

Electric Vehicle Batteries

Addressing Questions about Critical Materials and Recycling

HIGHLIGHTS

Electric vehicles are critical to reducing transportation pollution and solving the climate crisis, but manufacturing them at the necessary scale will require significantly increasing production of the batteries that power them. How batteries are made, what they are made of, and whether they are reused or recycled affect the sustainability of this crucial component. Even though batteries last many years, they eventually reach the end of their useful life for powering electric vehicles. Policies and incentives for recycling and reusing batteries, including strong health and labor standards, will further lessen the impacts of electric vehicles.

Battery electric vehicles (BEVs) are a key strategy for reducing air pollution and global warming emissions. They have zero tailpipe emissions, and even when powered by today's sources of electricity, their life cycle global warming emissions are significantly lower than those for vehicles fueled with gasoline or diesel (O'Dea 2019; Reichmuth 2020). However, the increased adoption of BEVs raises important questions about the availability, recyclability, and sustainability of battery materials.

Scaling up BEV manufacturing will mean increasing the production and processing of several materials used in today's lithium-ion batteries. Fortunately, strategies for recycling lithium-ion batteries offer the possibility of a sustainable, long-term supply of such materials, supporting the continued deployment of electric vehicles (EVs). However, implementing those strategies will require addressing a number of technical, economic, logistic, and regulatory barriers.



Recycling the cobalt, lithium, and other critical materials in electric vehicle batteries will help meet increased demand for materials as vehicle sales grow in future years and reduce the need to mine new materials. Recycling facilities are currently few and far between—Li-Cycle (shown above) is one of just 10 or so in the world operating today—underscoring the need for policies to help promote increased recycling.

Battery Materials and Their Availability

Battery packs in EVs contain hundreds, even thousands, of individual lithium-ion batteries, typically referred to as cells and often similar in size to AA alkaline batteries. Cells consist of two electrodes: the anode (the negative terminal of a battery in use) and the cathode (the positive terminal). When the battery is operating (discharging), lithium ions move from the anode to the cathode through an electrolyte (often a liquid) and a plastic separator that prevents the anode and cathode from coming into contact and short circuiting the cell. Electrons flow around the separator from the anode to the cathode through the device powered by the battery.

To facilitate smooth charging and discharging, battery packs consist of multiple cells bundled into modules. Combining several modules with additional packaging and thermal management systems creates the finished battery pack used in EVs.

Of the materials used in lithium-ion battery cells, the US government deems many to be “critical” (Box 1) (DOI 2018). These elements are crucial to battery performance, yet their supply is at risk, whether due to material shortages or because supplies are concentrated or processed in a single country (Bauer et al. 2010).

Different types of lithium-ion batteries are distinguished by the metals that make up the cathode. The choice of materials affects important battery characteristics such as longevity, cost, and energy density (the amount of energy a certain size battery stores). The choice also affects other battery components, such as thermal and power management systems.

The cathode, which accounts for roughly one-quarter of the cost of a battery, combines lithium with nickel, manganese,

cobalt, aluminum, or iron. Aluminum is also used as the cathode’s current collector and in packaging for the cell and module. The anode typically consists of graphite and a copper current collector.

Early lithium-ion battery cathodes relied heavily on cobalt. Today’s batteries use less cobalt per kilowatt-hour (kWh) of energy capacity, although it is still commonly used because it contributes to a battery’s energy density and chemical stability. Both the high price of cobalt and negative impacts of mining it motivate efforts to reduce the amount of cobalt in batteries. In 2018, lithium-ion batteries averaged 28 kilograms of cobalt per 100 kWh across all battery end uses and chemistries. This amount is expected to decrease by 60 percent by 2035 (Figure 1, p. 3).

