrid of internal combustion engines and electric engines), it focuses primarily on a comparison of the environmental effects of BEVs and ICEVs due to the technological distinction.

[8] Government agencies in the United States and elsewhere have monitored progress in integrating environmental objectives in passenger vehicle technology since the 1950s. U.S. agencies involved in this research include the U.S. Department of Energy (DOE, including the national laboratories), the U.S. Department of Transportation (DOT), and the U.S. Environmental Protection Agency (EPA).

and long-term environmental performance of the passenger vehicle sector as assessed from a systems perspective across the life cycle of the vehicles.[9]

CRS Products on Electric Vehicles and Related Technology

- CRS Report R46231, *Electric Vehicles: A Primer on Technology and Selected Policy Issues*, by Melissa N. Diaz.
- CRS Report R41709, *Battery Manufacturing for Hybrid and Electric Vehicles: Policy Issues*, by Bill Canis.
- CRS Report R45747, *Vehicle Electrification: Federal and State Issues Affecting Deployment*, by Bill Canis, Corrie E. Clark, and Molly F. Sherlock.
- CRS Video WVB00276, *Electric Vehicles: Federal and State Policy Issues*, by Bill Canis, Corrie E. Clark, and Molly F. Sherlock.
- CRS In Focus IF11017, *The Plug-In Electric Vehicle Tax Credit*, by Molly F. Sherlock.
- CRS In Focus IF11101, *Electrification May Disrupt the Automotive Supply Chain*, by Bill Canis.
- CRS In Focus IF10941, *Buy America and the Electric Bus Market*, by Bill Canis and William J. Mallett.

Life Cycle Assessment

This report examines the environmental effects of two types of passenger vehicles—BEVs and ICEVs—from a systems perspective, commonly referred to as "life cycle assessment" (LCA).[10] LCA is an analytic method used for evaluating and comparing the environmental effects of various products and processes (e.g., the environmental effects from the production and use of passenger vehicles). Practitioners use LCA as a method to inform policy development at local, state, federal, and international levels. Through LCA, policymakers can look to increase their understanding of the environmental effects and trade-offs of products. For example, BEV and ICEV technologies have many similarities (e.g., basic vehicle components) as well as many differences (e.g., source of fuel and the production and operation of the battery). Through the LCA approach, practitioners can assess the similarities and differences of these technologies and determine which characteristics are most relevant to an understanding of the types and intensities of environmental effects.

LCA practitioners strive to be comprehensive in their analyses, and the environmental effects modeled by many LCAs are based on a set of boundaries referred to as "cradle-to-grave."[11] Cradle-to-grave assessments in the transportation sector encompass the environmental effects

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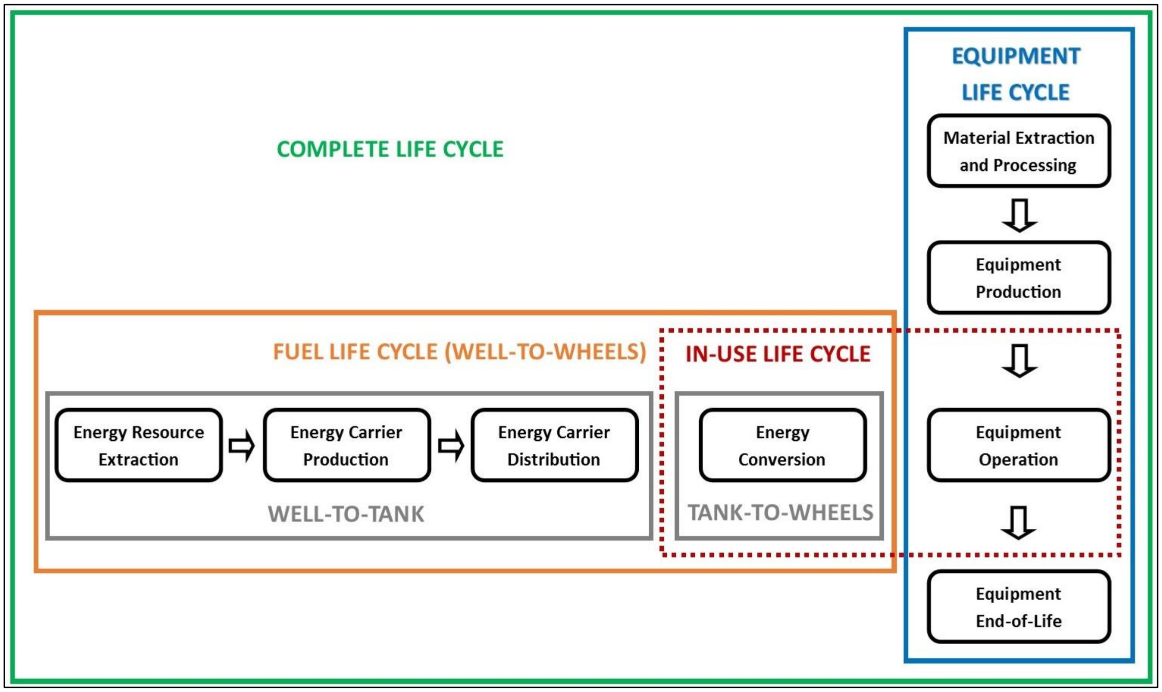
[9] The primary source materials for this report include research conducted by, and CRS correspondence with, the U.S. Department of Energy; Argonne National Laboratory (see U.S. Department of Energy, Argonne National Laboratory, "The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET®) Model, 2018," https://greet.es.anl.gov/; and J.B. Dunn, 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 and Environmental Science*, vol. 8 (2015), pp. 158-168, https://pubs.rsc.org/en/content/articlehtml/2015/ee/c4ee03029j (hereinafter Dunn et al., 2015)); the European Environment Agency (see European Environment Agency, "Electric Vehicles from Life Cycle and Circular Economy Perspectives, TERM 2018: Transport and Environment Reporting Mechanism (TERM) Report," EEA Report No. 13/2018 (hereinafter EEA Report No. 13/2018), https://www.eea.europa.eu/publications/electric-vehicles-from-life-cycle)); and the peer-reviewed academic research articles listed in the Appendix of this report.

[10] A "system" refers to a set of unit processes that are included in the LCA. In the case of vehicles, this could include the various steps necessary to manufacture a specific vehicle model (e.g., Nissan Leaf).

[11] "Cradle-to-grave" LCAs use a system boundary that considers impacts through the product life cycle (from raw material extraction to end-of-life disposal). Elsewhere in the report, practitioners refer to "Cradle-to-gate." "Cradle-to-gate" LCAs focus on production activities, and use a system boundary that considers impacts from raw material extraction through the manufacturing stage and exclude the use stage and end-of-life stage.

associated with the "complete" life cycle of the equipment (i.e., the vehicle) and its fuel (see **Figure 1**). LCA practitioners define the equipment life cycle to incorporate the environmental effects associated with the vehicle's raw material acquisition and processing, production, use, and end-of-life, including recycling options. The fuel life cycle includes the environmental effects associated with extracting, gathering, processing, transporting to market, and combusting the fuel in the vehicle and/or using the fuel for electricity generation to power the vehicle. All LCA practitioners necessarily exclude some considerations in their analysis because they define the system with specific boundaries. Whether certain factors external to the system boundaries are material to the results of a given analysis is an ongoing question for LCA practitioners and their target audiences.[12]

Figure 1. Simplified Illustration of the Complete Life Cycle of Vehicles and Fuels



Source: CRS, adapted from A. Nordelöf, M. Messagie, A. Tillman, M.L. Söderman, J. Van Mierlo, "Environmental Impacts of Hybrid, Plug-In Hybrid, and Battery Electric Vehicles—What Can We Learn from Life Cycle Assessment?" *International Journal of Life Cycle Assessment*, vol. 19 (2014), pp. 1866–1890.

LCA practitioners may focus on a variety of metrics to assess environmental effects, including air quality, water quality, or resource availability. They can use the results of an LCA to evaluate the intensity of certain environmental effects at various stages of the supply chain or to assess the intensity of environmental effects of one type of technology, fuel, or method of production relative to another, given consistent system boundaries and consistent functional units to enable comparison. For example, LCA practitioners can estimate emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs) arising from the development of a given product and express them in a single, universal metric (e.g., CO_2 equivalent [CO_2e]) of GHG emissions per functional

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[12] For a more detailed discussion on the methodologies, challenges, and opportunities for using LCAs for public policy application, see S. Hellweg and L. Milà i Canals, "Emerging Approaches, Challenges and Opportunities in Life Cycle Assessment," *Science*, vol. 344 (June 6, 2014), pp. 1109-1113.

unit (e.g., per unit of energy produced, unit of fuel consumed, or unit of distance traveled).[13] They may then use this result in comparing different life cycle stages, technologies, or fuels.

This report groups the environmental effects under the following categories (see text box "Life Cycle Assessment Environmental Effects" for more specificity):

- global warming potential—CO_2 emissions, other GHG emissions, and black carbon formation;
- air pollution potential—ozone (O_3) formation, volatile organic compound (VOC) emissions, carbon monoxide (CO) emissions, nitrogen oxides (NO_x) emissions, particulate matter (PM) emissions, and sulfur oxide emissions (SO_x), including sulfur dioxide (SO_2);
- human health and ecosystem effects—human toxicity; terrestrial acidification; eutrophication;[14] and terrestrial, freshwater, and marine ecotoxicity; and
- resource consumption—water consumption and mineral and fossil resource consumption.

As exemplified in the review of the published literature in the **Appendix** of this report, many LCA practitioners quantify and analyze the categories of global warming potential, air pollution potential, and resource consumption. Data for emissions of pollutants such as CO_2, other GHGs, and other air pollutants, as well as data for energy and mineral use, can be estimated with some robustness using the databases and modeling tools employed by most LCA practitioners.

Conversely, human health and ecosystem effects (e.g., human toxicity, freshwater eutrophication) are less commonly quantified and analyzed by LCA practitioners. These effects are based on second-order modeling assumptions (i.e., they are effects that potentially result from a given level of emissions). Many LCA practitioners assign greater difficulty to analyzing and quantifying these effects. Practitioners mention data variance and analytic uncertainties as reasons to find estimates in these categories less reliable. Further, the scale of these effects may vary, and their impacts may differ locally and globally depending upon regional variabilities, population size and characteristics, exposure rates, and the environmental regulations and management practices of the exposed areas. Thus, this report focuses on the primary emissions categories as opposed to the second-order health and ecosystem effects, specifically when expressing findings quantitatively. The report discusses the second-order categories qualitatively.

The subsequent sections examine the selected environmental effects categories identified above (i.e., global warming potential, air pollution potential, human health and ecosystem effects, and resource consumption) that occur at the various stages of the life cycle for BEVs and ICEVs, from raw material extraction through end-of-life management.

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[13] GHGs are quantified using a unit measurement called carbon dioxide equivalent (CO_2e), wherein the radiative forcing potential of gases are indexed and aggregated against one mass unit of CO_2 for a specified time frame. This indexing is commonly referred to as the Global Warming Potential (GWP) of the gas. For example, the Intergovernmental Panel on Climate Change (IPCC) 2013 Fifth Assessment Report reported the GWP for methane as ranging from 28 to 36 when averaged over a 100-year time frame. Consistent with international GHG reporting requirements, EPA's most recent GHG inventory (2018) uses the GWP values presented in the IPCC's 2007 Fourth Assessment Report, in which the GWP of methane was 25 when averaged over a 100-year time frame. The uncertainty in the GWP for a particular GHG could be of interest for policymakers.

[14] Eutrophication is the excessive loading of nutrients into a body of water, which induces algal growth. Excessive algal growth can lead to low-oxygen waters, which can result in fish kills and other effects.

Life Cycle Assessment Environmental Effects

Many environmental effects relate to one another. Below is a list of selected factors that LCA practitioners may evaluate. These may or may not have interdependencies. The definitions listed in the text box are sourced (and summarized) from the peer-reviewed academic research articles listed in the **Appendix** of this report.

- global warming potential: reporting all CO_2 emissions and other GHG emissions as CO_2-equivalents, indicating global and regional climate change, oceanic warming, and ocean acidification.
- black carbon formation: black carbon potential, indicating harm to human respiratory and cardiac function and contribution to climate change.
- ozone (O_3) formation: photo-oxidant creation potential, indicating how local air pollutants (NO_x and unburned hydrocarbons) build up ground-level ozone (i.e., smog) under the influence of sunlight, harming both human respiratory and cardiac function and agricultural crops.
- volatile organic compound (VOC) emissions: reporting all VOC emissions, indicating harm to human respiratory and cardiac function, as well as ozone formation.
- carbon monoxide (CO) emissions: reporting all CO emissions, indicating harm to human respiratory and cardiac function.
- nitrogen oxides (NO_x) emissions: reporting all NO_x emissions, indicating harm to human respiratory and cardiac function.
- particulate matter (PM) emissions: reporting all PM emissions, indicating harm to human respiratory and cardiac function.
- sulfur dioxide (SO_2) emissions: reporting all SO_2 emissions, indicating harm to human respiratory and cardiac function.
- human toxicity: indicating the potential harm of chemicals released into the environment on human health, based on both the inherent toxicity of the compounds and their potential doses.
- terrestrial ecotoxicity: indicating the potential harm of chemicals released into the environment on terrestrial organisms, based on both the inherent toxicity of the compounds and their potential doses.
- acidification: indicates the potential environmental impact of acidifying substances such as NO_x and SO_x.
- freshwater ecotoxicity: indicating the potential harm of chemicals released into the environment on aquatic organisms, based on both the inherent toxicity of the compounds and their potential doses.
- freshwater eutrophication: indicating the effect of macronutrients pollution in soil and water resources.
- water consumption: indicating the effects associated with the consumption and discharge of water resources for the production of products, materials, and energy.
- mineral resource consumption: indicating the effects associated with the extraction of raw material resources for the production of products, materials, and energy.
- fossil resource consumption: indicating the effects associated with the extraction of fossil fuel resources for the production of products, materials, and energy.

Life Cycle Stages

The type and the extent of environmental effects associated with BEV and ICEV life cycles can vary widely based on vehicle type, fuel type, and life cycle stage. This section provides a summary of the potential life cycle environmental effects of BEVs and ICEVs categorized sequentially by life cycle stage.

A. Raw Material Extraction and Processing

Generally, studies of the life cycle of BEVs and ICEVs combine the effects associated with raw material extraction and processing with the later stage of vehicle manufacturing and assembly; as a result, quantitative information specific to this first stage is limited. However, raw material extraction and processing is typically resource intensive, often requiring large volumes of water and energy and releasing emissions into air and water. For ICEVs, specific potential environmental effects associated with raw material extraction and processing are primarily related to petroleum production and refining under the fuel life cycle (see section "C. Vehicle In-Use"). For BEVs, specific potential environmental effects associated with raw material extraction and processing are related to fuel extraction and processing for electricity generation under the fuel life cycle (see section "C. Vehicle In-Use") and mineral extraction and processing for battery production under the vehicle life cycle (see below). Most BEVs rely on lithium-ion batteries.[15] While there are likely impacts associated with extraction of materials for other vehicle components (e.g., metals for vehicle frame and body), this section focuses on those components of ICEVs or BEVs that are unique for each vehicle type and that are potentially materially or energy intensive.

Factors Affecting the Raw Material Stage

A number of characteristics can affect LCA results for the raw material stage. In addition to vehicle type and size, other factors include the material composition—both of the vehicle body and of any batteries—and the location where these materials are sourced. As the industry is currently structured, the life cycle environmental effects of raw material extraction for battery production are largely beyond the borders of the United States and outside of the jurisdiction of the U.S. legislative and regulatory framework.[16]

Environmental Assessment of Selected Materials for the Car Body for ICEVs and BEVs

Production of ICEVs and BEVs requires a range of raw materials for the car body and for vehicle components. Materials in the car body include steel, aluminum, carbon fiber, and plastic. Differences in the materials required for BEVs and ICEVs are primarily due to the battery, power electronics, and electric motor in a BEV compared to the engine, transmission, and other drivetrain components of the ICEV.[17] BEV components contain copper, iron, nickel, and critical minerals.[18] Critical minerals used in BEVs include aluminum, cobalt, graphite, lithium, and

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[15] Lithium-ion batteries made up 70% of the rechargeable battery market in 2016; since then, BEV-driven demand for lithium-ion batteries has risen. Bloomberg New Energy Finance, "Electric Vehicle Outlook 2018," as reported in U.S. International Trade Commission Journal of International Commerce and Economics, "The Supply Chain for Electric Vehicle Batteries," December 2018, https://www.usitc.gov/publications/332/journals/the_supply_chain_for_electric_vehicle_batteries.pdf. While not included in the analysis for this report, other types of batteries are used for different vehicles and include nickel-metal hydride (widely used in hybrid electric vehicles), lead-acid batteries (internal combustion vehicles and electric-drive ancillary load vehicles), and ultracapacitors (for secondary energy-storage or power assist purposes). U.S. Department of Energy, "Batteries for Hybrid and Plug-In Electric Vehicles," https://afdc.energy.gov/vehicles/electric_batteries.html.

[16] Initiatives exist that try to address some of these issues; for example, the Extractive Industries Transparency Initiative (EITI) established a standard for governance to promote the open and accountable management of extractive resources (i.e., oil, gas, and mineral resources).

[17] EEA Report No. 13/2018, p. 14.

[18] EEA Report No. 13/2018, pp. 14-15. According to the National Research Council, a critical mineral "performs an essential function for which there are few or no satisfactory substitutes ..., and if there is a high probability that its supply may become restricted." National Research Council, *Minerals, Critical Minerals, and the U.S. Economy*, National Academies Press, 2008. For a list of critical minerals, see U.S. Department of the Interior, "Final List of Critical Minerals 2018," 83 *Federal Register* 23295, May 18, 2018.

manganese.[19] ICEV components contain copper, iron, and the critical mineral aluminum, among other materials.[20]

Aluminum is typically used in lightweighting vehicles—an approach that reduces the overall mass of a vehicle to improve fuel efficiency and performance. As the batteries for BEVs could otherwise add additional mass to a vehicle, BEVs often use more lightweighting materials than ICEVs. Aluminum processing is energy intensive and can result in the direct emissions of GHGs including perfluorocarbons, which can lead to more GHG emissions during the aluminum processing stage than the steel processing stage.[21] However, one study estimates that the use of aluminum, glass-fiber reinforced plastic, and high-strength steel (typical lightweighting materials that can replace conventional steel) can decrease vehicle life cycle energy use and GHG emissions for ICEVs.[22] Another study finds that lightweighting BEVs may be less effective in reducing GHG emissions than lightweighting ICEVs; however, the benefits differ substantially for different vehicle models.[23]

Environmental Assessment of Selected Materials Specific to BEVs

Lithium-ion batteries are made from critical minerals, including cobalt, graphite, and lithium. One study estimates that the steps for extracting and processing critical minerals are responsible for approximately 20% of the total GHG emissions from battery production.[24] The GHG emissions from extraction and processing depend upon the fuel source (e.g., electricity, heat, or fossil fuel) for the energy consumed during these activities. One study estimates that the potential human toxicity effects of the production phase to be between 2.2 and 3.3 times greater for BEVs than ICEVs.[25] The "production phase" of the study includes raw material extraction, processing, and

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[19] L.A-W. Ellingsen and C.R. Hung, *Research for TRAN Committee—Resources, Energy, and Lifecycle Greenhouse Gas Emission Aspects of Electric Vehicles*, European Parliament, Policy Department for Structural and Cohesion Policies, IP/B/TRAN/IC/2017-068 (Brussels, 2018) (hereinafter Ellingsen et al., 2018), pp. 33-34. For more information on critical minerals, see CRS Report R45810, *Critical Minerals and U.S. Public Policy*.

[20] J. Sullivan, J. Kelly, and A. Elgowainy, *Vehicle Materials: Material Composition of Powertrain Systems*, Argonne National Laboratory (August 2018), p. 12. (Hereinafter Sullivan et al., 2018).

[21] Perfluorocarbons (PFCs) typically have high global warming potentials compared to carbon dioxide. The electrolysis process in aluminum production can produce PFCs; primary aluminum production is a major source of PFCs. See EEA Report No. 13/2018, p. 16; Eric Jay Dolin, "PFC Emissions Reductions: The Domestic and International Perspective," *Light Metal Age*, February 1999, https://www.epa.gov/f-gas-partnership-programs/pfc-emissions-and-reductions-domestic-and-international-perspective.

[22] H.C. Kim and T.J. Wallington, "Life-Cycle Energy and Greenhouse Gas Emission Benefits of Lightweighting in Automobiles: Review and Harmonization," *Environmental Science and Technology*, vol. 47 (2013), pp. 6089-6097; X. He, et al., "Cradle-to-Gate Greenhouse Gas (GHG) Burdens for Aluminum and Steel Production and Cradle-to-Grave GHG Benefits of Vehicle Lightweighting in China," *Resources, Conservation and Recycling*, vol. 152 (2020), p. 104497.

[23] H.C. Kim and T.J. Wallington, "Life Cycle Assessment of Vehicle Lightweighting: A Physics-Based Model To Estimate Use-Phase Fuel Consumption of Electrified Vehicles," *Environmental Science and Technology*, vol. 50 (2016), pp. 11226-11233.

[24] H.C. Kim, et al., "Cradle-to-Gate Emissions from a Commercial Electric Vehicle Li-Ion Battery: A Comparative Analysis," *Environmental Science and Technology*, vol. 50 (2016), pp. 7715-7722 (hereinafter Kim et al., 2016).

[25] T. Hawkins, B. Singh, G. Majeau Bettez, A. Stromman, "Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles," *Journal of Industrial Ecology,* vol. 17 (2012), pp. 53-64; and T. Hawkins et al., "Corrigendum to: Hawkins, T. R., B. Singh, G. Majeau-Bettez, and A. H. Strømman. 2012. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. Journal of Industrial Ecology DOI: 10.1111/j.1530-9290.2012.00532.x," *Journal of Industrial Ecoloy*, vol. 17 (2013), pp. 158-160 (hereinafter Hawkins et al., 2013). The human toxicity potential (HTP) is a calculated index that reflects the potential harm of a unit of chemical if released into the environment. The range in magnitude accounts for the variety of electric vehicle options and the variety of electricity sources that recharge the battery. The higher human toxicity from BEVs can be

vehicle manufacturing; however, the toxicity effects are largely associated with disposal of mine tailings.[26] As discussed below, toxicity effects of other phases vary based on the fuel source of electricity during the BEV in-use stage.

Mining of selected materials for BEVs typically takes place in countries where health and safety precautions are generally considered to be less stringent than those in the United States. Activities associated with mining can produce GHG emissions, PM emissions, NO_x emissions, and other air pollutant emissions from fossil fuel combustion to operate mining equipment, or to generate heat or electricity for processing. In addition, some studies have raised concerns associated with mining and the bioaccumulation and toxicity of minerals among aquatic species.[27]

Cobalt

More than half of the global supply of cobalt comes from the Democratic Republic of Congo (DRC).[28] In the DRC, cobalt is mined using both conventional and artisanal methods. In conventional mining, cobalt is typically a by-product of copper or nickel mining activities. In artisanal mining, miners work independently of a company, generally relying upon manually intensive methods such as hand tools. Reports link such artisanal mining with environmental effects such as polluting soil and surface dust.[29] Conventional mining and smelting activities in the DRC leave tailings and slags that are leachable and potentially hazardous to the environment.[30] Mining activities in the DRC have been linked with elevated human exposure to cobalt and other metals.[31] Some estimate that uncontrolled growth in mining activities in Central Africa—including cobalt mining—could directly impact regions that provide key habitat for bird

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attributable, in part, to the additional copper and nickel requirements, which result in production chain disposal of sulfidic mine tailings. Other toxicity impacts are largely due to disposal of spoils from lignite and coal mining. Freshwater ecotoxicity and eutrophication effects from BEVs can be higher due to the associated effects of mining, processing metals, and burning coal to produce electricity.

[26] Mine tailings are waste generated from mining activities and typically are a slurry mixture of solids such as silt, sand, and other minerals, and water.

[27] EEA Report No. 13/2018, p. 17; K. T. Rim, K. H. Koo, and J. S. Park, "Toxicological Evaluations of Rare Earths and Their Health Impacts to Workers: A Literature Review," *Safety and Health at Work*, vol. 4 (2013), pp. 12-26 (hereinafter Rim et al., 2013); and G.A. MacMillan, J. Chetelat, and J. P. Heath, et al., "Rare Earth Elements in Freshwater, Marine, and Terrestrial Ecosystems in the eastern Canadian Arctic," *Environmental Science Processes and Impacts*, vol. 19 (2017), pp. 1336-1345.

[28] According to the U.S. Geological Survey, "identified world terrestrial cobalt resources are about 25 million tons. The vast majority of these resources are in sediment-hosted stratiform copper deposits in Congo (Kinshasa) and Zambia; nickel-bearing laterite deposits in Australia and nearby island countries and Cuba; and magmatic nickel-copper sulfide deposits hosted in mafic and ultramafic rocks in Australia, Canada, Russia, and the United States," U.S. Geological Survey, "Cobalt," *Mineral Commodity Summaries*, January 2018, https://minerals.usgs.gov/minerals/pubs/commodity/cobalt/.

[29] Evidence of increased oxidative DNA damage found among the exposed children (those who lived in the study area but were not engaged in mining) in the study points to an increased risk of cancer in later life; see C. B. L. Nkulu, et al., "Sustainability of Artisanal Mining of Cobalt in DR Congo," *Nature Sustainability*, vol. 1 (2018), pp. 495–504.

[30] Arthur Tshamala Kaniki and Kiniki Tumba, "Management of Mineral Processing Tailings and Metallurgical Slags of the Congolese Copperbelt: Environmental Stakes and Perspectives," *Journal of Cleaner Production*, vol. 210 (February 2019), pp. 1406-1413.

[31] Celestin Lubaba Nkulu Banza, Tim S. Nawrot, and Vincent Haufroid, et al., "High Human Exposure to Cobalt and Other Metals in Katanga, a Mining Area of the Democratic Republic of Congo," *Environmental Research*, vol. 109 (2009), pp. 745-752; S. Squadrone et al., "Human Exposure to Metals Due to Consumption of Fish from an Artificial Lake Basin Close to an Active Mining Area in Katanga (D.R. Congo)," *Science of the Total Environment*, vol. 568 (2016), pp. 679-684.

species.[32] In addition to environmental effects at the mining site, the recovery of cobalt (and nickel) from ores requires smelting, which without pollution controls can raise air quality concerns with the emission of sulfur oxides in addition to other air pollutants.[33]

Graphite

The United States is an importer of graphite. These imports come mainly from China.[34] Graphite mining tailings can have high heavy metal content, which can lead to soil contamination and other ecological impacts. A study of graphite mining in Luobei County in Heilongjiang, China, found farmland and residential areas within the watershed of the mining area to be affected by impacts from mining activities.[35] Further, reports link graphite mining and processing with air pollution, water pollution, and crop damage.[36]

Lithium

The United States also is an importer of lithium.[37] Production of lithium primarily relies on brine mining, but hard rock mining of spodumene, a mineral, can also produce lithium. Some have argued for further research to evaluate the environmental effects of lithium mining, including establishing a baseline for water consumption and understanding potential effects on wildlife and ecosystems.[38]

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[32] This region is known for high biological endemism, particularly for birds. Endemism refers to species that are restricted to a defined geographic location or habitat type. See D.P. Edwards, et al., "Mining and the African Environment," *Conservation Letters*, vol. 7 (2014), pp. 302-311.

[33] Smelting is a process that applies heat and a chemical reducing agent to an ore to extract out a metal. Dunn et al., 2015.

[34] China produced 67% of the world's graphite in 2017 and is the largest supplier of natural graphite by tonnage to the United States; see U.S. Geological Survey, "Graphite," *Mineral Commodity Summaries*, January 2018, https://minerals.usgs.gov/minerals/pubs/commodity/graphite/. For more information on China's mineral industry and critical minerals, see CRS Report R43864, *China's Mineral Industry and U.S. Access to Strategic and Critical Minerals: Issues for Congress*, by Marc Humphries.

[35] Zhang, L., Liu, X., Wan, H., and Liu, X., "Luobei Graphite Mines Surrounding Ecological Environment Monitoring Based on High-Resolution Satellite Data," Proc. SPIE 9263, Multispectral, Hyperspectral, and Ultraspectral Remote Sensing Technology, Techniques and Applications V, November 26, 2014, 92632N, https://doi.org/10.1117/12.2069232.

[36] See Peter Whoriskey, Michael Robinson Chavez, and Jorge Ribas, "In Your Phone, in Their Air," *Washington Post*, October 2, 2016, https://www.washingtonpost.com/graphics/business/batteries/graphite-mining-pollution-in-china/; Shu, J., Lui, L., Zhang, D., Zhang, W., Li, G., "Study on Ecological Restoration of Lands Disturbed by Mining Graphite," *China Environmental Science*, vol. 16, no. 3 (June 1996); and Sun, J.-B., Wang, X.-F., Liu, C.-H., Zhao, Y.-S., "Correlation and Change Between Soil Nutrient and Heavy Metal in Graphite Tailings Wasteland during Vegetation Restoration," *Journal of Soil and Water Conservation*, vol. 23, no. 3 (2009).

[37] The U.S. largely imports lithium from South America, with 53% of imports from Argentina and 40% of imports from Chile for the years between 2015 and 2018. Domestic production of lithium is limited to one brine operation in Nevada and two companies that produce downstream lithium compounds from domestic and imported lithium resources. Due to limited domestic activities, USGS withholds production data for the United States to avoid disclosing proprietary data. U.S. Geological Survey, "Lithium," *Mineral Commodity Summaries*, January 2020, https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-lithium.pdf.