New and low-cobalt cathode chemistries can offer improved battery performance through higher energy densities. Battery cathodes using less cobalt include nickel-cobalt-aluminum oxide (“NCA”) and some nickel-manganese-cobalt oxide (“NMC”) compositions. In addition, major manufacturers of light- and heavy-duty BEVs widely use cobalt-free cathodes based on lithium iron phosphate (“LFP”).¹

Still, even with significant reductions in the amount of cobalt or other critical materials, overall consumption will rise as more EVs are produced and the capacity of each vehicle’s battery increases. More than 60 gigawatt-hours (GWh)² of lithium-ion battery capacity has been deployed in roughly 1 million BEVs in the United States since 2010. EVs sold in 2019 alone accounted for more than one-quarter of the total battery capacity deployed (16 GWh) (Ambrose et al. 2020). The significant role of BEVs in reducing emissions from the transportation sector will continue this rising demand for materials.

In the 10 years since manufacturers deployed the first modern BEVs, the capacity of battery packs in passenger

BOX 1.

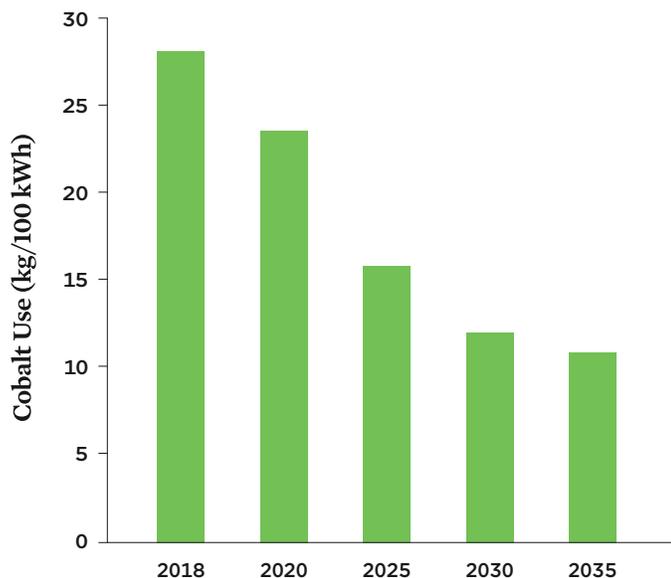
Rare, Precious, or Critical?

While often used interchangeably, the terms “rare earth metals,” “precious metals,” and “critical minerals” refer to different things. Despite their name, rare earth minerals, a group of metals on the periodic table, are not the rarest elements in Earth’s crust (Haxel, Hedrick, and Orris 2002). However, they are considered critical due to their importance in many technologies (e.g., lighting, displays) and the potential for disruptions in their supply. While rare earth minerals are used in electric vehicle motors, they are not components of lithium-ion batteries. Precious metals, such as platinum, gold, and silver, are generally the rarest elements in the earth’s crust. They, too,

are considered critical given their importance in technologies (e.g., catalytic converters in diesel and gasoline vehicles) and limited availability.

Several materials in lithium-ion batteries are critical, but they are neither rare-earth nor precious metals. These materials include lithium, nickel, manganese, cobalt, aluminum, copper, and graphite. Some are used primarily in other industries. For example, the production of stainless steel accounts for nearly 80 percent of global production of nickel. However, batteries consume more than half of the global production of lithium and cobalt (Miller and Moores 2019).

FIGURE 1. Reducing the Cobalt in Batteries



The high price of cobalt, the negative impacts of mining it, and higher-performing alternatives motivate efforts to use less of it in batteries.

Note: The amount of cobalt used per 100 kWh of battery capacity is based on actual (2018) and projected (2020–2035) global market shares of lithium-ion battery cathode chemistries and estimates of material demands for those chemistries.

SOURCES: NELSON ET AL. 2020; OLIVETTI ET AL. 2017; BENCHMARK MINERAL INTELLIGENCE 2019.

vehicles has increased while costs have decreased. Battery pack capacity in the first Nissan Leaf, released in 2010, was 24 kWh; the 2020 Tesla Model 3 has up to 75 kWh in capacity. With improved chemistries and larger energy capacities, the range of a passenger BEV has reached 400 miles on a single charge (Baldwin 2020). Meanwhile, between 2010 and 2020, the average price of battery packs decreased from \$1,200 per kWh to \$137 per kWh (Boudway 2020).