[38] D. B. Agusdinata, et al., "Socio-environmental Impacts of Lithium Mineral Extraction: Towards a Research Agenda," *Environmental Research Letters*, vol. 13 (2018), p. 123001.

Rare Earth Elements

BEVs use rare earth elements (REEs) in their magnets and batteries. REEs are moderately abundant in the earth's crust, with some in greater abundance than copper, lead, gold, and platinum.[39] However, most REEs are not concentrated enough to make them easily exploitable economically.[40] Rare earth elements often occur with other elements, such as copper, gold, uranium, phosphates, and iron, and are often a byproduct of their production.

Some studies have identified negative effects on human health associated with the mining of REEs, some of which are used in BEV magnets.[41] One REE used in BEV magnets is neodymium. Neodymium dust can irritate the skin, eyes, and mucous membranes, and neodymium dust can cause pulmonary embolisms and liver damage over long accumulated exposures.[42] Another REE that is used in BEV magnets is dysprosium. Soluble dysprosium salts are mildly toxic when ingested. Dysprosium can also pose occupational and safety hazards due to explosion risk.[43] Additionally, REE deposits often contain radioactive substances and present a risk of emitting radioactive water and dust.[44] For example, concerns over radioactive hazards associated with monazites (one type of deposit for REEs) have nearly eliminated it as an REE source in the United States.[45]

B. Vehicle and Battery Production

The second stage of the equipment life cycle is vehicle and battery manufacturing and assembly. While many parts of a vehicle do not necessarily differ between BEVs and ICEVs, several important components distinguish the technologies, including components for energy storage, propulsion, and braking (see **Figure 2** and **Figure 3**).[46] In general, components for vehicle body and auxiliary systems do not differ, and manufacturers can take advantage of existing production lines to benefit from economies of scale; however, some models incorporate lightweight materials to counteract the effects of heavier batteries.[47] The production of batteries, other BEV-specific components, and the use of alternative materials have differing environmental effects than traditional ICEV manufacturing. During the production process, much of the differing

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[39] There are 17 rare earth elements (REEs), 15 within the chemical group called lanthanides, plus yttrium and scandium. The lanthanides, which are all REEs, consist of the following: lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium.

[40] For more information on REEs, see CRS Report R41347, *Rare Earth Elements: The Global Supply Chain*, by Marc Humphries.

[41] Rim et al., 2013.

[42] Rim et al., 2013.

[43] Rim et al., 2013.

[44] Risks can be exacerbated by poor working conditions, inadequate ventilation, lack of awareness of safety precautions among workers and improper use of protective equipment.

[45] Monazites contain thorium, a naturally occurring radioactive metal, and its associated decay products, which can include radium. Waste generated from REE mining activities can be referred to as technologically enhanced naturally occurring radioactive materials (TENORM) and are subject to state and federal standards. For more information, see EPA, "TENORM: Rare Earths Mining Wastes," April 10, 2019, https://www.epa.gov/radiation/tenorm-rare-earths-mining-wastes.

[46] ICEVs have a fuel tank, engine, gearbox, and exhaust; BEVs have a traction battery pack, electric motor, including regenerative braking, and power electronics.

[47] See BMW i3 or Tesla vehicles, for example. EEA Report No. 13/2018, p. 22.

environmental effects profile of BEV technologies is attributable to the greater demand for electricity and other forms of energy required for battery production.[48]

Factors Affecting the BEV Production Stage

A number of characteristics, additional to the electricity generation mix used during production, can affect LCA results for vehicle production. These include vehicle mass, powertrain, material composition of components, fuel consumption, and lifetime driving distance. Generally the larger the vehicle, the more materials required for the vehicle, and the more energy required across the various life cycle stages. Changes to material composition may increase the energy consumption during manufacturing but may reduce vehicle weight and reduce fuel consumption during the in-use phase.[49] The longer the lifetime mileage of the vehicle and the battery, the less influence that production-related emissions have and the greater influence that the in-use stage emissions have over the total life cycle effects.[50]

Some additional characteristics affecting LCAs of BEV production include the size of the battery, the battery chemistry and configuration, and the manufacturing efficiencies. Different battery chemistries have different performance characteristics, with some batteries requiring more energy-intensive production processes or materials. Manufacturers that can take advantage of economies of scale and use the full capacity of production plants may reduce energy consumption per vehicle or battery produced.

As the industry is currently structured, the life cycle environmental effects of battery production are largely beyond the borders of the United States and outside of the jurisdiction of the U.S. legislative and regulatory framework.

Environmental Assessment of Battery Manufacturing

Many LCAs of BEV technologies find that battery production is potentially responsible for the largest proportion of energy use and subsequent environmental effects that occur during the manufacturing stage. Estimates range between 10% to 75% of manufacturing energy and 10% to 70% of manufacturing GHG emissions, depending on the approach taken and the electricity generation source (e.g., coal-fired, natural gas-fired, or renewable).[51] As for other BEV components, LCAs estimate contributions from the electric motor production to be 7% to 8% of total production-related emissions (including raw material extraction and processing) due to a high copper and aluminum content; and from the power train production to be 16% to 18% due to a high aluminum content.[52]

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[48] Ellingsen et al., 2018, p. 24.

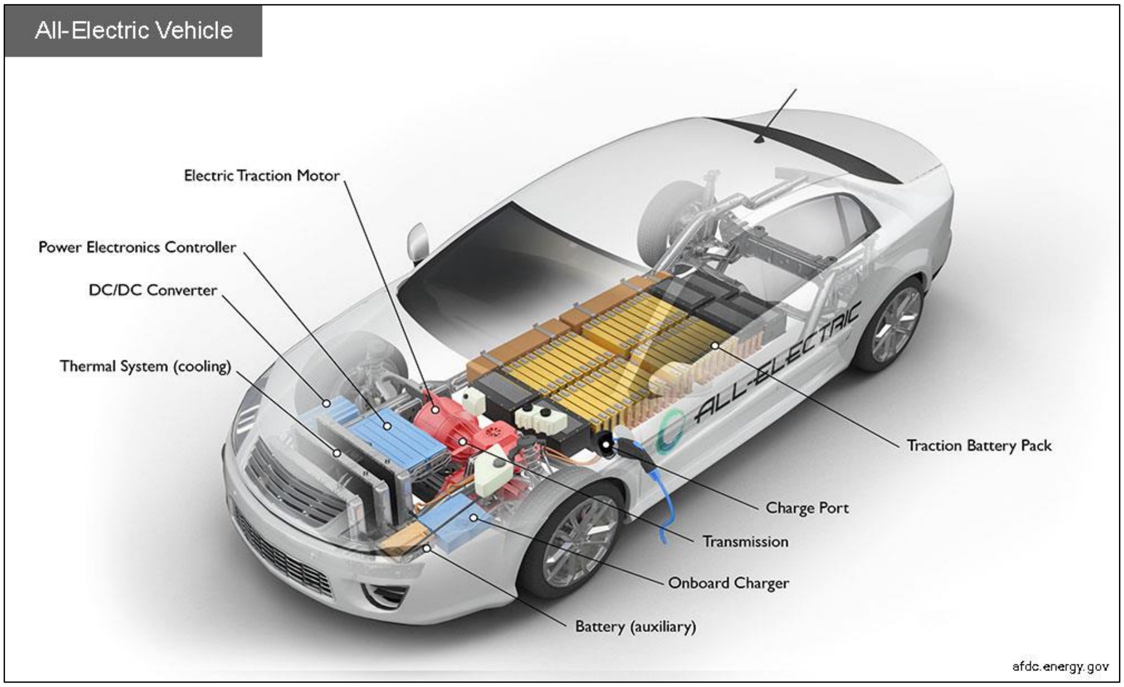
[49] Sullivan et al., 2018, pp.1-2.

[50] To allow comparison across different vehicle types, LCA practitioners typically express production impacts per distance driven and assume a lifetime mileage of the vehicle (or battery). LCA practitioners may assume different lifetime mileages in their analyses; these differences can lead to different estimates in lifetime impacts (e.g., GHG emissions). For more information, see EEA Report No. 13/2018, p. 27.

[51] A. Nordelöf, M. Messagie, A. Tillman, M. L. Söderman, J. Van Mierlo, “Environmental Impacts of Hybrid, Plug-In Hybrid, and Battery Electric Vehicles—What Can We Learn from Life Cycle Assessment?” *International Journal of Life Cycle Assessment*, vol. 19 (2014), pp. 1866–1890; R. Nealer and T. Hendrickson, “Review of Recent Lifecycle Assessments of Energy and Greenhouse Gas Emissions for Electric Vehicles,” *Current Sustainable/ Renewable Energy Reports*, vol. 2 (2015), pp. 66-73; and EEA Report No. 13/2018, p. 24.

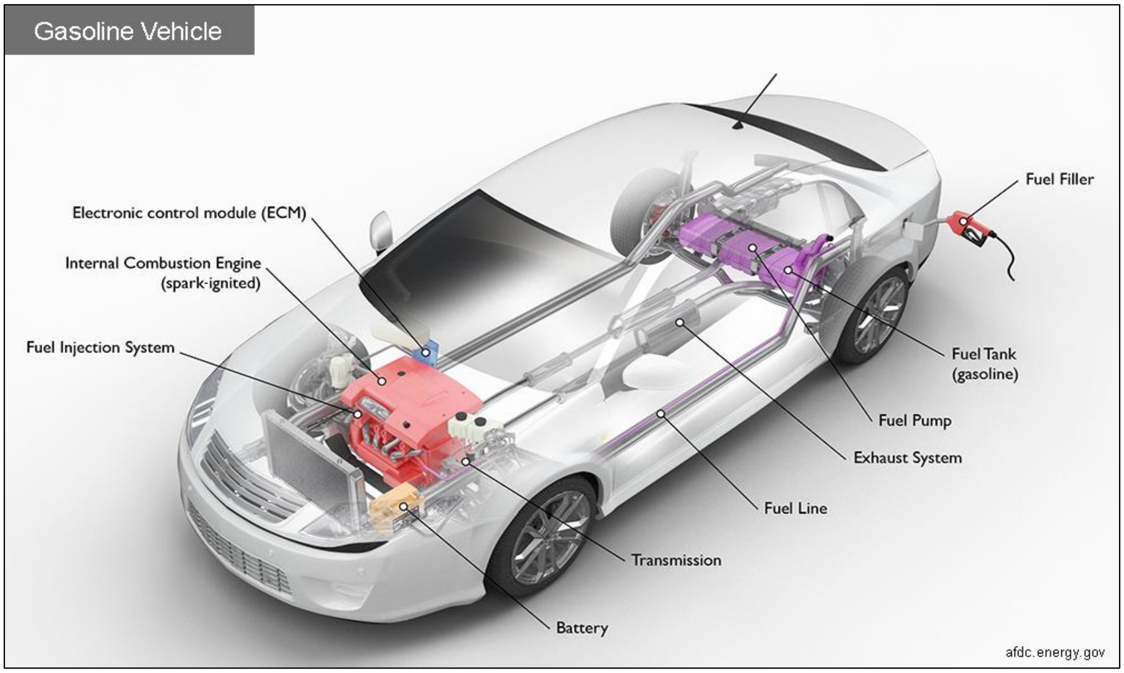
[52] Hawkins et al., 2013; and EEA Report No. 13/2018, pp. 24-27.

Figure 2. Components of a Battery Electric Vehicle



Source: Reproduced from U.S. Department of Energy, Alternative Fuels Data Center, https://afdc.energy.gov/vehicles/how-do-all-electric-cars-work.

Figure 3. Components of an Internal Combustion Engine Vehicle



Source: Reproduced from U.S. Department of Energy, Alternative Fuels Data Center, https://afdc.energy.gov/vehicles/how-do-gasoline-cars-work.

Steps in the production of lithium-ion batteries (the technology of focus for this report) include the preparation of anode and cathode materials, cell manufacture, and assemblage of multiple cells into a battery pack.[53] Cell manufacture largely occurs in Asia (e.g., Japan and South Korea are net exporters of battery packs).[54] Pack assembly is less complex and energy-intensive than cell manufacture. Packs are either assembled by a cell manufacturer and then delivered to automobile manufacturers, or are assembled by automobile manufacturers themselves.[55]

When comparing the GHG emissions from the production of BEVs and ICEVs (including those emissions from raw material extraction and processing), LCA practitioners generally find the impact of BEV production is greater than that of ICEV production. When GHG emissions of similarly sized BEVs and ICEVs are compared in the production phase, the GHG emissions of BEV production are commonly estimated to be between 1.3 and 2 times those of ICEV production.[56] Further, many LCAs report that emissions of NO_x, SO_2, and PM from BEV production are approximately 1.5-2.5 times higher than ICEV production.[57] This is largely due to the energy-intensive process of battery manufacturing and the current mix of sources for electricity generation in the manufacturing sector. This higher energy use has broader associated human health and ecosystem effects (depending upon fuel source and pollution controls).

The life cycle environmental effects associated with battery manufacturing vary greatly based upon the manufacturing location.[58]

C. Vehicle In-Use (Including the Fuel Life Cycle)

The environmental effects associated with the "in-use" stage of a vehicle correspond primarily to the life cycle environmental effects arising from the vehicle's source of energy (i.e., the fuel life cycle). For ICEVs, the source of energy is most commonly petroleum-based fuel (e.g., gasoline or diesel), which is extracted, processed, distributed, and then combusted in the vehicle's engine. For BEVs, the source of energy is electricity, which is generated at a power station (potentially from a variety of energy sources), transmitted, stored in a battery pack, and then used by the vehicle's motor. Beyond the fuel life cycle, some emissions may occur during the vehicle's operation stage, specifically in the form of PM pollution from brake and tire wear.[59]

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[53] Cell manufacture combines the prepared anode and cathode, electrolyte, collector, and separator materials into a container. Battery pack assembly includes the cells, battery casing, electrical system, thermal management system, and electric battery management systems.

[54] According to EEA Report No. 13/2018, p. 23, in addition to Japan and South Korea, China also produces battery packs. As China has a relatively large BEV market compared with other countries, China's battery packs may be directed to China's domestic BEV market.

[55] Ellingsen et al., 2018.

[56] Ellingsen et al., 2018; Kim et al., 2016; and EEA Report No. 13/2018, pp. 24-27.

[57] S. Rangaraju, et al., "Impacts of Electricity Mix, Charging Profile, and Driving Behavior on the Emissions Performance of Battery Electric Vehicles: A Belgian Case Study," *Applied Energy*, vol. 148 (2015), pp. 496-505. NO_x and SO_2 emissions are linked with acidification and eutrophication as well as human health impacts.

[58] Battery manufacturing for BEVs is an energy-intensive process that consumes more energy from electricity generation than similar production stages for ICEVs. While electricity may be used during the production stages of both vehicle life cycles, the GHG emissions associated with the electricity generation in a region have a larger impact on the battery manufacturing stage than other production stages. GHG emissions can vary depending upon the fuel mix of the electricity generation in a region. For example, according the U.S. Department of Energy, Argonne National Laboratory (ANL), Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET®) Model, 2018, the U.S. grid emits, on average, 505 gCO_2e/kWh (148,000 gCO_2e/MMBtu, including life cycle emissions) while the Chinese national grid is estimated to emit, on average, 760 gCO_2e/kWh.

[59] "Vehicles emit inhalable particulates from two major sources: the exhaust system, which has been extensively

BEVs do not emit GHG or other air pollutants during operation of the vehicle motor. However, emissions often occur from electricity generation upstream of the vehicle charging stage, including the upstream extraction, refining, and transportation of fuels used for electricity generation. In LCA, "upstream" refers to those life cycle stages that occur prior to the in-use stage—in the case of the fuel cycle, its extraction, processing, transport, and, if necessary, generation. "Downstream" typically refers to those life cycle stages that include in-use and end-of-life management—in the case of the fuel cycle, its combustion or use (see text box "Terminology in Transportation Sector LCAs").

ICEVs emit GHG and other pollutants downstream during vehicle operation through fuel combustion and upstream during the extraction, refining, and transportation of crude oil for the production of liquid transportation fuel, as well as distribution of the refined fuel.

Terminology in Transportation Sector LCAs

In addition to the "upstream" and "downstream" terms used in this report, LCA practitioners use certain terminology to enable comparisons between vehicle types with different power sources, fuel use, and associated effects. These terms are based on the concept of the fossil fuel life cycles for ICEVs, and they have been adopted for BEVs.

- Well-to-Tank (WtT) refers to any environmental effects from the processes needed to extract and transform crude oil into useable fuel for ICEVs. For BEVs, WtT refers to any environmental effects from electricity production occurring upstream of vehicle charging. WtT corresponds to the term "upstream."
- Tank-to-Wheels (TtW) refers to any environmental effects from the combustion of the fuel in the vehicle's engine for ICEVs. For BEVs, TtW refers to the direct environmental effects of driving the vehicle. TtW corresponds to the term "downstream."
- Well-to-Wheels (WtW) refers to the WtT and TtW stages collectively for both ICEVs and BEVs.

Factors Affecting the ICEV In-Use Stage

For ICEVs, the amount of GHG and other pollutants emitted during upstream processes are related to the characteristics of the crude oil resource; the methods and efficiencies of the extraction and refining processes; and the methods of fuel transportation and distribution. The amount of GHG and other pollutants emitted during downstream processes (i.e., vehicle operation) are related to the type and quality of the fuel combusted; the fuel efficiency of the vehicle and its engine; and the distance that the vehicle travels during its lifetime.[60]

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characterized and regulated; and non-exhaust sources including brake wear, tire and road wear, clutch wear and road dust resuspension. The non-exhaust sources have not been regulated because they are difficult to measure and control. However, with increasingly stringent standards for exhaust emissions, the non-exhaust fraction has become increasingly important." For more information, see California Air Resources Board, "Vehicle Non-Exhaust Particulate Matter Sources," at https://ww2.arb.ca.gov/resources/documents/brake-tire-wear-emissions. See also European Commission, "Non-Exhaust Traffic Related Emissions—Brake and Tyre Wear PM," at https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/non-exhaust-traffic-related-emissions-brake-and-tyre-wear-pm; and V. R. J. H. Timmers and P. Achten, "Non-Exhaust PM Emissions from Electric Vehicles," *Atmospheric Environment*, vol. 134 (2016), pp. 10-17.

[60] A number of CRS reports focus on the environmental effects and the statutory and regulatory requirements affecting transportation fuel production and vehicle use. See, for example, CRS Report R40506, *Cars, Trucks, Aircraft, and EPA Climate Regulations*, by James E. McCarthy and Richard K. Lattanzio; CRS Report R42986, *Methane and Other Air Pollution Issues in Natural Gas Systems*, by Richard K. Lattanzio; CRS Report R43497, *Tier 3 Motor Vehicle Emission and Fuel Standards*, by Richard K. Lattanzio and James E. McCarthy; and CRS Report R45204, *Vehicle Fuel Economy and Greenhouse Gas Standards: Frequently Asked Questions*, by Richard K. Lattanzio, Linda Tsang, and Bill Canis.

In the United States, environmental laws mitigate some of the environmental effects from the ICEV in-use stage. For example, the Clean Air Act (CAA) seeks to reduce air pollution in the United States, specifically requiring fuels and vehicles to produce fewer emissions. To meet the requirements of the CAA, EPA has taken several actions, including setting ambient air quality standards; requiring the use of emissions control devices and practices for industrial sources of pollution (e.g., crude oil and natural gas production, processing, and refining operations); requiring emissions control devices and cleaner burning engines in vehicles; removing lead from gasoline; requiring the use of reformulated gasoline; and requiring the supply of ultra-low sulfur gasoline and diesel fuel.[61]

Further, the Clean Water Act regulates surface discharges of water associated with crude oil and natural gas drilling and production as well as contaminated storm water runoff from production sites. The Safe Drinking Water Act regulates the underground injection of wastewater from crude oil and natural gas production and the underground injection of fluids used in hydraulic fracturing if the fluids contain diesel fuel. The Resource Conservation and Recovery Act regulates underground storage tanks. States and localities may also have environmental requirements.

Similarly, environmental laws and regulations in other countries may mitigate some of the environmental effects from the ICEV in-use stage. An analysis of other countries' activities is beyond the scope of this report.

Environmental Assessment of ICEV In-Use

The environmental effects of ICEVs occur upstream during the extraction, refining, and transportation of crude oil and refined products and downstream (i.e., locally) during vehicle operation.

With respect to the upstream stages, transportation fuels like gasoline and diesel are the product of a long process beginning with the exploration and extraction of the resource and leading to its treatment in refineries, transportation to distributors, and eventual delivery to consumers. Crude oil is commonly recovered from geologic formations in the ground through drilling and extraction activities by the oil and gas industry. Potential environmental effects associated with these activities include water quality issues (e.g., the potential contamination of groundwater and surface water from production activities); water management practices (both consumption and discharge); land use changes; induced seismicity; and air pollution. Pollutants emitted from crude oil and natural gas systems include, most prominently, methane (a potent GHG) and VOCs—of which the sector is one of the highest-emitting industrial sectors in the United States[62]—as well as NO_x, SO_2, and various forms of toxics. Further, the type and the extent of emissions from crude oil and natural gas systems depend heavily on the quality of the crude resource, the characteristics of the resource basin from which the fuel resource is extracted, and the subsequent refinery processes. For example, some crude oils and their production processes (e.g., Canadian oil sands

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[61] For more information on CAA requirements, see CRS Report RL30853, *Clean Air Act: A Summary of the Act and Its Major Requirements*, by Kate C. Shouse and Richard K. Lattanzio.

[62] The U.S. Environmental Protection Agency's 2014 National Emissions Inventory estimated VOC emissions from "oil and gas" stationary sources to be 3.23 million tons, from all stationary sources to be 8.26 million tons, and from all anthropogenic sources to be 16.48 million tons. Data for VOCs, as well as the other criteria pollutants and hazardous air pollutants (HAPs), which are pollutants known or suspected to cause cancer or other serious health effects, are derived from EPA's National Emissions Inventory, https://www.epa.gov/sites/production/files/2017-04/documents/2014neiv1_profile_final_april182017.pdf.

mining) may have on the order of seven times the GHG emissions that other crude oils and their production processes have (e.g., light, sweet oils from the U.S. Bakken region).[63]

Regarding the downstream (or vehicle operation) stage, gasoline and diesel transportation fuels are toxic and highly flammable liquids. The vapors given off when they evaporate and the substances produced when they are combusted (CO, NO_x, PM, and VOCs) contribute to air pollution. Burning gasoline and diesel also produces CO_2. The combustion of a gallon of gasoline and a gallon of diesel produce about 8.89 and 10.16 kilograms of CO_2 respectively.[64] According to EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–2018*,[65] the national inventory that the United States prepares annually under the United Nations Framework Convention on Climate Change,[66] the transportation sector is currently the largest contributor to anthropogenic GHG emissions in the United States. The agency estimates that transportation accounted for 28% of total U.S. GHG emissions in 2018, for a total of over 1,883 million metric tons of carbon dioxide equivalent ($MMTCO_2e$). The category of light duty vehicles (i.e., passenger cars and light trucks) contributed 1,055 $MMTCO_2e$. Thus, the combustion of fuel during the in-use stage is a major contributor to the life cycle environmental effects of ICEVs.

Factors Affecting the BEV In-Use Stage

For BEVs, the amount of GHG and other pollutants emitted during upstream processes are related to the fuel type and the energy efficiency of the power plant and transmission infrastructure used to power the vehicle. The amount of GHG and other pollutants emitted during downstream processes (i.e., vehicle operation) are related to the energy efficiency and other characteristics of the vehicle.

Upstream factors include the following:[67]

- **Electricity generation mix**: Different types of electricity generation are currently associated with very different environmental effects profiles per unit of electricity generated. These profiles include potential environmental effects during electricity generation and potential environmental effects during the extraction, processing, and transportation of the fuel used for electricity generation. Coal-fired power plants have the highest life cycle GHG, SO_x, and PM emission intensities. Nuclear, hydroelectric, and non-biomass renewable energy sources have lower GHG and other air pollutant emissions intensities, although their lifecycle emissions are not zero due to the construction and maintenance of the facilities, as well as potential fuel production and end of life management issues. Further, each type of power source has different energy, resource, and water consumption and use patterns. When assessing the life cycle environmental effects from an attributional standpoint, the average electricity generation grid mix for a country, region, or locality represents the total amount of electrical energy fed into the grid from each generation source over the course

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[63] For a comprehensive investigation into the WtW GHG emissions intensities of a variety of global crude oil types, see D. Gordon, A. Brandt, J. Bergerson, J. Koomey, "Oil-Climate Index," Carnegie Endowment for International Peace, 2015, https://oci.carnegieendowment.org/.

[64] U.S. Energy Information Administration, https://www.eia.gov/energyexplained/index.php?page=gasoline_environment.

[65] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–2018*, EPA-430-R-20-002, April 13, 2020.

[66] United Nations Framework Convention on Climate Change (U.S. Treaty Number: 102-38, October 7, 1992).

[67] For more discussion, see, for example, EEA Report No. 13/2018, pp. 38-43.

of the entire year, 24 hours per day. This calculation can determine the average environmental effects of the electricity supply.

- **Charging patterns**: While the average annual electricity generation mix is a useful approximation for the likely environmental effects of BEV charging, it does not account for the dynamics of electricity supply and demand. For a more accurate assessment, the environmental effects for any given charging event depend on the instantaneous electricity generation mix, which varies according to time of year, time of day, and the level of electricity demand. Thus, when assessing the life cycle environmental effects from a consequential standpoint, additional demand created by BEV charging may cause a shift in the electricity generation mix, resulting in either an increase or a decrease in the power sector's environmental effects, depending on the type of generation available to meet the additional demand. For example: BEV charging during times of higher renewable electricity supplies (e.g., during the middle of the day when solar photovoltaic (PV) generation is available) may help to integrate these supplies in the electricity generation mix, resulting in a less carbon-intensive mix with lower GHG and other air pollutant emissions on average. However, BEV charging at times that coincide with peaks in other energy use may produce higher GHG and other air pollutant emissions on average, as the extra demand may be met using carbon-intensive sources of electricity.
- **Transmission efficiencies:** Conversion losses during electricity generation and losses during transmission and charging can offset some of the in-use efficiency advantages of BEVs (see BEV engine efficiency discussion below). Because the average U.S. electricity mix includes low emission sources (e.g., nuclear, hydroelectric, solar, and wind), the improved in-use efficiency advantage of BEVs currently outweighs the conversion losses in the United States.[68] Locally, however, this balance is strongly dependent on the regional electricity generation mix.[69]

Downstream factors include the following:[70]

- **Engine efficiency:** The energy consumption of BEVs is dependent upon the energy efficiency of their motors, as is the case for ICEVs. In general, BEVs have higher in-use energy efficiency than ICEVs. BEVs convert over 77% of the electrical energy delivered from the grid for propulsion. ICEVs convert about 12%–30% of the energy stored in gasoline for propulsion.[71] The efficiency advantage of BEVs arises partly because of the higher efficiency of individual powertrain components (battery, motor, and transmission) and partly because of

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[68] See section "Review of the Findings from Dunn et al., 2015 (Updated)."

[69] See Lawrence Livermore National Laboratory, "Energy Flow Charts," at https://flowcharts.llnl.gov/commodities/energy.

[70] For more discussion, these factors are outlined in EEA Report No. 13/2018, pp 37-38.

[71] U.S. Department of Energy, "All-Electric Vehicles," https://www.fueleconomy.gov/feg/evtech.shtml, accessed February 5, 2020.

regenerative braking,[72] which can recapture roughly 10% to 20% of total energy used depending on driving style and conditions.[73]

- **Vehicle size and weight:** The energy consumption of BEVs is strongly correlated with vehicle size and weight, as is the case for ICEVs. Heavier and larger BEVs require more energy to accelerate, and they have greater rolling resistance and air resistance than smaller and lighter BEVs.[74] Further, BEVs are between 14% and 29% heavier than an equivalent-sized ICEV from the same manufacturer.[75] The extra weight of BEVs is largely due to the weight of the battery and the associated secondary weight increases required to strengthen the vehicle body. This extra weight diminishes the overall efficiency advantage of BEVs in comparison to ICEVs.
- **Driving style:** A key factor affecting energy consumption of BEVs is the extent to which regenerative braking can recuperate energy. Regenerative braking is most effective during gradual deceleration and descending hills. During sharp braking, a lower proportion of the energy can be recuperated and the use of mechanical brake pads is required. Therefore, under more aggressive driving conditions, the efficiency advantage of BEVs over ICEVs is diminished.
- **Auxiliary systems:** Another factor affecting the energy efficiency of BEVs is the degree of electricity consumption by auxiliary systems (e.g., heating and air conditioning). For most auxiliary systems (including air conditioning for cooling) the effect on energy consumption in BEVs and ICEVs is similar. However, for in-cabin heating, BEVs must draw energy from the battery, whereas ICEVs can make use of waste heat from the engine. Therefore, in cold conditions, the efficiency advantage of BEVs over ICEVs is diminished.

In the United States, environmental laws mitigate some of the environmental effects from the BEV in-use stage. For example, electric power generation, transmission, and distribution are part of the utility sector. As with the various sectors related to ICEV's in-use stage, EPA has taken several actions to reduce pollution from the utility sector.[76] States and localities may also have

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[72] Regenerative braking is unique to BEVs and enables the vehicle's kinetic energy to be converted back to electrical energy during braking (deceleration or downhill running). The converted electrical energy is stored in energy storage devices such as batteries, ultracapacitors, and ultrahigh-speed flywheels. See A. Doyle and T. Muneer, "Traction Energy and Battery Performance Modelling," in *Electric Vehicles: Prospects and Challenges* (Elsevier Inc. 2017), pp. 93-124.