While deposits of minerals used in lithium-ion batteries are distributed widely around the world, a few countries account for most of the known “reserves”—deposits that are technically, economically, and legally feasible to extract (Figure 2, p. 4). In 2019, the global production of cobalt, nickel, and manganese each exceeded 2 percent of today’s total reserves (e.g., a 50-year supply for current reserves and demand) and of lithium and graphite, less than 1 percent. As demand has grown, so have reserves with improved extraction methods and the discovery of new mineral deposits. Reserves that are more difficult to extract, however, could exacerbate the negative impacts of mining.

Extractive industries have earned a reputation for frequently violating human rights and degrading the environment. Cobalt mining in the Democratic Republic of Congo, a country with 70 percent of the world’s existing cobalt production and more than 50 percent of cobalt reserves, has well-documented negative impacts on the environment, community health, and human rights (NMIS, n.d.a; Amnesty International 2016). Public attention to issues surrounding cobalt mining has led to commitments by several automakers and battery suppliers to improve conditions through supply chain sourcing, although much more needs to be done (WEF 2020).

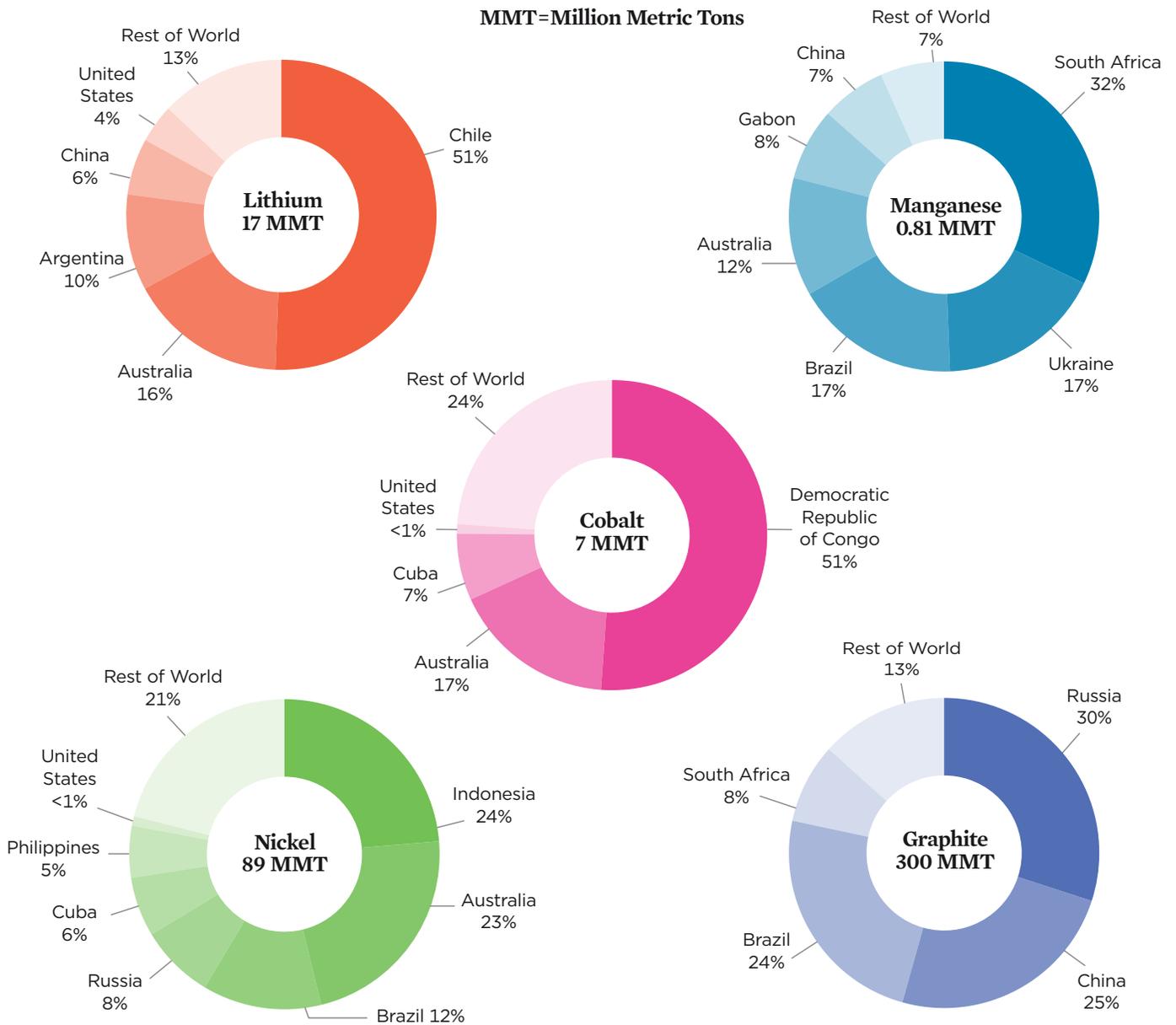
Demand for Battery Materials and the Role of Recycling