[73] See EEA Report No. 13/2018, and S. Rangaraju, et al., "Impacts of Electricity Mix, Charging Profile, and Driving Behavior on the Emissions Performance of Battery Electric Vehicles: A Belgian Case Study," *Applied Energy*, vol. 148 (2015), pp. 496-505.

[74] P. Egede, *Environmental Assessment of Lightweight Electric Vehicles* (Springer International Publishing: Basel, Switzerland, 2017).

[75] V. R. J. H. Timmers and P. Achten, "Non-Exhaust PM Emissions from Electric Vehicles," *Atmospheric Environment*, vol. 134 (2016), pp. 10-17.

[76] These include regulating NO_x, PM, and SO_x at power plants under CAA New Source Performance Standards; regulating mercury and other air toxics at power plants under the CAA National Emissions Standards for Hazardous Air Pollutants (NESHAP); controlling for interstate air pollution transport; controlling for benzene waste operations; requiring emission standards for stationary internal combustion engines, including reciprocating internal combustion engines (RICE); requiring emission standards for stationary combustion turbines; requiring reporting under a Greenhouse Gas Reporting Program; promulgating rules for cooling water intake structures under Clean Water Act §316(b) National Pollutant Discharge Elimination System (NPDES); and providing for effluent guidelines for steam electric power generation. A number of CRS reports focus on the environmental effects and the statutory and regulatory requirements affecting the utility sector. See, for example, CRS Report R45451, *Clean Air Act Issues in the 116th Congress*, by James E. McCarthy, Kate C. Shouse, and Richard K. Lattanzio; CRS Report R45299, *The Clean Air Act's*

more stringent environmental requirements, including regional GHG initiatives and renewable energy portfolio standards.

Similarly, environmental laws and regulations in other countries may mitigate some of the environmental effects from the BEV in-use stage. An analysis of other countries' activities is beyond the scope of this report.

Environmental Assessment of BEVs In-Use

The life cycle environmental effects attributable to the BEV in-use stage are minimal during downstream vehicle operation because BEVs do not emit CO_2 or other air pollutants through tailpipe exhaust. However, a variety of environmental effects may occur from electricity generation occurring upstream of vehicle charging, including the upstream extraction, refining, transportation and combustion of fuels used for electricity generation.

Most LCA practitioners report that emissions of many common air pollutants (including GHG, VOCs, CO, and NO_x) from BEVs tend to be lower than ICEVs on a per kilometer basis during the in-use phase of the vehicle life cycle (including the fuel life cycle). This is due to the energy efficiency advantages of electric motors and the incorporation of electricity sources with low emissions intensities in the electricity generation mix. A scenario in which BEVs emit more GHGs and other air pollutants than ICEVs is if a vehicle uses electricity derived primarily from coal as a fuel source. Some other common air pollutant emissions, however, specifically those more prevalent in coal combustion than petroleum combustion (e.g., SO_x, PM, toxics), are generally estimated to be greater in most scenarios for BEVs than ICEVs due to the inclusion of some percentage of coal-fired power in most modeled electricity generation mixes.

Further, the comparative impact of BEVs' and ICEVs' in-use air pollutant emissions on human health is dependent upon the location of emissions. In urban centers, street-level emissions of NO_x, PM, hydrocarbons, and other pollutants from ICEVs can lead to high local concentrations in densely populated areas. In contrast, emissions from power plants, *on average*, tend to occur away from densely populated areas, contributing to lower levels of background concentrations over larger areas.[77]

Environmental effects of BEVs also include potential effects on terrestrial and aquatic ecosystems. While LCAs of BEVs on ecosystems are less common than LCAs of GHG and other air pollutant emissions in the literature, these effects are nonetheless important. Generalized results from the selection of articles reviewed for this report suggest that the in-use environmental effects of BEVs are similar to that of ICEVs for terrestrial acidification, because the NO_x and SO_x emissions from coal-fired electricity generation counterbalance the NO_x emissions savings from the absence of tailpipe emissions. BEVs and ICEVs effects for terrestrial ecotoxicity are likely to be similar, as the primary cause is the release of zinc, copper, and titanium from tire and brake wear for which data on differences are limited.[78] In contrast, freshwater eutrophication and

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Good Neighbor Provision: Overview of Interstate Air Pollution Control, by Kate C. Shouse; CRS In Focus IF11078, *EPA Reconsiders Benefits of Mercury and Air Toxics Limits*, by Kate C. Shouse; CRS Report R45453, *U.S. Carbon Dioxide Emissions in the Electricity Sector: Factors, Trends, and Projections*, by Jonathan L. Ramseur; CRS In Focus IF10778, *Overview of the Steam Electric Power Generator Effluent Limitation Guidelines and Standards*, by Laura Gatz; and CRS Report R41836, *The Regional Greenhouse Gas Initiative: Background, Impacts, and Selected Issues*, by Jonathan L. Ramseur.

[77] For more discussion, see, for example, EEA Report No. 13/2018, pp 33-34.

[78] Estimates of local PM emissions from BEVs, and the comparison with those of ICEVs, vary considerably because of the difficulty of measuring them reliably in real-life conditions.

ecotoxicity effects of in-use BEVs are typically higher than those for ICEVs due to the emissions to water from the mining of coal required for electricity generation.

D. Vehicle End-of-Life

The final stage of a vehicle's life cycle is end-of-life. This stage can include reuse and recycling of vehicle components in addition to disposal. In terms of process, end-of-life vehicle treatment starts with deregistration and collection. The vehicle is then dismantled. Components containing hazardous materials, such as batteries and refrigerant gases, are collected, followed by recyclables and valuable materials for secondary use, including engines and tires. The vehicle shells left after the dismantling process are put into shredders. The shredded materials are separated and subsequently iron is separated from non-ferrous materials.[79]

Factors Affecting the End-of-Life Stage

Factors that can affect LCA results for the end-of-life stage include the manner in which the materials are disposed and whether or not materials are reused or recycled. Designing components or selecting battery chemistry to facilitate disassembly, reuse, or recycling could generally reduce potential impacts. However, for modeling purposes, LCA practitioners commonly allocate the effects of such changes to the subsequent vehicle that received reused or recycled components.

Environmental Assessment of End-of-Life Management

The environmental effects from the end-of-life stage—for both BEVs and ICEVs—contribute a smaller percentage to total life cycle environmental effects than other stages.[80] There is uncertainty with the data for end-of-life emissions, and the potential for reuse and recycling of components, including batteries, could further alter life cycle contributions. As BEVs increase in market share, the overall life cycle of the vehicles market is shifting away from a fuel-intensive portfolio to a materials-intensive portfolio. Some believe that this shift makes it increasingly important to have efficient recycling processes to recover materials.[81] Others are reportedly looking for "second-life" stationary energy storage applications for BEV batteries past their useful life in vehicle applications.[82]

Recycling can reduce the resource intensity of the raw material supply chain. For example, primary aluminum production is 20 times as energy intensive as scrap aluminum production.[83]

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[79] As described in EEA Report No. 13/2018, p. 47.

[80] EEA Report No. 13/2018, p. 7; Hawkins et al., 2012; and C. Tagliaferri, et al., "Life Cycle Assessment of Future Electric and Hybrid Vehicles: a Cradle-to-Grave Systems Engineering Approach," *Chemical Engineering Research and Design*, vol. 112 (2016).

[81] L. A-W. Ellingsen and C.R. Hung, *Research for TRAN Committee—Resources, Energy, and Lifecycle Greenhouse Gas Emission Aspects of Electric Vehicles*, European Parliament, Policy Department for Structural and Cohesion Policies, IP/B/TRAN/IC/2017-068 (Brussels, 2018).

[82] David Stringer and Jie Ma, "Where 3 Million Electric Vehicle Batteries Will Go When They Retire," *Bloomberg Businessweek*, June 27, 2018, https://www.bloomberg.com/news/features/2018-06-27/where-3-million-electric-vehicle-batteries-will-go-when-they-retire.

[83] International Energy Agency, *Greenhouse Gas Emissions from Major Industrial Sources—IV the Aluminum Industry*, Report No. PH3/23, Paris, 2000.

While some of the materials in BEVs have mature recycling industries, others do not. For example, the recycling of REEs from magnets used in BEVs is limited.[84]

Environmental Assessment of Battery Recycling

End-of-life batteries may affect the environment if improperly disposed.[85] A lead-acid battery[86] recycling market exists in the United States. According to EPA, in 2014 the rate of lead-acid battery recycling was approximately 99%,[87] making them one of the most recycled products in the United States.[88] Some see the lead-acid battery recycling market as a model for lithium-ion battery recycling; however, the typical automotive lead-acid battery is a mature technology that serves a different function than the lithium-ion battery for a BEV. The lead-acid battery has been the standard battery technology for most of the past century. Compared with a lithium-ion battery for a BEV, a typical automatic lead-acid battery is smaller, weighs less, and has a shorter lifetime.[89]

The recycling industry for lithium-ion batteries is less developed than for lead-acid in the United States. Reports estimate recycling rates for lithium-ion batteries to be less than 5% in the United States.[90] According to the U.S. Geological Survey, "one domestic company has recycled lithium metal and lithium-ion batteries since 1992 at its facility in British Columbia, Canada," and the same company established the first U.S. lithium-ion vehicle battery recycling facility in Lancaster, OH, in 2015.[91]

DOE has also announced a lithium-ion battery recycling prize and an associated battery recycling research and development center.[92] According to DOE, the Lithium Battery Recycling Prize is a "competition with a series of progressive down selections to incentivize the nation's innovators and entrepreneurs to develop and demonstrate processes that, when scaled, have the potential to

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[84] A. Tsamis and M. Coyne, *Recovery of Rare Earths from Electronic Wastes: An Opportunity for High-Tech SMEs*, Report on a study for the ITRE committee IP/A/ITRE/2014-09 (European Parliament, 2015).

[85] Waste management is subject to state and federal standards. Concerns over improper disposal also extends to internal combustion vehicles, which have fluids and materials—including batteries—that are subject to state and federal standards.

[86] The type of battery used in ICEVs to start the engine.

[87] U.S. Environmental Protection Agency, *Advancing Sustainable Materials Management: 2014 Fact Sheet*, EPA530-R-17-01, November 2016, p. 5.

[88] See A. D. Ballantyne, J. P. Hallett, and D. J. Riley, et al., "Lead Acid Battery Recycling for the Twenty-First Century," *Royal Society Open Science*, vol. 5 (2018), https://doi.org/10.1098/rsos.171368; U.S. Environmental Protection Agency, *Advancing Sustainable Materials Management: 2014 Fact Sheet*, EPA530-R-17-01, November 2016, p. 9.

[89] While an automotive lead-acid battery is smaller and lighter than a lithium-ion battery, the lead-acid battery is poorly suited for electric vehicles due to a lower energy density than a lithium-ion battery. Automotive lead-acid batteries are typically designed to deliver 12 volts of electricity to start a gasoline combustion engine within a vehicle and run other automotive components. For more information on how automotive batteries work, see CRS Report R41709, *Battery Manufacturing for Hybrid and Electric Vehicles: Policy Issues*, by Bill Canis.

[90] Mitch Jacoby, "It's Time to Get Serious About Recycling Lithium-Ion Batteries," *Chemical and Engineering News*, vol. 97 (July 14, 2019), https://cen.acs.org/materials/energy-storage/time-serious-recycling-lithium/97/i28.

[91] U.S. Geological Survey, "Lithium," *Mineral Commodity Summaries*, February 2019, p. 98, https://minerals.usgs.gov/minerals/pubs/commodity/lithium/. DOE awarded $9.5 million to the company in 2009 to construct the Ohio facility for lithium-ion vehicle batteries; see U.S. Geological Survey, "Lithium," *Mineral Commodity Summaries*, January 2018, p. 98, https://minerals.usgs.gov/minerals/pubs/commodity/lithium/.

[92] U.S. Department of Energy, "Energy Department Announces Battery Recycling Prize and Battery Recycling R&D Center," press release, January 17, 2019, https://www.energy.gov/eere/articles/energy-department-announces-battery-recycling-prize-and-battery-recycling-rd-center.

profitably capture 90 percent of all lithium-based battery technologies in the United States."[93] DOE's first lithium-ion recycling R&D center, the ReCell Center, will focus on research topics to enable profitable recycling for industry adoption. One goal of the center is closed-loop recycling, where materials from spent batteries are recycled directly into the vehicle battery manufacturing process, which would minimize energy use and material waste by eliminating mining and processing steps.[94] In addition to reducing concerns about the generation and disposal of hazardous waste, the availability of material supply, and environmental effects associated with production, some research shows that recycling batteries and recovering multiple minerals has been found to maximize both energy savings and emission reductions during material production.[95] Studies have shown that the recycling and reuse of materials within BEV batteries could reduce primary energy use and result in reductions in GHG emissions of up to 50% across the battery production process.[96]

Studies also indicate that the impact of battery recycling and reuse depends upon the type of battery technology and the materials used in the battery. For lithium-ion batteries, one study found that recycling could reduce the ecological impact of the battery by more than 20%.[97] Reports found the reduction or substitution of select materials (such as gallium in lithium-ion batteries) within the batteries influenced the ecological impact of the battery system.[98]

Different recycling methods have different potential environmental effects. Two recycling methods considered for lithium-ion battery recycling are hydrometallurgical and pyrometallurgical recycling. Hydrometallurgical recycling extracts materials from the battery by dissolving the battery in a liquid. This chemical leaching process has the capability of capturing metals and lithium. Pyrometallurgical recycling first chemically transforms the materials through a kiln firing process and then leaches the material to recover slag and metals. Pyrometallurgurical recycling is considered to be a cost-effective material recovery process and is less water intensive than hydrometallurigical recycling; however, pyrometallurgurical recycling is typically more energy intensive and can emit more air pollutants than hydrometallurgical recycling.[99]

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[93] U.S. Department of Energy, *FY2020 Congressional Budget Request*, vol. 3, part 2, March 2019, pp. 26-27.

[94] For further information on ReCell research priorities, see Argonne National Laboratory, "DOE Launches Its First Lithium-Ion Battery Recycling R&D Center: ReCell," press release, February 15, 2019, https://www.anl.gov/article/doe-launches-its-first-lithiumion-battery-recycling-rd-center-recell.

[95] J. B. Dunn, L. Gaines, J. Sullivan, M. Q. Wang, "The Impact of Recycling on Cradle-to-Gate Energy Consumption and Greenhouse Gas Emissions of Automotive Lithium-Ion Batteries," *Environmental Science and Technology*, vol. 46 (2012), pp. 12704-12710.

[96] Dunn et al., 2015; T. P. Hendrickson, O. Kavvada, N. Shah, R. Sathre, C. D. Scown, "Life-Cycle Implications and Supply Chain Logistics of Electric Vehicle Battery Recycling in California," *Environmental Research Letters,* vol. 10 (2015), 014011.