The electrification of cars and trucks will need to accelerate to avoid the most severe impacts of global warming. By one estimate, the number of passenger BEVs on US roads could increase from roughly 1 million today to 43 million by 2035 and globally from 5 million to 245 million (BNEF 2019).³ Such growth will significantly increase demand for the minerals used in batteries. Accounting for projected changes in battery chemistry, global production of lithium, nickel, manganese, cobalt, and graphite for lithium-ion batteries across all end uses could increase five- to seventeen-fold over the next 20 years, depending on the material (Figure 3, p. 5). This could strain the availability of these materials at today’s levels of economically recoverable resources and manufacturing capacity.

While producing many more BEVs will require new raw materials in the near term, recycled materials from used batteries could meet a significant portion of new demand in the future. Widespread battery recycling can create a more stable domestic source of materials for battery production, reduce the demand for raw materials, and minimize the risks of geopolitical disruptions of the supply chain. Assuming 95 percent collection and recovery of the relevant metals as an upper bound, as well as a shift toward low-cobalt and no-cobalt chemistries, the United States could meet about 30 to 40 percent of the anticipated material demand for lithium, nickel, manganese, cobalt, and graphite in passenger BEVs with recycled battery materials by 2035 (Figure 4, p. 6).⁴

Recycled materials from used batteries could meet a significant portion of new EV battery demand.

FIGURE 2. Reserves of Materials Used in Lithium-Ion Batteries, by Country



Reserves of minerals currently used in lithium-ion batteries are distributed around the world, but individual minerals are concentrated in a few countries.

SOURCE: NMIS, N.D.B.

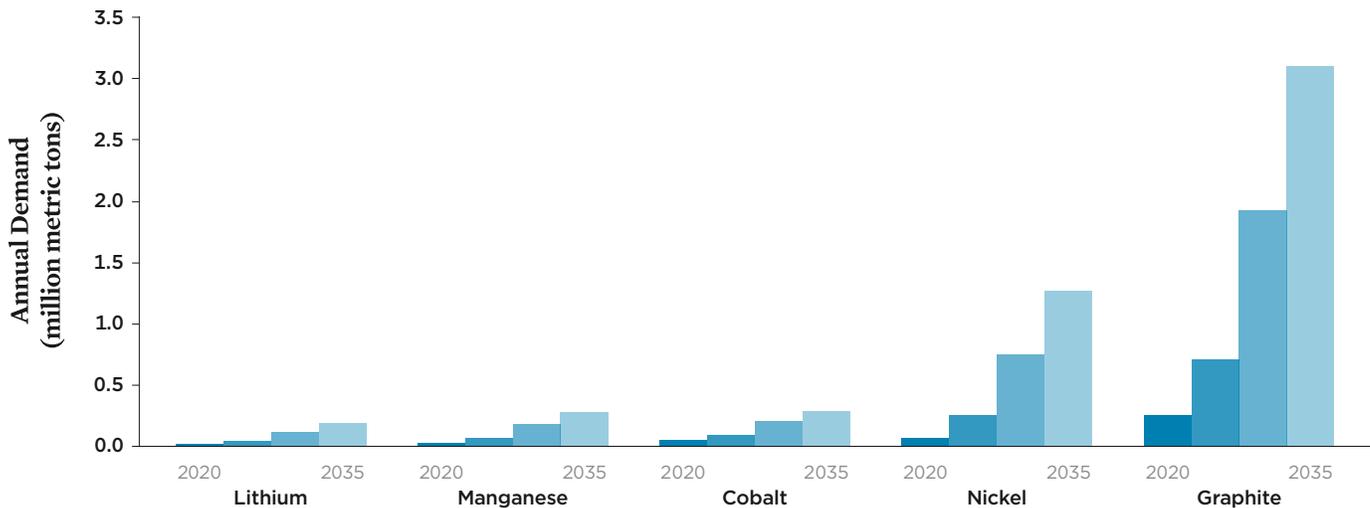
The Role of Batteries in Electric Vehicle Emissions

For conventional vehicles, their operation represents their largest contribution to global warming emissions. Roughly 90 percent of global warming emissions from combustion

vehicles occur at the tailpipe. In contrast, all global warming emissions associated with BEVs occur “upstream.” That is, they come from manufacturing vehicles and generating electricity to power them.

Work by the Union of Concerned Scientists and others has found that, based on today’s average sources of electricity

FIGURE 3. Projected Annual Global Demand for Battery Materials



Meeting the expected demand for lithium-ion batteries across all sectors will significantly increase demand for minerals.

Notes: Global demand for lithium-ion batteries reflect projected changes in the market share of different battery chemistries. Material demand is based on an estimate that passenger EVs comprise 55 percent of total battery demand in 2020 (2.2 million annual EV sales), increasing to 72 percent in 2035 (35 million annual EV sales). A 50 kWh capacity is used for EVs along with a 3 percent annual increase in battery gravimetric energy density (beginning with 150 watt-hours per kilogram in 2020). Estimates of global demand include an upstream materials efficiency of 90 percent to account for loss of material during refining and processing steps.

SOURCES: NELSON ET AL. 2020; OLIVETTI ET AL. 2017; BENCHMARK MINERAL INTELLIGENCE 2019; BNEF 2019.

in the United States, the total global warming emissions associated with BEVs are about 55 percent lower than those of gasoline vehicles. In parts of the country with higher levels of renewable energy—California, for example—BEVs reduce emissions by more than 70 percent. And the emissions associated with BEVs will continue to decline as the nation derives more of its electricity from renewable resources (Reichmuth 2020; Ambrose et al. 2020; Needell et al. 2016).

Upstream emissions from extracting and refining fuels and raw materials are also important considerations. For example, producing and processing crude oil into gasoline contributes an average of 24 percent of the fuel’s overall life cycle global warming emissions in the United States, depending on the source of the oil (Gordon et al. 2015; Cooney et al. 2017).