[97] L. Unterreiner, V. Jülch, and S. Reith, "Recycling of Battery Technologies—Ecological Impact Analysis Using Life Cycle Assessment (LCA)," *Energy Procedia*, vol. 99 (2016), pp. 229-234 (hereinafter Unterreiner et al., 2016). For more information on stationary energy storage technologies, see CRS Report R45980, *Electricity Storage: Applications, Issues, and Technologies*, by Richard J. Campbell.

[98] Unterreiner et al., 2016.

[99] T. P. Hendrickson, O. Kavvada, N. Shah, R. Sathre, C. D. Scown, "Life-Cycle Implications and Supply Chain Logistics of Electric Vehicle Battery Recycling in California," *Environmental Research Letters*, vol. 10 (2015), 014011.

A Discussion of the Published LCA Literature

Literature analyzing the life cycle environmental effects of BEV technology—both in isolation and in comparison to ICEV technology—is extensive and growing. However, as the literature grows, so does the range of results. From this literature, CRS selected 38 peer-reviewed articles to assess, published from 2008 to 2019 (see the **Appendix**). The criteria used to select the articles included (1) the article's inclusion in Scopus and Web of Science databases, (2) the impact factor of the journal that published the article,[100] and (3) the extent to which the LCA focused on the full life cycle of BEVs in comparison to ICEVs. A great number of detailed studies exist that focus on specific stages and/or technologies (e.g., a specific battery type or vehicle type or stage of life); these studies were not included in this review.

Review of the Findings from Selected LCAs

The selected articles diverged greatly in their results. The divergence is due to the differing system parameters of each study, including the selected goals, scopes, models, scales, time horizons, and datasets. Differences among the scopes of the studies included, *inter alia*, (1) the number and types of environmental effects categories modeled; (2) the specific vehicle and battery technologies modeled; (3) the choice of vehicle and battery lifetimes modeled; and (4) the geographic locations modeled, including the particular electricity infrastructure. Further, the studies employed different modeling assumptions (e.g., attributional, consequential),[101] GHG emissions datasets (e.g., EcoInvent; the Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model [GREET®]), electricity grid databases (e.g., eGRID, EPA's CEMS, National TSO/DSO), and energy forecasts (e.g., International Energy Agency, U.S. Energy Information Administration). While each article may be internally consistent based upon the assumptions within it, analysis across the articles is difficult. Because of these divergences and complexities, CRS sees significant challenges to quantifying a life cycle assessment of BEV and ICEV technologies that incorporates all of the findings in the published literature. A review of the literature, however, can speak broadly to some of the trends in the life cycle environmental effects as well as the relative importance of certain modeling selections.

Regarding the global warming potential effects of BEV technology, the quantitative results from the selected articles have a wide variability. Excluding results obtained from stylized LCAs (i.e., those whose role is to denote an extreme state rather than a real-world situation), the findings of the articles reviewed for this report span from approximately 50 grams of carbon dioxide equivalent emissions per vehicle kilometer traveled (gCO_2e/km) (Van Mierlo, et al., 2017, presenting the full LCA results of a BEV in the Belgium environment) to 292 gCO_2e/km (Bohnes, et al., 2017, assessing the full LCA results of a BEV introduced in the Danish market in 2016, using short-term marginal electricity mix).[102] As stated previously, this divergence is due to the

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[100] An "impact factor" measures the number of citations that an average article in a journal receives in a particular year. The impact factor applies to the journal where an article is published and does not measure the impact of an individual article.

[101] Attributional methodology typically utilizes average data for each unit process within the life cycle. Consequential methodology, on the other hand, aims to describe how physical flows can change as a consequence of an increase or decrease in demand for the product system under study. Unlike attributional, consequential methodology includes unit processes inside and outside of the product's immediate system boundaries. It utilizes economic data to measure physical flows of indirectly affected processes.

[102] CRS was unable to produce a comparably reliable range of values for ICEVs from the journal articles.

differing system parameters of each study, including the selected goals, scopes, models, scales, time horizons, and datasets.

Many authors, however, have noted the role of a specific factor, the CO_2e intensity of the modeled electricity generation mix, as a statistically significant modeling selection. Marmiroli et al., 2018, investigates this hypothesis through an analysis of results correlating a BEV's life cycle emissions to the carbon intensity of the electricity generation mix from which the vehicle draws its power. In this study, the authors find that "despite the wide-ranging scopes and the numerous variables present in the assessments, the electricity mix's carbon intensity can explain 70% of the variability of the results."[103]

Review of the Findings from Dunn et al., 2015 (Updated in 2019)

As stated in the previous section, although a number of LCAs are available, CRS sees significant challenges to quantifying a life cycle assessment of BEV and ICEV technologies that incorporates all of the findings in the published literature. Therefore, to provide an internally consistent summary in graphical form, this report presents the results from one study: Dunn, J. B., Gaines, L., Kelly, J. C., James, C., and Gallagher, K. G., "The Significance of Li-ion Batteries in Electric Vehicle Life-Cycle Energy and Emissions and Recycling's Role in Its Reduction," *Energy and Environmental Science*, 2015, as updated by the authors using the DOE, Argonne National Laboratory (ANL), GREET® 2018 dataset.[104]

Dunn et al., 2015 (updated) analyzes a broad range of environmental effects, with vehicle types, life stages, and geographic coverage well matched to the scope of this CRS report. While comprehensive, Dunn et al., 2015 (updated) and the GREET® database have limitations and analytical uncertainties based upon the modeling assumptions, as discussed below.[105]

Dunn et al., 2015 (Updated) Modeling Assumptions

Dunn et al., 2015 (updated) examines the environmental effects categories modeled by the DOE, ANL GREET® 2018 LCA database. It is a "complete" LCA using attributional modeling for average annual U.S. and California electricity grid data and average ICEV, PHEV, and BEV data. Input assumptions are listed below (as well as in the initial study, Dunn et al., 2015):

- Year: 2017 simulation year; this corresponds to a 2017 electricity generation grid with model year (MY) 2012 vehicle technology to account for the average age of vehicles on the road.
- Grids examined: U.S. and California average (505 and 283 gCO_2e/kWh, respectively).
- Vehicle lifetime: 278,659 km (173,151 miles). Vehicle lifetime is based on ANL's VISION model, which in turn derives from a statistical evaluation of annual vehicle miles traveled (VMT) for vehicles over their lifetime and the

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[103] B. Marmiroli, M. Messagie, G. Dotelli, J. Van Mierlo, J., "Electricity Generation in LCA of Electric Vehicles: A Review," *Applied Sciences,* vol. 8 (2018), p. 1384 (hereinafter Marmiroli et al., 2018).

[104] The LCA dataset used by the U.S. Department of Energy, Argonne National Laboratory, for presentation in this report is the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET®) Model, 2018, https://greet.es.anl.gov/. J. C. Kelly and his team at Argonne National Laboratory provided updated inputs and data to CRS.

[105] The GREET® model and database is widely used, in part because of its accessibility and usability; however, GREET® does not conform fully to the principles and framework in ISO 14040 for LCA. (See https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4643755/.)

survivability of those vehicles. ANL uses the same VMT for each vehicle. The rationale is as follows: PHEV has no range limitation so should be equivalent to ICEV; a BEV with a 300 mile range is treated here as equivalent to an ICEV.

- PHEV all electric range: 64 km (40 miles).
- BEV range: 482 km (300 miles). The BEV in the Dunn et al., 2015 study had a range of 110 km, and its efficiency was higher than that of the 300 mile range vehicle in the updated dataset.
- ICEV fuel economy: 9.02 liters (L)/100 km (26.08 miles per gallon [MPG]).
- PHEV fuel economy: 3.42 L/100 km (68.84 MPG). The PHEV's charge depleting (CD) and charge sustaining (CS) modes are 2.4 L/100 km, and 6.1 L/100 km (38.3 and 99.5 miles per gallon gasoline equivalent [MPGGE],[106] respectively). The blend between them is 49.9% CD and 50.1% CS.
- BEV fuel economy: 2.81 L/100 km (83.56 MPGGE). The fuel economies are based on ANL's research in association with the vehicle simulation team (the Autonomie team).

Selected Environmental Effects Categories

Figure 4 through **Figure 13** present the Dunn et al., 2015 (updated) LCA findings for several environmental effects categories compared across model year (MY) 2012 ICEV, PHEV, and BEV powered by the U.S. and California electricity grids (2017 average) and divided into stages for the vehicle cycle (battery), vehicle cycle (other than battery), upstream fuel cycle ("Well-to-Tank"), and in-use fuel cycle ("Tank-to-Wheel"). In **Figure 4** through **Figure 13**, the scale of the environmental effects (i.e., the y-axis) varies greatly given the range of different pollutant types. The effects of those emissions are not proportional by mass (to the extent that they are at all comparable).

Dunn et al., 2015 (updated) finds that in comparison to the life cycle of ICEVs in the United States, the life cycle of lithium-ion BEVs (inclusive of two selected battery chemistries) emits, on average, an estimated 33% less GHGs (**Figure 4**), 61% less VOCs (**Figure 5**), 93% less CO (**Figure 6**), 28% less NO_x (**Figure 7**), and 32% less black carbon (**Figure 10**) when analyzed using an averaged U.S. electricity grid mix. However, the life cycle of lithium-ion BEVs emits, on average, an estimated 273% more SO_x (**Figure 8**) and 15% more fine PM (**Figure 9**). Further, in comparison to the life cycle of ICEVs, the life cycle of lithium-ion BEVs consumes, on average, an estimated 29% less total energy resources (**Figure 11**) and 37% less fossil fuel resources (**Figure 12**). However, the life cycle of lithium-ion BEVs consumes, on average, an estimated 58% more water resources (**Figure 13**). These results are global effects, based on the system boundaries and input assumptions of the study. The study does not assess human health or ecosystem effects.

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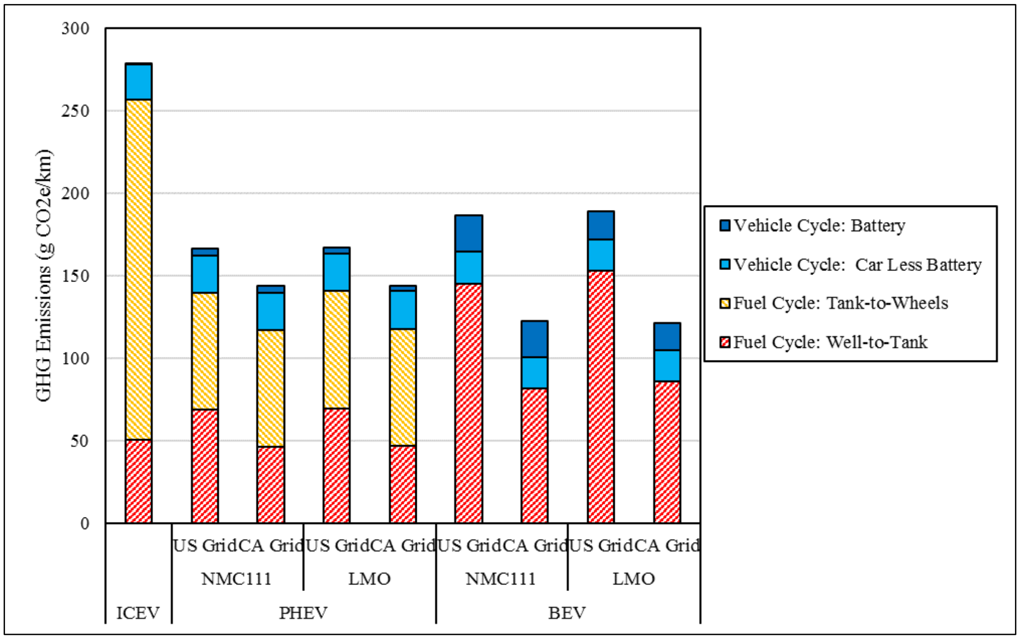
[106] The U.S. Environmental Protection Agency uses a fuel economy value, "miles per gallon gasoline equivalent," for vehicles that do not use liquid fuels. According to the agency, the value "represents the number of miles the vehicle can go using a quantity of fuel with the same energy content as a gallon of gasoline. This allows a reasonable comparison between vehicles using different fuels." See https://www.epa.gov/fueleconomy/text-version-electric-vehicle-label.

Figure 4. Life Cycle Assessment: Global Warming Potential

(Comparison of MY 2012 ICEV, PHEV, and BEV for U.S. and California Electricity Grid, 2017 Average)



Source: J. B. Dunn, L. Gaines, J. C. Kelly, C. James, C., 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 and Environmental Sciences*, 2015, as updated by the authors using the most recent U.S. Department of Energy, Argonne National Laboratory (ANL), Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET®) Model, 2018, https://greet.es.anl.gov/.

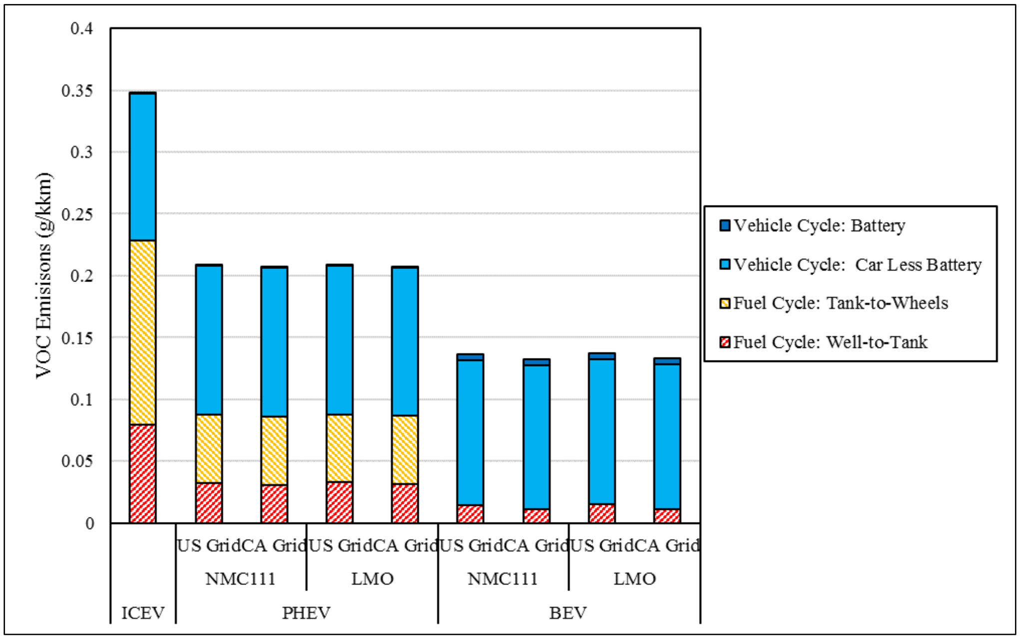
Notes: Global warming potential measured in grams carbon dioxide equivalent emissions per vehicle kilometer traveled averaged over the lifetime of the vehicle (gCO_2e/km); model year (MY) 2012 internal combustion engine vehicle (ICEV); MY 2012 plug-in hybrid electric vehicle (PHEV); MY 2012 battery electric vehicle (BEV); United States electricity grid, 2017 average (US Grid); California electricity grid, 2017 average (CA grid); lithium-ion battery with $LiNi_{0.4}Co_{0.2}Mn_{0.4}O_2$ cathode materials paired with graphite anodes (NMC111); lithium-ion battery with a $LiMn_2O_4$ cathode material paired with graphite anodes (LMO). See Dunn et al., 2015 (updated) system parameters and input assumptions listed below.