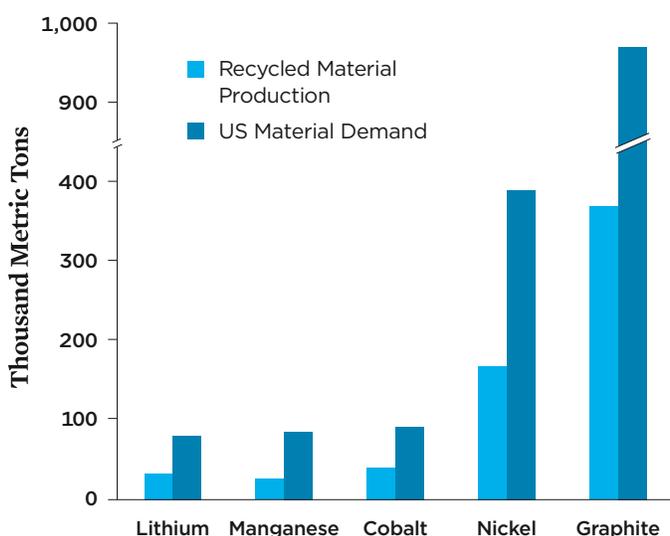
For BEVs, battery and vehicle manufacturing can contribute 14 percent to 24 percent of a BEV’s life cycle global warming emissions depending on where and how batteries are manufactured, as well as on the sources of raw materials (Ambrose et al. 2020). Overall, manufacturing a BEV contributes about 70 grams of carbon dioxide–equivalent emissions per mile (g CO₂e/mile) compared with 40 grams for a comparably sized gasoline vehicle. But because a BEV’s operating-related emissions (i.e., vehicle charging) are relatively low,

the total global warming emissions for BEVs on the average grid in the United States are less than half those for gasoline vehicles (200 g CO₂e/mile vs. 450 g CO₂e/mile).

Increasing the efficiency of battery manufacturing while also increasing the share of renewable energy used in assembling battery cells could reduce the global warming emissions associated with battery manufacturing by more than 40 percent (Figure 5, p. 7). Because recycling batteries reduces the need for extracting, refining, and transporting new minerals, it reduces not only emissions but also other impacts associated with these processes. Increasing the amount of renewable energy used to charge an electric vehicle, however, results in the most significant reductions in global warming emissions over the life cycle of an EV.

Recycling batteries reduces the need for extracting, refining, and transporting new minerals.

FIGURE 4. Meeting US Passenger EV Battery Demand with Recycled Materials, 2035



A significant portion of demand for battery materials could be met by recycling, transitioning to low-cobalt cathode formulations, and high levels of material recovery.

Note: Material supply and demand is based on the weighted average of US passenger EV sales and cathode market shares. The analysis is based on an on-road passenger BEV population of roughly 1 million today, increasing to 43 million in 2035, and assumes 95 percent of metals from retired batteries are recovered.

SOURCE: BNEF 2019; DUNN ET AL., FORTHCOMING.

Reusing and Recycling Batteries

When an electric vehicle comes off the road, whether due to its age or an accident, its battery must be processed in some way. Potential end-of-life pathways include reusing the battery in other applications (“second life”), recycling the battery’s materials, and disposal. Even if a battery is reused, eventually its materials need to be recycled or disposed of. Most interest in battery recycling focuses on the cathode, which contains the highest-value materials (Box 2, p. 8). Understanding the opportunities for and barriers to recycling is critical to reducing the amount of mining needed for battery materials.

When an EV battery pack reaches the end of its useful life in a vehicle, it is still likely to retain more than two-thirds of its initial energy storage capacity—for example, the range of a BEV decreasing from 300 to 200 miles (Hossain et al. 2019). In some cases, such batteries could be refurbished for use in another vehicle or in a lower-power, stationary application. For example, a market could emerge for using second-life batteries for low-cost energy storage for utilities and electricity

consumers (Mobility House 2018; Mobility House 2016). With the growing use of BEVs, the economic potential for reusing their batteries could further decrease the cost of new EVs and increase the value of used EVs.

Globally, fewer than a dozen facilities recycle EV batteries today, with a combined material processing capacity of less than 100,000 metric tons annually. For 50 kWh batteries with a gravimetric energy density of 150 watt-hours per kilogram, this recycling capacity corresponds to 300,000 EV batteries per year, or roughly 10 percent of global annual EV sales today, but 1 percent of expected annual sales in the early 2030s (BNEF 2019). In the United States, such facilities are especially limited in both number and processing capacity. One key to enabling greater recycling capacity in the United States will be increasing the domestic manufacturing of batteries.

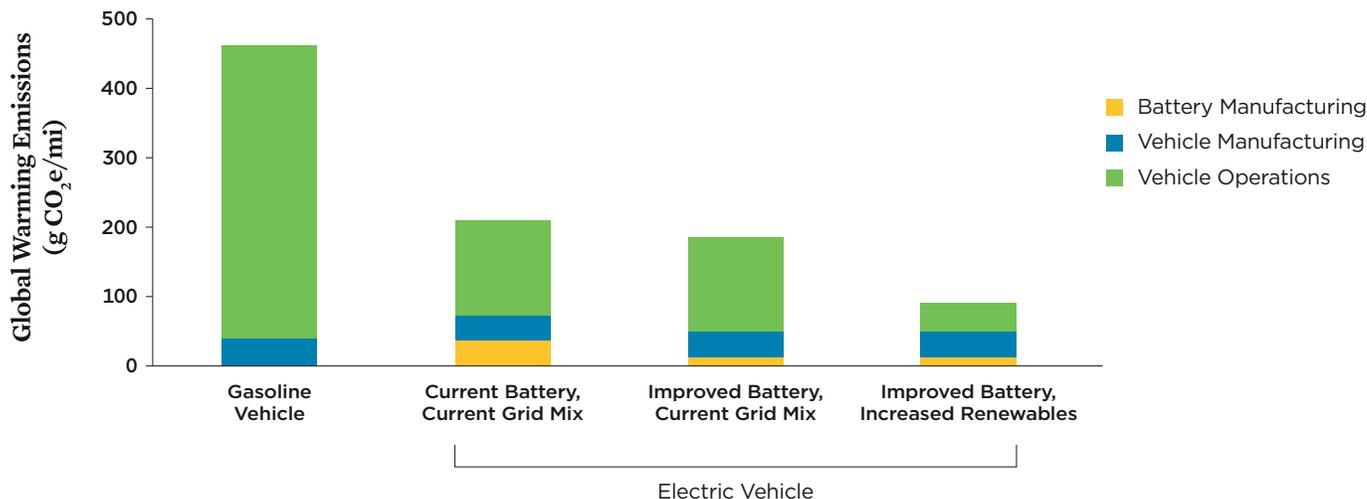
Public Policy for Responsible Battery Management

Public policy will play an important role in enabling the widespread reuse of EV batteries and promoting the recycling of their constituent materials. Currently, national and regional policies for waste management and recycling do not consider the impact of large flows of EV batteries primarily because the BEV market did not exist when such policies went into place.

Lessons learned from recycling policies targeting consumer electronics and other automotive components can inform material handling and recycling policies for EV batteries. In addition, the United States can draw on the experience of other countries with major BEV markets, some of which are beginning to consider policies to address these issues. For example, China recently enacted extensive policy and guidelines for recycling EV batteries and promoting second-life uses (MIIT 2018). The policy directs manufacturers to design batteries that enable easier recycling and to provide technical information on proper storage and management. China also places responsibility for recycling on the vehicle manufacturer, a mechanism known as “extended producer responsibility.” The European Commission recently proposed extensive measures that would require collection of used batteries and set standards for recycled content in new batteries (EC 2020).

On a global level, the World Economic Forum has organized corporations, governments, and public interest groups around the world with the aim of solving key data transparency challenges related to EV batteries (WEF, n.d.). This consortium is developing standards for labeling batteries and sharing data, with the goal of providing access to critical information about battery chemistry and condition. Such information, mostly unavailable today, is critical for second-life and recycling

FIGURE 5. Mine-to-Wheel Life Cycle Global Warming Emissions of Different Passenger Vehicle Types



The total global warming emissions of EVs are far below those of vehicles powered by internal combustion engines. With increased use of renewable energy for battery manufacturing and vehicle charging, the benefits of EVs will become even more dramatic.