Dunn et al., 2015 (updated) examines all environmental effects categories modeled by the DOE, ANL GREET® 2018 LCA database. It is a "complete" LCA using attributional modeling for average U.S. and California electricity grid data and average ICEV, PHEV, and BEV data. Input assumption are as follows, as well as in the initial Dunn et al., 2015. Year: 2017 simulation year; this corresponds to a 2017 electricity generation grid with model year (MY) 2012 vehicle technology to account for system lag. Grids examined: U.S. and California average (505 and 283 gCO_2e/kWh, respectively). Vehicle lifetime: 278,659 km (173,151 miles). Vehicle lifetime is based on ANL's VISION model, which in turn derives from a statistical evaluation of annual vehicle miles traveled (VMT) for vehicles over their lifetime and the survivability of those vehicles. ANL uses the same VMT for each vehicle. The rationale is as follows: PHEV has no range limitation so should be equivalent to ICEV; a BEV with a 300 mile range is treated here as equivalent to an ICEV. PHEV all electric range: 64 km (40 miles). BEV range: 482 km (300 miles). The BEV in the initial Dunn et al., 2015 study had a range of 110 km, and its efficiency was higher than that of the 300 mile range vehicle in the updated dataset. ICEV fuel economy: 9.02 liters (L)/100 km (26.08 miles per gallon [MPG]). PHEV fuel economy: 3.42 L/100 km (68.84 MPG). The PHEV's charge depleting (CD) and charge sustaining (CS) modes are 2.4 L/100 km, and 6.1 L/100 km (38.3 and 99.5 miles per gallon gasoline equivalent [MPGGE], respectively). The blend between them is 49.9% CD and 50.1% CS. BEV fuel economy: 2.81 L/100 km (83.56 MPGGE). The fuel economies are based on ANL's research team associated with vehicle simulation (the Autonomie team). These results are global effects.

J. C. Kelly and his team at Argonne National Laboratory provided updated inputs and data to CRS.

Figure 5. Life Cycle Assessment: Volatile Organic Compounds

(Comparison of MY 2012 ICEV, PHEV, and BEV for U.S. and California Electricity Grid, 2017 Average)

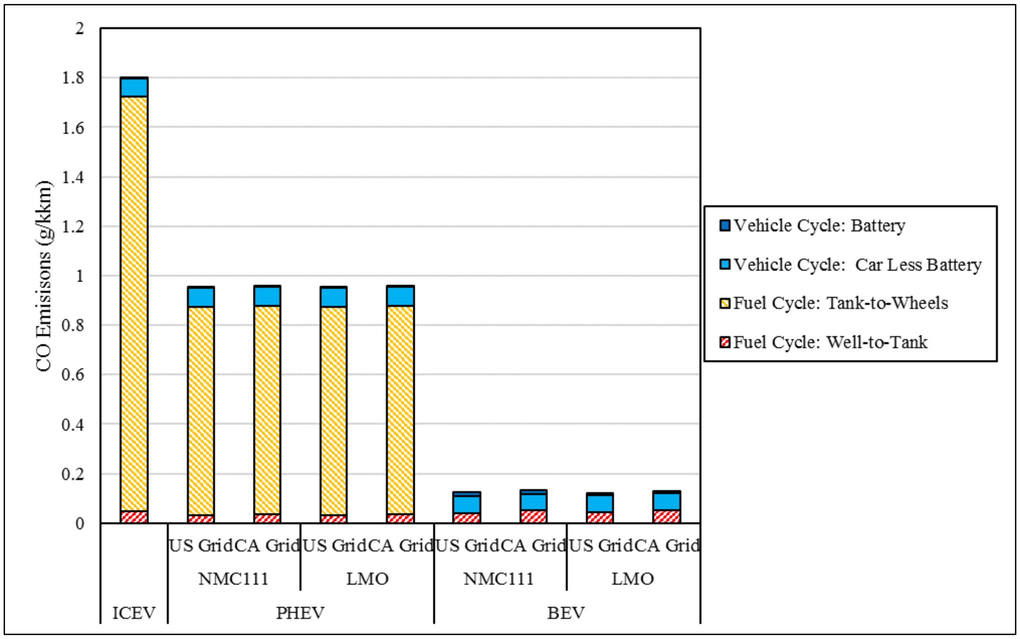


Source: Dunn et al., 2015 (updated).

Notes: Volatile organic compound emissions (VOC) in grams per vehicle kilometer traveled averaged over the lifetime of the vehicle (g/km); see **Figure 4** for additional notes.

Figure 6. Life Cycle Assessment: Carbon Monoxide

(Comparison of MY 2012 ICEV, PHEV, and BEV for U.S. and California Electricity Grid, 2017 Average)

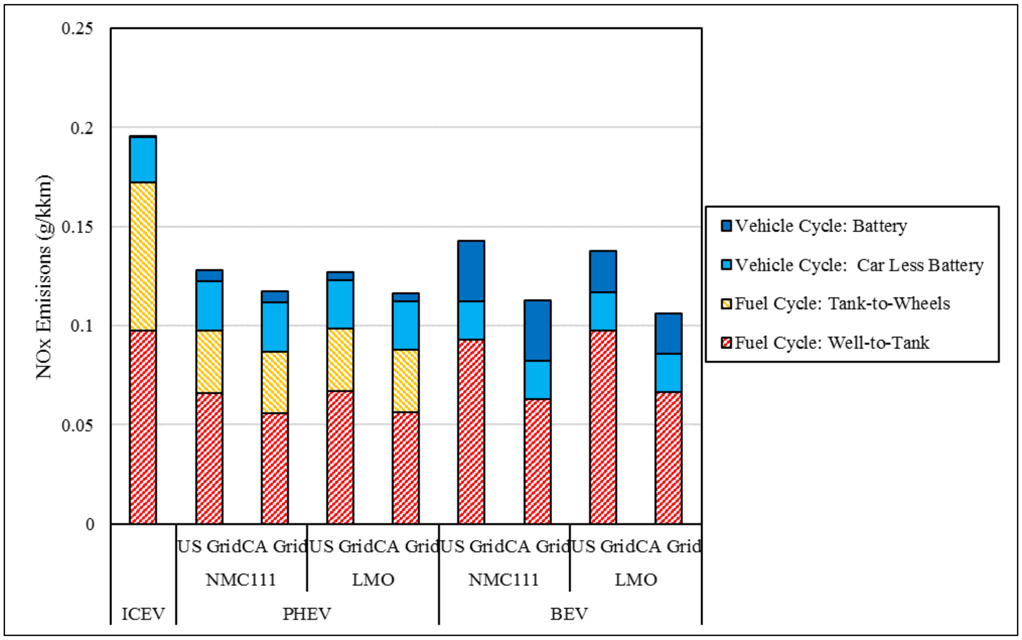


Source: Dunn et al., 2015 (updated).

Notes: Carbon monoxide emissions (CO) in grams per vehicle kilometer traveled averaged over the lifetime of the vehicle (g/km); see **Figure 4** for additional notes.

Figure 7. Life Cycle Assessment: Nitrogen Oxides

(Comparison of MY 2012 ICEV, PHEV, and BEV for U.S. and California Electricity Grid, 2017 Average)

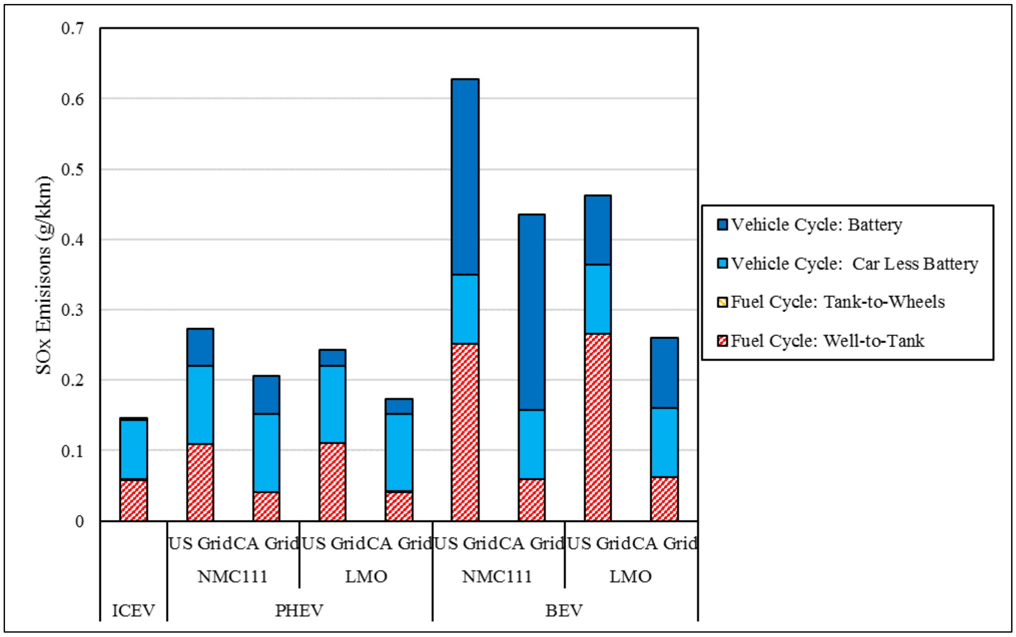


Source: Dunn et al., 2015 (updated).

Notes: Nitrogen oxides emissions (NO_x) in grams per vehicle kilometer traveled averaged over the lifetime of the vehicle (g/km); see **Figure 4** for additional notes.

Figure 8. Life Cycle Assessment: Sulfur Oxides

(Comparison of MY 2012 ICEV, PHEV, and BEV for U.S. and California Electricity Grid, 2017 Average)

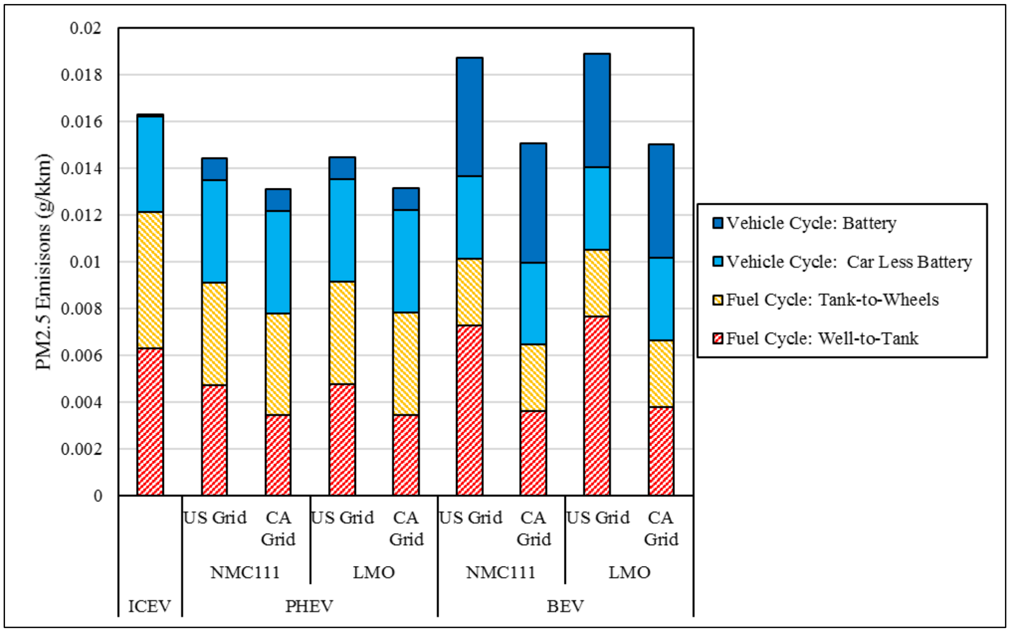


Source: Dunn et al., 2015 (updated).

Notes: Sulfur oxides emissions (SO_x) in grams per vehicle kilometer traveled averaged over the lifetime of the vehicle (g/km); see **Figure 4** for additional notes.

Figure 9. Life Cycle Assessment: Fine Particulates

(Comparison of MY 2012 ICEV, PHEV, and BEV for U.S. and California Electricity Grid, 2017 Average)

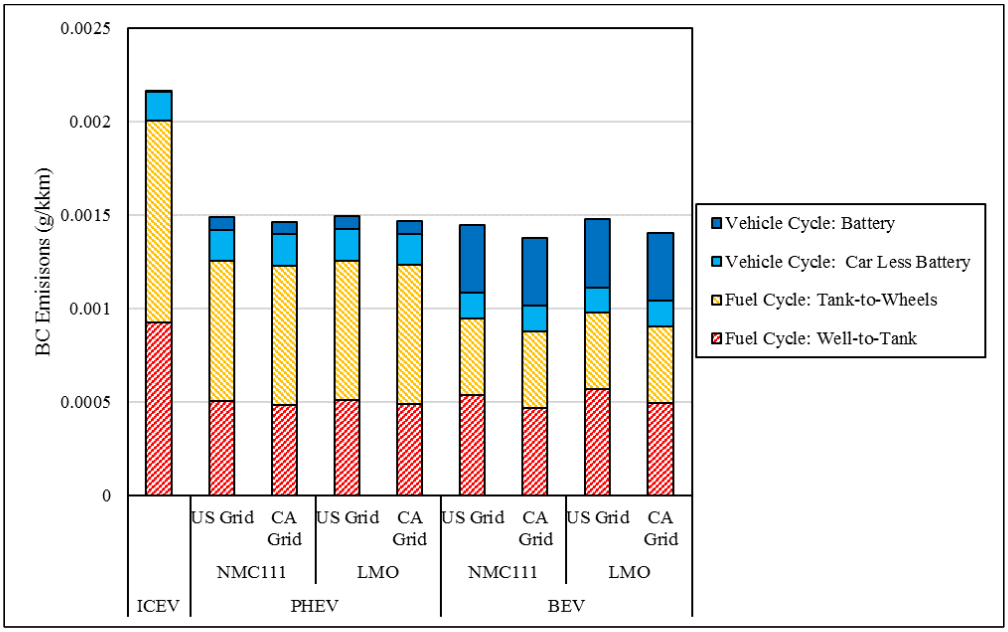


Source: Dunn et al., 2015 (updated).