Notes: All scenarios assume average US vehicle lifetime mileage (155,000 miles), fuel economy (28 mpg), and electrical grid. They also assume a BEV with a 250-mile all-electric range, 60 kWh battery pack, and today’s EV life cycle battery emissions of 85 kg CO₂e/kWh. The “improved battery” scenario assumes reductions in cathode cobalt content, changes in the sourcing of battery materials (e.g., nickel), using 100 percent renewable energy for battery assembly processes, and 100 percent “direct recycling” of cathode materials. The “increased renewables” scenario assumes electricity sourced primarily from renewables (73 percent), a reasonable and achievable target based on the estimated makeup of California’s sources of electricity in 2030.

SOURCES: AMBROSE ET AL. 2020; CIEZ AND WHITACRE 2019; DAI ET AL. 2019; EIA 2019.

applications and would enable the tracing of batteries’ properties (e.g., chemical make-up, capacity, cycle/charging history) through the chain of ownership.

As the transition to a low-carbon, electric transportation system continues, battery recycling and reuse will become an increasingly important strategy for mitigating the potential adverse impacts of producing raw materials, disposing of waste, and securing more reliable, less damaging sources of battery materials. Such a strategy should aim at securing several essential outcomes:

- Ensuring a resilient supply of future battery materials and avoiding the need for additional development of new raw material resources;
- Planning the infrastructure needed to recycle and repurpose batteries;
- Sharing information to ensure that owners, reusers, and recyclers can access important information about battery systems;
- Encouraging battery reuse and responsible logistics to maximize the useful life of batteries and ensure the safe handling of used batteries; and
- Providing incentives and establishing requirements for sustainable practices “from mine to wheel.”

Several state, national, and global policy actions would provide the necessary framework to achieve greater reuse and recycling of battery materials:

- Set content targets for incorporating recycled materials into new battery cells as a strategy for closing the loop on the EV battery life cycle and increasing recycling.
- Set guidelines for facility permitting and land use to enable the safe transportation, storage, and recycling of used batteries.
- Set standards to label batteries with their cell chemistry and provide access to battery cycle and history data.
- Develop a waste designation for EV batteries that enables collection, responsible third-party reuse, and recycling for material recovery.
- Adopt and enforce international environmental and labor standards for mining and material processing and utilize independent third-party auditors to oversee mandatory compliance for battery suppliers.

With the growth of the BEV market, it is time for federal and state governments and international bodies to set requirements for the collection of used batteries, revise policies governing the classification and transport of used batteries, and set standards to ensure that batteries are recycled using

BOX 2.

The Stages of Battery Recycling

Battery recycling has three general stages:

- Pretreatment primarily consists of mechanically shredding and sorting plastic and metal materials.
- Secondary treatment involves separating the highest-value materials in the cathode from the aluminum collector foil with a chemical solvent.
- The final step is separating the cathode materials through leaching chemicals (“hydrometallurgy”), electrolytic reactions, and/or heat treatment (“pyrometallurgy” or “smelting”).

safe and responsible methods. As the number of BEVs increases, so too will opportunities to make batteries from recycled materials. Realizing this future demands action today as we move forward on reducing transportation pollution and solving the climate crisis.

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ENDNOTES

- 1 NCA batteries have 0.12 kg cobalt per kWh. Depending on the ratio of nickel to cobalt, NMC batteries have 0.08 kg to 0.25 kg cobalt per kWh (Nelson et al. 2020).
- 2 One GWh (one million kilowatt-hours) is equivalent to the annual electricity demand of approximately 90 single-family homes (EIA, n.d.).
- 3 Estimate includes only full battery electric vehicles.
- 4 Recycling rates for lead-acid batteries have exceeded 97 percent in the United States since the 1990s (Turner 2015). However, lead-acid battery recycling at an Exide facility in Southern California has resulted in the contamination of 7,500 homes (Barboza and Poston 2018).

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