Notes: Fine particulates emissions ($PM_{2.5}$) in grams per vehicle kilometer traveled averaged over the lifetime of the vehicle (g/km); see **Figure 4** for additional notes. $PM_{2.5}$ is particulate matter with a diameter of less than 2.5 microns.

Figure 10. Life Cycle Assessment: Black Carbon

(Comparison of MY 2012 ICEV, PHEV, and BEV for U.S. and California Electricity Grid, 2017 Average)

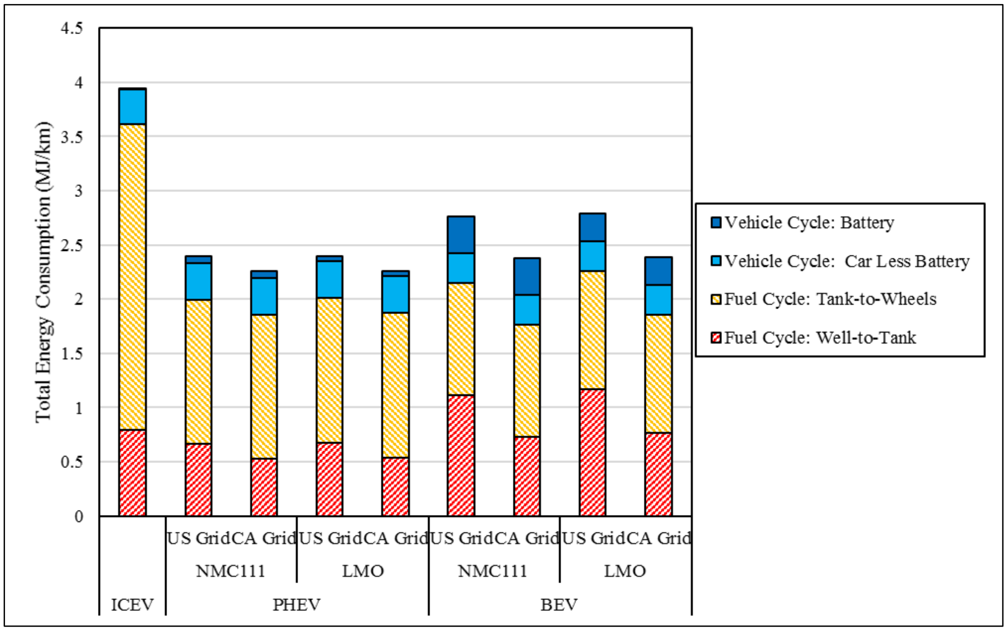


Source: Dunn et al., 2015 (updated).

Notes: Black carbon emissions (BC) in grams per vehicle kilometer traveled averaged over the lifetime of the vehicle (g/km); see **Figure 4** for additional notes.

Figure 11. Life Cycle Assessment: Total Energy Consumption

(Comparison of MY 2012 ICEV, PHEV, and BEV for U.S. and California Electricity Grid, 2017 Average)

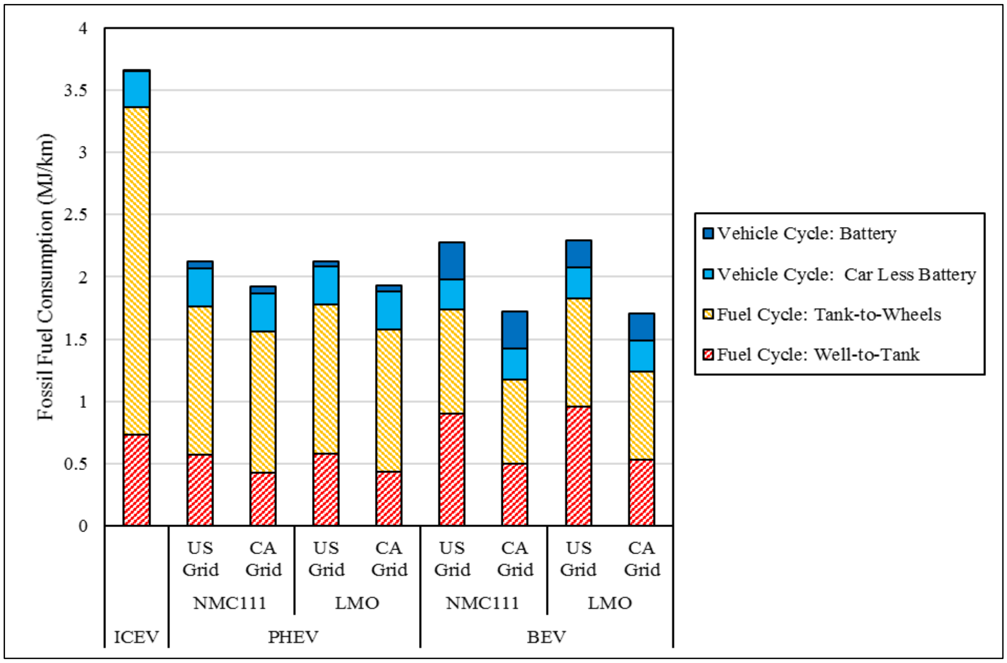


Source: Dunn et al., 2015 (updated).

Notes: Total energy consumption in megajoules (a gallon of gasoline contains roughly 120 megajoules) per vehicle kilometer traveled averaged over the lifetime of the vehicle (MJ/km); see **Figure 4** for additional notes.

Figure 12. Life Cycle Assessment: Total Fossil Fuel Consumption

(Comparison of MY 2012 ICEV, PHEV, and BEV for U.S. and California Electricity Grid, 2017 Average)

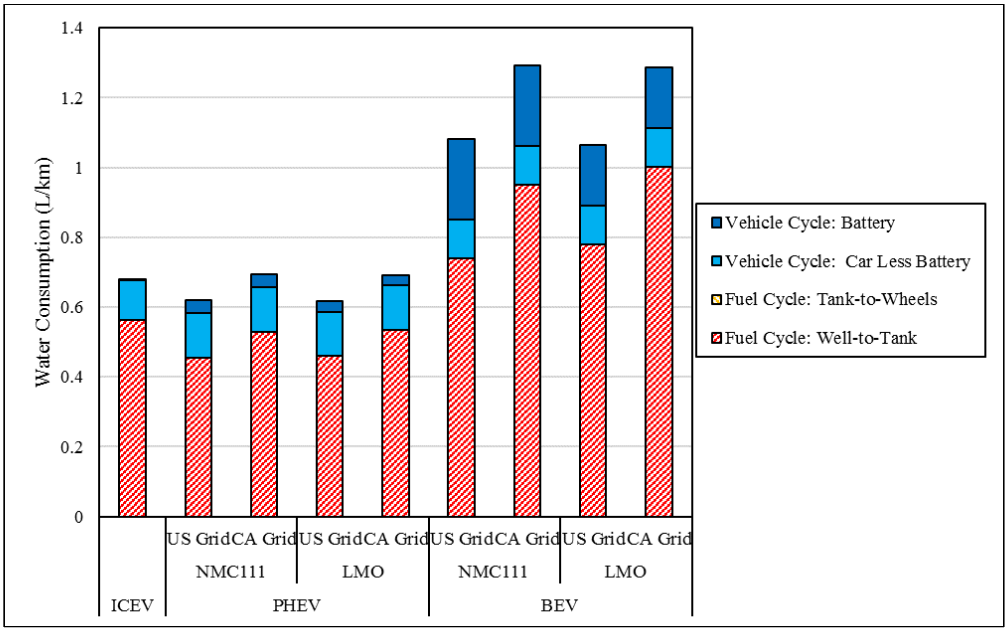


Source: Dunn et al., 2015 (updated).

Notes: Total fossil fuel consumption in megajoules (a gallon of gasoline contains roughly 120 megajoules) per vehicle kilometer traveled averaged over the lifetime of the vehicle (MJ/km); see **Figure 4** for additional notes.

Figure 13. Life Cycle Assessment: Water Consumption

(Comparison of MY 2012 ICEV, PHEV, and BEV for U.S. and California Electricity Grid, 2017 Average)



Source: Dunn et al., 2015 (updated).

Notes: Water consumption in liters per vehicle kilometer traveled averaged over the lifetime of the vehicle (L/km); see **Figure 4** for additional notes.

Issues for Consideration

Summary of Findings

Broadly speaking, the 38 LCAs reviewed for this report show that in most cases BEVs have lower life cycle GHG emissions than ICEVs. In general, GHG emissions associated with the raw materials and production stage of BEVs are between 1.3 and 2.0 times higher than for ICEVs. This can be offset by lower in-use stage emissions, depending on the electricity generation source and the lifetime vehicle miles traveled. BEVs offer greater local air quality benefits than ICEVs, due to the absence of tailpipe exhaust emissions. Both BEVs and ICEVs are responsible for upstream air pollutants emissions during the production and in-use stages.

The volume of literature on human toxicity and ecosystem effects is limited in comparison with that on GHG and other air pollutant emissions. These effects are based on second-order modeling assumptions (i.e., they are effects that potentially affect human health and ecosystems because of a given level of emissions and exposures). Many LCA practitioners assign greater difficulty to analyzing and quantifying them. They mention data variance and analytic uncertainties as reasons to find estimates in these categories less reliable. Further, the scale of these effects may vary, and their impacts may differ locally and globally depending upon regional variabilities, population size and characteristics, exposure rates, and the environmental regulations and management practices of the exposed areas.

Studies generally suggest that BEVs could be responsible for greater human toxicity and ecosystems effects than their ICEV equivalents, based on current mining and recycling technologies. These potentially different effects from BEVs result from the additional mining and processing of metals to produce batteries and from the mining and combustion of coal to produce electricity. Increased freshwater ecotoxicity effects from BEVs may likewise result from the additional mining requirements. Other impacts are more complicated to compare. Acidification depends largely on the assumptions made regarding the tradeoff in BEVs between increased emissions from battery production and electricity generation versus the absence of tailpipe emissions. In addition, the limited literature on terrestrial ecotoxicity suggests that BEVs and ICEVs have similar effects across their life cycle, dominated by emissions of metal particles from tire and brake wear during the in-use stage.

Considerations Affecting Life Cycle Performance

A range of key variables associated with vehicle design, vehicle choice and use patterns, vehicle end-of-life options, and the electricity generation mix employed during production and use can influence the life cycle environmental effects of BEVs, and their advantages or disadvantages relative to ICEVs. Overall, CRS notes that the most discussed variables associated with the life cycle environmental effects of BEVs in the literature reviewed for this report are as follows:

- **Electricity generation mix.** Power systems that supply electricity to the different life cycle stages of BEVs (processing, production, use, and end-of-life) have different emission intensities per kWh of electricity generated. These emission factors depend upon the fuel source of the electricity generators and the upstream processes that went into producing the fuel. Differences in the emission factors for the electricity grids employed during the various life cycle stages of BEV production and use will change the total life cycle emissions of BEVs. Future changes to the fuel source of electricity generators could change the emission factors of the electricity grids and potentially change the total life cycle emissions of BEVs.
- **Vehicle size and other characteristics.** Generally the larger the vehicle, the more materials required for vehicle and battery, and the more energy required across the various life cycle stages. Charging and use patterns (e.g., in-cabin heating) may also contribute to greater energy requirements.
- **Modeled vehicle lifetime mileage.** The longer the modeled lifetime mileage, the less influence that production-related emissions have and the greater influence that in-use emissions have over the total life cycle effects.
- **Battery chemistry.** Different battery chemistries have different performance characteristics. For example, higher specific energy density batteries would require less material to deliver the same level of vehicle range than other batteries. Batteries with higher life expectancy could extend lifetime mileage beyond other batteries. Some battery chemistries are better suited for recycling than others. New chemistries could further change the total life cycle effects. In addition to federal research and development efforts into new chemistries, some industry stakeholders are reportedly exploring approaches to reduce potential effects of batteries.[107]

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[107] For example, Samsung SDI has reportedly developed lithium-ion batteries that have reduced the amount of cobalt relative to nickel and is working toward removing cobalt entirely. Material ratios vary for a lithium nickel manganese cobalt oxide battery. Common cathode combinations are often one-third nickel, one-third manganese, and one-third cobalt. Other combinations increase nickel such as 60% nickel, 20% manganese, and 20% cobalt for the cathode. Samsung SDI reports combinations above 90% nickel, with 5% cobalt and 5% manganese. Samsung SDI is also

Issues Regarding LCA and Policy Development

The International Organization for Standardization (ISO) released a systemized framework for conducting LCAs during the period 1997–2000, and updated it in 2006. As noted in ISO's 2006 update (ISO 14040),[108] LCA is one of several environmental management techniques (e.g., risk assessment, environmental performance evaluation, environmental auditing, environmental impact assessment, and benefit cost analysis) and may not be the most appropriate technique to use in all situations. Because all techniques have limitations, it is important for policymakers to understand those that are present in LCA. The limitations include the following:

- LCA typically does not address the economic or social aspects of a product.
- The nature of choices and assumptions made by the practitioner of an LCA (e.g., system boundary setting, selection of data sources and impact categories) may be subjective.
- Models used to analyze inventory or to assess environmental effects are limited by their assumptions, and may not be available for all potential effects or applications.
- Results of LCA studies focused on global and regional issues may not be appropriate for local applications, and vice-versa (i.e., local conditions might not be adequately represented by regional or global conditions).
- The accessibility or availability of relevant data or data quality (e.g., gaps, types of data, aggregation, averaging, and site-specificity) may limit the accuracy of LCA studies.
- The lack of spatial and temporal dimensions in the inventory data used for assessment introduces uncertainty in the results. This uncertainty varies with the spatial and temporal characteristics of each environmental effect category.

The ISO recommends that the information developed in an LCA study is best used as part of a much more comprehensive decisionmaking process or used to understand the broad or general trade-offs of different product or policy choices.

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recycling lithium-ion batteries to recover cobalt and other components. Additionally, a cooperative pilot project was created by BMW, BASF, Samsung SDI, and a development agency to examine how to improve living and working conditions for artisanal cobalt miners. See Kang Seung-woo, "Samsung SDI to Make Cobalt-Free EV Batteries," *The Korea Times*, February 12, 2018, http://m.koreatimes.co.kr/phone/news/view.jsp?req_newsidx=244074; Ceclia Jamasmie, "Electric Car Dreams May Be Dashed by 2050 on Lack of Cobalt, Lithium Supplies," *Mining*, March 16, 2018, http://www.mining.com/electric-cars-dreams-may-shattered-2050-lack-cobalt-lithium-supplies/; and Edward Taylor, "BMW Joins Project to Improve Conditions for Cobalt Mining in Congo," *Reuters*, November 29, 2018, https://www.reuters.com/article/us-bmw-cobalt-congo/bmw-joins-project-to-improve-conditions-for-cobalt-mining-in-congo-idUSKCN1NY1UQ.

[108] See International Organization for Standardization, "ISO 14040: Environmental Management—Life Cycle Assessment—Principles and Framework," 2006.

Appendix. LCA Bibliography

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